Whittemore’s Science and Practice of Pig Production

THIRD EDITION

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Preface and Acknowledgements

The first edition of *The Science and Practice of Pig Production* was by far the most extensive book that I had written. It was the result of a challenge that I should prepare a book of adequate scale and breadth to deal comprehensively with the whole international spectrum of the science and practice of pig production. The temptation to gather a consortium of authors and edit a multi-author title was resisted. I wanted this book to have cohesion and purpose, and to demonstrate an integrated philosophy. I wished to take the reader through the subject, examining the knowledge offered from a perspective that, although multi-dimensional, nevertheless sprang from a coherent and individual source. This could only be done by single authorship.

The second edition of the book had substantive additions, a good number of alterations and a few deletions. The opportunity to update had been timely, as much has happened in pig production and science since the first edition was written, but perhaps especially in biotechnology, meat and carcass quality, the understanding of growth, animal welfare, genetic improvement, disease and health, and some aspects of feeding and nutrition. Interestingly, the same subjects tend to figure in the major updates of this third edition.

For the third edition I decided that I could no longer support the contention that a single author could cover the scope of this book, and so a panel of international authorities was invited to join me in revising the text. In order to maintain the cohesion of a single text, and keep faith with the original principles of the book, I decided that the book should have a senior editor (Ilias Kyriazakis). The recognition given to all those who have contributed to the third edition is detailed on the Contributors page. I would like to acknowledge here the support and efforts of Professor Kyriazakis and the new contributors.

Although it remains the case that much of the work in the body of this book was completed over more than 30 years of research at Edinburgh, the new text now contains substantial bodies of information from other international centres, and this is recognised by the new panel of authors. One author cannot possibly have complete knowledge in breadth and in depth. For all of us, this dilemma can only be solved through learning from others and benefiting from their counsel, and this we have all done over many years of production and industry practice, university learning, scientific research and consultancy. We are pleased to be able to acknowledge formally the great debt we owe to all those from whom we have accumulated information, knowledge and wisdom.
The precious resource of input from the named authors, and all those around them, has nonetheless been subject to interpretation and to filtration. Such is the consequence of editing a large book. The editors, therefore, but especially myself, must bear responsibility for the final content.

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Chapter 1

Introduction

The prime agricultural purpose of the pig is to provide human food (fresh, cured or processed), so pig production is necessarily preoccupied with the quality of the pig meat and the efficiency of its production. The pig grows rapidly, reproduces at a high rate and is accommodating in its eating habits. Historically, the pig was often seen as a scavenger; a rural scavenger in fields and woodlands, and an urban one using human food by-products and waste. These roles have ensured that the pig has been used as a domesticated agricultural animal widely throughout the world, but usually in small population sizes such as would facilitate by-product utilisation and encourage simple husbandry practices.

Recent history has seen the demand for high-quality pig meat products rise world-wide due to the increasing world population and improving human nutritional aspirations. This has raised the profile of the growth and reproductive characteristics of the pig. Simultaneously, improvements in other branches of agricultural practice have made available substantial quantities of cereal, legume and oilseed grains not appropriate – or not needed – for human consumption. The industrialisation of human food preparation has added to the changing environment by moving the availability of food by-products and waste away from the local and diversified domestic level and toward centralised manufacturing points. There has been a change in the nature and objectives of pig production over recent decades. Especially there has been created a large-scale integrated agricultural industry, producing substantial quantities of high-quality meat products which may be readily traded within and across international boundaries. The agricultural and biological sciences have been well set to serve pig production over its recent evolution, and the result has been a staggering example of the successful application of science to industry to the benefit of humankind. The modern pig industry bears little or no resemblance to that of only a few decades ago; either in its structure or in its method of trading, or in its definitions of quality in the end-product, or in its breeding, feeding, housing, health and management.

The major changes are often perceived in terms of sophistication and scale; and associated with the latter, intensification. Coping with these changes has demanded of science – and science has provided – new husbandry practices, new understandings of growth, reproduction and health, new appreciations of welfare and the environment, new nutritional approaches, and modern genetic improvement techniques. However, above all has been the essential placing of the application of science in
the context of latter-day production and marketing. Biological response is interpreted in terms of not only physical outcomes but also financial consequences.

Numerous small herds (<100) of breeding sows abounded as recently as two decades ago, but the major activities of pig meat production have now come to lie with the big integrators, often backed by corporate money, and where breeding, production, marketing, processing and consumer sales are closely coordinated. It is difficult to achieve efficiency of modern intensive pig production with unit sizes of less than 250 breeding sows, while 500+ would be unexceptional. Some of the larger operations will have a number of standard-built units spread about a locality, and managed from a central company headquarters (as, for example, in the US Carolinas). North America, originally the home of the family-sized hog farm, now leads the big operators, with many companies having more than 10000 breeding sows and a significant number more than 100000. This pattern is followed now in Spain (where two companies each have around 100000 sows and each grow for slaughter 2 million or so meat pigs annually), Italy and Asia; while in the other European countries many pig producers remain individual owner-managers, albeit with units of 200–5000 sows.

While trends in pig production have had some degree of commonality worldwide, there remains diversity in international production practice and end-product objectives. Thus, although a high proportion of the sciences cognate to pig production are transferable across national barriers, the way the scientific information is used may need to vary widely. The most useful aspects of the scientific information base are those that address basic causes of biological and economic response, and not those that lay out the responses themselves in the form of rules and recommendations.

Throughout, the book argues causality and logic before presenting outcomes, and tries to avoid the bald presentation of the results of this or that production investigation as if the latter were to embody some form of universal truth; which of course it would not. It is fundamental to an international text that along with the description of phenomena must go their understanding. Universality lies in the depth of the understanding of biological and economic processes, not necessarily in the accuracy of their description. Nevertheless, pig production is a quantitative as well as a qualitative activity. Meat of given quantity and definable characteristic requires to be produced from feedstuffs of quantifiable nutritional value when given to specific pig genotypes in describable environmental, managemental and economic circumstances. Where possible, therefore, factors impinging upon the production process are expressed in hard and quantifiable terms. After all, it is only through quantification that the absolute and relative importances of the various aspects of the sciences and practice of pig production can be compared, judged and ultimately used.

The world’s pig industry is a success story founded in the application of science to management. The extent of the success thus far is well illustrated in Figures 1.1 and 1.2. However, there is no reason for complacency, and a great deal more can be done to improve the level of efficiency of output and the quality of the end-product.
Most pig production enterprises world-wide are under-achieving, and there is a considerable disparity in production efficiency between different nations. Compared to the presently known potential, the world’s pig industry falls far short. Application of scientific principles and sound production practices can redress that short-fall.

**Fig. 1.1** Rate of increase in sow productivity (northern European data).

**Fig. 1.2** Rate of improvement in feed usage per kilogram live weight gain. The 1970s saw the introduction of high nutrient density diets in significant quantities (northern European data).
Chapter 2

Pig Meat and Carcass Quality

Introduction

World pigmeat production has risen linearly in the latter half of the twentieth century, with some authorities estimating a doubling in output over this time. At present, 50% of pig production is from Asia and the Pacific (one-third of the world’s pigs are in China), 30% from Europe and the former USSR, 13% from North America and the remaining 5% from Africa and South America. The world’s expansion has taken place almost entirely in Asia and the Pacific (over 300%), expansions in Europe, the former USSR and North America being only around 40% since 1970. The popularity of pig meat differs widely throughout the world. Of all the meat eaten in Scandinavia 60% is pig meat, in the European Community 50%, in Japan 45% and in North America 35%, but in Argentina only 5% of all meat eaten is pig meat. World-wide, pig meat is the most popular of all available meats.

It may be taken for granted that pig meat product must first be needed (i.e. there must be a market), and next be safe to eat. It must also be efficiently produced (competitively priced) and at the required level of quality. However, increasingly meat production must satisfy further criteria in relation to production method and production environment, which must be both sustainable and ethical.

Within recent history, the pig has been bred for both supreme fatness (the required commodity being lard) and supreme leanness (the required commodity being muscle). Whether the acceptable pig carcass be fat or lean depends much upon national predilection. As industrialisation develops, the desire for lean meat appears to dominate the definition of carcass quality. Eastern European, Japanese and North and South American tastes are, like Western Europe, demanding progressively lower levels of meat fat content. Asian pigs, numerous in China and the Pacific countries, are overfat by Western standards, and it is likely that some desire to reduce fatness will take place there as well. Nevertheless, one nation’s lean pig remains another nation’s fat pig.

In Europe, the pig meat market used to be for mass product at low price. Indeed, general advancement of knowledge in pig production has resulted in the real cost of pig meat now being a mere 30% of what it was 40 years ago. There are now 12 000 000 sows in the European Union and 120 000 000 pigs in total. The average European consumption of pig meat per head per year is more than 40 kg. There is substantial cross-border trade in pig products, a trend that will increase if the present export ambitions of some countries (including the USA) come to be realised. In the
UK there are 800,000 sows and 8,000,000 pigs in total. Fifteen million pigs are slaughtered annually, producing some 1,000,000 tonnes of pork, bacon and ham product. Half of the bacon eaten in UK is imported, and about half of that comes from Denmark, with a quarter from the Netherlands and a further quarter from the Irish Republic. The UK exports about the same amount of pork as it imports (100,000 tonnes), but the importation of bacon and ham is some 350,000 tonnes, and there is no effective export trade. The UK public consumes 15 kg per head per year of fresh pork and 7 kg per year of bacon and ham. There is also further consumption of pork through prepared pig meat products. Italy imports substantial quantities of meat products from pigs slaughtered at live weights of below 120 kg but exports substantial quantities of meat products from pigs slaughtered at live weights above 150 kg. Japan has been traditionally supplied from Taiwan, but Denmark and the USA have recently expanded their export business to Japan.

Fat reduction, now readily achievable to its optimum level, was initiated originally not by consumer discrimination against fat but by the economics of pig production and pig processing, both of which benefit from a lean carcass. Pig markets still tend to divide into two types: one uses pig meat as a substrate for a huge variety of manufactured meat products and satisfies a continuing need for low-cost meat; the other, of increasing importance, attends to the consumer supply of pork and bacon meat of high eating quality. This latter market needs carefully prepared cuts, a low level of subcutaneous fat, an adequate level of intramuscular fat and a large mass of lean tissue, giving a high perception of eating pleasure – meat that is juicy, tender and tasty, avoiding all suggestion of dryness, paleness, taint or toughness. It should not be presumed, however, that a demand for lean pig meat is universal. Indeed, the production of lean genotypes for the northern European pig meat consumer can be the cause of a need for remedial action in southern Europe and in Asia, where a much higher level of fat is required – at least for the present.

Producers may be reluctant to accept the restraints imposed on them by a meat trade concerned primarily with product quality. Conversely, the trade may be slow to allow producers to profit from the benefits of new techniques and streamlined production practices. Such problems will remain with an industry which in many countries continues to be based upon adversarial trading and mistrust at each interface of the production chain. The successful future of pig industries the world over is likely to require the benefits of integration between breeder, producer, feed compounder, meat packer and retailer. The producer needs effective lines of communication with the market. If that communication generates information that is useful, both producer and meat trader will profit.

Marketing

Europe is an example of an industrialised economy with primary agriculture contributing 2–5% of Gross Domestic Product (GDP) and employing 3–8% of the work force. The livestock sector comprises some 50–60% of total farm income. Food and
drink manufacture represents a surprisingly large 10–15% of the manufacturing sector, contributes at least 2% of GDP and employs around 3% of the work force. Twelve percent of overall consumer expenditure is on food, being some 20% of household expenditure. Of the total food expenditure, some 40% comprises meat, dairy products and eggs, of which some one-fifth of the cost can be traced back to the primary product, four-fifths being added value in the manufacturing, processing and retail sectors. Half of the meat purchased by consumers is derived from pigs, and the trend continues to favour pig meat consumption over other meats.

Live pigs are marketed at any time subsequent to weaning (which can be between 6 and 20kg and at 3–8 weeks of age). Pig meat can come from suckling pig at one extreme, and from 180kg animals destined for the production of large Italian Parma hams at the other. National consumption patterns cause pigs to be finished and consumed at a wide variety of weights between these extremes. As the mature size of many Asian pig types is so much less than European types, slaughter weights are usually less. In many European countries 50–80kg live weight is the traditional butcher range for the production of small, fresh pork joints bought and consumed locally, while in Japan, Australia, North and South America and all the countries of Europe 90–120kg live weight is the traditional range for industrial processing at meat packing plants which distribute fresh pork joints, cured bacon products and delicatessen lines. Animals used for the production of hams which are dry-cured by slow and natural processes (such as prosciutto in Italy and Serrano in Spain) are usually finished to substantially greater live weights. Cull sows weighing 120–300kg may command a useful price according to the state of the market. Meat from cull sows can be satisfactorily incorporated into a range of products, and it can be cost-effective to sell culled animals in good body condition when the price is satisfactory. Adult male pigs that have been used for breeding are inappropriate for human consumption, the meat being coarse and often tainted. This criticism does not apply to fast-grown entire males of European breed types slaughtered at less than 110kg.

Prime meat is usually found at around 30–60% of mature size (Figure 2.1). At less than 30% there is a tendency toward lack of flavour, whilst at greater than 60% there is a tendency toward lack of tenderness. Pig types of larger mature size merit a higher slaughter weight, and it is noticeable that conventional slaughter weights in the European pig industry have been increasing over recent years. Most pigs used for processing and meat packing in industrialised countries have a mature weight
of between 250 and 350 kg, while in Asian types mature weight can be as low as 150 kg.

The primary pig production industry may segregate into specialised farm types; often breeders or feeders. Specialised breeding units will move weaned or grower pigs at weights of 7–10 kg (weaners) or 20–40 kg (growers) to grow-out units, which will feed the weaners to the next stage or, in the case of growers, to finished weight. Such systems allow concentration of resources, skills and preferences. Frequently, breeder units are small, being part of mixed family farming enterprises. Grow-out units, on the other hand, tend to be larger and more industrialised, and may buy from many sources of supply. Such specialisation may lead to more problems than solutions, unless the ill-effects of transport and trading in young animals are avoided, variability in type of pig supplied is minimised and disease incursion eschewed. Modern enterprises are best structured either (1) as breeder/finisher operations where a single unit both breeds and grows the pigs to final specification or (2) as a multi-site operation under single management control integrated at each step. Single-step operations also allow a more effective relationship between ultimate customer and primary producer; thus meat quality aspects as perceived by the meat packer and retailer may be effectively relayed back to the breeder. Choice of pig type or hybrid by the breeder is of vital interest to grower, packer and retailer. Any discontinuity of production flow, such as an industry based on separate businesses dealing with the breeding and feeding aspects of the production process, can only serve to obscure an optimum policy and hold back the development of the industry.

Within any one nation, or group of inter-trading nations, the pig industry has potential for expansion or contraction. The extent of this potential is directly linked to the number of producers who have alternative sources of income available to them. When pig prices are good the size of the breeding herd is expanded and new herds are begun. This may be achieved readily by retaining for breeding purposes female stock originally destined for slaughter, or by the purchase of extra hybrid breeding stock replacements. These animals will produce young some 6 months later, and a further 6 months downstream additional slaughter pigs become available for sale. At this point supply is enhanced and prices will ease back. The elasticity of demand for pig products is such that although customers will purchase more pig meat as prices fall and it becomes cheaper, the ability to eat more does not keep pace with the falling price. Pig prices will continue to fall for approximately a further year or so, at which point breeding herds will begin to be reduced in both size and number. This process may take another year before a shortage of available slaughter pigs becomes evident and prices begin to strengthen again. This simplistic pig cycle (Figure 2.2) is obfuscated by fresh meat butchers equalising prices of various meats, and also by fluctuations in the world supply of pig feed ingredients. Grain and soya prices are relatively independent of pig price because grains are used for purposes other than the feeding of pigs. When pig feed ingredient prices are low, producers can tolerate a reduced pig carcass price for a longer time before needing to retract. A combination of favourable international grain prices and
favourable pig carcass prices will produce a profit bonanza and an accelerated rate of expansion.

The ebb and flow of the pig cycle as a result of pig and grain prices is more apparent in countries where capital expenditures do not figure largely. For an industrial-based intensive pig industry with high capital investment in its buildings, the availability of money at satisfactory interest rates acts as a regulator on the entrepreneur’s ability to either expand when times are good or contract when they are not.

Consumption patterns

The estimated world consumption of animal products (millions of tonnes) is as follows: milk 400 (steady), pig 63 (rising), beef and veal 48 (steady), poultry 33 (rising), eggs 20 (steady), farmed fish 8 (rising), sheep and goat 6 (steady). Pig meat accounts for more than 40% of the world’s meat consumption and is produced from about 850 million pigs (about 60 million breeding sows). The European Community has about 120 million pigs from which come 14 million tonnes of pig meat. This gives the European Community more than 20% of world pig meat production. Within the Community more than 30% of pig meat production comes from Germany, about 12.5% from each of France, the Netherlands, Italy and Spain, while the UK and Denmark produce around 10% each. About 25% of pig meat consumed in the European Community is eaten fresh, the rest being cured or processed into products with a greater or lesser degree of added value.

Notwithstanding some fat being necessary in meat to allow optimum meat quality (particularly with regard to succulence, taste, texture and cookability), the report of the UK Committee on Medical Aspects of Food Policy relating to diet and cardiovascular disease makes specific mention of the need for a reduction in the level of fats in the human diet. The incidence of heart disease is commonly thought to be reduced by increasing the ratio of polyunsaturated fatty acids to saturated

Fig. 2.2  The cyclical nature of pig prices. These are further subject to influence from the price of competitive meats, prevailing feed price and the availability of capital.
fatty acids in the diet. It would appear that saturated fatty acids with less than 18 carbon atoms in the chain are the most likely to increase the risk of coronary heart disease. Some 40% of the total energy in the diets of many people in the industrialised world comes from fat of vegetable or animal origin. The proportion of total dietary energy from fats has been rising inexorably over recent years; and it is perhaps this simple statistic that is the more relevant. Meanwhile, there has been a simultaneous dramatic reduction of fat in pig meat, down from about 30% of the total carcass in the 1960s to about 15% or less in an 80 kg carcass of today. Subcutaneous backfat measurements have been reduced by genetics, nutrition and feeding management by about 0.5 mm annually. Pig subcutaneous fatty tissue contains about 70% lipid, and two thirds or more of all fat on a pig carcass may be found in the subcutaneous depots. For top grade bacon and pig meat products, backfat depth targets at the P2 site for pigs of 90 kg live weight can be as low as 10 mm. Given the potential of pig meat to be extremely lean, it may be assumed that on health grounds alone the consumption of pig meat and pig products will continue to further increase.

Medical wisdom advises that fat consumption should fall to around 30% of total diet energy, and that the polyunsaturated fatty acid:saturated fatty acid ratio in dietary fat should be around 1.0. Presently in many countries of the Western world the ratio is about 0.3. The Committee on Medical Aspects of Food Policy has suggested 0.45 as an achievable target. As about half of all diet fat comes from animal products (including milk, milk products, eggs and meat), and as some meat fats have a poor polyunsaturated:saturated fatty acid ratio, there may be consumer benefit in the identification of meat and meat products low in fat, but what fat there is being high in polyunsaturated fatty acids, as is the case for pig meat. The ratio of polyunsaturated:saturated fatty acids in pig meat is a good 0.7.

The polyunsaturated fatty acids in the meat are of two distinct types: the \( n-6 \) (omega-6) fatty acids including linoleic acid (18:2) which reaches the highest concentration of all the polyunsaturated fatty acids and the \( n-3 \) (omega-3) fatty acids of which \( \alpha \)-linolenic acid (18:3) has the highest concentration. (The nomenclature \( n-6 \) or \( n-3 \) refers to the location of the double bonds in the chain. In ‘18:2’, etc. the number before the colon refers to the number of carbon atoms in the chain and the number after the colon refers to the number of double bonds. The more double bonds, the more unsaturated the fat.) 18:2 and 18:3 are precursors of the ‘long chain polyunsaturated fatty acids’ of the \( n-6 \) and \( n-3 \) series respectively. These are metabolically important compounds, being constituents of cell membranes and substrates for the formation of eicosanoids which are regulatory molecules. A ratio of \( n-6:n-3 \) polyunsaturated fatty acids in the diet of less than 4.0 is recommended and most Western diets are much higher than this. The value in pig meat is around 7.0, too high. This is due to a high level of 18:2 which is the major fatty acid in the grains and oilseeds used for producing pig diets. Pigs are very efficient at transferring dietary fatty acids into muscle and fat tissue. The high polyunsaturated:saturated fatty acid ratio in pig meat is due to this efficient transfer of 18:2, but on the other hand this upsets the \( n-6:n-3 \) ratio. Research at Bristol University has shown that the
balance can be corrected using whole linseed or linseed oil. This plant is unusual in having a high 18:3 content. Likewise, the valuable long-chain n-3 polyunsaturated fatty acids can be increased in meat by feeding fish oils to the pig. This can produce higher levels than those formed naturally from 18:3 in a series of enzymatic steps.

Muscle from lean pigs is very low in fat, around 3–5% in muscle defatted on the plate and around 1% in muscles from which all carcass fat is removed. This is the true intramuscular lipid or marbling fat. Muscles differ in marbling fat levels, with the loin muscle (longissimus dorsi) being relatively high in fat compared with other muscles in the carcass. The fat tissue in lean pigs is also high in 18:2. This is because dietary fat forms a high proportion of body fat in lean pigs, compared with the pig’s own synthesis of saturated and monounsaturated (one double bond) fatty acids. In conclusion, modern pig meat is low in fat and high in polyunsaturated fat and therefore makes an important contribution to a healthy diet. We also have the means to raise n-3 fatty acids in pig meat.

People in most advanced European countries eat about 70–90 kg of total meat per person per year; this is about 30% less than in the USA. In the UK much less pig meat is eaten, in both absolute and proportional terms, than in Denmark, Germany or the Netherlands (Table 2.1). In the UK the consumption of imported cured pig meat and pig meat products accounts for 30–40% of total consumption and comes from a variety of sources, including Denmark, the Netherlands, Poland and Germany.

The annual average meat consumption per person per year in the European Community is 5 kg of sheep meat (falling), 25 kg of beef meat (steady), 15 kg of poultry (rising) and 40 kg of pork and bacon (rising). The European Community is 100% self-sufficient for pig meat overall. The total tonnage of production from the European Community is 14 million tones, the major contributors being Germany, the Netherlands, France and Spain. The European Community has around 12 million sows from which this production comes.

In terms of value for money, pig meat is a better buy than beef or lamb, and rivals chicken and turkey. Pig meat is highly versatile, being used for fresh meat joints, cured joints, bacon, cooked meats (fresh and cured), processed products, pâté, barbecue ribs and many specialised lines of sausages, delicatessen items and so on.

The efficiency of transfer of animal feed into pig meat is high (Figure 2.3) and continues to improve with new production technology. Increasing the range of pork and bacon products available to consumers (Figure 2.4) is probably the most appropriate way now open for further expansion of the pig meat sector.

Quality assurance

In the middle years of the twentieth century, food shortages in many developed countries, the need to save on imports, and successive governments’ policies to research and produce an ample supply of subsidised food led to dramatic increases in the output of agricultural product (including pigs) from farms. The social and eco-
The economic milieu of the time encouraged a definition of efficiency as being synonymous with a high level of output and a reduction in costs. The animal industries developed in an environment that encouraged the intensification of livestock enterprises. Pig production was intensified into specialised production units using environmentally controlled housing, high stocking density, animal restraint, prophylactic measures for control of disease, feed additives to promote growth, and ever more concentrated and sophisticated dietary and feed management regimes.

Government-supported research institutes and universities, together with leading farmers and the agricultural allied trades produced a flow of knowledge which facilitated the modernisation of livestock enterprises. Pig production was intensified into specialised production units using environmentally controlled housing, high stocking density, animal restraint, prophylactic measures for control of disease, feed additives to promote growth, and ever more concentrated and sophisticated dietary and feed management regimes.

Table 2.1. Pig meat consumption world-wide.

<table>
<thead>
<tr>
<th>Population (millions)</th>
<th>Pig meat consumption (kg per head)</th>
<th>Notes</th>
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<tbody>
<tr>
<td>Denmark</td>
<td>5</td>
<td>45</td>
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<tr>
<td>Germany</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>The Netherlands</td>
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<td>15</td>
</tr>
<tr>
<td>China</td>
<td>1100</td>
<td>20</td>
</tr>
<tr>
<td>Japan</td>
<td>120</td>
<td>15</td>
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</tbody>
</table>

1 In the last 40 years pig meat consumption in Europe has nearly doubled.
2 Of total meat consumed, pig meat is 65% in Denmark and 35% in North America.
3 It is possible that in some countries the consumption of pig meat is nearing saturation. The German people eat about as much pig meat as the British people eat all meats combined.
4 The Netherlands and Denmark are more than 200% self-sufficient and are massive exporters. The UK is 70% self-sufficient and is a significant import of North America and (especially) Japan are also significant pig meat importers (the latter mostly from Taiwan). The European Community as a whole is 100% self-sufficient.
5 Of the 14 million tonnes of pig meat consumed in the European Community, some 1.4 million tonnes of pork and bacon are eaten annually in the UK. Total UK meat consumption (million tonnes) is as follows: beef and veal 1.0; mutton and lamb 0.4; pork and bacon 1.4; poultry 1.1. On a per capita basis, pork and bacon consumption is around 25 kg per head per year. In comparison, 43% of all meat consumed in the EC is pig meat, and the total meat consumption is also rather greater than in the UK. Within the UK 1.0 million tonnes of pig meat is produced from 800 000 sows producing around 15 million pigs per year. The UK is 70% self-sufficient, the remaining 0.4 million tonnes being imported. Of the total pig meat consumed in the UK one-third is eaten as pork, one-third as bacon and one-third as processed products and cooked ham. The proportion of total income spent upon food is relatively low. Only 12% of total consumer expenditure is on food, of which one-quarter is spent on meat and one-third of all meat expenditure is upon pig products. It is an interesting trend that the non-household consumption of pig meat products (catering products, restaurants, etc.) is increasingly important.
come now to be seen by some sectors of the community as unsustainable were knowingly put aside in order to achieve the more pressing short-term goals of readily available food for hungry nations, and of import saving.

The present call in many countries for modifications to livestock production practices stems broadly from three sources. First is the demand that taxpayers’ money should no longer be used to support the output side of an industry whose profligacy already makes a further call on taxpayers to deal with surpluses. Second, now that food is plentiful, is the demand that food quality and safety should be paramount. Third is the demand that meat be produced in sustainable and environmentally sensitive ways which take account of such issues as the animal’s health and welfare, the pollution of air, land and water and the utilisation rate of non-renewable resources, especially fossil-fuel energy.

In passing, it may be noted that human food poisoning through the consumption of animal product is primarily (in approximately equal share) by *Salmonella enteritidis*, *E. coli* and *Campylobacter* species. The incidence of food poisoning by *Salmonella typhimurium* has decreased over recent years. *Salmonella enteritidis* has
been associated mainly with poultry meat and eggs, *Salmonella typhimurium* and *E. coli* with cattle products, and *Campylobacter* may be found in a wide range of meats and also in milk.

The effective greening of the livestock industries, such as has so far occurred, has been achieved through two substantive forces: (1) the availability of technologies that facilitate the necessary changes in production practice; and (2) the actual change in production practices by livestock producers, driven largely by the needs (a) to comply with legislation and with codes of good agricultural practice, and (b) to ensure that the market for their products is not lost.

**Introduction of Farm-Assured quality assurance schemes**

A recent survey found over 50% of food purchasers to be concerned about farming methods, especially the way in which livestock were kept, but also about the use of hormones and medicines.

It is evident that the behaviour of livestock farmers is changing with regard to satisfying prospective purchasers of the acceptability of livestock products. There is recognition by farmers that the environmental imperative requires to be both demonstrated and independently monitored and verified. With this in mind, various Farm-Assured schemes have been developed. In general, Farm-Assured pig meat schemes have the following characteristics:
The costs of the schemes are met by producer levies (usually on a livestock headage basis) or by subscription from participating farmers and meat processor members.

Livestock products are indicated at the point of sale by a clear label Mark which indicates to the purchaser the special nature and quality of the product.

There are usually three separate components to most Quality Assurance Schemes:

(a) **Product specification** set to a level above the average for the sector and above the legal limit. This usually relates to aspects of consumer acceptability, such as the content, form and quality of the product, and its appearance, taste, flavour, composition, freshness, naturalness, integrity and handleability.

(b) **Codes of best practice** and achievement of certain stated standards of performance. These may cover: (i) animal welfare; (ii) feeding, husbandry, methods of animal rearing and care; (iii) health and medication; (iv) use of feed additives, drugs and chemicals; (v) transportation; (vi) slaughter procedures; (vii) hygiene; (viii) individual animal identification from birth to slaughter; (ix) meat processing practices; (x) waste management procedures and avoidance of environmental pollution; (xi) independent inspection and monitoring to verify that the standards of performance and codes of best practice have been adhered to, with the likelihood of enforcement and sanction for non-compliance by the withdrawal of the Mark from any misguided livestock producer.

(c) **Food safety** is now considered a central part of human food assurance. Assurance schemes first protect against the presence of physical contaminants in the form of ‘foreign bodies’ in the meat. Next is protection against chemical contaminants. These might be noxious materials contaminating the meat, the presence of banned substances (such as exogenous hormone growth promoters) or unwanted residues of allowable medicines. Nowadays, the high profile aspects of food safety concern the possibility of zoonoses passing from animals to man. The zoonoses of major interest are tuberculosis, *E. coli* (O157), spongiform encephalopathies, salmonellosis, listeriosis, trichinosis, *Brucella*, *Cryptosporidium* and *Campylobacter*. Of these, trichinosis, *Salmonella* and *Cryptosporidium* are important in pigs. Trichinosis has been eradicated in most pig populations in Europe, *Cryptosporidium* may be a cause of water contamination, but it is *Salmonella* (usually *typhimurium*) that is presently exercising those setting quality assurance standards. Although the incidence of transfer from pig to man is not at all common (in Denmark, there were only about 80 cases of *Salmonella* infection from pigs), nevertheless the public would wish to be assured that the source of their meat is not contaminated with *Salmonella*. As a ubiquitous organism, *Salmonella* cannot be eradicated from the environment, but it can be removed (or kept to insignificant levels) in pig herds. This is somewhat
easier in housed pigs than those kept outdoors. ELISA tests of meat juices at the slaughterhouse suggest that 15–25% of European pigs have been challenged with *Salmonella*. This is not to say that they are carrying the organism, nor that they present any risk, but it is to say that some level of the organism shared the pig’s environment at some time. The pattern tends to be of many herds that are completely free, some that carry low levels and a very few that carry high levels. This means that schemes targeting herds with repeatedly high counts are likely to be successful in reducing the incidence in a national pig population as a whole. The slaughterhouse may report high meat juice ELISA counts back to the producer. The veterinary practitioner can then determine if the organism is present at a high rate in the herd by counting the concentration of the organism in faeces. Positive results can elicit an eradication programme targeted at the farm environment, the feed, the buildings and of course the pigs themselves. Farms repeatedly found in the highest bracket of contamination may be excluded from the quality assurance scheme. Such programmes are proving successful in reducing *Salmonella* on pig farms.

There is presently no clear line on the point of principle as to whether Farm-Assured livestock products should be the exception, defining quality superior to the norm, or the rule, defining the expected standard. Clearly, if a Farm-Assured scheme represents a burden of cost upon specific livestock producer members, then extra returns are expected to cover those costs. This will require either (1) a pricing structure that recognises and rewards superior quality, or (2) an increase in the amount of product sold. Some Farm-Assured schemes have the objective of favouring a sub-set of livestock producers (the members) with superior prices, while some aim to forestall a decline in product sales; yet others have a general ambition to increase product turnover at the expense of imported livestock products or vegetarian non-livestock products. In the first of these cases it is necessary for a minority of producers to be trading under the Farm-Assured label Mark. In the second and third it is necessary for the majority of producers to be embraced by the scheme.

Individual retail outlets may decide upon a policy of offering the customer choice of ‘Farm-Assured’ or ‘conventional’ livestock products and create price differentials between them. Alternatively, there may be a policy within a retailing group, or within a particular store, to stock only ‘Farm-Assured’ meat products, giving the explicit message that no other is considered by the store to be of adequately high standard, and that the mission of the retailer is oriented toward the welfare of animals and the protection of the environment. Even within a fully ‘Farm-Assured’ environment, particular products may be labelled by retailers as ‘green’ without necessarily achieving the extreme of being organic. In this case, the product will have satisfied rigorous quality assurance criteria, such as identified under codes of best practice and Standards of performance outlined above, together with fulfilling particular
requirements regarding animal freedom, absence of intensive production practices, and the naturalness of the production process. This sector of the market is increasing quite rapidly, and sales of ‘green’ pork meat are significant.

Expansion of organic livestock farming

Organic farming has many definitions. Originally to do with avoidance of ‘artificial’ farming methods developing in the twentieth century, such as the use of inorganic fertilisers, weed killers, insecticides, antibiotics and hormone drugs, organic farming has now attracted interest as the means to ensure extensification, reduction in production levels and environmental protection. Environmental damage is presumed to be associated with contemporary farming methods, and, vice versa, environmental protection with farming methods that are traditional and, ultimately, organic. Although interest in organically farmed produce increased in the 1990s, with many multiple stores offering agricultural products labelled ‘organic’, it was chiefly in relation to fruit and vegetables and less commonly to livestock products such as meat. There is a view that the organic whole-food movement is associated to some extent with vegetarianism, in which context organic meat might be something of a contradiction.

The production of organic sheep and beef meat from low-input extensive (organic) pastures is neither especially difficult nor extortionately costly. Organic pork, on the other hand, requires to be fed on organically grown cereals and proteins which have high-opportunity costs as they are also of value for direct human consumption. This may be sufficiently large a premium to create consumer resistance, even in an environmentally aware buying public, and there is evidence of price resistance in the purchasing of organic livestock products by the consumer. Nevertheless the demand for organic meat seems to be growing slowly. Sales of free-range livestock products are presently mainly restricted to hen eggs, but there is now some developing interest in free-range pork. Extensively reared pigs may not, however, be organically fed; the tendency to extensification, where it exists, usually targets niche markets with special concern for animal welfare issues.

It now seems unlikely that the route to environmentally acceptable livestock farming is exclusively via organic farming, the ethical extremes of which may not be perceived by the public as necessary to ensure an adequate level of ‘greenness’ in livestock products. It is important to disassociate organic farming methods from farming methods that are simply environmentally acceptable and of increased sustainability; the latter requiring action on the part of livestock producers radically different from the conventional farming methods of the 1970s and 1980s, but not so extreme as the organic farming methods. In any event, organic farming would not be able to satisfy the volume demands of purchasers of meat products. It is possible that a more appropriate standard for an adequate level of environmental sensitivity may be that seen in the better Farm-Assured quality schemes, together with lower, less intensive input systems.
**Pig meat quality**

*Fatness*

In comparison with sheep and beef meat there is less effect of anatomical position of the joint on the quality of pig meat. However, back and loin joints (*longissimus dorsi* muscle) are particularly appropriate for using fresh, grilled or fried, while the ham is good for roasting and, of course, for curing. Imaginative cutting techniques (Figure 2.5) do much to increase the product range and the consumption of pig meat. Modern jointing methods trim the subcutaneous fat on the carcass to the level required, use natural muscles as the basis for jointing, produce a range of products suited to current demand and present the meat in a convenient way for handling and cooking.

Fat levels demanded on pork products vary widely amongst pig-eating nations, but there is an almost universal trend toward reduction in desired fat levels unavoidably associated with the meat joint. Often the public demand for lean meat is greater than the indigenous pig type can provide, as is the case in North America. In this event, considerable fat trimming is necessary if the product is to be popular.

Fat reduction has represented the most dramatic aspect of improvement in pig meat quality over the last 25 years. Pig carcasses have become leaner through an

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*Fig. 2.5* Imaginative cutting techniques enhance the product range and broaden consumer choice (courtesy: Meat and Livestock Commission, UK).
improved understanding of nutritional requirement and through selective breeding for lean types. Pig meat now rivals poultry for leanness, and is considerably less fatty than beef or sheep meat. The fat that there is in lean pig meat is also lower in lipid content than is the case with ruminants, and the lipid itself is higher in linoleic acid (polyunsaturates). As the fat content of the animal is reduced, so the percentage of water in the fatty tissue that is associated with the meat joints rises. Where the fatness of the pig is gauged through the subcutaneous fat depth (mm) at the P2 site, then the percentage of water in dissected fatty tissue may be approximated as 35–1(P2).

As fat levels reduce, the fatty tissues themselves become softer (due to an increasing proportion of unsaturated fatty acids) and wetter. Soft fat has positive benefit to some curing processes, and, of course, in human nutrition contexts. However, more usually if the meat is sold with the fat on, either fresh or having been processed by modern factory methods, soft fat is seen as disadvantageous. Soft fat is not so pleasant to eat, it makes slicing and packing difficult, and gives the meat a reduced shelf life.

A distinction is required here between lipid depots found within the muscle itself (intramuscular or marbling fat) and the subcutaneous lipid, the latter being the major depot of fat in pigs. Polyunsaturated fatty acid concentrations are higher in muscle than subcutaneous fat because, apart from the lipid in fat cells, which has a similar composition in both, muscles contain phospholipids in membranes which are very unsaturated. If the level of linoleic acid in backfat increases above 150 g linoleic acid per kg of fat, the possibility of soft fat problems arises. However, leaner pigs and higher energy diets (higher in fat) are driving this level up and values of 200 g per kg are now commonly seen, up from 100 g per kg in the 1970s. Soft fat is not a problem within muscle, but too-high levels of unsaturated fat limits shelf life because these fats readily oxidise.

Soft subcutaneous fat in pigs is positively associated, in any breed or sex, with leanness itself; although there is a tendency for entire males to have slightly softer fat than females, even at the same level of fatness. Pig fat usually contains around 40% C18:1, 13% C18:2 and 1% C18:3. Unsaturated fatty acids in the diet, especially substitution of stearic (C18:0) with linoleic (C18:2), influence the type of fat deposited in the body, rendering it softer (Figure 2.6). The content of linoleic acid in pig fat, and its consequent softness, is also related to the rate (in terms of g per day) at which fat is deposited. At 50 g daily fat deposition, tissue fatty acids would comprise about 15% linoleic; while at 200 g daily fat deposition the tissue fatty acid would comprise about 10% linoleic. Given the relatively high level of unsaturated fatty acids in pig fat, it is not surprising that high levels of the anti-oxidant vitamin E in the diet (100–200iu/kg) will protect against oxidation during processing. This causes rancidity, limiting the shelf life of pork.

Leaness, when taken to extremes in pigs, can also lead to the fat becoming lacy and splitting away from the lean (Figure 2.7). Splitting fat can be a problem where the packer wishes to prepare cuts with some fat left on, as is the case with bacon. Fat separation is less of a problem where the joint is sold as lean alone, as would be the case for pig loins comprising solely the longissimus dorsi muscle.
Backfat depth (usually at the P2 site; Figures 2.8 and 2.9) is often the major criterion of assessment of quality in pig carcasses at the point of payment to the producer. Single-point measurement of fat (and muscle) depth has been replaced in some abattoirs by automatic multiple-point measurements down the length of the carcass using a battery of grading probes. There is some improvement in precision of estimation of fat and lean content of the carcass as a result. Electromagnetic scanning of the whole carcass and ultrasound scanning at many points of measurement are presently being used, but it remains to be seen whether the benefits of faster on-line carcass handling and better precision of lean yield estimation outweigh the extra capital and recurrent costs of such equipment. Where the meat is sold with the subcutaneous fat left on, fat depth is absolutely crucial to quality perceptions at the point of purchase and consumption; however, subcutaneous fat levels become of minor importance if the meat is trimmed and prepared before sale.
The vast majority of carcass grading is achieved by physical measurement of fat depth with a simple probe (or rule on the cut carcass side) (Figure 2.8), or with the physical identification by light reflectance of the interface between fat and muscle and then, on the other side of muscle, between muscle and fat (Figure 2.9). Both of these methods have the tremendous advantages of cheapness, accuracy and simplicity. More sophisticated methods may use ultrasound (sound reflectance) or total body electromagnetic scanning (TOBEC), which relies on the electrical conductivity of muscle being greater than that of fat. Considerable promise is presently being shown by systems using an array of ultrasonic scanners giving a three-dimensional image over the whole carcass. From this image, regression equations can be used to calculate the percentage lean in the whole carcass, and individual muscle size and fat depths. Like all such systems, calibration is needed for specific populations of pig type and pig slaughter weight. Computerised X-ray tomography (CT) synthesises the X-ray images of body tissues from multidimensional measurements, giving a true indication of soft tissue structure in the form of a cross-sectional map through the body and thus allowing analysis of fat and lean components. This is presently proving a highly effective (if expensive) piece of research equipment for measuring body composition in the live animal. The ultimate in sophistication is the use of nuclear magnetic resonance (NMR) which identifies the molecular structures of lean, fat, water and bone and from which visual images can be constructed. NMR technology is not yet developed for agricultural use.

Fig. 2.9 Probe measurement at the P2 site of both fat and muscle depth (courtesy: Meat and Livestock Commission, UK).
**Leanness**

At the point of purchase, following effective cutting, pig meat quality is often defined in terms such as the colour, water-holding capacity and firmness of the lean meat itself.

A tendency toward pale, soft and exudative (PSE) muscle is identifiable in about 8% of European carcasses. The severity of the condition is not usually sufficient to reduce the acceptability of the meat, but in some 4% of cases curing and processing potential is reduced and the fresh meat sold loses moisture and lacks tenderness. The actual determination of free-fluid water lost by dripping (drip loss) from the meat joint post-slaughter is a direct determination of the severity of the presence of PSE. The incidence of PSE is highly variable amongst different meat-packing plants, some showing incidences of up to 25%. There is a strong and direct relationship between the care and handling of the pigs pre-slaughter and the incidence of PSE post-slaughter.

Some pig breeds are more susceptible to their meat being PSE. This tends to be associated with muscularity and nervousness. The prevalence of PSE is markedly higher in the Pietrain breed type than in the Duroc and Large White types. A single gene (the so-called halothane gene) is involved, and this can be readily identified by blood test. Most countries can now control the presence of the gene, and in some it has been completely eradicated, to the considerable benefit of both pig welfare and meat quality.

Live pig muscle is red and has a pH of about 7 (Figure 2.10). After slaughter, while the carcass is warm, energy metabolism lowers the muscle pH (muscle glyco- gen goes to lactic acid), reduces the colour to pink and increases the wetness.

![Fig. 2.10a Assessing meat quality. Pale, dark and normal muscle. The muscles to the left and centre are of low quality; the one on the left is pale, soft and exudative (PSE) (courtesy: Meat and Livestock Commission, UK).](image)
Normally the fall in pH is gradual, ultimately reaching about 5.5, 24 hours after slaughter. However, if this muscle metabolic activity is prolonged, or excessively rapid, then the pH may drop below 6 within an hour or so of slaughter, instead of the more usual time of 4–6 hours after slaughter. It is the rapidity of the acidification of the muscle that causes the resultant carcass muscle tissues to be unacceptably pale, soft and exudative.

The whitening of the muscle is clearly visible, as is its increased ‘shine’. Measurement of optical reflectance can therefore give indicative readings for the incidence and severity of PSE. PSE is the result of soluble proteins precipitating, the muscle fibre cell membranes leaking as they become depleted of energy, and intramuscular fluid rich in lactic acid being exuded from within the fibres. This process is enhanced in pigs carrying two copies of the halothane gene and in pigs generally that are stressed just before slaughter (i.e. acute stress). In general, it may be surmised that there is an increased likelihood of PSE if acidity occurs too rapidly and the meat shows a pH of less than 5.8 measured 45 minutes post-slaughter, normal pH\textsubscript{45} values being 5.8–6.4.

Dark, firm and dry (DFD) muscle is less commonly seen in pigs and may be attributed to poor handling between the farm and abattoir and depletion of muscle glycogen through excitement. The pH of such meat tends not to fall and to remain around or above 6.5, 45 minutes post-slaughter, and to have an ultimate pH of above

Fig. 2.10b Assessing muscle quality by measuring pH in the leg. Regular pH monitoring could improve meat quality.
6.0. Chronic stress depletes the muscle glycogen, and there will be inadequate levels at the time of slaughter. This leads to inadequate lactic acid production and a consequent failure to reach an adequately low pH. In bad cases the meat is inedible. When less acute, the meat lacks flavour, but may be relatively tender. The high pH favours bacterial spoilage of meat.

PSE is therefore due to one of two causes or both: one is mishandling and pig stress, the other is the genetic constitution of the pig. These interact such that susceptible pigs, when stressed, will show a high frequency of PSE meat, whilst if unstressed the rate of PSE can be halved, even in fully susceptible animals. PSE is closely related to the presence in the genotype of the halothane gene. Pigs suffering from porcine stress syndrome (PSS), which is also caused by the halothane gene, are especially susceptible to PSE. However, all pigs are susceptible to reduction in meat quality through PSE if they are badly handled and stressed before or during slaughter, especially if mixed into new groups, during the course of transportation to the slaughterhouse, in the slaughterhouse holding pens and at the point of slaughter. Holding pens should be small and, if conditions are good, a dwell-time of 1–4 hours after delivery is usually satisfactory. If transportation has been of high quality and transportation time short, it can be beneficial to slaughter pigs immediately upon delivery. In hotter weather water sprays can help reduce pre-slaughter stress.

An important contributor to tenderness in pig meat is the ageing/conditioning process in which the muscle fibre structure is degraded by proteolytic enzymes. The valuable cuts such as the loin and leg are vacuum packed and placed in a chiller at 1°C for around 10 days, during which time tenderness, evaluated by a taste panel or mechanically, markedly improves. An important group of proteolytic enzymes active post-mortem are the calpains. These are also active during growth as part of the cyclical synthesis-degradation process by which muscle growth occurs. Within the calpain system is an inhibitor, calpastatin, and recent work suggests that levels of this increase under the influence of stress hormones (such as β-adrenergic agonists) before slaughter. Although not yet proven, these observations could explain why stressed animals tend to produce tough as well as pale watery meat.

Pigs may be rendered unconscious by electrical stunning or by carbon dioxide gas. The objective of stunning is to render the animal insensitive to pain prior to death by exsanguination through severance of the carotid arteries. Electrical head-stunning will produce unconsciousness for 30–60 seconds, after which the animal will begin to recover. Exsanguination should therefore occur 15–25 seconds after stunning. Return to consciousness is evidenced by the return of breathing and by a blinking reaction if the eye is touched. Stunning by delivery of the electrical impulse from the head through to the body (rather than through the head alone) causes cardiac arrest, so the animal is likely to be killed; but this technique may also cause an increase in the incidence of broken bones, blood splash in the meat and loss of carcass value. Stunning (anaesthesia) may also be achieved by immersion in carbon dioxide (70% CO₂) for 60 seconds, after which the animal should remain recumbent and relaxed for 40–60 seconds after returning to atmospheric air. This is particularly favoured in Denmark, but there is a view elsewhere that this method may
be stressful and unpleasant as the gas is pungent and may cause breathlessness, respiratory distress and convulsion.

The electrical wave form is commonly 50Hz AC cycle, which is appropriate for low-voltage stunning; high-voltage stunning may use a 100–1600 Hz cycle, the latter appearing to give less blood splash and limb breakages. Stunning is achieved through the flow of current; that is, voltage/resistance. The higher the resistance, the less will be the current. Resistance is usually about 150 Ohms if the electric tongs are placed correctly either side of the brain, just forward and below the ears, but more resistance occurs if the tongs are applied incorrectly across the neck behind the ears. At low voltage (50–100 V) 0.5 amps of current (500 milliamps) can be generated. When applied effectively for 3–7 seconds (sometimes 15 seconds is recommended to ensure a full stun), this will produce unconsciousness for a period of some 30 seconds. The European Union may seek to impose a minimum standard of 1.3 amps at the point of delivery, which implies voltages of 240 V or more. High-voltage stunning (up to 600 V) may be encouraged, and this would almost certainly necessitate the use of automatic stunning systems and the induction of cardiac arrest. In view of the importance of the amperage delivered to the whole stunning process, the amps, and not just the voltage, could be displayed with benefit on visible meters.

The lower the voltage, the longer the current requires to be applied, and application of current for longer than 8 seconds may predispose to PSE. It appears that a voltage of 150 V, raising some 0.5 amps, for 8 seconds may be satisfactory, but quicker stunning will result from higher voltages (for example, 210 V for 3 seconds), and amperages up to 1.3. Use of hand-held tongs operated amongst a group of pigs held together in a stunning room appears less preferable to stunning at the termination of a conveyer chute along which the pigs quietly walk in an orderly single-file queue. The variable influence of different abattoirs upon strains of pigs of different susceptibility to PSE is shown in Figure 2.11. Susceptibility to PSE meat (but not necessarily its occurrence) may be as high as 50% for halothane-positive (nn) animals, 10% for halothane-negative animals (NN) and 20% for the first cross between the two (Nn).

Pre-slaughter stress increases the likelihood of mortality, reduces carcass yield and may have a dramatic negative influence upon meat quality. Optimum transportation time from farm to abattoir should not exceed 3 hours, and there should be no stops, but in the UK 20% of pigs do not reach the abattoir within 18 hours.
of loading. Tolerable mortalities between loading and slaughter should be 0.1%, but in some situations 1%, of pigs may die at this time, and to accept such high losses as routine is not acceptable from either welfare or efficiency points of view. Pigs should not be fasted before loading for slaughter as this causes losses in carcass yield and in liver weight. Ideally, pigs should be fed 6 hours before loading, which, in good conditions, will allow some 12 hours between the last feed and slaughter. As the number of pig plants in northern Europe is only about 20% of the number two decades ago, it follows that distances between the farm and the abattoir are increasing. This negative trend, as far as the pigs are concerned, is exacerbated by these fewer plants being also much larger than the more numerous smaller plants, and larger plants tend to be more liable to expose the pigs to stressful circumstances. Acutely stressful situations will produce PSS (porcine stress syndrome) and PSE. Longer-term stress will produce meat that is DFD. It is possible that up to 10% of pigs in northern Europe may now be showing symptoms of PSE. This number may be greater in poor plants but less in good plants. Of course, the incidence is higher in stress-susceptible (nn) pigs and lower where the animals are well handled.

Optimum conditions during transport and at the abattoir are likely to include:

- no mixing of pigs before or during transportation;
- necessary marking completed the day before transportation;
- feeding 6 hours before loading;
- slopes on loading ramps no greater than 20%;
- well-ventilated vehicles;
- at least 0.4 m² allowance in vehicles for each 100 kg of transported pig;
- transportation time 3 hours or less, with no stops;
- pigs to remain in lairage for no more than 3 hours;
- long, narrow lairage pens with solid floors and 0.7 m² allowance for each 100 kg of live pig;
- well-ventilated lairage;
- pigs showered from above (having the dual effect of keeping them cool and clean);
- the animals moved slowly and easily and in small groups (5–12); no electric goads or other goading implements;
- careful handling immediately before stunning;
- automatic handling systems rather than human herding and goading.

It has been suggested, but remains to be corroborated, that selection for fast-growing lean strains of pig seems to have increased the proportion of white muscle fibres in comparison to red. About 80% of muscle fibres are white in highly improved genotypes, as compared to about 30% in wild boars. White muscle fibres are characterised as being of lower locomotor function, thicker in dimension, having less intramuscular fat, and being more able to produce lactic acid but, because of poorer blood supply, less able to remove it. All these characters have been recently suggested, but not yet adequately proven, to tend toward a susceptibility for lower flavour, reduced tenderness and a higher risk of PSE. Improvement of the quality
of lean pig meat, now that the problems of excessive fat are readily resolved by genetic selection, is a major objective of breeding and feeding programmes.

Notwithstanding the negative consequences of the colour of pig meat being too dark, in some countries, such as Japan, a deeper pink colour is preferred to pale white meat. The higher levels of red fibres in Duroc and Berkshire meat is purported to give increased eating quality. In other nations the reverse is the case, and pork (alluding to chicken) has been referred to as ‘the other white meat’.

Given that the meat is presented with an acceptably low level of subcutaneous and intermuscular fat (the first requirement of meat quality), subsequent benefit may be achieved from retaining at least 1% of intramuscular fat within the muscle. The eating quality of lean appears to be positively related to its intramuscular fat content. This phenomenon is well-known in beef and sheep meat but is also pertinent to the succulence of pork; Figure 2.12 refers to improved white pigs. The genetic improvement of pigs has led to dramatic reductions in fat, which does appear to have caused reductions over the years in tenderness (Table 2.2) but not acceptability, which has risen because, above all, the consumer perceives quality in terms of leanness. With pig meat most of the fat is held in subcutaneous fatty depots, intramuscular fat only increasing from 0.5% in lean pigs to about 3% in fat pigs. In general, the best eating quality is achieved at levels of fatness associated with P2 backfat depths at 100kg live weight of between 8 and 14mm. At below 8mm the quality of the lean falls, while above 14mm the meat is too fatty. Over the range of 0.5–3% intramuscular fat it is possible to show small improvements in succulence, tenderness and flavour. Fatness levels of greater than 3% adversely affect eating enjoyment, while at less than 1% fat in the muscle loss of tenderness and succu-

Table 2.2. Trends in fatness and tenderness scores.

<table>
<thead>
<tr>
<th>Year</th>
<th>Percentage lean meat in carcass</th>
<th>Percentage fat in carcass</th>
<th>Percentage fat in longissimus dorsi muscle</th>
<th>Taste and tenderness score of muscle (1–5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>40</td>
<td>40</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>1975</td>
<td>50</td>
<td>30</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td>1990</td>
<td>60</td>
<td>20</td>
<td>1.0</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Fig. 2.12 There is a small but positive influence of fat in the lean tissue on eating quality. Note the low levels of fat in these muscle samples from European hybrid pigs.
lence may be noted by the consumer. Levels of intramuscular fat of below 1% would be expected to be associated with pigs whose P2 backfat depths were less than 8 mm. Recent studies have shown that, even at equal fatness, *ad libitum*-fed fast-growing pigs give more tender and more juicy meat than counterparts that have their feed restricted and grow slower. This could be due to a greater rate of proteolysis in muscles which are being rapidly accreted, and therefore more rapidly turned over. A high activity of proteolytic enzymes (including calpains) may allow muscles to tenderise more easily post mortem. In this work all the pigs were of low fatness, although naturally the *ad libitum*-fed pigs are usually fatter than pigs that are restricted in their feed allowance, because the former have been allowed to eat much more food.

Discriminating consumers, favouring fat and flavour, may define quality differently to the conventional consumer who favours leanness and tenderness. Leanness at the point of purchase may, however, detract from enjoyment at the point of consumption through the predisposition of lean meat to being slightly tougher. Post-slaughter treatment, processing and cooking techniques are crucial to the creation of a satisfactory pork product. Chilling the carcass too rapidly so that the muscle temperature falls below 10°C while it is still capable of contraction (within about 5 hours of slaughter) causes muscle shortening. This is a major cause of tougheness in all species. It can be overcome by electrical stimulation of the carcass before chilling, which depletes muscle energy stores so contraction does not occur under the influence of low temperatures. This is less common in pig than beef abattoirs. A more widely used method is hip (pelvic) suspension of the carcass during the early stages of chilling. This stretches the vulnerable loin and leg muscles so they cannot easily contract and shorten. Prolonging the ageing/conditioning time from 1 day to 10 days also improves meat tenderness through the action of proteolytic enzymes. More recently, marinades have been used to improve primarily the juiciness but also the tenderness of meat. These cause moisture to be retained within the muscle structure which is important for optimum eating quality. Finally, the cooking of meat by the consumer greatly affects eating quality. A low final internal temperature (rare) improves tenderness and juiciness, but a high internal temperature (well done) encourages the development of flavour at the expense of tenderness. Extremes of cooking temperature probably have the greatest of all these post-slaughter effects.

There has been some interest in the use of particular breeds, or particular breed mixtures, as a top-crossing sire for the production of high eating quality pork. For example, the Duroc and Hampshire breeds have been cited in both America and Europe as useful to impart superior meat quality to the progeny of Large White × Landrace hybrid mothers. The Duroc breed has some reputation for robustness and carries more bone, but is not as prolific as the White hybrid. The Duroc lacks in ham shape, and may tend to fatness and slower growth. However, there is an interestingly higher percentage of intramuscular (marbling) fat than with the conventional White breeds (2–4% rather than 1–2%). This extra fatness within the (redder) muscle fibres is said to give extra flavour, tenderness and succulence for fresh and processed meat. As an approximation, the percentage marbling fat in conventional
White breeds is approximately equal to $0.1 \times (P2)$, whereas the equivalent relationship for the Duroc employs a multiplier of 0.2. Marbling fat is a heritable characteristic and a genetic test could raise the level in breeds other than the Duroc (such a test is not yet available).

The level of marbling fat can be raised by increasing fat deposition in the later stages of growth before slaughter. Reducing the protein or lysine content of the diet whilst keeping energy the same increases fatness and since marbling fat is a late-developing fat depot it is the adipose cells in muscle that are the most stimulated at this stage. Recent work at Bristol has shown that a significant increase occurs even if this diet change is made only 20 days before slaughter at 100kg. Subcutaneous fat was also increased but less than intramuscular and not enough to penalise carcass grade.

Possible improvement to eating quality in general, by enhancing the intramuscular fat of any breed type, may have been overestimated. It remains to be proven that fresh meat from breeds with higher levels of intramuscular fat does indeed make for better eating. While some work has shown advantages in intramuscular fat for imparting qualities of succulence, flavour and tenderness, other recent studies have suggested that such fat may have little to offer to the flavour and tenderness characteristics of fresh pork meat. Perhaps these conflicting results are evidence of differences either between populations of pigs or between populations of pork tasting panels.

There remains conjecture as to whether the fat quality and quantity in the meat is best manipulated by nutritional means or by genetic selection. Certainly, while nutrition readily influences overall fatness, the site of deposition of the fat is largely genetically inspired. Further, it is becoming apparent that flavour, tenderness and succulence are unlikely to be quickest improved for the immediate future by progressive genetic selection; rather these meat characteristics may be enhanced through correct choice of feed, of slaughter weight and slaughter age, pre-, peri- and post-slaughter handling, and the maturing, cutting and preparation of the meat prior to consumption.

Lower temperature cooking increases tenderness and juiciness but not flavour in pork. Cooking temperature is twice as important as any other single factor influencing eating quality – such as the animal having 50% of Duroc genes, the use of high-level feeding, or conditioning the meat post mortem for 10–12 days. Electrical stimulation of the meat can have a similar beneficial effect on tenderness to hanging and ageing; but over-cooking remains the greatest single cause of toughness in pig meat.

Supermarkets in industrialised nations now trade the largest market share of pig meat products. They are invoking elements of quality in addition to leanness, flavour and tenderness. In particular, perceived needs in terms of quantity and price have been replaced by needs measured in terms of quality and method of production. Supermarket buyers are catering for consumers concerned about the welfare of the pigs, the husbandry methods used, the housing conditions, the breeding and feeding of the pigs, general health and hygiene, absence of specific diseases, freedom from
the use of feed additives and growth promoters, animal handling practices, transport and lairage conditions, efficacy of stunning method, carcass handling and carcass treatments, and processing conditions. Many of these aspects of pig meat production are likely to be prescribed for producers wishing to enter quality assurance schemes and to provide products to specific supermarket requirements. In a word, it is the supermarkets that have come to control the production process. Meanwhile, given that adequate leanness has now been attained in many populations of pigs, producer attention is being paid to the enhancement of flavour and the increase in the nutritional worth of pig meat through manipulation of the pig diet. This particular discipline is becoming a developing area of pig nutrition research.

In addition to PSE and intramuscular fat, other meat quality factors known to be under genetic control are the yield of processed meat and boar taint. Processing yield is affected by the RN (Rendement Napole) gene, which is found chiefly in the Hampshire breed. Carriers have a lower ultimate pH than normal which reduces water-holding capacity.

An integrated approach to meat quality improvement therefore involves combining genetic, feeding regime and processing factors together into a ‘Blueprint’ as first developed by the British Meat and Livestock Commission in the early 1990s. The time has come to update the Blueprint as more factors of importance for meat quality have been revealed since then. The principles behind the Blueprint approach have been widely taken up around the world as well as by the British supermarkets. Important non-genetic factors controlling meat quality are as follows:

- Positive growth rate improves tenderness.
- Meat from fatter carcasses has slightly higher eating quality.
- Pre-slaughter stress produces PSE (acute) or DFD (chronic) and reduces tenderness (increased calpastatin).
- Rapid chilling produces tough meat – counteracted by electrical stimulation or hip suspension.
- Prolonging ageing/conditioning from 1 to 10 days improves tenderness and flavour.
- Low protein diets increase marbling fat which improves juiciness.
- Manipulating the fatty acid composition of the diet affects fat firmness. High polyunsaturates produce soft fat, while saturated fat sources (e.g. palm products) harden it.

**Meat from entire male pigs**

Entire males are much less fat than castrates. In the fat, males (being leaner) have a higher proportion of polyunsaturated fatty acids, which is a health-positive character. At 90kg an entire male of an improved European strain will have around 10–12% of body lipid, whereas a castrate will have 16–18%. This attribute, together
with faster and more efficient growth, makes the entire male an attractive proposition for the production of bacon and pork. Where the production costs for 1 kg of lean meat from entire males are taken as 100, equivalent costs for gilts and castrates are 108 and 116.

In many countries of the world no males are ever castrated and entire pigs are invariably sold for slaughter at all weight ranges. In other countries nearly all the males are obligatorily castrated. In the UK all and in Spain most male pigs used for meat are now sold entire. In Germany all are castrated. British male pigs go both for fresh meat production and for bacon curing, giving skin-on rashers with large eye muscles and low fat thickness. There remains a view, with some basis in objective evidence, that entire males should in general be slaughtered at less than 110 kg if they are to be used for meat. The previous trend world-wide toward the cessation of castration for all meat pigs slaughtered at less than 100 kg during the last two decades may now have slowed due to the fear of consumer resistance to boar taint.

Set against the problem of boar taint in entire males, the ‘mutilation’ of surgical castration in young pigs (1–2 days of age) when no anaesthetic is used is an increasingly important issue. Individual European countries may ban castration on welfare grounds except under veterinary supervision and use of anaesthetics, and the European Food Safety Authority is presently advising the European Commission on a Europe-wide view. Procedures for reducing boar taint or measuring it are urgently needed.

The evidence is strengthening to the effect that the highest quality of meat cannot be obtained from entire males. Although fatter and less economical to produce, the castrated male not only can be taken to a greater slaughter weight (thus increasing muscle size), but also will be more tender and flavoursome.

Boar taint is caused by high concentrations of the male hormone androstenone, a product of testosterone metabolism, and by skatole produced by fermentation in the hind gut. Skatole is an indole formed by degradation of tryptophan by gut bacteria.

Concentrations in body fat above about 1.0 ppm for androstenone and 0.25 ppm for skatole cause an offensive odour during cooking and an off-putting flavour when eating pork although not everybody can smell or taste boar taint. The estimate of how many boars fall into this category is variable, from 5 to 30%, apparently depending on the genetic constitution of the pigs and the country where the work was carried out.

Recent research has explained how high levels of androstenone and skatole are found together in some male pigs. Skatole from the gut is metabolised in the liver, resulting normally in low blood and fat levels. However, in some individual males, and commonly in the Meishan breed, the amount of the enzyme responsible, P4502E1, is low. This enzyme is inhibited by androstenone so individuals or breeds with high circulating testosterone and androstenone concentrations demonstrate reduced skatole breakdown and it is then taken up at higher levels by fat tissue along with the high circulating androstenone. This knowledge of the genetic control of boar taint will hopefully lead soon to a genetic test.
The incidence of skatole taint in pigs is positively related to stocking density, the extent of body contamination with faeces and urine (proportion of time spent lying in faeces and urine), the amount of faeces and urine present in the pen in which the pigs may lie, and environmental temperature. Thus male pigs densely stocked in dirty pens at high temperatures are more likely to have skatole taint than pigs stocked at lower densities in clean pens and at lower temperatures.

Boars should only be purchased by meat abattoirs and processors under tight contractual arrangements from known producers who can guarantee fast, uninterrupted growth and offer high-level feeding to the animals in a healthy and clean production environment. Pigs failing to meet these minimum criteria should be diverted from the bacon and fresh pork market and used elsewhere in the meat chain.

In Australia, male pigs can be immunised against GnRH (gonadotrophin releasing hormone), which suppresses testosterone production and reduces boar taint. This seems to be effective at reducing taint without losing the high efficiency and leanness characteristics of the entire male. However, it may not be 100% effective and its use in Europe where growth hormones are banned seems unlikely.

Other approaches to reducing boar taint include diet ingredients which change fermentation characteristics in the hind gut to reduce skatole production. These include molassed sugar beet feed, a fermentable fibre source. Possibly the traditionally low UK slaughter weight resulted in less of a boar taint problem than in countries where slaughter weights are higher. Another approach to reducing taint is therefore to slaughter at lower weights. However, the relationship between body weight and androstenone and skatole concentrations is not close.

In Denmark, a sophisticated on-line sampling and measuring system for skatole has been developed. However, it is rather slow and does not measure androstenone. Various ‘electronic nose’ devices have been tested for identifying tainted carcasses, but none is suitable for abattoir use. If tainted meat is detected by meat inspectors, carcasses can be directed towards processed products rather than fresh meat. However, no processing procedure reliably masks highly tainted meat.

The odour of boar taint is variously described as musty, sweaty, dirty or mothballs; in contrast to other taints more linked to diet ingredients. Fish oil above about 1% of the diet causes fishy taints and high levels of polyunsaturated fatty acids produce rancid taints where the fat oxidises. Fatty acids are the main diet ingredients that influence meat flavour.

Boar taint is the main meat quality problem in entire male pigs. Other issues such as softer fat and greater fat splitting/separation are more problems of over-leanness. These can be overcome by nutritional changes, although the entire male has softer, less cohesive fat tissues than the castrate even at the same fat thickness.

Given the substantially greater production efficiency of the entire male, and the perceived welfare benefit of leaving pigs entire, it is perhaps remarkable that more countries have not followed the UK’s lead in entire male production. However, current thinking relating to the benefits of castrated males with respect to a higher slaughter weight and better meat quality would suggest that entire male pig production may have placed the UK in a disadvantageous position. Further, it is not
evident that the balance of welfare benefit lies entirely with avoiding castration at a very early age. Entire males are ill-content penned with each other’s company at live weights above 75 kg, when sexual activity and aggression develop in a seriously disruptive way.

Shape and meatiness

Some pig types are more meaty than others and have a characteristic blocky ‘meat-line’ shape. These types may often but not always carry the ‘halothane gene’ thus named because the animals react to the anaesthetic halothane. Where this association occurs, the reaction can be used as a marker for muscle shape and meatiness. A genetic test for definitive identification of halothane gene carriers is available. Halothane reactors are found at various levels in pig populations (Table 2.3) and differ between strains within breeds. Amongst breeds and crosses containing 40–70% of the gene, its presence is associated with:

- about 2.5 percentage units more carcass lean;
- about 1% higher killing-out percentage;

Table 2.3. Incidence of the ‘halothane gene’ and associated stress susceptibility, meaty and blocky characteristics.

<table>
<thead>
<tr>
<th>‘Breed’²</th>
<th>Occurrence (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large White</td>
<td>} 0</td>
</tr>
<tr>
<td>Duroc</td>
<td>} 0</td>
</tr>
<tr>
<td>Hampshire</td>
<td>} 0</td>
</tr>
<tr>
<td>Norwegian Landrace</td>
<td>} 0</td>
</tr>
<tr>
<td>Danish Landrace</td>
<td>} 0</td>
</tr>
<tr>
<td>British Landrace</td>
<td>} 0</td>
</tr>
<tr>
<td>Swedish Landrace</td>
<td>} 0</td>
</tr>
<tr>
<td>Dutch Landrace</td>
<td>} 0</td>
</tr>
<tr>
<td>Dutch Large White</td>
<td>} 0</td>
</tr>
<tr>
<td>German Landrace</td>
<td>} 0</td>
</tr>
<tr>
<td>Belgian Landrace</td>
<td>} 0</td>
</tr>
<tr>
<td>Pietrain</td>
<td>} 0</td>
</tr>
</tbody>
</table>

1 The halothane gene can now be selected-out of positive populations following DNA testing. Occurrences of 0 are therefore now possible to achieve in all pig populations, given the willingness to embark upon rigorous testing and eradication regimes.

2 Breed definition is no longer an adequate descriptor of pig type or genetic composition. Some breeds termed ‘Large White’, for example, may show a percentage of halothane-positive individuals in the population. Also many pig ‘breeds’ available from breeding companies are produced from a variety of gene sources and often defy definition other than that provided by the breeder. Such definitions may relate more to what the animal is purported to do, and in what circumstances it should be used, rather than to what breeds or genes are included in its make-up.
• about 10 mm reduced carcass length;
• about 25% of the carcasses liable to PSE muscle (5% liability in normal pigs, 25% liability in homozygote halothane-positive pigs);
• one or two pigs less weaned per litter;
• an appetite reduced by about 10–20%;
• growth slowed by about 10–20%;
• an increase in drip loss;
• bigger longissimus dorsi muscle area (+5 cm², to attain 45 cm² at the P2 site when 90 kg live weight);
• up to 12 mm more depth of the longissimus dorsi muscle at the probe site;
• bigger, more rounded and meatier hams (20% increase in shape score);
• less bone;
• higher mortality in the growing/finishing stage (10% as against 2% in conventional pigs).

Pure-bred Belgian Landrace and Pietrain pig types, and many strains of German Landrace, show benefits over the Large White pig types of up to 4 percentage units more lean (61% v. 57% in the carcass sides, Figure 2.13), up to 3 percentage units better killing-out percentage (76% v. 73%) and less carcass bone and smaller heads (the lean:bone ratio being about 6:1 as against about 5:1). In consequence of the greater muscle mass and reduced carcass bone, meaty strains of pigs have a higher percentage of lean meat in their carcass at any given backfat depth than do conventional white strains of pigs. Therefore, grading on fat depth alone will erroneously discriminate against blocky meat-type pigs. It is especially where mixed populations of pigs are forwarded to the meat packer that measurements in addition to fat depth should be taken if the correct assessment of carcass lean content is to be made. Such additional measurements would be the depth of the eye muscle, and a visual assessment score of the shape of the hams themselves. The danger of predicting lean percentages on the basis of fat depth alone is illustrated in Figure 2.14.

Other characteristics of halothane-positive pigs include smaller litters (10–20% less pigs weaned), slower growth rate (10–20%) and a tendency to drop dead when stressed (porcine stress syndrome; PSS), such as when loaded for transportation or held in abattoir lairage.

![Fig. 2.13](image)

**Fig. 2.13** At any given fat depth, the meat-type breeds of pigs have a higher percentage of lean meat. Their shape is more blocky and muscular, and the content of bone is less. Meat pigs which are homozygous for the blocky character will have up to 4% units more lean tissue at the same fat depth. Heterozygotes with 50% of the character will have 2% units more.
The characteristic shape of meat strains (Figure 2.15) is short and blocky with well-filled, rounded hams, the rear view being more omega-shaped than $n$-shaped. The blocky muscling character also shows clearly in size of the loin and in the eye muscle (longissimus dorsi) area (Figure 2.16). At 80 kg live weight the pure-bred Large White and the Pietrain will have about 35 and 40 cm$^2$ of eye muscle respectively; at 100 kg live weight the two breeds will have respectively 45 and 55 cm$^2$. In

![Fig. 2.14 Comparative relationships between predicted and actual lean percentage for 'Large White' and 'meat-line' strains of pigs.](image)

![Fig. 2.15 Carcasses of meat-type and white-type genotypes showing the difference in conformation.](image)
Fig. 2.16a Pig loins. Note that the one on the left is of lesser muscle volume than the one on the right, which is preferred.

Fig. 2.16b Differences in muscle shape. Chump end of leg (left) and loin (right) typical of meat-type pig genotypes. Note the rounded shape of the loin.
comparison, some traditional American breeds may have only 40 cm² of eye muscle at 100 kg live weight, which would be associated with a lean meat content of only 53% in the carcass. A well-tried breeding strategy is to make a heterozygote top-crossing meat sire line from a halothane negative grandparent female and a halothane positive grandparent male. This parent meat sire is then used on halothane negative parent females to produce the slaughter generation that will exhibit a high level of the benefits from the gene, and a low level of disbenefits.

There is great activity amongst pig breeders at present to retain all the positive attributes of the halothane gene but to exclude the gene itself, with its associated problems. A definitive DNA test is used. Genetic selection for rounded ham shape, muscle content and eye muscle area, simultaneous with selection against the halothane gene in previously positive pig breeds, has yielded positive results without the need to risk halothane stress susceptibility. In beef animals, it would appear that the degree of muscling may be associated with a loss of the myostatin gene. A negative association between muscularity and eatability is increasingly probable, but not yet proven.

Suffice to say that the search for quality in pig meat has elicited many production variations, many harking back to the situation before the ‘intensification’ of husbandry systems and the ‘genetic improvement’ of pigs by selection for fast lean growth.

Carcass quality and grading standards

Pig carcasses may be divided in many different ways, consistent with the huge variety of bone-in joints and bone-out products that come from the pig. Primary breakdown may follow a scheme such as that shown in Figure 2.17. Although it is characteristic of the pig carcass that the value of the cuts does not differ according
to position in the body nearly to the same extent as for beef and lamb, because of a lesser tenderness gradient, the most valuable parts are nevertheless in the loin (rump back) and ham areas.

The chemical composition of the empty body of a 100 kg entire male meat pig with a P2 backfat measurement of 10 mm will be around 67% water, 17% protein, 13% lipid and 3% ash. The physical composition in terms of muscle, fat, bone, offals and so on is shown in Figure 2.18.

Usually payment for pig carcasses is on the basis of their weight, adjusted for some assessment of carcass quality, as defined in a grading scheme. Individual grading schemes may contain many or few criteria. The more criteria, the greater the likelihood of a carcass being found unacceptable on the basis of one or other
of them. Some example criteria are given in Table 2.4. Standards of over-fatness can be matched by standards of under-fatness. Minimum fat levels (often around 8 mm P2) are required for the eating quality of lean meat as well as to help maintain the quality of the fat itself. In some schemes a single factor, such as level of fatness, may be the prime controller of value and payment received by the producer. Often, criteria of considerable importance to carcass quality, such as the quality of the lean and fat, may play no part in grading standards and the payment schedules. In some instances a flat-rate payment is made for the carcass mass regardless of quality or grade attainment, while in other instances payment is made strictly per kilogram of lean meat produced. For some types of meat production it is the breed of pig and the method of rearing and feeding that are the vital criteria of quality. For others, such as for the production of Italian Parma hams, the first necessity is for a ham size of 12 kg; in effect, a pig of 160 kg or more live weight.

Where live weight is the only effective determinant of producer reward, the industry tends toward low efficiency and the product tends toward low quality, there being no alternative incentive. Some aspects of the pig market in the Americas operated in this manner until quite recently. It may be said that it was the demands of the European farmers for greater efficiency, and the demands of the largely pig-meat-eating European consumers for less fat pigs, that brought about the creation of the genetically improved modern strains of European hybrid pig which are now used for meat production world-wide. Such demand was not appreciated at that time by farmers in the Americas, who paid less for their pig feed and whose consumers were not so discerning toward pork quality issues.

As has traditionally been the case with cattle and sheep, in some countries the shape of the live pig, or the pig carcass, may be paramount as a criterion of carcass

---

**Fig. 2.18** Physical composition of a high-quality entire male meat pig with 10 mm P2 fat depth.
quality. The fullness of the muscle either side of the backbone and the roundness of the ham are often much sought after as indicators of lean muscle mass. In some breeds of pig, however, roundness of the ham and fullness of shape merely indicate fatness. However, when these characteristics are found in the European meat-line strains and breeds, there may indeed be a positive relationship between the shape of the pig and its lean content. These important differences in the correct interpretation of shape for different genotypes can be separated out only by the objective measurement of lean muscle mass (as well as the measurement of fat depth). Lean percentage can be measured reasonably objectively and directly from the depth of fat and muscle in the middle region of the back, for example around the P2 position (Figure 2.8). Comprehensive automatic systems can now be created which measure shape, while simultaneously probing at many different points down the back and on the ham for determination of fat and lean depth. The same equipment is likely to be able to take automatic measurements of muscle colour and pH. The possible presence of taints, such as those related to androstenone and skatole, require either the human nose, following heating of the fat, or sophisticated on-line chemical analysis techniques.

Table 2.4. Example criteria for grading of pig carcasses.

<table>
<thead>
<tr>
<th>Carcass dead weight (kg)</th>
<th>'Pork' 60</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>'Bacon' 60–80</td>
</tr>
<tr>
<td></td>
<td>'Manufacturing' &gt; 80</td>
</tr>
<tr>
<td>Fat depth (mm)</td>
<td>P2</td>
</tr>
<tr>
<td></td>
<td>P1 + P3</td>
</tr>
<tr>
<td>Midline at:</td>
<td>midback</td>
</tr>
<tr>
<td></td>
<td>loin</td>
</tr>
<tr>
<td>Ham fat</td>
<td>shoulder</td>
</tr>
<tr>
<td>Muscle depth (mm)</td>
<td>P2 site</td>
</tr>
<tr>
<td>Midback site</td>
<td></td>
</tr>
<tr>
<td>Ham</td>
<td></td>
</tr>
<tr>
<td>Length (mm)</td>
<td>Carcass</td>
</tr>
<tr>
<td>Shape (visual or objective score)</td>
<td>Hams</td>
</tr>
<tr>
<td></td>
<td>Eye muscle area</td>
</tr>
<tr>
<td></td>
<td>Eye muscle shape</td>
</tr>
<tr>
<td>Distribution of joints</td>
<td>Fores/hams/loins/belly</td>
</tr>
<tr>
<td>Sex</td>
<td>Entire male/female/castrate</td>
</tr>
<tr>
<td>Muscle quality</td>
<td>PSE</td>
</tr>
<tr>
<td></td>
<td>Juiciness</td>
</tr>
<tr>
<td></td>
<td>DFD</td>
</tr>
<tr>
<td></td>
<td>Texture</td>
</tr>
<tr>
<td></td>
<td>Colour</td>
</tr>
<tr>
<td></td>
<td>Tenderness</td>
</tr>
<tr>
<td></td>
<td>Flavour</td>
</tr>
<tr>
<td></td>
<td>Taint</td>
</tr>
<tr>
<td>Fat quality</td>
<td>Wetness</td>
</tr>
<tr>
<td></td>
<td>Tendency to split</td>
</tr>
<tr>
<td></td>
<td>Firmness</td>
</tr>
<tr>
<td></td>
<td>Taint</td>
</tr>
<tr>
<td></td>
<td>Colour</td>
</tr>
<tr>
<td></td>
<td>Texture</td>
</tr>
<tr>
<td></td>
<td>Flavour</td>
</tr>
</tbody>
</table>
Where grade is assessed on fat depth alone, good carcass shape may not be adequately rewarded. At equal fat depth the meat-line breed types are likely to have more lean than the conventional Large White and Landrace breed types. In consequence, although some types of high-conformation pigs may contain a higher percentage of lean meat in the carcass, these animals being fatter at the P2 site are liable to be down-graded. The importance of the muscle measurement, in addition to the measurement of fat for the effective and objective prediction of percentage carcass lean in mixed pig populations, is exemplified in Table 2.5. At equal P2 fat depth, homozygote halothane-positive pig types may be estimated to have some 4 percentage units more lean meat than the Large White types (as has been shown in Figure 2.13).

Most grading standards and payment schedules relate to fatness (often as backfat at the P2 site, Figure 2.8), within a given weight band. A scheme may, for example, limit head-on carcass dead weight to between 60 and 75 kg and pay a premium price for pigs of less than 12 mm P2; imposing a maximum price penalty for pigs of more than 16 mm. Equivalent schemes might pertain for pork carcasses of below 60 kg carcass weight, and cutter and heavy pig carcasses of above 75 kg carcass weight (Table 2.6). Stepped grade schemes using fat depth as the criterion of assessment fail to utilise known relationships between fatness and lean yield, and the European Community grade scheme helps to improve this position by presenting each class in terms of the percentage of carcass lean meat (Table 2.7). Lean meat percentage may be predicted from equations of varying degrees of complexity and efficacy. A simple prediction of percentage lean in the carcass side would be:

\[
\text{Percentage lean in carcass side} = 68 - 1.0 \ P2 \tag{2.1}
\]

or:

\[
\text{Percentage lean in carcass side} = 65.5 - 1.15 \ P2 + 0.076 \text{ carcass weight} \tag{2.2}
\]

Most UK pigs of 65–70 kg carcass weight have a P2 measurement of 12 mm or less. However, in many other parts of the world, particularly those where improved European hybrids are not being used, pigs may still be found with carcass fat depth at the P2 site in excess of 20 mm.

<table>
<thead>
<tr>
<th>Carcass weight (kg)</th>
<th>Fat depth (mm at P2 site)</th>
<th>Muscle depth (mm at P2 site)</th>
<th>Predicted percentage of lean meat content</th>
</tr>
</thead>
<tbody>
<tr>
<td>64</td>
<td>13</td>
<td>60</td>
<td>55 By fat depth alone 58 By fat depth and muscle depth</td>
</tr>
<tr>
<td>66</td>
<td>12</td>
<td>64</td>
<td>57 By fat depth alone 59 By fat depth and muscle depth</td>
</tr>
<tr>
<td>67</td>
<td>12</td>
<td>52</td>
<td>57 By fat depth alone 57 By fat depth and muscle depth</td>
</tr>
</tbody>
</table>

Table 2.5. Prediction of lean meat content of pigs with different muscle depths. See also UK MLC (1990) Pig Yearbook.
Stepped grading schemes, such as described in Tables 2.6 and 2.7, fail to take immediate advantage of the calculation of the absolute amount of lean meat provided from knowledge of the estimated percentage lean in the carcass side and the carcass weight. It would be more logical for payment schedules to be continuous rather than stepped, and based on the absolute amount of lean meat yielded. It follows from the natural growth pattern of the pig that the lighter animals within any allowed weight band have a lower fat thickness. As pigs become heavier fatness increases; on average every 10 kg carcass weight increase is associated with about a

### Table 2.6. Examples of stepped grade schemes for 55 and 80 kg carcass weight pigs with emphasis on leanness.

<table>
<thead>
<tr>
<th>P2 fat depth (mm)</th>
<th>Price/kg dead weight (% of average price)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50–60 kg dead carcass weight</td>
<td></td>
</tr>
<tr>
<td>&lt;8</td>
<td>120</td>
</tr>
<tr>
<td>8–12</td>
<td>110</td>
</tr>
<tr>
<td>12–16</td>
<td>100</td>
</tr>
<tr>
<td>&gt;16</td>
<td>80</td>
</tr>
<tr>
<td>75–85 kg dead carcass weight</td>
<td></td>
</tr>
<tr>
<td>&lt;10</td>
<td>90²</td>
</tr>
<tr>
<td>10–14</td>
<td>120</td>
</tr>
<tr>
<td>14–18</td>
<td>100</td>
</tr>
<tr>
<td>&gt;18</td>
<td>80</td>
</tr>
</tbody>
</table>

1 The average price for 60 kg dead weight pig carcasses would be likely to be some 10–20% higher than for 80 kg carcasses, depending on market demand locally for the two types.

2 Notice that the imposition of a minimum as well as a maximum fatness can reduce problems associated with over-leaness.

### Table 2.7. The European Community grade scheme based on lean meat percentage.

<table>
<thead>
<tr>
<th>Percentage of lean meat in carcass¹</th>
<th>EC grade class</th>
<th>Percentage of UK pigs in each EC class</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;60</td>
<td>S</td>
<td>17</td>
</tr>
<tr>
<td>55–59</td>
<td>E</td>
<td>58</td>
</tr>
<tr>
<td>50–54</td>
<td>U</td>
<td>21</td>
</tr>
<tr>
<td>45–49</td>
<td>R</td>
<td>3</td>
</tr>
<tr>
<td>40–44</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>&lt;40</td>
<td>P</td>
<td></td>
</tr>
</tbody>
</table>

1 Lean meat percentage may be estimated from agreed equipment and equations, for example:

- **Estimation by Intrascope probe measurement of P2 fat depth:**
  - Lean meat % = 65.5 – 1.15 P2 + 0.076 Wc
  - Where Wc is the carcass weight

- **Estimation by Hennessy probe measurements:**
  - Lean meat % = 62.3 – 0.63 P2 – 0.49 ribfat + 0.14 ribeye muscle depth + 0.022 Wc

- **Estimation by Fat-o-meter probe:**
  - Lean meat % = 59.0 – 0.58 P2 – 0.32 ribfat + 0.18 muscle depth

Equations valid over range Wc = 30 – 120 kg

Measurements including eye muscle depth more accurately credit pigs with superior shape.

Stepped grading schemes, such as described in Tables 2.6 and 2.7, fail to take immediate advantage of the calculation of the absolute amount of lean meat provided from knowledge of the estimated percentage lean in the carcass side and the carcass weight. It would be more logical for payment schedules to be continuous rather than stepped, and based on the absolute amount of lean meat yielded. It follows from the natural growth pattern of the pig that the lighter animals within any allowed weight band have a lower fat thickness. As pigs become heavier fatness increases; on average every 10 kg carcass weight increase is associated with about a
1% unit decrease in lean meat percentage and with about a 1 mm increase in P2 backfat thickness. Thus as the potential value of the carcass increases with increasing weight, the likelihood of it being down-graded because of over-fatness is also increased. The (unjust) consequence is a diminished price paid for each and every kilogram of lean meat provided, whilst the total mass of lean meat would, of course, be greater. Further illogicality follows from the stepping of the scheme itself. Whilst an 80 kg carcass of 10 mm P2 may indeed be worth 20% more than one of 15 mm P2 (Table 2.6), it is not logical that the same 20% difference in value also pertains for the 1 mm difference between 13.5 and 14.5 mm P2. These inconsistencies would be ameliorated by a grading scheme that paid for each kilogram of lean meat yielded. Within a given breed type, as already described, this could be estimated from a knowledge of the carcass weight and the P2 backfat measurement. Given the calculation of percentage lean in the carcass side, a payment schedule such as depicted in Figure 2.19 might be envisaged. The slope of the line is critical to the cost–benefit of producing leaner pigs, and such a slope may well need to represent a 2% increase in price paid per kilogram of carcass dead weight for each percentage unit increase in lean meat content.

Effective determination of percentage lean, however, requires knowledge of not just fatness but also lean muscle mass.

While predictions in the form ‘Percentage lean = k – n P2’, where k is around 70 and n around unity, may be adequate for Large White breed types, or for use within given pig populations, the equation fails to allow for the meatier pig strains which carry more lean at any given P2. If only P2 fat measurements are available, a more universal equation form may be ‘Percentage lean = b P2\(^{-k}\)’, where k is around 0.21 and b indicates the degree of blockiness of the strain of pig concerned, and ranges between 90 for unimproved Large White and Landrace breeds and 100 for pure-bred Pietrain and Belgian Landrace types.

While shape can be a helpful guide to improving predictions of leanness made primarily on the basis of fatness, it is liable to errors from subjectivity and, of course, gross errors where a rounded ham is not associated so much with muscle mass as with fat mass. Lean mass can really only be effectively determined by a combina-
tion of measurements of fatness and of leanness itself. This is helped if muscle depth is also measured, usually by probe (see Figure 2.8), and the use of prediction equations such as:

\[
\text{Percentage lean meat in carcass side} = 59 - 0.90 \text{ P2 fat depth} + 0.20 \text{ eye muscle depth} \quad (2.3)
\]

A pig with 10mm P2 fat and 55mm of muscle depth is estimated to contain, by use of this equation, 61% of lean meat. A poor pig with 45mm of muscle depth and 20mm of P2 fat would be estimated to contain 50% of lean meat in the carcass side. Carcasses with greater than 65% of lean meat may be judged as over-lean and prone to reduced muscle quality.

There are presently a wide range of alternative methods for measuring the percentage of lean in the carcass, ranging from the simple to the complex. Amongst the alternatives are:

- pig weight (on a presumption that percentage lean will reduce from around 60% in lighter pigs to around 50% in heavier pigs);
- visual appraisal (on the presumption that rounded rear quarters are representative of muscle mass), which can be ‘sophisticated’ by visual imaging;
- linear measurement of fat depth and muscle depth with ruler, intrascope, Hennessy probe, Destron, Fat-o-meter, etc. (regression equations with high degrees of accuracy can predict percentage lean well from fat depth alone and very well from a combination of fat depth and muscle depth); linear measurements may be made at a single point (e.g. P2) or at multiple points using a battery of grading probes, thereby increasing precision;
- ultrasonic measurement of fat and muscle depth (as for above, slightly less accurate, but can also be carried out on the live animal);
- electromagnetic scanning (the conductivity of muscle is higher than that of fat);
- electrical impedance (again operates on the readiness of electricity to flow through the muscle mass rather than the fat mass);
- computerised X-ray tomography (CT) (differentiates between fat and muscular tissue and can therefore give a direct estimate of percentage lean across the whole of the carcass, compared to linear measurements of fat and muscle depth which rely on predictions and take place at given points); Figures 2.20 and 2.21 show outputs from CT scans;
- nuclear magnetic resonance (as for CT, can determine directly muscle and fat mass);
- physical dissection of a sample joint or the whole carcass side (the most direct determination of percentage lean but is somewhat destructive);
- chemical analysis (the absolute determination for carcass protein, lipid, water and ash; totally destructive; does not necessarily give a direct determination of lean and fat – the water in both muscle and fatty tissue can vary – nor does it necessarily relate to eating value).
Fig. 2.20  Computer tomography (CT) scans of two pigs selected for different traits illustrating the difference between a specialist sireline pig (H.C. Large White, right-hand image) and a general purpose line (Q.M. Duroc, left-hand image). Scans taken at the 2nd lumbar vertebra showing the eye muscle area. Air is black, fat is dark grey, muscle is light grey and bone is white. These images are reproduced with the permission of Newsham Hybrid Pigs Ltd and Dr M.J. Young of the SAC-BioSS CT Unit.

Fig. 2.21  Computer tomography (CT) scans of two pigs through the middle of the ham muscle. Note the well-developed muscles and absence of fat on the right-hand scan (H.C. Large White) compared to the left-hand scan (Q.M. Duroc). Air is black, fat is dark grey, muscle is light grey and bone is white. These images are reproduced with the permission of Newsham Hybrid Pigs Ltd and Dr M.J. Young of the SAC-BioSS CT Unit.
Such niceties as the exact prediction of carcass lean are not considered necessary in many countries where shape, judged by visual assessment, is considered to cover all the required criteria for carcass and meat quality. Thus Table 2.8, typical for parts of Spain, emphasises the importance of ham shape within relatively broad categories of fatness.

### Carcass yield: killing-out percentage (ko%)

The carcass weight of a pig is usually between 70 and 80% of its live weight. The loss is mostly blood and internal organs, as shown in Figure 2.18. The carcass weight of the pig conventionally includes the head, feet, tail and skin.

The gut content in pigs is usually around 5% of the live weight; it is somewhat greater with high fibre diets due to both elevated quantities of digesta in the caecum and colon and the additional water that the presence of fibre attracts to the gut lumen. Killing-out percentage (ko%) will increase by about 0.75 percentage units for each 1 MJ increase in dietary energy density. It is necessarily lower for pigs slaughtered with full stomachs than with empty ones; so there is an important effect of time between the last feed and slaughter (about 0.1 percentage units reduction

<table>
<thead>
<tr>
<th>Mid-back fat depth at the mid-line (mm)</th>
<th>Ham shape score (1–3)</th>
<th>Carcass grade given (1–5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10–20</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10–20</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>10–20</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>20–30</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>20–30</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>20–30</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>30–40</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>30–40</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>30–40</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

1 Ham shape scores:
in ko% for each hour between time of on-farm weighing and food withdrawal and weighing after slaughter).

Boars have a lower carcass yield than gilts or castrated males, due mostly to the removal of the testes and, in the case of older males, the need to remove a greater amount of cartilaginous tissue in the fores.

Transportation distance and the time between removal from the farm and the moment of slaughter each have additive effects on carcass yield, primarily through stress and disturbance, causing progressive water loss from the body and a consequentially ‘drier’ carcass at the point of slaughter. Killing-out percentage can decrease by 0.1 percentage units or more for each hour of transportation time. Carcass yields of greater than 75% are difficult to achieve if transport distances are much greater than 100 km, and the time between departure from the farm and stunning much greater than 6 hours. Provision of water sprays and drinkers and satisfactory reception and holding pens at the slaughterhouse may help to maintain carcass yield; but positive effects tend to be limited.

The major influences upon carcass yield are live weight, fatness and genotype. At live weights of 50–60 kg, ko% percentage may often be little more than 70, whilst at live weights of 100–120 kg values approaching 80% may be possible. There are two reasons for this: (1) the carcass grows relatively faster than the guts and the latter therefore comprises a progressively lesser proportion of the whole animal as it increases in size; ko% increases by about 0.1 percentage units for each kilogram increase in slaughter weight between 80 and 120 kg live weight; (2) heavier animals tend to be fatter, and fatter animals kill-out better than leaner animals at any given weight. Killing-out percentage increases by about 0.1 percentage units for each millimetre increase in P2 backfat depth between 8 and 18 mm P2. This latter is in some part because in pigs most of the fat is deposited in the carcass (subcutaneous and intermuscular) and only about 10% is in the abdomen, to be discarded with the internal organs.

Killing-out percentage may be estimated for Large White and Landrace type pigs, all other factors being equal, from equations such as:

\[ \text{ko\%} = 66 + 0.09 \, W + 0.12 \, P2 \]  \hspace{1cm} (2.4)

where \( W \) is the live weight and \( P2 \) is the measurement of backfat depth (mm).

Equations to estimate ko% tend not to be universal as is already apparent from the foregoing discussion of the benefits of the halothane gene and/or a blocky shape together with lower bone and gut mass. Pigs of the Pietrain and Belgian Landrace type will kill-out some 2 or more percentage units higher than pigs of the Large White and Landrace type. The causes of this improvement probably are a lower proportion of the offal per unit live weight and a tendency to carry more of the total body fat in the carcass. Pigs with lower mature size will be, at any given weight, of a higher degree of maturity. The proportion of gut to carcass will be less than for heavier maturing types, and the ko% will be greater.
Choice of carcass weight and carcass fatness

For every kilogram increase in live weight, P2 back fat depth increases by 0.1–0.2 mm, but this is highly dependent upon genotype and feeding regime. The positive relationship between fatness and weight would indicate that the correct slaughter weight for sexes and strains that tend to be fatter should be toward the lighter end of the market, whilst that for sexes and breed types that are naturally thinner should be toward the heavier end. It is germane to production tactics that, unless controlled, fatness will increase faster than body weight, fatness accelerating disproportionately rapidly. This is well illustrated by the prediction of subcutaneous fat (kg) \( (Y) \) from carcass weight \( (X) \) in one particular population of pigs:

\[
Y = 0.0002 X^{2.54}
\]  

Total protein mass \( (Pt) \) accumulates at a slightly slower rate than live weight and at a distinctly slower rate than P2 fat depth. Thus for a group of unimproved well-fed pigs grown at the University of Edinburgh from 20–220 kg live weight \( (LW) \) in the early 1970s:

\[
P2 = 0.149 LW^{1.093} \text{ (exponent > 1; P2 gains relatively faster than live weight)}
\]

\[
Pt = 0.192 LW^{0.941} \text{ (exponent < 1; Pt gains relatively slower than live weight)}
\]

\[
Pt = 1.33 P2^{0.788} \text{ (exponent much < 1; Pt gains relatively much slower than P2)}
\]

While the rule is clear that heavier pigs are invariably fatter than lighter pigs, and as carcass weight increases so does fat depth, the relationship is not so strong for modern genotypes of lower fatness and greater mature size. Thus for 1980 (unimproved)

\[
P2 (mm) = 0.38 \text{ head-on-carcass weight} - 10
\]

whilst for 1990 (improved)

\[
P2 (mm) = 0.15 \text{ head-on-carcass weight} + 2.0
\]

This is a logical consequence of the modern improved pig being of lower physiological maturity and a lower proportion of final weight at the given slaughter weight.

Given ultrasonic techniques for the measurement of carcass fatness in the live animal, pigs could, if required, be sent off to slaughter at any given target P2 fatness. However, targeting to sale within a given backfat range can be antagonistic to targeting to sale within a given weight range; and the narrower these ranges become the more difficult it is to meet both simultaneously.

Fatness is considered as normally distributed through the pig population. However, as average fatness reduces, so the possibility of normal distribution lessens
and that for skewness increases (Figure 2.22). Given the biological distributions for fatness and for weight at any given age, it is often the case that there is greater benefit to the producer to sell at pre-selected calendar dates rather than to try to meet arbitrary and narrow standards for weight and fatness. Such beneficial marketing arrangements would be particularly easily handled if the producer and the retailing organisations were effectively integrated.

Presently, most pigs are slaughtered within the live weight range 90–120kg, and the head-on-carcass dead weight is usually around 75% of the live weight. Particular markets demand slaughter weights of lower and higher than the conventional range (such as for light, fresh butcher pork at one extreme, and for large, naturally slow-cured gourmet hams at the other extreme). With increasing mature size of modern selected pigs, and with their genetic improvement toward faster rates of lean growth and higher percentages of lean in the carcass, there is a natural (and necessary) tendency for slaughter weights to increase. The current European norm is for live weight at slaughter to be around 110kg.

The need to minimise transportation distances from point of production to point of slaughter will limit opportunities for choice of meat-packer outlets, but locally there usually exists a range of grade and price schedules from which an optimising choice must be made. However, within-schedule choice of production tactics may be even more vital than between-schedule. Pigs may be placed at will somewhere within a range of carcass dead weight limits, and equally the pigs may be placed at will within the range of fat limits described (together with their appropriate penalties and bonuses). For example, it may be more profitable to elect for a reduction in price per kilogram in return for an increase in the weight of pig at the point of sale.

As slaughter weight increases, it follows that the cost per unit of pig product reduces due to the fixed costs (especially those relating to the upkeep of the breeding herd) being defrayed over a greater amount of carcass weight sales. This particular trend is further helped on account of the intestines being proportionately slower growing than the body of the pig as a whole, thus causing carcass yield to improve with increasing slaughter weight (Figure 2.23). However, as weight increases so does the likelihood of fatness (Figure 2.24) and of consequential down-grading. Reduction in weight at despatch is often an effective means of reducing fat and improving grade returns.
Heavier weights at slaughter are also associated with reduced efficiency of food conversion (Figure 2.25). This is partly due to the fatness effect (1 kg of fatty tissue gain requiring about three times as much food as 1 kg of lean tissue gain), but in lean pig strains is mostly due to the maintenance effect, maintenance representing a non-productive on-cost. At 70 kg live weight a growing pig uses about 0.75 kg of food just for maintenance alone, whilst at around 120 kg food usage for maintenance has risen to 1.25 kg. Costs per kilogram of carcass meat in the conditions pertaining in Table 2.9 appear to be minimised at around 75–100 kg carcass weight. In general, the tendency is for optimum weight to be increasing year on year. Reductions in variable costs (feed) relative to fixed costs will force optimum weight upwards. If small-sized pigs are required at slaughter, profitability can only be attained if the higher production costs are adequately balanced by greater returns per kilogram.

**Table 2.9.** Influence of weight at slaughter on costs of producing 1 kg of pig carcass (all costs scaled to those at 100 kg live weight).

<table>
<thead>
<tr>
<th>Live weight of pig (kg)</th>
<th>Carcass weight (kg)</th>
<th>Fixed costs per kg carcass</th>
<th>Feed costs per kg carcass</th>
<th>Total costs per kg carcass</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>35</td>
<td>188</td>
<td>58</td>
<td>125</td>
</tr>
<tr>
<td>75</td>
<td>55</td>
<td>133</td>
<td>75</td>
<td>104</td>
</tr>
<tr>
<td>100</td>
<td>75</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>125</td>
<td>95</td>
<td>88</td>
<td>167</td>
<td>101</td>
</tr>
<tr>
<td>150</td>
<td>117</td>
<td>83</td>
<td>150</td>
<td>113</td>
</tr>
</tbody>
</table>
The tendency of recent decades has been for slaughter weight to increase. This is consistent with the production of larger maturing genotypes. Carcass weights differ widely according to country of origin, with the UK having the lowest (traditionally 66 kg dead weight). The norm is between 75 and 100 kg, except for speciality products such as Parma ham for which a carcass weight of 130 kg would not be exceptional.

The number of factors interacting upon optimum slaughter weight is legion, variable and highly dependent upon fluctuating market conditions. The particularly potent forces are weaner costs, feed costs and the price received per kilogram of carcass. Optimisation is best done with the help of some computer-aided decision-making process associated with response prediction modelling techniques.

Although fatness may result in a loss of revenue per kilogram, optimum profit may not always be synonymous with premium pig price and maximum leanness. The benefits of increasing pig weight at slaughter may more than offset the consequences of increased pig fatness – which may in any event be ameliorated by controlled feeding such as described in Table 2.10. The extent of feed intake control needed is much dependent upon the grade scheme and the penalty that is imposed for fatness. In many circumstances these penalties are inadequate to dissuade producers from opting for a low input cost system (low feed quality), a high slaughter weight and a fat pig. Mixed groups of entire male and female pigs fed *ad libitum* will result in the females being fatter than the males. Fat levels can be reduced by controlled feeding, but the growth rate and efficiency of the males will be curtailed. Once sufficient benefit is shown to ensue from reducing fat levels in the female, then controlled feeding appears to be called for; otherwise action to improve grading may actually be contraindicated. Just as for choice of weight at slaughter, the complexities of optimisation of level of fatness will require computer-aided decision-making if the right solution is to be determined. Sets of standardised tables for optimum weights and fatnesses at slaughter will obfuscate rather than enlighten.

### Problems of variation

In any production system there is variation; the less well-managed the production process, the greater the variation. In Figure 2.26, both Farm A and Farm B have the same mean P2 backfat depths, but low-variation Farm A will have relatively few

<table>
<thead>
<tr>
<th></th>
<th>Entire males</th>
<th>Females</th>
<th>Castrated males</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved strains</td>
<td><em>Ad libitum</em></td>
<td><em>Ad libitum</em></td>
<td>Slight restriction</td>
</tr>
<tr>
<td>Commercial strains</td>
<td><em>Ad libitum</em></td>
<td>Slight restriction</td>
<td>Medium restriction</td>
</tr>
<tr>
<td>Utility strains</td>
<td>Slight restriction</td>
<td>Medium restriction</td>
<td>Heavy restriction</td>
</tr>
</tbody>
</table>

1 Many ‘improved’ strains of pigs have been bred for leanness by means of selection for reduced appetite.
over-thin and over-fat pigs, and proportionately more at around the average. If premium prices are paid for pigs of between 10 and 14 mm, then despite both farms having the same average P2 backfat depth, Farm A will be much more profitable, with fewer outgrades than Farm B. Common causes of increased variation are disease, poor feeding management and poor housing.

Additional difficulties arise when more than one standard has to be met simultaneously. Often there are four main categories of carcass assessment:

- carcass weight
- carcass fatness
- carcass shape
- meat quality.

Shape and meat quality are primarily determined by pig type and pig and meat handling facilities at the abattoir; fatness and carcass weight are both under the short-term control of the producer. Given a weight range of, say, 70–80 kg dead weight, and a maximum fatness of, say, 14 mm P2, there are more likely to be outgrades with carcasses at the heavy end of the weight range than at the light; because as pigs get heavier they also get fatter. While pigs are often individually weighed before despatch, they are rarely checked for fat depth. There is increasing pressure on fatness, and therefore some logic in measuring fat depth on individual pigs before despatch, and sending the fatter pigs away at the lower end of the allowed weight range in order to ensure that a high proportion of the pigs meet the fat depth target. Due to the counteracting forces described above, it is not easy for producers to handle simultaneously a decreasing window size with regard to fat depths and a decreasing window size with regard to weight. The production cost of manipulating the diet and management of individual pigs in order to produce all pigs of similar fatness and weight would be high. Adjustment of carcass character after slaughter by action taken by the meat processor might often be cheaper than trying to produce carcasses ex-farm that are individually styled to the needs of the pig processing line (Figure 2.27). Greater overall efficiency might result from the strategy of the pig processor and pig producer accepting the presentation of a range of carcass weights and a range of carcass fatnesses. This strategy would cost a little extra at the proces-
However, the benefits to the producer would be legion. The need to weigh and measure individual pigs would be obviated, and a whole fattening house could be cleared at one time and at a predetermined date. Such proposals as these require close integration between pig producer and pig processor.

Variation in pig fatness at any given weight has also exacerbated the problem of very lean pigs (those with less than 8 mm P2). These problems have become particularly apparent since grade scheme requirements have progressively reduced the level of maximum fat allowed (Figure 2.28). The position is further inflamed by the additional complication that, as average fatness decreases the distribution for fatness within the population of pigs ceases to be normal and becomes skewed (Figure 2.22). This skewness makes the system highly sensitive at around the point of minimum fatness.

Fig. 2.27 Pigs can now be produced that are very lean. Bacon rasher (a) has 3 mm of skin and 4 mm of fat, giving a P2 of 7 mm. An alternative strategy is slaughter at a heavier weight (or use a blocky type, or both) which will give a bigger eye muscle (b) but predisposes to more fat. The undesirable fat can be trimmed back to 10 mm depth by removal of the skin and the first layer of fat (c). This latter pig is likely to have had a P2 fat measurement in excess of 16 mm P2. Both types of product (a) and (c) are readily available. Many customers prefer the trimmed rasher with the larger muscle, although the pig giving rasher (a) was by far the most lean.

Fig. 2.28 With a mean of 13 mm (distribution), few if any pigs have problems of meat quality. Such a mean would give an acceptable proportion of top grade pigs if the maximum fat measurement was 16 mm P2. With a mean of 9 mm (distribution b), many pigs will have meat quality problems if an acceptable proportion are to achieve top grade in relation to a maximum fat measurement to 12 mm.
Manipulation of carcass quality by control of feeding

Whilst for many pigs there are few or no grading standards, and for others the standards include measures such as conformation, in many environments pig grading can be considered as primarily dependent upon backfat depth. This is strategically most influenced by breed and genetic merit but tactically most influenced by nutrition.

Growth analysis presents a view of sequential waves of protein and lipid growth as weight and age progress. However, fatness, far from being related simply to age and weight, is more a function of the level of nutrient supply in relation to the level of nutrient need for maintenance + maximisation of potential daily lean tissue growth rate. Modern strains of meat pigs may never contain more than the 150 g lipid per kg live weight which was already evident in extreme youth at 3 weeks of age. There is therefore little ground for counting age and weight as the only or major contributors to body fatness in pigs grown for meat.

Although the long-range strategy for fatness reduction and the meeting of grading standards must be genetic, the tactics, for animals of any given genetic composition, will depend upon the knowledge that fatness is greatly influenced by the quality and the quantity of food. The major tactical mechanism open to producers to manipulate grade and to achieve target grading standards is through the control of the nutrition of the growing pig. Animals grown in nutritionally limiting circumstances may never fatten until maturity of lean body mass is achieved. With fast-growing improved breeds of larger mature body size, classical fattening may be difficult to obtain during the course of the rapid (immature) growth phase unless high levels of feed intake are achieved. For more normal strains of pig, for all castrated males and for the majority of females, there is a simple and direct relationship between the amount of food eaten (or given) and the level of fatness in the slaughter pig.

Protein

Lean tissue comprises protein and water. The relationship between daily dietary supply of protein and daily lean growth is linear up to the point at which protein deposition rate is maximised. While increasing diet protein is creating an improvement in lean tissue growth rate, the fatness of the pig will be progressively and proportionately diminished. Alternatively, diets that do not adequately provide for the requirement of absolute amounts of protein will fail to allow maximum lean tissue growth. Energy not utilised for the business of protein synthesis will be diverted to fatty tissue growth. However, excessive protein reduces dietary energy level. The energy yielded from protein by deamination is about half of the assumed digestible energy of the protein. The effective energy value of a diet containing an excess of protein will therefore fall as the deamination rate rises, with the resultant diminution of energy available for fat deposition. Overall, increasing the dietary concen-
tration of protein and offering a higher rate of daily protein supply will increase the percentage of lean and decrease the percentage of fat in the carcass; this response is, however, curvilinear in terms of its cost–benefit at higher levels of protein supply. The role of protein concentration in carcass quality is shown in Figures 2.29 and 2.30.

**Level of feed (energy)**

As a 10kg piglet may usually contain about 15% lipid, and as modern improved strains of pigs may reach slaughter weight with the same 15% of body lipid, it may be surmised that the balance of fat to lean in the growth will be rather constant over the growing period. An increase in the ratio of dietary energy to dietary protein over the growing period is only required to the small extent needed to cover for the increase in maintenance requirement as the animal grows. Where variation in body composition occurs, the greatest single determinant of that variation in growing pigs is the quantity of feed consumed (Figure 2.31). In normal growth the linear response of lean tissue to increase in feed supply is coupled with a minimum level of fat. In the limited feed supply phase there is a relatively constant relationship between daily gains of fat and lean over a range of growth rates. The minimum fat:lean ratio is thus an important determinant of body composition during this phase. This
minimum fat:lean ratio is a characteristic of sex and breed type. Males and improved breeds have a lower minimum fat:lean ratio. Fatty tissue growth above this minimum can only be achieved when feed supplies increase such as to exceed the need for maintenance, maximum potential rate of daily lean tissue growth rate and the minimum level of fat in normal gain. Feed supply may be said to be unlimiting when the plateau for daily lean tissue growth rate is reached. At this point excess energy is diverted to lipid metabolism and the animal fattens. High levels of feeding thus induce fattening, whilst lower levels will preclude it. In young pigs of 5–40kg or so the physical bounds of appetite may restrict feed supply to the limiting range. Above 40kg this is usually no longer the case and, given an unlimited feed supply, the animal will fatten in direct proportion to the extent of the over-supply of food. Pigs with limited appetites may never be able to eat enough to fatten before slaughter weight is attained; whilst pigs with lower potential for lean tissue growth rate or with higher appetites will be likely to fatten for a considerable proportion of their growth, and these animals will need their feed intake to be closely controlled if fattening is to be avoided (see Table 2.10).

Even while feed supply is inadequate to maximise lean tissue growth, there is some deposition of a minimum level of fat in normal growth as the animal strives for its preferred ratio of lipid:protein in the body. If this minimum level of fatness in normal growth gives backfat depths at slaughter weight that are in excess of the premium grade standard, then only severe reductions in feed supply and growth rate would bring about a significant reduction in fatness and a lipid:protein ratio in the body lower than that which the pig would prefer. Equally, in the case of some entire males, the minimum ratio may give backfat depths at slaughter that are below the minimum. In this latter case adequate fatness can only be achieved by luxury levels of feed intake.

Pigs of high genetic merit may have higher lean tissue growth potentials, lower minimum fat ratios or both. Such animals will be thinner at low feed intakes and more difficult to fatten as feed level increases. Excessive fatness is feasible for all pigs, but only if the feed intake level achieved is sufficient to maximise lean tissue.
growth rate and be defined as ‘unlimited’ in the example in Figure 2.31. It is evident, in order to optimise production and achieve grading targets, that the feed supply that will maximise lean tissue growth without generating excessive fat must be closely identified.

Overall, ad libitum feeding will be associated with fat carcasses if the pigs are of high appetite or low genetic merit. Controlled feeding to a ration scale will reduce fatness, but may also reduce daily gain. Given that the daily lean tissue growth potentials are greatest for entire males and worst for castrates, the results from the Meat and Livestock Commission Stotfold Research Station given in Table 2.11 illustrate most satisfactorily the relationship between feeding level and fatness, and the way in which sex and feed level interact with regard to carcass quality. Example feeding scales for controlled feeding are shown in Figure 2.32.

### Table 2.11. Influence upon carcass quality and growth performance of two levels of feeding and three sexes of pigs. (From the Meat and Livestock Commission Stotfold Station.)

<table>
<thead>
<tr>
<th></th>
<th>Ad libitum feeding</th>
<th></th>
<th>Controlled feeding</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male</td>
<td>Female</td>
<td>Castrate</td>
<td>Male</td>
</tr>
<tr>
<td>Daily feed intake (kg)</td>
<td>2.1</td>
<td>2.1</td>
<td>2.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Daily live weight gain (kg)</td>
<td>0.86</td>
<td>0.79</td>
<td>0.82</td>
<td>0.72</td>
</tr>
<tr>
<td>Killing-out percentage</td>
<td>75</td>
<td>77</td>
<td>76</td>
<td>75</td>
</tr>
<tr>
<td>Backfat depth (mm P2)</td>
<td>11.6</td>
<td>12.0</td>
<td>14.7</td>
<td>10.3</td>
</tr>
<tr>
<td>Carcass lean (%)</td>
<td>57</td>
<td>56</td>
<td>53</td>
<td>59</td>
</tr>
<tr>
<td>Lean growth (g/day)</td>
<td>390</td>
<td>360</td>
<td>340</td>
<td>330</td>
</tr>
</tbody>
</table>

**Fig. 2.32** Controlled feeding scales, incremented weekly toward a given maximum. The higher scale is appropriate for pigs with higher lean tissue growth rates, or in circumstances where fatness is not heavily discriminated against.

Manipulation of slaughter pig value by control of the production process

The pig industry is better served when the production and meat packing sectors are integrated. This allows the competitive (exploitative) marketing interface between pig producer and meat packing plant to be removed. Nevertheless, most producers do face difficult marketing decisions at the point of sale of their product, and the
outcome of those decisions has a dramatic effect upon the financial viability of the operation. Until recently, pig production was about maximising the weight of pig meat leaving the farm and minimising the cost of its production; now equally important is the quality of the consumer’s eating experience.

Of the total costs of production of edible pig meat:

- 15% is in the production step;
- 10% is in slaughtering;
- 25% is in processing and packing;
- 20% is in distribution;
- 30% is in retailing.

Reducing costs of production therefore has only a small effect on the profitability of the sector overall. Much greater effects are had by adding value post slaughter and increasing the price the consumer is willing to pay by enhancing the quality of the end product. The total size of a market will be increased if the product is far distant from any expression of consumer dissatisfaction. Unfortunately, in some cases pig meat is not distant enough from an expression of dissatisfaction at the point of eating; and this constrains market expansion and disallows price increase.

Pig producers may adjust their marketing strategies for slaughter pigs through the mediums of:

- weight at sale (influenced by throughput targets, quality of pig, local market requirements);
- fatness at sale (controlled through feed level, feed nutrient specification, genetics);
- choice of meat packer (influenced by geographical location, price offered, method of payment, differentiation for quality);
- meat quality at sale (controlled through genetics, feed nutrient specification, management, handling).

Of production costs, the greatest singular variable cost elements are those for feed and for weaners. The financial margin over feed and weaner costs can be expressed on the basis of an individual pig (per pig) or on the basis of the pen space available in a year (per pig place per year). The latter value has the advantage of allowing for the real rewards of increased pig throughput which can come from increasing the rate of growth or selling the pigs at a lighter weight. The example in Figure 2.33 shows, for this particular case, that although the best margin per pig is achieved when selling at a higher slaughter weight, the best margin per pig place per year occurs at a lower slaughter weight.

**Weight at sale for carcass meat**

Optimum weight at sale interacts particularly with the severity of any penalty there may be against fat. The less severe the penalty, and the less likely the pigs are to become fat, the higher will be the optimum slaughter weight (Figure 2.34). Within
any given scheme for quality payment there is a further interaction with feeding level. Figure 2.35 shows the position for pigs despatched to a meat packer which discriminates against fat carcasses. The figure lends support to the benefits of controlled versus appetite feeding, particularly at the higher slaughter weights. However, controlled feeding may not always be appropriate just because the grading scheme is severe. The imposition of too strict a ration scale can militate against margin optimisation through excessive reduction in growth rate and throughput. This negative effect of ration control becomes particularly marked at the higher live weights. The pattern of response shown in the figures would also be different following an increase in the price of animal feed ingredients – particularly cereals – which would tend to favour a reduction in weight at slaughter and a decrease in feed allowance. Alternatively, in some countries it is common practice for flat-rate payments to be made for all pigs regardless of their level of fatness. This will stimulate higher rates of feeding, heavier slaughter weights and fatter pigs.

The cost of producing or buying weaners has the same predictable effect of any unavoidable cost upon a production system; as the cost of weaners goes up, it becomes progressively more beneficial to increase the slaughter weight of individ-
ual pigs – thereby spreading the fixed weaner cost over a greater amount of product sold (Figure 2.36).

**Fatness at point of slaughter**

It is evident that for the same or lesser input costs, a leaner pig would be more profitable than a fatter one if a buyer pays a premium for leanness. It is equally evident that if the buyer is indifferent to fatness, the relative benefits of a fat or lean pig at any given weight will depend upon the feed costs per kilogram of live weight gain – regardless of the composition of that gain. A cheap food and a fat pig may give a poorer feed conversion ratio, but not a poorer monetary conversion ratio; this latter option may therefore be profitable. Fatness rarely acts as the single variable in a marketing decision. Fatter carcasses may result from an increase in carcass weight, and so create a conflict of tactic. Fatness may also be a consequence of faster growth, greater throughput and a higher volume of pigs sold. Both of these latter elements of overall performance bring financial benefits which may outweigh the penalty that can result from a reduction in carcass quality.

Given the background of a strong and practically linear response of fatness to feed intake itself, the interrelationships between pig type (growth rate, carcass quality) and feed intake may be seen in Figure 2.37. While pigs not predisposed to being fat will always be more profitable than those that are, there is an interaction to the extent that an increase in feeding level and fatness improves the position in the former case (pigs not likely to become fat) but worsens it in the latter (pigs likely to become fat).

Both backfat depth and percentage carcass lean will show a distribution (skewed for the former and normal for the latter) about the mean value. Increase in the proportion of animals falling into the top quality category will often require sacrifices
in terms of a lower weight at the point of sale and/or lower growth rates, and/or higher specification (higher cost) diets. In order to encourage the pigs at the poorer end of the distribution curve to fall into the top quality category for carcass leanness, the benefits of greater growth rates, weights at sale, etc. will require to be foregone in the case of all those pigs already positioned at the better end of the distribution curve, and which did not require extremes of treatment to achieve success. For the benefit of the few, therefore, the majority are unlikely to have been performing optimally. There may therefore be financial disadvantage in a production strategy that places a high proportion of all the pigs into the best grading classification – even when premiums are high (Figure 2.38). To achieve 95% top grade pigs may bring maximum processor satisfaction but not maximum producer profit.

**Choice of market outlet**

In a non-integrated chain structure, pig slaughterers and meat processors differ amongst themselves as to their preferred weight of pig and preferred level of fatness. There will be further differences in the average prices offered and the extent of the financial benefit that might be available for meeting quality criteria. The importance of choosing the right processor for pigs of different levels of fatness is exemplified in Figure 2.39. The figure relates to an increasing level of fatness at sale which has been achieved by increasing the level of feeding of a balanced diet. It shows the influence of pig fatness upon financial margin under three different payment schedules: (a) with a low penalty for carcass fatness, (c) with a high penalty for carcass fatness and (b) intermediate. For pigs destined for meat packer (a), the benefits of faster growth rate clearly outweigh problems of increased level of fatness; whereas the
exact opposite is the case for pigs destined for packer (c). It should not be assumed, however, that the position depicted in Figure 2.39 is in any way static; quite the contrary, it is highly dynamic and dependent, amongst other things, on the relative price of feedstuffs as compared to pig carcass meat. If pig prices stay high, the quality differentials remain the same, but if feed prices fall, then the response to schedule (b) will take on the shape of that now shown for schedule (a); it will become profitable to produce fatter pigs. The system is therefore particularly sensitive to changes in pig and feed prices.

**Marketing opportunities: calculations for particular cases**

**Case 1: An alternative contract**

An attractive flat-rate contract for 70kg pigs is offered to a producer already doing well, with a quality premium scheme for 90kg pigs. A 17.5% crude protein diet is fed to a restricted scale and the farm margin was 7000 units of currency per year. The lighter weight flat-rate contract may be determined to be unattractive (Table 2.12) unless and until the pigs are fed generously, while the best solution for slaughter at either weight includes the use of two (rather than one) diets. The best solution seems to be for all pigs to be fed generously, but those with a predisposition to

**Table 2.12.** Calculation of farm margin (units of currency per year) when pigs are slaughtered at 70kg or 90kg live weight under different production circumstances.

<table>
<thead>
<tr>
<th></th>
<th>70kg slaughter</th>
<th>90kg slaughter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restricted feeding of a single medium-quality feed</td>
<td>5500</td>
<td>7000</td>
</tr>
<tr>
<td>Generous feeding of a single medium-quality diet</td>
<td>9000</td>
<td>4000</td>
</tr>
<tr>
<td>Generous feeding of two diets (grower + finisher)</td>
<td>12000</td>
<td>9000</td>
</tr>
</tbody>
</table>

![Fig. 2.39 Influence of level of fatness caused by level of feeding upon financial margin when the pigs are marketed to three different processors which discriminate against fat to varying degrees: (a) low level of discrimination; (c) high level of discrimination; (b) intermediate.](image)
be fat (castrated males) being drawn out for slaughter at 70 kg while the others remain to grow on to 90 kg.

Case 2: Pigs that are too fat

A producer is alerted by the meat processor that the pigs are no longer acceptable unless something is done to make them less fat. Upon investigation of the accounts, it becomes apparent also that the unit is running at a loss. Mixed female and castrated commercial-type pigs are fed a limited feed allowance using two diets: one of a higher quality for 20–50 kg live weight pigs, and one of a lower quality for 50–90 kg live weight pigs. Table 2.13 shows at (o) the current performance. Grading could be improved in five obvious ways: (a) reduce slaughter weight, (b) further increase protein content of the diets and incur extra costs, (c) reduce daily feed allowance, (d) find a market for entire male pigs and stop castrating or (e) use an improved strain of pig.

Reducing slaughter weight (a) is no help because it is not sufficient to reduce backfat depths by an adequate amount; throughput is increased, however, resulting in more pigs sold (at a loss!). Nor is increasing the cost and quality of the diets (b) any help. Reducing the feed allowance (c) seems to be an appropriate short-term tactic that can be put into effect immediately and will prevent the present rate of financial loss, whilst also substantially improving the grading. Longer-term strategies would need to include finding a market for entire male pigs and stop castrating or (e) use an improved strain of pig.

Reducing slaughter weight (a) is no help because it is not sufficient to reduce backfat depths by an adequate amount; throughput is increased, however, resulting in more pigs sold (at a loss!). Nor is increasing the cost and quality of the diets (b) any help. Reducing the feed allowance (c) seems to be an appropriate short-term tactic that can be put into effect immediately and will prevent the present rate of financial loss, whilst also substantially improving the grading. Longer-term strategies would need to include finding a market for entire male pigs and stop castrating or (e) use an improved strain of pig.

Table 2.13. Calculations to determine the comparative advantages of various tactics and strategies for a 600-place fattening house to resolve a problem of poor carcass quality: (o) presents the current performance; (a) reduces slaughter weight; (b) increases diet quality; (c) reduces feed; (d) ceases castration; (e) improves the quality of the pig.

<table>
<thead>
<tr>
<th></th>
<th>(o)</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(e)</th>
<th>(cde)</th>
<th>(bde)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily live weight gain (kg)</td>
<td>0.69</td>
<td>0.68</td>
<td>0.68</td>
<td>0.59</td>
<td>0.71</td>
<td>0.70</td>
<td>0.60</td>
<td>0.73</td>
</tr>
<tr>
<td>Feed conversion ratio</td>
<td>2.79</td>
<td>2.75</td>
<td>2.82</td>
<td>2.84</td>
<td>2.69</td>
<td>2.74</td>
<td>2.78</td>
<td>2.57</td>
</tr>
<tr>
<td>Pigs with P2 &lt; 14 mm</td>
<td>26</td>
<td>34</td>
<td>33</td>
<td>59</td>
<td>62</td>
<td>43</td>
<td>86</td>
<td>91</td>
</tr>
<tr>
<td>(top grade) (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual throughput of pigs through unit ('000)</td>
<td>2.11</td>
<td>2.23</td>
<td>2.09</td>
<td>1.81</td>
<td>2.15</td>
<td>2.13</td>
<td>1.84</td>
<td>2.23</td>
</tr>
<tr>
<td>Monetary margin over feed and weaner costs (per pig)</td>
<td>7.50</td>
<td>7.00</td>
<td>6.10</td>
<td>10.32</td>
<td>12.03</td>
<td>9.84</td>
<td>12.75</td>
<td>13.24</td>
</tr>
<tr>
<td>Annual monetary margin for unit</td>
<td>-3.43</td>
<td>-3.83</td>
<td>-6.44</td>
<td>0.05</td>
<td>6.54</td>
<td>1.66</td>
<td>4.78</td>
<td>10.12</td>
</tr>
</tbody>
</table>
Case 3: Improving upon excellence

A breeding company multiplier supplies stock to a second commercial unit also under its ownership. The meat processor consistently praises the high quality of the pigs received. Good quality diets are fed at restricted levels to mixed entire and female stock. The commercial unit is in profit [Table 2.14, (o)], but only just. The simple expedients of increasing the feed scale and slaughtering some 3 kg heavier (a) are able to double the profits without materially harming the good grading performance; the latter being important to sales of hybrid breeding females from the parent multiplier herd.

<table>
<thead>
<tr>
<th></th>
<th>(o)</th>
<th>(a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily live weight gain (kg)</td>
<td>0.65</td>
<td>0.72</td>
</tr>
<tr>
<td>Feed conversion ratio</td>
<td>2.52</td>
<td>2.49</td>
</tr>
<tr>
<td>Pigs with P2 &lt; 14 mm (%)</td>
<td>98</td>
<td>91</td>
</tr>
<tr>
<td>Annual throughput of pigs through unit ('000)</td>
<td>1.99</td>
<td>2.11</td>
</tr>
<tr>
<td>Monetary margin over feed and weaner costs (per pig)</td>
<td>14.03</td>
<td>15.58</td>
</tr>
<tr>
<td>Annual monetary margin for unit</td>
<td>3.95</td>
<td>8.60</td>
</tr>
</tbody>
</table>

Table 2.15. Calculations to examine the comparative advantages of four diets of differing quality and price.

<table>
<thead>
<tr>
<th>Diets</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude protein (g/kg)</td>
<td>150</td>
<td>175</td>
<td>200</td>
<td>225</td>
</tr>
<tr>
<td>Crude fibre (g/kg)</td>
<td>60</td>
<td>50</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Oil (g/kg)</td>
<td>30</td>
<td>45</td>
<td>55</td>
<td>60</td>
</tr>
<tr>
<td>Price (£/t)</td>
<td>140</td>
<td>155</td>
<td>165</td>
<td>175</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Responses</th>
<th>Daily live weight gain (kg)</th>
<th>0.68</th>
<th>0.78</th>
<th>0.84</th>
<th>0.86</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Feed conversion ratio</td>
<td>2.97</td>
<td>2.62</td>
<td>2.49</td>
<td>2.42</td>
</tr>
<tr>
<td></td>
<td>Pigs in top grade (%)</td>
<td>26</td>
<td>50</td>
<td>55</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>Annual throughput ('000)</td>
<td>2.11</td>
<td>2.38</td>
<td>2.52</td>
<td>2.61</td>
</tr>
<tr>
<td></td>
<td>Monetary margin over feed</td>
<td>6.21</td>
<td>9.39</td>
<td>10.14</td>
<td>9.00</td>
</tr>
<tr>
<td>and weaner costs (per pig)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual monetary margin for the unit</td>
<td>-6.13</td>
<td>2.60</td>
<td>5.49</td>
<td>3.24</td>
<td></td>
</tr>
</tbody>
</table>

Case 4: Difference between diets

A producer feeding the pigs *ad libitum* from self-feed hoppers is offered four alternative diets to be given from 20–90 kg (Table 2.15). The feeds are of different qualities and different prices. Feed 3 is calculated to be the best option, but the carcass
quality and grading profile is not really good enough. On the unit, it is ascertained that feed intake can be restricted if the slides on the hoppers in the finishing house are closed down to reduce the rate of feed flow. When the feed supply is restricted, diets 3 and 4 both calculate to perform equally well. Growth rates fall to around 0.75 kg per day, but up to 80% of pigs can now fall into top grade, and the margin rises to around £10000 for the year. The choice between diets 3 and 4 has thus become relatively insensitive.

**Sensitivities**

Comparing sensitivities is a vital part of assessing marketing opportunities, and these will change with fluctuations in the price of pigs, the price of pig feeds and the premium paid for quality with respect to both diet inputs and carcass outputs. The above cases related to carcass grade premiums of around 10% or more of the average price per kilogram of dead weight. Greater or lesser grade differentials would result in quite different conclusions to the various calculations.

The essential qualities of marketing opportunity calculations are their dynamism and sensitivity to prevailing circumstance. Such calculations are complex but nevertheless need to be repeated often if they are to be useful. As with all business forecasting of this nature, management decision-taking is made considerably simpler if the calculations are completed through the medium of computer simulation models; as indeed has been the case here.
Introduction

The purpose of growth is to reach maturity; the impulsion for growth is generated from current state (mass, size), age and (importantly) nutrient supply. Maturity itself has many definitions; the ability to breed is reached well before (about 50%) attainment of final size or weight. Final size may be best judged in terms of lean body mass rather than total mass due to variable, and highly nutritionally dependent, fatty tissue levels being possible in the mature pig. Expected mature lean mass and the time of its being reached is the basis of growth analysis, and it is evident that with genetic selection for increased daily lean tissue gain there has been an increase in mature lean tissue mass. Lean tissue comprises around 22% of protein, and the mature protein mass of modern pigs selected for fast lean tissue growth rate appears to be in the region of 35–55 kg. Mature live weights of different breeds and strains of pigs may vary from 150–400 kg. Improved European hybrid females may reach 300–350 kg without being unduly fat, but unimproved sows may become no heavier than 250 kg, at which weight they are obese.

Growth is usually understood to relate to gain in size, brought about by cell multiplication (as in pre-natal cleavage) and cell enlargement (as in post-natal muscle growth). As a part of cell enlargement there may also be simple incorporation of material directly into cells (as in the inclusion of lipid into fatty tissue). Muscle fibre number is largely determined at the point of birth, so observed animal growth in lean tissue is primarily due to increase in muscle fibre size. Pre-natal factors that may increase total muscle fibre number are therefore likely to have a permanent effect on post-natal growth rate; it seems that there is a positive correlation between fibre number and potential rate of growth. It would appear that the physiology and nutrition of the gravid sow may influence fetal muscle fibre number. Small pigs at birth may have become small through inadequate nutrition in utero, they may have a lower fibre number and therefore may grow slower. It is possible that even early pregnancy nutrition can influence fibre number, while late pregnancy nutrition may influence birth weight through both muscle fibre number and size, but mostly the latter.

Development relates to changes in the shape, form and function of animals as growth progresses. The blocky Pietrain, Belgian and German Landrace-type pigs develop in a way that results in meatier hams and larger loin muscles. In general,
as pig carcass weight increases, so does the area of the eye muscle. This rate of increase in muscle is greater and reduces later in the case of Pietrain pig types, while with the Meishan pig type the rate is less and reduces earlier, with Large White/Landrace types intermediate. Fatty strains of pigs will develop in such a way as to be a different shape from lean strains. Rounded hams in an unimproved strain of Large White will be indicative of fat, not lean.

The study of changes in body proportions and body shape during progress to maturity has not received as much attention as that of overall tissue growth. As a pig develops the differential deposition of fatty tissues in the various parts of the body is not particularly evident. Most pigs lay down some two-thirds of their fat as subcutaneous fat, and about one-third internally, the latter mostly as intermuscular fat and fat around the kidneys and intestines. Subcutaneous fat tends to be laid down in a way such that, although different parts of the body have different amounts of fat, these do not develop in marked sequence. A young fat pig will carry a similar balance of fat in its various depots as an older fat pig. Perhaps another reason for development (rather than growth) receiving scant attention is because pigs differ from beef and lamb in having a smaller gradient in eating quality and acceptability between the various parts of the body.

In contrast, the absolute rate of growth is a prime determinant of the efficiency of conversion into meat because of the savings in food used for maintenance (Figure 3.1). Maintenance costs occur daily, utilising food but yielding no product. A pig growing slowly will incur the same daily feed maintenance costs as one growing fast, but will have less product to offset the fixed cost of that feed. The ratio of daily lean tissue growth to daily fat tissue growth is second only to the rate of overall growth as a controller of the efficiency of feed use, because the feed energy cost of fatty tissue growth is more than three times that of lean tissue growth on account of the differing water content of these two tissues (Figure 3.2).

The relative rates of growth of bone, muscle and fatty tissues are important considerations in the provision of meat for human food. The ratio of lean to bone contributes to carcass value whilst the amount of fat on the meat is a vital indica-
tor of product quality, with subsequent ramifications for meat processing and retailing practices, although, as mentioned earlier, the desired ratio of fat to lean varies widely amongst the various world markets. Relationships between bone, muscle and fat growth will, of course, also affect the development of the animal. At any given weight, animals grown slowly and being of greater age will tend to have a higher ratio of bone to fat. Animal body shape is strongly influenced by the extent and the position of the fat cover. The rounded shape of a sucking pig is likely to be due to the high covering level of subcutaneous fat. However, this is not invariably the case, as, for example, with pigs of the Pietrain and Belgian Landrace type, in which a well-rounded rear quarter indicates high lean meat yield. Thus, as the weight of the pelvic limb increases, the proportion of fat in the limb also increases, but at a much greater rate in fatty pig types than in lean ones.

Growth occurs through the accretion of bone, fatty and lean tissues in the body. It is a result of a positive difference between the continuous anabolic and catabolic processes associated with tissue turnover. Because most fatty tissues are turned over slowly, there is a close association between the absolute amount of fatty tissue anabolised and the absolute amount accreted. On the other hand, lean tissue turns over rapidly, such that accretion may be only 5–20% of the total protein anabolised; the less mature the pig the higher will be that proportion.

**General composition of the body**

The approximate physical composition of slaughter pigs has been presented earlier in Figure 2.18. The crude carcass, after removal of offals, intestines and blood, comprises about 75% of a meat pig, but of this some 11% is head, feet and skin, leaving
about 64% of carcass side. The carcass side may be dissected into edible fatty and lean tissues, the proportions of which vary according to pig sex, genotype, nutrition and slaughter weight. A lean, head-off, skin-off, feet-off carcass side may usually comprise 10% bone, 23% fatty tissue and 66% lean tissue (of the crude carcass, respective percentages would be 11, 30 and 58; leanness of carcasses is often expressed in terms of percentage of dissectable lean in the carcass for purposes of quality assessment).

The chemical composition of the whole body of the growing pig varies with the lean : fat : bone ratio, but averages about 64% water, 16% protein, 16% lipid and 3% ash, with a small amount of (liver) carbohydrate.

At any given weight and sex, higher levels of feeding will increase the percentage of fat, while at any given weight and level of feeding the entire male is considerably leaner than the castrated male, with the female intermediate (around 60% carcass lean for the entire male; and 56 and 58% for the other two sexes respectively). As already appreciated from Chapter 2, increase in body weight is usually associated with a progressive increase in fatness unless feed intake is restricted. Table 3.1 shows the chemical composition of the body of pigs as they grow, and demonstrates the increase in fatness and the decrease in the water : protein ratio, as well as the dramatic effect that feed intake control can have upon fatness. Protein content is found to be relatively much more stable a proportion of the total body than fat content; the former usually varying between extremes of 14 and 18%, while the latter may vary from 5–40%.

The composition of pigs as they grow can be expressed in the form of an allometric relationship \( Y = a \cdot X^b \), where \( Y \) is the component and \( X \) the empty body weight. Values in Table 3.2 indicate for pigs fed to appetite the general direction of developmental changes in body components through growth. Pigs fed less and/or of improved genotype have relatively less fat and more lean at any given empty body weight. Table 3.2 indicates the following: that between 20 and 160 kg live weight, amounts of carcass fatty tissue and lipid are growing relatively faster than the body as a whole (this effect is stronger in the castrate than the entire male, with the female intermediate); body water varies in proportion to protein and inversely to lipid; and

### Table 3.1. Chemical composition of pigs (%).

<table>
<thead>
<tr>
<th></th>
<th>At birth</th>
<th>At 28 days</th>
<th>Full-fed</th>
<th>Restrict-fed</th>
<th>150 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>77</td>
<td>66</td>
<td>60</td>
<td>68</td>
<td>63</td>
</tr>
<tr>
<td>Protein</td>
<td>18</td>
<td>16</td>
<td>15</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>Lipid</td>
<td>2</td>
<td>15</td>
<td>22</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td>Ash(^1)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

\(^1\) The mineral composition of the fat-free body tissue of pigs was measured by Spray and Widdowson [Spray, C. M. and Widdowson, R. A. (1950) *British Journal of Nutrition*, 4, 332] in terms of grams of mineral per kilogram of fat-free body tissue as follows: calcium 12.0; phosphorus 7.9; potassium 2.8; sodium 1.5; magnesium 0.45; iron 0.09; zinc 0.03; copper 0.003.
The relative growth rate of protein is close to that of the total empty body as a whole (but more so for entire males than castrates, again with females intermediate).

The low body content of lipid at birth, although adjusted within the first month of life, may reappear after weaning due to loss of fat at this time when the lipid:protein ratio may fall back from >1:1 to <0.5:1. In one experiment, young growing pigs of 19.6 kg empty body weight contained 16.6% protein, but only 10.7% lipid. Even for these generously fed pigs it was not until 50 kg live weight had been reached that the balance of lipid to protein was redressed. The relationship between lipid mass ($L_t$) and protein mass ($P_t$) for females grown from 20–200 kg was found to be:

$$L_t = 0.250 P_t^{1.74}$$  \(3.1\)

Changes in the general composition of the body with the progression of live weight and time are shown graphically in Figures 3.3 (chemical components) and

<table>
<thead>
<tr>
<th></th>
<th>b</th>
<th>a</th>
<th>Values for Y when X = 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissected edible lean</td>
<td>0.97</td>
<td>0.41</td>
<td>36</td>
</tr>
<tr>
<td>Dissected edible fat</td>
<td>1.40</td>
<td>0.030</td>
<td>19</td>
</tr>
<tr>
<td>Dissected bone</td>
<td>0.83</td>
<td>0.16</td>
<td>7.3</td>
</tr>
<tr>
<td>Whole body protein</td>
<td>0.96</td>
<td>0.19</td>
<td>16</td>
</tr>
<tr>
<td>Whole body water</td>
<td>0.86</td>
<td>0.93</td>
<td>49</td>
</tr>
<tr>
<td>Whole body lipid</td>
<td>1.50</td>
<td>0.020</td>
<td>20</td>
</tr>
<tr>
<td>Whole body ash</td>
<td>0.92</td>
<td>0.049</td>
<td>3.4</td>
</tr>
</tbody>
</table>

1 Live weight = 1.05 empty body weight.

Recent work confirms b values for lean of 1.0–1.1 and for fat of 1.3–1.6; and a values for lean of 0.34–0.37 and for fat of 0.01–0.03; dependent upon breed type. Also confirmed are b values for protein of 0.87–0.97 and for lipid of 1.4–1.6; and a values for protein of 0.19–0.30 and for lipid of 0.01–0.03; dependent upon breed type.

---

**Fig. 3.3** Weights of lipid and protein body components of *ad libitum*-fed pigs in relation to increase in live weight. Notice the relative constancy of the lipid:protein ($L_t:P_t$) ratio ($\approx 1:1$) between 25 and 100 kg live weights. (Adapted from Whittemore, C.T., Tullis, J.B. and Emmans, G.C. (1988) *Animal Production*, 46, 437–45.)
3.4 (physical components). A generalised expression for the way protein and lipid masses increase as pigs age is given in Figure 3.5. Both curves show acceleratory and deceleratory phases linked by a period of linear growth. The asymptote for lipid is substantially greater (at least two times) than that for protein, and occurs later in time; there being serial progression of time at maturity for lean and fat. Lipid mass does not exceed protein mass until 150+ days of age. It is germane that at present in Europe and North America, an appropriate condition for slaughter is when the lipid:protein (Lt:Pt) ratio is about 1:1 at ages around 130–170 days and live weights around 80–110 kg. In other countries, however, pigs require to be heavier, older and fatter, when Lt:Pt can be 2 or more. The proposition that final mature lipid mass (Lt\text{max}) may be about twice the final mature protein mass (Pt\text{max}) is probably reasonable for pigs:

\[ \text{Lt}\text{max} = 2 \text{Pt}\text{max} \]  (3.2)

The relationships between bone and muscle, and ash and protein are relatively constant (ash = 0.03 live weight or 0.20 protein) due to the use of bone as the support
structure for muscle. In contrast, although the lean content of the body varies somewhat inversely with fatty tissue, the relationship is not especially good and this is due in part to the changing water content of lean. Usually, dissected lean tissue (muscle) contains 70–75% water, 5–15% fat and 20–25% protein. In a very young pig the water content of lean can be as high as 80%, but in a mature animal the water content of lean may well be less than 70%. Although carcass dissected lean may be estimated by the rule of thumb,

\[
\text{Carcass dissected lean} = 2.4 \text{Pt}
\]

where Pt is the total body protein mass, the relationship between body water and body protein is allometric. Calculations of total body water (Yt) from an expression such as:

\[
Yt = 4.11 \text{Pt}^{0.89}
\]

allow for the reduction in the amount of water associated with each unit of protein as the animal grows.

Fatty tissue contains 10–25% water, 2% protein and 70–80% lipid. Because the growth of fat is so variable a proportion of the total growth, fat is poorly predicted from the knowledge of either muscle mass or live weight. Most of the variation in fat growth is due to the level of nutrient supply; the more food, the fatter the pig. So where food is limited the growth of fat in relation to lean is much more predictable and may be represented as a constant proportion of protein over much of the growth period. Although it is generally agreed that in the course of normal growth pigs become fatter as they grow in size, the point at which such fattening begins is highly dependent on sex, genotype and feed level. Improved male pigs may contain no more than 12% of lipid over the totality of a 10–110 kg growth phase, while unimproved castrates may readily achieve 25% lipid over the same growth increment. Female pigs are intermediate. Naturally, pigs will only demonstrate their propensity to fatten if feed supply is adequate to allow it.

It is generally helpful to consider the principles of growth primarily in terms of the growth of protein and lean, and to allow fat to follow protein in the form of some given relationship when nutrition is limiting, but to be independent of protein and dependent on feed supply when the latter is ample.

Growth curves

Given adequate environmental conditions, animals will increase their weight with increasing time as they grow to attain mature size. The slope (b) in Figure 3.6 describes the rate of increase in weight with time, while an asymptote (A) describes mature size. A has a strong genetic component and will differ between pig types. Modern strains of pigs selected for lean gain have higher growth rates (b) than unselected. Different values for A (mature weight) could be associated with similar or different values for b. In general, however, time at maturity (t₁) is not as open to
variation as A. As possible differences in absolute weight at maturity are many times greater than the possible differences in absolute weight at birth (although there is invariably a strong positive correlation, animals with greater mature weights having greater weights at birth), it is not reasonable to suppose that all of the absolute difference in A between two animal types could be accounted for by absolute differences in birth weight. It is inevitable, then, that A and b are positively related; greater mature size being associated with faster rates of growth, and positive selection for growth rate resulting in greater mature size.

Faster-growing strains of pigs will have breeding sows that are bigger and heavier, and which will have higher maintenance requirements, and need more space in stalls, farrowing crates and in loose housing. The higher feeding, housing, management and care costs of large females in breeding herds producing slaughter generation pig meat are a matter of some concern to those who will see efficiencies from having smaller sized females. However, large females may have counter-balancing benefits of enhanced productivity from a larger uterine capacity and a greater milk production potential. Three strategies may be considered for dealing with the disadvantages, if such are perceived, of large mature size. The first is to maintain a small-sized female breeding population but to use upon it a large-sized top-crossing sire, which at least will impart 50% of fast-growing genes to the slaughter generation. The second is to try to control the size of the breeding female by environmental constraints (such as a strict nutritional rationing regime) and thus to deny the attainment of ultimate mature size. In the case of breeding pigs this would be unwise as there would be a catastrophic effect upon subsequent reproduction. The third strategy is to modulate the growth curve by genetic selection so as to increase the value of b to b₁ (rate of growth) without concomitant increase in A to A₁ (see Figure 3.6). This can be achieved only by a reduction in t₁ to t₂, and the attainment of mature size at an earlier time. Unfortunately, it would seem that this last strategy is difficult to achieve at the present time by conventional genetic selection techniques. In any event, it is not self-evident that the intrinsic advantage of
small size in breeding sows is particularly great, as the larger animals can have greater sizes of conception products (especially piglet birth weight) and higher lactation yields.

Figure 3.5 described the gain in mass over time in terms of a general sigmoidal curve (with acceleration and deceleration phases linked by a point of inflection), and Figure 3.6 is consistent with the upper part of such a curve. The classical growth curve depicted in Figure 3.7 is frequently misinterpreted. It is wrongly assumed (1) that the curve begins its acceleration at birth (it actually begins at conception), (2) that puberty is always associated with the point of inflection (which it is not) and (3) that the accelerating and decelerating phases are mirror images of each other (which they are not). Such wrong assumptions are sadly often made and incorrectly determine vital issues such as: the potential rate of growth in animals; the point at which growth can be maximised; the period of growth over which optimum live weight gain can be made; the best time of slaughter for meat; and expectations for the beginning of the reproductive cycle.

It is fundamental to the understanding of growth that the two phases (acceleration and deceleration) are disassociated one from the other and considered separately. It can be agreed that embryonic and early (fetal) growth, comprising cell multiplication, must be self-acceleratory, and there will be a relationship between current mass and accretable mass (for it is ridiculous to suppose that a 0.5 kg animal can grow at a rate of 500 g/day, but it is not ridiculous to suppose that a 10 kg animal could do so). Equally, it can be agreed that late growth to maturity must indeed be deceleratory if mature size is to be rationally attained (if the system does not slow down, then it could not ultimately stop). However, the intervening period between early and late growth need not necessarily be any mathematical continuation of these two phases nor, being so differently driven, need the acceleratory and deceleratory phases be of similar quantitative constitution. The intervening period between accelerating and decelerating growth is of prime importance for the
production of human food from pigs as it spans the major proportion of the time between weaning and slaughter (the former usually occurring at around 28 days of age, and the latter usually at or below the attainment of 50% of mature size). There can be no *a priori* assumptions about constancy of the percentage growth rate or the number of new cells being proportional to the mass of the existing cells once the phase of fetal growth is past; post-natal growth is more a function of increase in cell size and of cell filling than of cell number, and there may be more self-evident truth in tending toward an assumption of constancy of absolute growth rate post-natally rather than toward constancy of percentage growth rate. In brief, there is good reason to presume that rather than an instant moment of ‘linearity’ at the point of inflection, there is more probably a rather lengthy and sustained period of linear growth; occurring precisely over the important growth period of animals grown for meat.

In many agricultural circumstances acceleration of growth post-natally may be indicative of nothing more, or less, than a progressive release from feed limitations in early life, such as with chicks and calves weaned on the day of birth. Indeed, where nutrition and environment are unlimited, there is evidence that absolute rate of growth can be extremely high in the young animal. Piglets given *ad libitum* milk in early life may experience more than 300 g average daily gain in the first post-natal days and up to 500 g daily by day 6. This shows not only that the potential in a sucking pig for growth is above the 200–400 g possible from the milk yield of the sow alone, but also that the potential is a remarkably high percentage of its body weight (nearly 15%). Twenty-one day weights above the 7 kg average for litters of pigs sucking productive and well-fed sows are not in any way exceptional, and individual piglet weights of up to 12 kg attained at Edinburgh at 28 days (rather than the normal expected 8–9 kg) again indicate the difference between potential and commercial achievement. Given unlimited nutrition and an excellent environment, it may be that the maximum absolute rate of growth can be achieved early in life and be relatively constant through most of the growth period. Such a proposition refutes the idea that achievable growth rate is somehow related to the mass of body already attained – as might be assumed from a strict interpretation of conventional sigmoidal growth theory. Also refuted is the corollary to the evenly balanced sigmoidal growth curve around a central point of inflection, which is that daily gain \( \frac{dW}{dt} \), as a function of age or weight, is a quadratic, symmetrical response peaking at 0.5 of mature weight.

Nonetheless, depictions of growth in the form of quadratic function still persist in many elementary explanations, and this is particularly unfortunate as it fails to recognise early growth potential, and misunderstands the growth process that is so important to efficient production of pig meat.

It is realistic to forward a view that rates of gain approaching the maximum may be reached early in life and be maintained over a significant part of the growth phase. This presents a broadly linear assumption of potential growth once the pre- and immediate post-natal phases are past and before the approach to maturity is begun. Expressed in terms of the influence of time \( t \) upon daily live weight gain
(dW/dt) a relatively flat top response may therefore be described, as in Figure 3.8. The decline in growth rate as maturity approaches is less steep than the incline in early life, producing an offset curve of growth for which the early and later phases are different in nature and not counterbalancing mirror images.

### Lean and protein growth

The above discussion of potential growth rate points towards a phenomenon that might better be described by a Gompertz curve (Figure 3.9), whose point of inflection at time \( t^* \) occurs at 0.37 of mature size and which is characterised by a substantial period of effectively linear or constant growth, particularly from 0.1 of maturity (about 30kg live weight for a pig) to 0.6 of maturity (about 180kg live weight for a pig). The Gompertz curve also effectively handles the steeper increase in growth in early life and the more gentle decline in growth as maturity is approached; so better contrasting the impetuosity of youth with the reluctance of old age. (In passing, because of its elongated ‘middle section’ the Gompertz function is also rather adept at fitting linear data sets.)
The upper limit, or potential, for protein growth, by definition, is unknowable, but may be implied from its being presumed to be approached under nutritional and environmentally unlimiting conditions. As protein growth is both highly desirable and highly efficient, its maximisation is of intense interest. The description of protein growth potential as a function of pig weight, age or stage of maturity is a prerequisite to the estimation of nutritional requirement and the derivation of best production strategies. The use of a Gompertz curve to describe potential growth in non-limiting conditions has proved useful. However, it is fundamental to the discipline of curve fitting that the curve of choice is that which best fits the data in the light of an appropriate biological hypothesis. What does not hold true therefore is a proposition that an animal grows as if it were tracking a Gompertz curve in any predetermined way. The use of the curve is a convenient way of describing what is a complex of at least three phenomena (early, mid and late growth) within the confines of one single mathematical expression. The use of expressions in this way may obfuscate as well as enlighten.

The relationship between weight at a time $t$ according to the Gompertz function is expressed as:

$$W = A.e^{-e^{-B(t-t^*)}}$$  \(3.5\)

where $A$ is the live weight (W) at maturity (kg), $B$ is the growth coefficient and $t^*$ is the point of inflection (days). Maximum growth occurs at $1/e$ (0.37) of $A$, and the rate achieved will be $(A.B)/e$. However, the curve is helpfully rather flat topped. For improved White genotypes appropriate values for $A$ appear to range between 300 and 400 kg W, whilst values for $B$ may be in excess of 0.012; $t^*$ is usually about 180 days of age. Unimproved genotypes of different breeds may have lower values for both $A$ and $B$. $(A.B)/e$ readily calculates to greater than 1 kg daily live weight gain for improved genotypes.

Daily live weight gain ($dW/dt$) in relation to pig age may be calculated with the differentiated function of Equation 3.5, but is neither especially logical nor useful. More utility is obtained if gain is expressed in relation to pig weight. In this latter case, at any given value for $W$, weight gain is calculable as:

$$dW/dt = B.W.\ln (A/W)$$  \(3.6\)

Potential daily live weight gains using different values for $A$ and $B$ are given in Table 3.3.

As has been said, the most important component of the daily live weight gain is protein, as this controls both production efficiency and product quality. Daily protein retention (Pr) measured by slaughter experiment at Edinburgh for unimproved entire male pigs was found to be 122 g daily between 20 and 105 kg, 144 g daily between 20 and 150 kg, and 101 g daily between 20 and 200 kg. The relative constancy of the rate of protein retention over much of the growth phase was confirmed, and the Gompertz curve derived from the experimental data is presented in Figure 3.10.

Values for $A$ and $W$ expressed directly in terms of protein mass (rather than live weight) allow calculation of the daily rate of protein retention at any given body
protein mass. Different pig genotypes and sex can be described in terms of their values for B and for A. By the simple determination and presentation of two numerical values the potential for protein retention at any given weight can be estimated. With this knowledge optimum nutritional and management strategies for any given pig type may be elucidated. These two values for B and for A are pivotal to the effective production of meat from pigs. Figures 3.11 and 3.12 show curves calculated for the equation \( \frac{dW_p}{dt} = B \cdot W_p \cdot \ln \left( \frac{A_p}{W_p} \right) \), where \( W_p \) is the protein mass at any given time (t) and \( A_p \) is the protein mass at maturity. In shortened nomenclature, \( \frac{dW_p}{dt} \) is referred to as \( Pr_{\text{max}} \) (for the maximum potential daily rate of protein retention at any given point in growth), \( A_p \) is referred to as \( P_{\text{tmax}} \) (for mature body protein mass) and \( W_p \) is referred to as \( P_t \) (for current body protein mass). Thus:

\[
Pr_{\text{max}} = P_t \cdot B \cdot \ln \left( \frac{P_{\text{tmax}}}{P_t} \right) \tag{3.7}
\]

Figure 3.11 describes values for B and A (as \( P_{\text{tmax}} \)) of 0.0105 and 37.5 kg, indicative of castrated male pigs of unimproved genotype, while Figure 3.12 describes values for B and A (as \( P_{\text{tmax}} \)) of 0.0125 and 47.5 kg, indicative of entire male pigs of improved genotype. It is apparent that the maximum value for \( Pr \) occurs at a higher live weight in Figure 3.12 than in Figure 3.11, the former referring to an animal of greater mature size. Other sexes and types would fall within intermediate values.

The shape of both curves argues well for the possibilities for rapid early growth and argues adequately for the tendency toward a relatively stable value for potential protein growth over much of the commercially active growing phase to slaughter.

### Table 3.3.
Potential rates of daily live weight gain (g) calculated by use of the Gompertz function \( \frac{dW}{dt} = B \cdot W \cdot \ln \left( \frac{A}{W} \right) \) for unimproved and improved pigs.

<table>
<thead>
<tr>
<th>Live weight of pig (W, kg)</th>
<th>Unimproved pigs</th>
<th>Improved pigs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( B = 0.009 )</td>
<td>( B = 0.011 )</td>
</tr>
<tr>
<td></td>
<td>( A = 250 )</td>
<td>( A = 300 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>W (kg)</th>
<th>( \frac{dW}{dt} ), g</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>518</td>
</tr>
<tr>
<td>50</td>
<td>724</td>
</tr>
<tr>
<td>75</td>
<td>812</td>
</tr>
<tr>
<td>100</td>
<td>825</td>
</tr>
<tr>
<td>150</td>
<td>690</td>
</tr>
<tr>
<td>200</td>
<td>402</td>
</tr>
</tbody>
</table>

**Fig. 3.10** Daily rate of protein retention (\( Pr \)) in relation to pig body weight (W). (Adapted from Whitney, C.T., Tullis, J.B. and Emmans, G.C. (1988) *Animal Production*, 46, 437–45.)
In many circumstances interest lies with the expression of Pr as a function not of Pt, but of the more readily measured live weight (W). The equation now takes the form:

\[ Pr_{\text{max}} = W.B.\ln \left( \frac{A}{W} \right) \] (3.8)

which may be compared with Equation 3.7. B values of around 0.0016 have been measured.

For practical purposes a simple value for the maximum rate of protein deposition Pr\(_{\text{max}}\) would be reasonable between 20 and 120 kg live weight, and pragmatic rules for genetic selection and for the determination of nutrient requirement could, if necessary, be based on a simple value pertaining during most of the active growth period; this single value being dependent (inter alia) upon sex and genotype.

Table 3.4 suggests values for B (as in Equation 3.7) and for Pt\(_{\text{max}}\), and for maximum attainable daily rates of protein deposition Pr\(_{\text{max}}\) as appropriate to different types and sex of pigs. Values offered range from 0.0095–0.0135 for B, from 32.5–52.5 kg for Pt\(_{\text{max}}\) and from 115–260 g for Pr\(_{\text{max}}\).
Growth in all three sexes of the meat pig, with the exception of entire males used for breeding, is interrupted by slaughter, usually at about 30–50% of mature size (80–140 kg). Growth in the female breeding sow is interrupted by the incursion of conception and pregnancy. Pregnancy dramatically affects the rate of protein retention, creating a marked downturn in the rate of maternal growth. Nevertheless, derivation of nutrient requirements for a growing sow requires knowledge of the pattern of accretion of body protein (and lipid), and the Gompertz function (Equation 3.5) is as adequate a descriptor of later growth as early growth; however, the numerical values used must allow for the presence of the reproductive processes in the post-pubertal female, which disrupt the pre-pubertal pattern and lengthen the time course for the approach of mature mass. Comparison of adequately fed breeding animals involved in consecutive pregnancies and lactations with serially slaughtered growing pigs over the uninterrupted growth period of 20–200 kg W shows breeding animals to have reduced growth (that is a reduced value for B, the growth coefficient) from the point of first conception. Values for body protein content (Pt, kg) for adequately fed sows are presented in Figure 3.13. With an initial value for Pt at first conception of 16.6 kg, respective gains from one conception to the next conception over the four following parities were 11, 8, 5 and 2.5 kg. The B value, at 0.0048, is at best only half of that likely to have pertained prior to conception. It is evident that the rate for Pr measured for these sows can only be regarded as observed performances under the duress of the reproductive cycle and not as any indication of what may have been a preferred pig growth target. It is also equally clear that the initiation of the reproductive processes is the cause of the inflection of the growth curve, and not its consequence.

### Table 3.4. Values for B, Pt<sub>max</sub> and Pr<sub>max</sub> (kg) suggested for different types and sex of selected meat pigs.

<table>
<thead>
<tr>
<th></th>
<th>B&lt;sub&gt;p&lt;/sub&gt;</th>
<th>A&lt;sub&gt;p&lt;/sub&gt; (Pt&lt;sub&gt;max&lt;/sub&gt;)</th>
<th>(B.A)/e (Pr&lt;sub&gt;max&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Utility:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>entire male</td>
<td>0.0105</td>
<td>37.5</td>
<td>0.145</td>
</tr>
<tr>
<td>female</td>
<td>0.0100</td>
<td>35.0</td>
<td>0.130</td>
</tr>
<tr>
<td>castrated male</td>
<td>0.0095</td>
<td>32.5</td>
<td>0.115</td>
</tr>
<tr>
<td><strong>Commercial:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>entire male</td>
<td>0.0115</td>
<td>42.5</td>
<td>0.180</td>
</tr>
<tr>
<td>female</td>
<td>0.0110</td>
<td>40.0</td>
<td>0.160</td>
</tr>
<tr>
<td>castrated male</td>
<td>0.0105</td>
<td>37.5</td>
<td>0.145</td>
</tr>
<tr>
<td><strong>Improved:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>entire male</td>
<td>0.0125</td>
<td>47.5</td>
<td>0.220</td>
</tr>
<tr>
<td>female</td>
<td>0.0120</td>
<td>45.0</td>
<td>0.200</td>
</tr>
<tr>
<td>castrated male</td>
<td>0.0115</td>
<td>42.5</td>
<td>0.180</td>
</tr>
<tr>
<td><strong>Nucleus:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>entire male</td>
<td>0.0135</td>
<td>52.5</td>
<td>0.260</td>
</tr>
<tr>
<td>female</td>
<td>0.0130</td>
<td>50.0</td>
<td>0.240</td>
</tr>
<tr>
<td>castrated male</td>
<td>0.0125</td>
<td>47.5</td>
<td>0.220</td>
</tr>
</tbody>
</table>
Changing the shape of the potential growth curve

The shape of the actual (achieved) growth curve is readily changed by nutrition, environment and indeed pregnancy. For any given individual, however, the shape of the potential curve is, arguably, an intrinsic character. Genetic selection may, however, be imposed upon a population to artificially change the intrinsic characteristics of that pig population. If individuals in an existing population grow according to case (a) in Figure 3.14, and that population is then selected for improvements in lean tissue growth rate, then the slope of the relationship of weight (W) with time (t) will be steepened in the direction of the arrow and towards case (b). If time at achieving maturity is delayed only a little (which appears so), then the undeniable consequence is an increase in A, the mature size. Given the composition of Equation 3.6 it is unremarkable to propose that selection for increased daily gain would necessarily result in an increase in mature weight (A). Because enhancement in growth rate is a basic goal in pig production, as in other branches of animal production, then it should not be too surprising to note that genetic selection and breed substitution have consistently resulted in the creation of larger animals; in the case of not only pigs, but also sheep, cattle and fowl. However, perhaps the greatest change in mature size over recent years has indeed been with the domestic pig, consequent upon the high selection pressure that has been placed upon lean tissue growth rate in many genetic improvement schemes. The possibility of increasing growth rate without concomitant increases in mature size remains an intriguing but distant ambition for animal breeders.

Populations of animals conforming to case (b) in Figure 3.14, as well as growing faster and maturing larger, have higher maintenance requirements in their adult breeding herds and fatten less readily. As may be interpreted from the figure, at any
given weight pigs conforming to case (b) will be less mature than those of case (a). Conventional slaughter weights for case (a) animals, maintained for use with case (b) animals, will ensure a meat of lower physiological maturity derived from animals at a lesser proportion of their potential final size; increased size at maturity bringing with it an increase in optimum slaughter weight. Figure 3.14 would also tend to suggest that if pig age has a substantive effect on the attainment of puberty (which it has), then case (b) animals will reach breeding age at heavier weights, while nevertheless also being physiologically younger at a given weight.

Fatty tissue and lipid growth

Little pigs gain fat rapidly in early life, with special help from their mothers’ milk with 8% content of fat. The most rapid phase of fat growth may well have occurred in the pig before 4 weeks of age, whereas maximum lean impulsion may not be reached until rather later. Whilst there is less than 2% of fat in a pig at birth, by 21 days of age there is usually more than 15%. Modern pigs may never be fatter than when 21 or 28 days of age at the point of being weaned; it is possible that maximum fatness (as a proportion of body weight) has been attained within the first month of a 4–7 month growth time to slaughter. Carcass pigs can achieve slaughter weight at 100 kg readily with less than 15% of fat in the carcass, and pigs now rival broiler fowl as being the leanest meat available for human consumption. Over-fat pigs are no longer excusable, for although pigs do tend to get fatter as they get bigger modern strains of pig are fundamentally lean up to relatively high carcass weights. Fatness control is simple with modern pig strains because pig fatness is primarily a function of feed intake. Feed intake control will cause the achievement of any required level of fat at any required carcass weight.

Feed intake, and not rules relating to time and weight, is the crux of body composition change and of carcass fatness in meat-producing pigs. The following nutritional conditions are those that will cause fattening to occur:

- when the diet is imbalanced (at any pig weight), providing excess energy in relation to protein (see Chapter 13);
- when food intake exceeds the needs of maintenance and lean tissue growth (at any pig weight);
- when, for sound physiological reasons, the body places fat accretion above lean accretion in its order of priority (as is the case between birth and weaning, during pregnancy when preparing for lactation, or in expectation of times of feed shortage);
- when mature lean mass is achieved and ingested feed has no other function to satisfy other than fat growth.

At this point it is helpful to split total body lipid (Lt) into three components: essential fat; a minimum preferred level of target fat; and depot fat. An irreducible base level of fat is essential to normal metabolic function; this is probably about 4% lipid
in the whole body \((Lt = 0.04 \text{ W})\). The preferred level of target fat is the minimum level of fatness at which, having achieved that target, the animal feels sufficiently physiologically comfortable to partition and prioritise available nutrients toward lean tissue growth rate and other functions such as pregnancy and lactation. At levels of fatness below this target, the achievement of target lipid levels will detract from the achievement of potential rates of protein retention (and of reproduction), as the physiological priority will be to the former and not the latter function. Lipid gains may be conventionally expressed in terms of a given relationship with lean or protein gains. Because protein gains will be restrained until target levels of fat are reached, then at all times prior to the lean tissue growth rate reaching its maximum potential, the ratio of lipid gains to protein gains \((Lr:Pr)\) will reflect directly the proportion of fat in the gain that is most likely to achieve the minimum preferred level of lipid to protein in the total body \(– (Lt:Pt)_{\text{pref}}\).

While the preferred level of target fat is a physiological necessity for normal growth, surplus or depot fat is quite differently a means of either (1) dealing with excess energy present in an imbalanced feed or (2) creating a depot store of energy in the body in preparation for some prospective food shortage. The full extent of depot fat storage in the pig is largely unknown, although pigs with more than 50% of the body present as lipid are entirely credible, if highly uneconomical. However, it would be unusual to find even obese contemporary pigs carrying more than 30–40% body fat. By definition, depot fat should probably be excluded from a quantitative description of growth on the grounds of the four conditions that allow fattening to occur, and which have been described above; perhaps with the singular exception of the fattening of a very young pig, which in any event may be justified by the use of a higher target fat value.

In comparison to the daily gains of protein \((Pr)\), it would appear that for the young pig, minimum target gains of lipid \((Lr)\) are around or above equivalence:

\[
(Lr:Pr)_{\text{min}} = 1
\]  

(3.9)

The reason for this, it may be surmised, is that once the preferred minimum ratio for \(Lt:Pt\) has been reached, then gains will follow the same ratio until such time as \(Pr_{\text{max}}\) is attained; thus while \(Pr < Pr_{\text{max}}\), then \((Lr:Pr)_{\text{min}} \approx (Lt:Pt)_{\text{pref}} \approx 1:1\). These equivalences are seminal to any rational understanding of growth in meat-producing animals. The numerical value here given as unity is variable with species, genotype and sex \([\text{\(Lr:Pr)_{\text{min}}\text{ values of 0.5 being realised in improved male pigs, but values of 2.0 being possible in some unimproved castrated types]}\]]

Target fat levels during normal growth between weaning and puberty, expressed in terms of \((Lt:Pt)_{\text{pref}}\), are given in Table 3.5. It will be evident that selection has resulted in reduction of \((Lr:Pr)_{\text{min}}\) and also \((Lt:Pt)_{\text{pref}}\) as well as an increase in \(Pr_{\text{max}}\) (see Table 3.4). This, however, is consequent upon simultaneous selection against \(Lr\) and \(Lt\) as well as for \(Pr_{\text{max}}\) and \(Pt_{\text{max}}\). There is no physiological reason why high values for \(Pr_{\text{max}}\) should necessarily be associated with low values for \(Lr\).

Given the tendency to identify an animal as having a preferred minimum ratio of lipid to protein in its body \([(Lt:Pt)_{\text{pref}}]\, and to have assigned a nominal value of
l:1, which is variable according to sex and genotype, it is reasonable to ask under what circumstances a different ratio to those in Table 3.5 may be tolerated. Self evidently, ratios greater than that preferred are actually sought if the animal is preparing for hard times when energy demand may exceed energy supply; that is before weaning, before lactation and before seasonal feed shortages. Ratios of less than that preferred may be tolerated (but not sought) if the animal is in nutrient supply deficit; such as post-weaning or during lactation when body fat is inexorably diverted to supply energy. The physiological minimum for fatness has been suggested as about 5% of the body weight, or \( \text{Lt:Pt} \approx 0.3 \). However, physiological minima will almost certainly depend on physiological state. Thus the minimum for sustaining life will be lower than the minimum for initiating an energy-demanding activity such as conceiving a pregnancy. The concept of \((\text{Lt:Pt})_{\text{pref}}\) does, however, allow a viewpoint from the animal in deciding whether it is physiologically ‘fat’ or physiologically ‘thin’. If it is ‘fat’, then depot fat can be made available for other production purposes. If it is ‘thin’, then the animal will drive toward \((\text{Lt:Pt})_{\text{pref}}\) by prioritising lipid deposition over other production purposes. There will therefore be an ongoing tendency toward the attainment of \((\text{Lt:Pt})_{\text{pref}}\) if the existing state is either greater or lesser.

There is no prima facie case evident for failing to analyse the potential for the daily rate of nutritionally unlimited lipid retention \(L_r_{\text{max}}\) with the same paradigm as the analysis found appropriate for protein retention. It may be presumed that, given unlimited nutrition, there is rapid advance of lipid accretion to a maximum point; after which an asymptote of mature lipid mass is attained (see Figure 3.3). It may also be presumed that these characteristics may be described by the use of \(B\) and \(L_r_{\text{max}}\) terms within the framework of a Gompertz function. It may be taken that \(B\) could be considered as common for all of the protein, lipid and ash components, and \(L_t_{\text{max}}\) could be set as a simple ratio to \(P_t_{\text{max}}\). It would appear from various data

### Table 3.5. Values for the target minimum ratio of body lipid to body protein \((\text{Lt:Pt})_{\text{pref}}\) in meat pigs.

<table>
<thead>
<tr>
<th></th>
<th>((\text{Lt:Pt})_{\text{pref}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility:</td>
<td></td>
</tr>
<tr>
<td>entire male</td>
<td>0.9</td>
</tr>
<tr>
<td>female</td>
<td>1.1</td>
</tr>
<tr>
<td>castrated male</td>
<td>1.2</td>
</tr>
<tr>
<td>Commercial:</td>
<td></td>
</tr>
<tr>
<td>entire male</td>
<td>0.7</td>
</tr>
<tr>
<td>female</td>
<td>0.9</td>
</tr>
<tr>
<td>castrated male</td>
<td>1.0</td>
</tr>
<tr>
<td>Improved:</td>
<td></td>
</tr>
<tr>
<td>entire male</td>
<td>0.5</td>
</tr>
<tr>
<td>female</td>
<td>0.7</td>
</tr>
<tr>
<td>castrated male</td>
<td>0.8</td>
</tr>
<tr>
<td>Nucleus:</td>
<td></td>
</tr>
<tr>
<td>entire male</td>
<td>0.4</td>
</tr>
<tr>
<td>female</td>
<td>0.5</td>
</tr>
</tbody>
</table>

\(^1\) Where \(P_r < P_{r_{\text{max}}},\) a similar ratio \((L_r: P_r)_{\text{min}}\) may be found in the gain.
sets that $L_{t_{\text{max}}} \approx 2.0\text{–}4.0$. $P_{t_{\text{max}}}$, depending on sex and genotype – lower values for improved males, higher values for unimproved castrates and intermediate values for females. If the Gompertz function is used for both fat and protein growth, and mature fat mass is greater than mature protein mass ($L_{t} > P_{t}$), then $L_{r} : P_{r}$ will widen as growth proceeds, and the peak of lipid growth will occur at a substantially higher level and at a greater body mass than that at which the peak of protein growth occurs. There will be a sequence in tissue growth, with the time of most rapid lean gains proceeding the time of most rapid fat gains (Figure 3.15).

Lipid maturity can be expressed as an allometric relationship with protein. The great frequency with which, since Huxley in 1932, allometry ($Y = aX^{b}$) has been found to be a useful and closely fitting model to describe the relative growth rate of tissues would support the view that the rate parameter $B$ may indeed be taken as a single value, characteristic of sex and genotype and common to all three major chemical components (protein, lipid and ash) accumulated in circumstances of unrestrained nutrients. It may also be safely surmised that an allometric relationship already used to describe relative tissue weights, as in Table 3.2, can also be used to describe the relationship between protein and lipid growth ($L_{t} = 0.151P_{t}^{1.7}$ may, for example, be calculated when $L_{t_{\text{max}}} : P_{t_{\text{max}}}$ is 2:1).

Although these propositions are fundamental to attempts to describe uncompromised animal growth patterns, the potential limits to lipid growth frequently fail to be attained due to (1) limited nutritional circumstances, (2) nutrient provision being prioritised to protein retention, (3) the incursion of the reproductive cycle or (4) the uneconomic nature of obesity. This has meant that such descriptors for $L_{r_{\text{max}}}$ and $L_{t_{\text{max}}}$ impinge less frequently upon practical descriptions of growth than the equivalent descriptors for $P_{r_{\text{max}}}$ and $P_{t_{\text{max}}}$. Where $L_{r}$ (the achieved rate of lipid reten-

![Fig. 3.15](image-url) The paradigm for potential rate of unlimited lipid growth, with a peak of fatty tissue growth substantially greater than and occurring later than that of protein tissue growth.
tion) is less than $L_{r_{\text{max}}}$ (the potential rate), then lipid growth may be analysed through three quantities which merge to create a continuum. These are the concepts of minimum physiological fatness ($L_t = 0.05 W$), minimum fatness in normal positive growth ($L_t : P_t_{pref}$) and storage fattening during growth or upon maturity when depot fat is laid down.

After the attainment of puberty there is a new dimension – that of pregnancy. Pregnancy creates an enhanced level of target daily lipid gain which is probably greater than quantitative equivalence to the daily rate of protein gains, as shown in Figure 3.13, and by the relationship $L_t = 1.1 P_t^{1.1}$.

Most of the extra fat laid down in pregnancy is used to fuel lactation. Breeding sows with greater than 30% of total lipid in the body ($L_t > 0.3 W$) are presumed likely to have reproductive problems due to over-fatness. Breeding sows with less than 17% body lipid are liable progressively to lose reproductive efficacy in terms of increased time taken to return to oestrus after weaning, reduced ovulation rate, reduced success for embryo implantation and survival and reduced piglet birth weight.

While for full-fed unimproved genotypes a body fat mass twice that of the protein mass ($L_t > 2 P_t$) used to be unremarkable, it would appear that the body content of lipid in the contemporary adult sow should preferably be maintained at one and a half times the protein content ($L_t = 1.5 P_t$), or approximately 20–25% of the total body weight as lipid ($L_t \geq 0.2 W$). The lipid content should never drop below equivalence with the body content of protein ($L_t = P_t$), otherwise reproductive capacity will be compromised.

The pattern of lipid gains in Figure 3.13 suggests that an initial value of $L_t$ of 22 kg at first conception may be followed by conception to conception gains for parities 1–4 of 16, 12, 7 and 4 kg $L_t$ respectively. Gains of $L_t$ are thus approximately equal to 1.5 $P_t$. Within each parity, pregnancy gains of $L_t$ were, of course, greater than this to allow for lactation losses.

**The special case of early growth**

Having been born with only 1–2% of lipid, which is less than the ‘physiological minimum’, of 4% body lipid, the neonate pig is being entirely reasonable when it puts lipid gains above protein gains in its order of priority for nutrient partitioning so that it may first achieve minimum fatness and then next approach, as rapidly as possible, the preferred $L_t : P_t$ ratio. In this way the baby pig can have a body lipid content of 15–20% by 21–28 days of age. To achieve these dramatic changes in body lipid, $L_r$ in early life is self evidently much in excess of $P_r$. The trauma of weaning, however, usually reduces total body lipid content to 10% of body weight or less before more normal positive growth rates are resumed.

The remarkable ability of the young pig to grow rapidly in early post-natal life is not restricted to lipid growth. Total body growth rate potential is perhaps even more outstanding. The impressive nature of post-natal live weight gains possible in
a young pig is only exceeded by the apparent inability of pig producers world-wide to fully exploit the potential that is on offer. However, the growth potential of young pigs is remarkable only in comparison with conventional agricultural expectation, not in relation to many other animal species such as the newly hatched pigeon, the young rabbit, the seal and the whale, all of which grow, in proportion to their current size, even more spectacularly than the fastest growing young pig. In the first week of life the baby pig consumes about four times its maintenance requirement, the baby seal six times maintenance, while the baby whale consumes eight times main-
tenance. Even the human baby conforms to the pattern of rapid early life growth; between the 4th and 7th week of age, R.J.W., when 4kg live weight, gained 290g weekly, a rate of growth that (if maintained) would have resulted in a 154kg 10-
year-old.

In terms of their potential, healthy pigs of 5kg live weight can readily be shown to grow 600g daily in circumstances of unlimited nutrition. Growth increments of 10% or more of current body weight are achievable between birth and about 8kg live weight; B values within Equation 3.6 having been measured up to 0.02 for young pigs at Edinburgh. Figure 3.16 (as measured) presents only conservative possibil-
ties for the growth of sucking pigs, the particular animals tracked here having no access to supplementary feed of any kind. Loss of growth impulsion toward the later stages of the period of measurement shows the consequences upon potential growth of a food supply source (mother’s milk) unable to keep up with pig requirement and growth potential.

The tremendous impulsion found in the early growth of mammals is likely to be associated with survival mechanisms, and may constitute an exception to the Gompertz assumption which seems to hold so well elsewhere throughout growth to maturity. When analysing achieved growth rates of young pigs, however, gains made do appear to fit the Gompertz assumptions of slower growth in early life, with subsequent acceleration, but this is not reflective of any natural law; it is more likely to be accounted for by the following three phenomena:

(1) Expression of growth curves over a substantial period of the whole life fail to account for perturbations in one small sector; that is, the curve is dominated
by the majority of the growth pattern and cannot properly express the exceptional early growth phase.

(2) Young animals are not offered unlimited feed supply, and growth is thereby restrained below potential through the medium of nutrient limitation.

(3) The young pig is usually weaned in the middle of the early growth period (at around 21–28 days of age), and the consequences of weaning are often both a compromised health status and a severely reduced nutrient intake. As the trauma of weaning is recovered from, an acceleratory phase of growth re-emerges (Figure 3.17).

Young pigs would grow considerably faster than they do on commercial production pig farms if conditions were more close to ideal, and the relatively slower rates of growth actually experienced are consequent upon the imposition by man of a variety of restraints, rather than any natural growth pattern. Figure 3.16 can be taken as indicative of reasonable and conservative expectations for pre-weaning growth performance of young pigs, and Table 3.6 shows some regularly achieved post-weaning performances of pigs at Edinburgh maintained under unexceptional conditions.
Weight loss by negative fat growth

Negative growth is not the reverse of positive growth, and cannot be open to a similar mathematical approach. Fat loss is invariably the consequence of an imbalance between energy demand and energy supply, the difference being made up from internal nutrient resources. The anabolism of fatty tissues may cease entirely before protein anabolism even slows down, while the breakdown and utilisation of body lipid and the build-up of body protein can proceed simultaneously (the former fuelling the latter). Negative fat growth happily utilises the surplus fat in body depot stores; the purpose for the original deposition of body lipid depots being to protect against the very imbalance between nutrient demand and nutrient supply, such as often occurs after weaning and during lactation, when intake of ingested energy fails to measure up to metabolic requirements. Fat catabolism, however, may often bite deeper into target fat if demand for energy is strong enough. In this way the absolute lipid content of the pig (Lt) may be found to fall below target levels. While fat reduction by utilisation of the depot stores down to target body fat content levels may be considered as a normal aspect of pig bodily function, incursions into target fat will undoubtedly bring with it negative consequences, and optimum body function cannot be expected thereafter, until such time as target lipid levels have been restored.

Negative growth therefore has an important contribution to make to normal growth and reproductive processes, but in so doing may dramatically influence body composition, and is only a normal phenomenon provided that it relates to storage depot fatty tissues. Thus, according to the level of feed intake in lactation, lactating sows may, during the suckling period, lose lipid up to levels even as high as 20 kg. Fat loss in lactating sows is closely related to weight loss:

Fat loss (kg) during 28 day lactation = 7.5 + 0.3 live weight loss (kg)

which indicates that even at sow body weight stasis there is some 7.5 kg of fatty tissue catabolised during lactation, or some 250 g per day. More usually sows will lose about 10 kg of live weight in lactation, creating normal fatty tissue loss levels of around 10 kg in the course of a lactation, or around 500 g of fat daily. The pregnant mammal anticipates impending lactation and lays down depot fat during pregnancy in order to lose it subsequently through the milk. Daily losses of fat by lactating dairy cows can be more than 1 kg per day. In terms of metabolic body weight, these amounts are similar to those found in the pig; about 10 g/kg metabolic body weight (W^{0.75}). Similar rates of loss also occur in lactating ewes. Because fat losses can be counterbalanced by water gains, the energy value of weight loss can be considerably in excess of the gross energy value of pure fat (40 MJ); energy values for live weight loss for lactating animals as great as 90 MJ/kg live weight have been recorded. Body fat losses during lactation must be made back during the subsequent pregnancy or progressive fatty tissue depletion will occur as the breeding sow ages, and the Lt:Pt ratio will fall below the preferred minimum level (often given as 1:1).
Fat losses by newly weaned baby pigs will relate to the extent of the pre-weaning fat stores built up, and the physiological need to maintain fat in the face of post-weaning nutritional stress. Weaned baby pigs preferentially lose subcutaneous fat rather than internal fat (the ratio of the rates of fat losses being about 9:1). Immediately after weaning pigs will usually show weight stasis, live growth impulsion picking up about 1 week later (Figure 3.17). The extent of this post-weaning check may vary from 2 days to 2 weeks, depending upon both pre-weaning and post-weaning management, housing and nutrition. It is apparent that weaning is a traumatic time for young sucking animals. Pigs of 28 or 21 days of age at weaning have body compositions approximating to 15% protein and 15% lipid, but only 7 days after weaning, whilst the protein content may have remained relatively stable at around 15%, the lipid content may well have fallen to well below 10%. Sometimes the percentage fat in the total body of the young weaned animal can be halved within the week. This apparent numerical anomaly, of losing in proportion of fat, but not gaining in proportion of protein, is due to the water in the empty body which increases to counterbalance fat losses.

Figure 3.18 shows data from four separate experiments. In experiments 1 and 2 pigs were weaned at 28 and 21 days of age respectively, and the compositions shown at these ages therefore relate to the sucking pig. In experiment 3 the pigs were weaned at 14 days of age, and the composition given therefore pertains to 7 days post-weaning. It is apparent that not only has weaning brought about a great reduction in the percentage of fat, but also fat losses have been compensated for on a proportional basis by the addition of water. At 55, 53 and 42 days of age, pigs in experiments 1, 2 and 3 had failed to make good their post-weaning fatty tissue losses [gaining lipid at only half the rate of protein (Lr ≈ 0.5Pr)], but pigs on experiment 4 had done so. These latter pigs were given an unconventional diet with a high energy:protein ratio. Over the period of the experiments the composition of the post-weaning live growth in experiments 1, 2 and 3 was about 50% protein and 7% fat, but in experiment 4 there was more fat than protein in the gain (about 15% protein and 19% fat).

In a further experiment negative lipid growth was studied in greater detail. Control sucking pigs were left on the dam, whilst the experimental treatment piglets were weaned. Piglets were taken at 2-day intervals, during which time the weaned pigs only managed to maintain weight stasis. The suckled pigs, however, gained 300 g per day. For the weaned piglets, regression relationships between gains of the chemical components and gains of the empty body weight were drawn up as follows:

\[
\begin{align*}
\text{WG (g/day)} &= 0.56 \text{ EBWG} + 53 \\
\text{LG (g/day)} &= 0.29 \text{ EBWG} - 56 \\
\text{PG (g/day)} &= 0.15 \text{ EBWG} - 4
\end{align*}
\] (3.11) (3.12) (3.13)

These relationships are illustrated in Figure 3.19 which presents the compositional proportionality with respect to total gain. The slope of the protein line is 15%, and it resolutely passes close to zero. At body weight stasis, some 50 g of lipid is lost from
the body daily; and this from pigs that are themselves only 5 kg in weight (that is, 15 g/kg metabolic body weight, or about 50% more than from the lactating cow). The counterbalancing chemical component was, of course, water, for which there were positive gains of 50 g at weight stasis.

At low daily live weight gains (below 200 g) lipid losses are seen to support protein gains, and there are quite a range of gains over which lipid loss and protein retention occur simultaneously. Physical dissections of the tissues showed that at zero live weight gain and rapid subcutaneous tissue loss, simultaneous tissue gains were taking place, mainly in the heart, lungs, liver, intestines and other essential body components.

Patterns of negative growth associated with the utilisation (and subsequent recovery) of depot fat stores in breeding sows are shown in Figure 3.20, which demonstrates lipid losses both post-weaning and during lactation. Failure to allow recovery of depot stores by the provision of energy supply in excess of the
Fig. 3.19 Relationships between total gain and the components of the gain. (Calculated from Whittemore, C.T., Taylor, H.M., Henderson, R., Wood, J.D. and Brock, D.C. (1981) *Animal Production*, 32, 203.)

Fig. 3.20 Changes in lipid content of the body of pigs consequent upon fatty tissue losses after weaning and during lactation.
immediate needs of protein growth or pregnancy anabolism would inevitably lead to progressive decline of fat levels, and ultimately the reduction of total body lipid below target level, with inevitable unfortunate consequences for pig health and productivity.

**Compensatory or catch-up growth**

Rates of protein deposition less than the potential \( Pr < Pr_{\text{max}} \), or alternatively rates of lipid deposits less than required to achieve the preferred ratio of lipid to protein in the body \((Lt:Pt)_{\text{pref}}\), are natural consequences of growth limitation such as would follow from an inadequate nutrient supply, or the imposition by the animal of priority demands imbalancing the preferred body condition. A return to maximisation of protein retention \( Pr = Pr_{\text{max}} \) and rates of lipid retention above \((Lr:Pr)_{\text{min}}\) to achieve \((Lt:Pt)_{\text{pref}}\) may be welcomed by the growing pig. This compensating impulsion is described in Figure 3.21. Animals gaining fat in excess of the level preferred and making protein gains less than preferred may subsequently use the stored excess fat to grow protein and return to \((Lt:Pt)_{\text{pref}}\) (a), while animals making inad-

---

**Fig. 3.21** From the original idea of Kyriazakis and Emmans at Edinburgh, showing the tendency for pigs to return to their preferred body composition \((Lt:Pt)_{\text{pref}}\). The value for \((Lt:Pt)_{\text{pref}}\) will depend upon sex, genotype and physiological state. Animals moved away from their preferred body composition (by circumstances of inadequate nutrient supply) will have a tendency to return to their preferred body composition.
equate lipid gains may subsequently increase energy metabolism in order to achieve fast lipid growth and return to \((Lt:Pt)_{\text{pref}}\).

Whilst a conservative shortfall in protein retention rate below maximum is unlikely to elicit any special response outside the principles of normal growth adumbrated earlier, it is reasonable to expect that if the shortfall is serious the pig may sense an increase in difference between achieved protein mass and potential protein mass for any given temporal age, and may wish to reduce such a difference by making some effort to ‘catch up’. This would imply the need for levels of maximum protein retention above \(Pr_{\text{max}}\), the previously assumed maximum, and therefore present something of a conundrum. The proposition that lost muscle growth can be ‘caught-up’ later by specially high – and efficient – levels of ‘compensatory’ growth is particularly attractive to those whose management systems may predispose to loss of potential growth in the first place.

Negative protein growth (rather than reduced positive growth) is an unusual and metabolically disruptive phenomenon indicative of severe nutritional imbalance or deficit. It would appear that catabolism of muscle protein, with resultant degeneration of essential tissue, may occur during lactation in sows suffering feed protein deprivation and for whom milk synthesis for the good of the offspring has priority over the good of self. It is also reasonable to suppose that the pig will volunteer its body protein tissue to support its life (maintenance needs) before choosing to expire from starvation with a full complement of musculature. Such may indeed be necessary in conditions of highly seasonal nutrient supply patterns. For purposes of the science of the domestic pig, however, it can be taken that negative protein growth is indicative of management failure, and will have repercussions for productivity. The discussion of compensating growth is therefore limited to its possibilities subsequent upon reduced (and not negative) rates of protein retention, and, as such, the redressing of lost potential gain is deserving of attention:

* First, it may be proposed that the pig has no interest in compensatory fat gain beyond achievement of target fatness.
* Second, it may be proposed that any pig will maximise protein growth in times of nutritional adequacy. If adequate nutrition follows a period of nutritional deprivation, then the rate of protein retention will be seen to increase in the normal course of events. If ‘control’ animals were themselves performing below potential, but assumed to be performing at potential, then the re-alimented group will have all the appearances of ‘catching up’, but will not, in fact, be doing any such thing and will merely be functioning within the accepted principles.
* Third, it may be proposed that any pig making true compensatory gains need not necessarily invoke the idea of super-metabolic efficiency. It is merely enough to have an elevated feed intake over the normal expectation for pigs of that given weight. If protein retention was restrained previously by limitations to feed intake, then enhancement of intake will naturally lift protein retention rate.
Fourth and last, it follows from the above that true compensatory growth should be defined strictly as occurring: (1) when previous failure to achieve rates of Pr = Pr\(_{\text{max}}\) are resultant from a nutritional shortage which may be overcome by a compensating elevation of appetite above previously found maximum levels; and (2) when the previous potential rate of protein retention (Pr\(_{\text{max}}\)) is exceeded as an integral part of the true catch-up process.

There is no reason to believe that compensation of the type covered under conditions (1) and (2) above could be in any way advantageous to the production process. The period of growth during which Pr is less than Pr\(_{\text{max}}\) can only result in a loss of efficiency, which, if ever made good, will incur increased food usage overall in the attainment of any given final weight. Growth restraint in one period of life to exploit compensatory gains in a subsequent period could only be an economic consideration if food was particularly expensive in the period chosen for restraint, and particularly cheap in the period chosen for catching up.

The concept of compensation is nevertheless most intriguing from the point of view of growth analysis because if it exists, then its existence shows that the pig has a particularly clear view of its actual position in comparison to its optimum position on the preferred growth track; that is, the pig can simultaneously have close quantitative knowledge of its body composition (likely), its body size and weight (possible) and its age (less likely). Furthermore, compensation infers that the pig is ready to adjust in good times a situation previously existing in harsh times when expectations were not achieved.

From experimental data available to date it is evident that pigs do recognise deviations from a preferred lipid:protein ratio, and it is possible that they also recognise deviations from a preferred weight for age. Thus growing pigs created by nutritional imbalances to be excessively fat or lean will, given the chance, readjust body composition to the preferred Lt:Pt ratio. Further, previously restricted pigs may, upon re-alimentation, show short-term levels of protein retention greatly in excess of levels previously understood to be the maximum possible. Most interesting of all, young growing pigs placed into luxury energy status by the previous encouragement of generous levels of depot lipid stores may, upon being subsequently presented with a diet of exceptionally high protein, achieve the most remarkable rates of protein retention and daily live weight gain. The experimental pigs of Kyriazakis, prepared in this way, achieved daily gains of 0.925kg at a live weight of 13kg. Whether this performance was or was not above Pr\(_{\text{max}}\), however, still remains speculative.

The fascination of science for compensatory growth should not delude those concerned with commercial production into the mistaken belief that the pig, through mechanisms of compensatory growth, can make amends for deficiencies in production or nutrition. This is not the case, and there has been no evidence forwarded either by science or experience to suggest that optimum growth efficiency would be achieved by any other route than allowing the rate of protein retention (Pr) to approximate to the maximum potential available (Pr\(_{\text{max}}\)) at all times.
Change in size and shape

The proportions of the pig’s carcass that comprise the major body parts, fore, middle and hind, change little relative to the whole as the pig grows. Neither are there large differences in meat quality and value. Developmental changes in the body mass with growth have not, until recently, attracted much attention. However, this position is changing with the movement toward quality meat production and the clear differences in pig shape which are emerging with the increasing use of the ‘blocky’ sire lines, on the one hand, and maternal types showing converse body form, on the other.

As has been evident from the foregoing, pig growth is conventionally expressed in terms of weight. However, pig growth may also be characterised in terms of change in size and shape. Shape and size are better descriptors of growth than weight, as they add further dimensions of body form, proportionality and body condition. Unfortunately, weight is easy to determine accurately and objectively, while size and shape are not. Recent advances in the technology of visual imaging and its analysis, made by the team at the Silsoe Research Institute, have raised new possibilities for the characterisation of growth. Images are captured with a camera of the plan area of the backs of pigs as they eat (Figure 3.22). This area dimension (A4, cm²) is closely related to live weight:

\[
\text{Live weight (kg)} = 0.050 \times A4 - 34
\]

with weight being readily determined from the visual image. The slope (0.05) of this relationship is rather robust, but the constant is somewhat pig-type specific. This would be expected as the outline shape varies with breed type. Indeed, the visual imaging system has been found to be able to distinguish between breed types with some 70% accuracy, apparently identifying differences in the shape and size of ham and shoulder. A pig will grow at some 15 cm² daily (0.75 kg), and change in size is picked up by a remote camera with similar efficacy to change in weight, but with less pig disturbance. Given the market value of differing muscle size and form, there may also be a possibility for visual imaging to value the live pig more accurately than does weight alone.

Fig. 3.22 The ‘A4’ plan area of the back of a growing pig, as seen in visual image analysis. The same image will yield linear dimensions such as the width across the hams.
Growth response to feed supply

The frame for growth analysis often requires an assumption of adequate nutrient supply, although circumstances presumed adequate are frequently to be found wanting upon closer examination. It is a self-evident truth that growth can only occur when there is provision of sufficient nutrients. Feed intake is therefore a prime determinant of the rate of weight gain, of body composition and of carcass quality in meat-producing animals (Table 3.7).

In young pigs the response of protein retention to feed intake is linear up to maximum appetite; while in slightly older animals (Figure 3.23) protein retention reaches a plateau at higher levels of feed intake. In these studies from Australia high intakes were achieved, as 36 MJ of digestible energy per day is more usually associated with 70 kg pigs than with those of 35 kg. It is evident from this work and other

<table>
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<tr>
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<td>Female</td>
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<td>8</td>
<td>16</td>
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<tr>
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<td>12</td>
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<td>12</td>
<td>20</td>
<td>17</td>
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1 The energy content of fatty tissue is about 36 MJ and that of lean tissue about 5 MJ per kg. The fatty content of meat is therefore well indicated by the energy content.

Fig. 3.23  The linear response of protein retention to feed intake followed by a plateau at about 35 MJ digestible energy and 125 g per day of protein retention (note the high feed intake achieved). (Calculated from Campbell, R.G., Dunkin, A.C., Taverner, M.R. and Curic, D.M. (1983) Animal Production, 36, 185, 193.)
studies undertaken elsewhere that protein growth responds linearly to balanced protein and energy intake up to a maximum point, at which it plateaus. Given high feed intakes (and proper protein:energy balance in the diet), the plateau may be attained relatively early in life.

The linear/plateau response for protein retention to feed intake shown in Figure 3.24 relates to pigs of around 50 kg live weight. A plateau occurs at the maximum growth potential for the animal, which in case (a) is 500 g of lean daily. In case (b) the maximum potential is 750 g lean growth rate daily. (a) and (b) may be different genotypes, or perhaps different sexes. In pigs the entire male has a much higher potential for lean tissue growth than either the female or, particularly, the castrate (Table 3.8).

During the linear phase for lean growth, fatty tissue growth will be restrained to a minimum level (Lr:Pr)\text{min} on the assumption that under conditions of normal growth the animal prefers to target for lean whilst maintaining some minimal level of fat in normal live weight gains (Figure 3.24). In these cases [(a) and (b)] the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.24.png}
\caption{Effect of increase in feed level upon the growth of lean and fatty tissues in the whole body of pigs of 50 kg live weight. The point at which the linear response for lean growth reaches its plateau divides the model into two zones: the linear response to the left of that point and the plateau response to the right. To the left, gains will have a constant ratio of fat:lean, while to the right gains will have an increasing ratio of fat:lean. The ratio of fat:lean in the gains will tend to be a constant function of sex and genotype until lean tissue growth rate reaches the plateau of its maximum potential.}
\end{figure}

<table>
<thead>
<tr>
<th>Potential lean tissue growth rate (g/day)</th>
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<tr>
<td>Entire male</td>
<td>700</td>
</tr>
<tr>
<td>Female</td>
<td>600</td>
</tr>
<tr>
<td>Castrated male</td>
<td>500</td>
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minimum ratio of fat to lean is about 1 of fat to 4 of lean. Until feed intake is sufficient to maximise lean tissue, the animal will not fatten whilst it is growing and there will be relative constancy in the composition over a wide range of body weights. Animals given diets of low nutrient density may be expected to remain in the nutritionally limited phase of growth, and have constant body compositions over much of their growth to maturity.

Figure 3.24 is also useful in clarifying the essential difference between leanness and lean tissue growth rate. Where feed supply is low, pigs can be lean while having a poor lean tissue growth rate; whereas where feed supply is high, pigs can be fat while having a good lean tissue growth rate.

One of the consequences of the hypothesis laid out in Figure 3.24 is that animal breeders must provide a test regime which supplies feed in excess of the requirement to achieve maximum lean tissue growth in the best candidates, or differences between the improved and unimproved genotypes will fail to be distinguished. In the case of the example illustrated for pigs of around 50kg live weight, minimum feed supply for distinguishing between genotypes is around 2.3kg. In case (a), 2kg of food per day will bring about fattening, whereas in case (b), maximum lean tissue growth rate has yet to be achieved. As soon as the feed supply fully satisfies maximum potential for lean tissue growth, rapid fattening occurs and feed conversion efficiency worsens. To the left of this break point (the point where the linear response becomes a plateau) may be described as nutritionally limited growth; to the right of this break point may be described as nutritionally unlimited. Two kilograms of feed therefore represents unlimited nutrition for pig (a) but limited nutrition for pig (b).

It should come as no surprise to animal breeders that selection against fat so often brings about a reduction in appetite (Chapter 13); ad libitum intake being pushed to the left along the feed supply scale in Figure 3.24 (that is, feed supply is reduced), and thus the lower appetite of the pigs moves feed supply into the nutritionally limited (low fat) rather than nutritionally unlimited (high fat) area of growth response of unselected, fat pigs. Pigs selected only for live weight gain tested on an ad libitum feeding regime would be expected to make substantial positive improvements in daily feed intake and daily lean tissue growth rate, but the pigs may also become fatter.

Strain and sex differences may also be revealed in the ratio of fat to lean in nutritionally limited growth. In pigs the ratio can vary from less than 0.5 of fat to 4 of lean for entire males of improved strains, to more than 2 of fat to 4 of lean for castrates of unimproved strains. Selection against fat in meat is more likely to diminish this minimum fat ratio – as shown in the example in case (c) (Figure 3.24) – than to increase lean tissue growth rate. Fat reduction can therefore be achieved either by selecting for animals of type (c) or by insuring that nutrient intake remains limited.

The propositions put forward here are fundamental to pig production strategies. They state that there is a maximum lean tissue growth rate, and that this is some-
what independent of animal weight and age over the major period of interest for meat production. They further assume linear responses up to the maximum. They govern the circumstances in which animals cannot become fat, and give rules for feeding to maximise efficiency of feed use and growth rate whilst minimising fatness. Animals with higher lean tissue growth potentials can consume greater amounts of food with consequently improved feed efficiency and no increase in fatness. Entire males of improved genotype do not fatten because appetite is low in relation to potential growth rate. Selecting for greater appetite would initially enhance growth and not fatness, but as lean potential is approached further selection for appetite will bring about fat pigs.

Young animals will have lower appetites and will therefore be more likely to find themselves in nutritionally limited growth. The same would apply for older animals that have been bred for lower appetites, or that are given low quality feeds, such that within appetite their achieved nutrient intake is low. Older animals with higher inherent appetites have a better chance of finding themselves in nutritionally unlimited growth (Figure 3.25). This also goes for animals given higher nutrient density diets. This is the major reason why animals fatten as they get heavier or are fed more energy-dense diets.

Whilst growth potential may therefore be satisfactorily described in terms of biological constants and mathematical functions, the achieved rates and composition of gains in pigs are most directly influenced by nothing more complex than the level of nutrient intake achieved at any given moment. This is not to suggest, however, that growth is not predictable. Far from it. Having determined the envelope of potential response, the achieved response can be accurately calculated from knowledge of nutrient intakes and balances, as will be described in later chapters.

Fig. 3.25 As animals get older and bigger their ability to eat more feed increases. This means that older pigs are more likely to become fat than younger pigs. However, if the diet nutrient density also diminishes with age, the likelihood of fattening decreases.
Hormonal manipulation of growth

The endocrine system is the intermediary between the intrinsic (genetic) instructions relating to the quantity and quality of growth that is required of any individual, and the enactment of those instructions through the biochemical processes accreting protein, lipids, ash and associated water.

Growth can therefore be manipulated at three levels:

1. Through genetics – by artificial selection. Gene make-up changes influence growth responses through the mediation of the hormonal complex.
2. Through the endocrine system – by direct reduction or enhancement of body hormones.
3. Through the environment –
   a. by increase or decrease in the supply of nutrients for metabolism;
   b. by direct stimulatory influence of nutrient absorption upon anabolism – amino acid and energy absorption may stimulate growth hormone, insulin and insulin-like growth factor (IGF) release;
   c. by increase or decrease in the level of environmental stressors; these influencing hormones are antagonistic to both appetite and anabolism.

Normal growth is regulated through a hormonal complex including, amongst others, growth hormone (GH), insulin, IGFs, thyroid hormones, glucocorticoids, epinephrine, androgens and oestrogens. Growth manipulation can be achieved by increasing the concentration of anabolic hormones in the system, including exogenous administration, or by increasing the sensitivity of target organs to existing hormone concentrations, or by diminishing the effects of feedback control systems (this latter diminution may be achieved either by compromising the feedback system or by desensitising the primary system to the effects of the feedback by immunisation).

Growth hormone, IGFs, insulin and thyroid hormone interrelate within a hormonal complex which is itself subject to a layer of controller and feedback mechanisms. Growth hormone from the pituitary stimulates tissues directly, induces the synthesis of IGF-I and IGF-II and sensitises fatty tissue to lipolytic hormones. Growth hormone releasing factors (GHRH) from the hypothalamus impinge upon the pituitary, influencing output rate. Somatostatin is released from the hypothalamus as a feedback response to growth hormone and IGFs; somatostatin controls (restricts) growth hormone release, together with some degree of lesser restraint upon insulin, glucagon and thyroid hormone (ameliorating the strength or effect of somatostatin, for example by immunisation against it, will enhance growth by reducing somatostatic inhibitory effects). The IGF hormones themselves increase the rate of energy metabolism and stimulate fatty tissue growth to some extent, but, most importantly, act directly to increase the rate of protein accumulation in body tissues, and decrease the rate of protein breakdown. IGFs appear to be synthesised, and to act at a multitude of sites in addition to the liver. The IGFs stimulate and mediate
many of the primary hormones involved in promoting growth (especially growth hormone), and represent a major hormonal influence upon daily gains of lean and fatty tissues. Faster growing animals will show elevated blood levels of insulin, growth hormone and IGFs. It has been suggested that the circulating concentration of IGF may be correlated to both present and prospective growth rate and body size, and be relatively heritable.

The main effects of some of the major hormones associated with growth are presented in Table 3.9. Fat growth is usually enhanced by positive support or conversion of glucose to fatty acids, while it is restrained by encouragement of fatty acid oxidation. Lean growth requires active glucose metabolism for creation of the high levels of energy needed, together with a high level of stimulation of amino acid anabolism and protein accretion. The catecholamines act through beta-adrenergic receptors and may also stimulate insulin, growth hormones and thyroid hormones. Androgens and oestrogens have been available as exogenously administered anabolic agents acting both directly on lean tissues to enhance their growth, and indirectly by encouraging release of growth hormone, insulin and thyroid hormones. In-feed androgen/oestrogen growth promoting agents were available for use formerly as growth promoting agents. Present interest in hormonal growth enhancers and manipulators is concentrated primarily on the readily available manufactured growth hormone, and also upon the highly effective beta-adrenergic agonists.

It is evident that in normal and natural circumstances, without any exogenous interference, fast-growing animals show elevated levels of growth hormone. DNA technology regarding the insertion of genes that induce specific proteins has enabled the bacterial manufacture of ‘man-made’ pig growth hormone, or recombinant porcine somatotrophin (r-PST), whose composition and action are almost indistinguishable from natural pig growth hormone, as secreted from the pig’s own pituitary gland. (It appears that r-PST itself may have one amino acid different and one more amino acid in the chain; and, of course, the different methodology of delivery and the inability to also manipulate the interrelating hormones are bound to influ-

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<td>Growth hormone</td>
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ence mode of action.) When delivered into the hormonal complex via the blood system, r-PST brings about dramatic increases in lean growth rate (about +10%), carcass meat content (about 5% units of lean in the carcass side, from 55–60%) and reductions in fatness (about −25%). There are also some negative effects upon appetite, which is usually reduced. It would appear that at normal levels of circulating hormone, there are no serious adverse consequentials of the use of r-PST to pig health. However, if physiological dose rates are used, no negative, or positive, consequences would be expected in view of the exogenous hormone being similar in form or action to the endogenous. The possibility of negative health effects must, however, increase as significant performance change upon dosing is achieved, significant performance change being the objective of the exercise. In trials, evidence of respiratory and locomotor disorders has been clearly seen, and there is disquiet about these unexpected, unwelcome and unacceptable consequences of r-PST dosing. Resolution of this issue is awaited. Following r-PST treatment, there may also be some loss of muscle tenderness over and above any direct consequence upon meat quality of a large reduction in fat.

Beta-adrenergic agonists are in the family of catecholamines including endogenous norepinephrine and epinephrine (adrenalines). The catecholamines stimulate adrenergic receptors with consequences not only for heart rate and bronchodilation but also for lipolysis. Beta-adrenergic agonists which are analogues of epinephrine have been manufactured, amongst others, as cimaterol, clenbuterol and ractopamine. These substances decrease fat mass (about −10%), may increase muscle growth, increase leanness (about +10%) (but also change muscle fibre structure and decrease meat tenderness) and also improve growth rate and feed efficiency (although the latter is unfortunately likely to be through a reduction in the level of feed consumption). On account of their diverting nutrients from fat growth to protein growth these substances are sometimes referred to as 're-partitioning agents'.

In addition to being different in mode of action, the beta-adrenergic agonists are also importantly different from r-PST in that they are orally active (whereas PST must be delivered into the bloodstream). This facilitates administration, but increases human hazard.

Exciting as the responses of pigs to exogenous hormones might be, it still remains to be ascertained:

(1) whether the consumer will accept pork products as being of the highest quality in the broadest sense when that consumer has knowledge that the pigs concerned have been treated with exogenous hormone preparations (however safe these may be shown);

(2) whether the same benefits of increased growth rate, efficiency and leanness cannot be achieved more economically and more simply through conventional genetic selection for lean tissue growth rate.

These comments are made in the knowledge that steroids, beta-agonists and growth hormone are considered important to livestock production in some countries, the
latter especially where the pigs are over-fat and carcasses can be made acceptable by r-PST administration. However, most European genotypes are now as lean as is compatible with minimum standards of meat juiciness, flavour and tenderness, and the need to reduce fat content by exogenous hormone intervention is no longer an issue.
Chapter 4
Reproduction

Introduction

Reproduction has a major impact on the efficiency and productivity of pig production systems. In contemporary systems a breeding sow can spend over 90% of her time either pregnant or lactating, while in the top 10% of UK pig units only 17 days a year, on average, are non-productive. Given that the fixed costs of the breeding herd (including labour, feed and space) are similar regardless of whether a sow produces 16 or 26 piglets a year, the number of viable piglets produced per sow is a major factor in the efficiency of commercial units. Furthermore almost 60% of gilts and first litter sows are culled for reproductive failure, abortion, poor rearing ability or small litter size. These problems occur when the females should be at their most productive and point to the importance of reproduction to the success of pig production systems.

Reproductive efficiency is usually defined as the number of piglets produced per sow per year. This measure includes two key components: the numbers of piglets produced per litter and the number of litters produced per year. There is considerable variation in both these traits between different herds, suggesting that multiple factors are involved and that there are opportunities for improvement. Increasingly, reproductive success in the pig focuses not only on the number of piglets produced, but also on the quality of the piglets. In this sense quality includes the health and well-being of the piglets, their suitability for their production environment and the extent to which they meet consumer expectations of quality.

A chronological description of the reproductive process in the pig is provided here, beginning at the point of conception and including intra-uterine, pre-pubertal and pubertal development. The form and function of mature reproducing boars and sows is considered and, in females, this is extended to pregnancy, parturition and lactation. The role and future applications of assisted reproductive technologies in contemporary pig production are also considered.

Throughout the reproductive life of an animal, reproductive processes are under close hormonal control, while the hormonal system itself is influenced by external factors such as environment and nutrient supply. For a fuller description of the role of the reproducively important hormones, the reader is referred to the sections describing male and female reproduction below.
Development of the reproductive system during intra-uterine life

Pigs destined for meat production spend longer in utero than between birth and slaughter. The period during intra-uterine life represents an important period both for the development of the reproductive capability of the fetus and for the long-term post-natal viability and quality of the resultant offspring.

The sex of the fetus depends upon its genetic make-up (chromosomal sex), gonadogenesis (gonadal sex) and the formation and maturation of accessory reproductive organs (phenotypic sex). Sex determination occurs at fertilisation and depends on whether an oocyte is fertilised by a sperm bearing an X or a Y chromosome. A gonadal ridge is first seen in the pig fetus on day 21 of pregnancy and primordial germ cells that are similar in both sexes are present by days 22–24. Until about day 26 of pregnancy the fetal reproductive system develops to form two sexually non-differentiated gonads, a pair of ducts (the Wolffian and Müllerian ducts) and associated tissues. The presence of a single gene called SRY on the Y chromosome is sufficient to induce testicular differentiation. In females, the absence of SRY testis-determining factor and the presence of two X chromosomes allow the ovaries to develop. The second step of sexual differentiation, known as secondary differentiation, leads to the development of internal and external genitalia. In mammals, female differentiation is believed to be the default pathway, which is overridden in male fetuses by the testicular hormones anti-Müllerian hormone (AMH), testosterone and dihydrotestosterone. AMH, produced by Sertoli cells, suppresses the development of the Müllerian ducts, which would form the oviducts and uterus, while testosterone, secreted by Leydig cells, induces the formation of the epididymis, vas deferens and seminal vesicles. The external genitalia (urethra, prostate gland, penis and scrotum) are formed in the presence of dihydrotestosterone. Abnormalities in the differentiation and development of gonads and ducts can result in varying degrees of intersexuality.

Testicular descent begins at about day 60 of fetal life, with both testes being present in the scrotum by day 90. Luteinising hormone (LH) and testosterone concentrations mirror testicular development during pre-natal life. Overall, testicular development from the early fetal period to sexual maturity lags behind body growth, although testicular growth exceeds body growth from the late pre-natal stage to 3 weeks post-partum, primarily because of Leydig cell development.

In female fetuses the gonad differentiates into an ovary containing egg nests or gamete cells by day 30 of pregnancy and by mid-gestation primordial follicles are recognisable. Primary and secondary follicles appear late in gestation. Follicle stimulating hormone (FSH)-secreting cells have been identified in 70-day-old fetuses and serum levels of FSH, LH and prolactin increase prior to birth. The egg nest arrangement of gamete cells disappears by 1–2 weeks after birth. During early fetal development, the oogonia are produced by mitosis. The number of oogonia increases markedly from 5000 at 20 days after mating to a peak of 1100000 by 50 days after mating. Thereafter, mitotic activity ceases and some germ cells are lost by necrosis.
Meiotic divisions begin about day 40 of embryonic development, which will result in several million germ cells by day 50. Porcine oocytes are held in a pre-meiosis resting stage (diplotene) from day 50 of fetal life. The final stage of meiotic maturation does not occur until after puberty.

The environment to which the gilt or sow is exposed during pregnancy can affect the development of the reproductive tract of both male and female fetuses. For example, exposure to endocrine disrupting compounds such as dioxin in mid-gestation can increase the incidence of genital abnormalities including cryptorchidism and wolffian duct anomalies. Alterations in nutrient supply during pregnancy alter the timing of changes in fetal ovarian development. For example, intra-uterine growth-retarded piglets, reflecting inadequate nutrient supply during intra-uterine life, have delayed ovarian follicular development at birth.

### Functional competence of the gonads and reproductive endocrine axis

Functional competence is not achieved simultaneously in all components of the reproductive system. For example, in the boar, mounting activity occurs relatively early, but sequential patterns of sexual behaviour are not observed until after 5 months of age. Primary spermatocytes are present in the seminiferous tubules from 10 weeks of age, but mature spermatozoa are not present in the seminiferous tubules or in the ejaculate until 20 and 22 weeks of age, respectively. Boars are normally considered to be sexually mature at 30 weeks of age, although the number of spermatozoa and the semen volume continue to increase until 18 months of life.

In females, tertiary ovarian follicles develop at 8 weeks after birth. Thereafter, follicular development is dependent on gonadotrophins. Indeed, the ovaries are capable of responding to exogenous gonadotrophins from about 60 days of age, well before the animal reaches natural puberty. For example, a single injection of pregnant mare serum gonadotrophin (PMSG) followed by human chorionic gonadotrophin (hCG) induces ovulation in 90% of gilts at 90–130 days of age, but few of them exhibit oestrus or remain pregnant.

During the pre-pubertal period the ovaries contain numerous small follicles (2–4 mm in diameter) and several medium sized (6–8 mm) follicles. Ovarian weight increases as ovarian follicles develop. The hormone feedback mechanisms that control changes in reproductive hormone concentrations become established during the pre-pubertal period. For example, the negative feedback control of LH release by ovarian steroids is absent at birth and developed by 8 weeks of age.

During the first 60 days of life the uterus undergoes a variety of morphological changes including the appearance and proliferation of uterine glands, development of endometrial folds and growth of the myometrium. These changes are independent of ovarian steroids and proceed normally in ovariectomised gilts. Between days 60 and 80 both uterine weight and uterine growth rate increase dramatically and
continue to increase until puberty, reflecting the uterotrophic effects of ovarian oestrogen.

**Puberty**

Male and female animals are considered to have reached puberty when they are able to release gametes and exhibit sexual behaviour.

Gilts usually reach puberty at between 6 and 8 months of age. Puberty is believed to occur following a reduction in the activity of neural inhibitory mechanisms and/or a decrease in the negative feedback action of ovarian steroids. These changes lead to the simulation of pulsatile GnRH release, episodic LH secretion and hence ovarian activity.

In boars, the first ejaculates occur at between 5 and 8 months of age, although the number of spermatozoa and the semen volume continue to increase during the first 18 months of life. Sexual behaviour in the boar increases during the second month of life and appears to be unrelated to endocrine changes. Boars approaching puberty show bisexual behaviour, mounting oestrous females and becoming immobile when mounted by an adult boar. The differentiation of sexual behaviour is slow and still incomplete at puberty.

**Age of puberty**

Many piglets are born to gilts. For example, in the UK it has been estimated that between 15 and 25% of litters are produced by gilts. Given that gilts have smaller litters and longer rebreeding intervals than sows, the percentage of gilts in a herd can have a marked effect on overall productivity. The efficiency of the herd can be reduced still further if gilts are present in the herd for prolonged periods prior to their first successful mating. For this reason, there is considerable interest in developing means to reduce the age at first mating. Any attempts to advance the age of puberty should take into account the lifetime productivity of the animal.

The age of puberty is influenced by nutritional status, body weight, season, breed, disease status, social environment and management practices. The presence of boars reduces both the age and the weight at which gilts achieve puberty. Puberty occurs later in gilts penned individually compared to group-housed contemporaries.

**Breed differences – opportunity to harness increased reproductive efficiency**

While there are some differences between breeds in the age of puberty onset, the most dramatic recorded breed differences are those between Chinese Meishan pigs and those from White breeds. The average age of puberty in the Meishan gilt is around 115 days, i.e. approaching half of the interval between birth and puberty in White breeds. Greater understanding of the factors that promote early puberty may
provide opportunities to reduce the lengthy non-productive birth to puberty interval in commercial genotypes.

**Drawbacks of mating at first post-pubertal oestrus**

It is well established that fertility following mating at the first oestrus is lower than following mating at the second or third oestrus. This is due to the higher proportion of immature oocytes in first oestrus gilts. The general practice is to mate gilts for the first time at a live weight between 120 and 135 kg and after one or two oestrous cycles.

**Reproduction in the male**

**Anatomy and function of the mature reproductive tract**

The reproductive tract of the mature boar comprises a pair of testes and the epididymis lying outside the abdomen in the scrotum, the accessory glands (the prostate, seminal vesicles and bulbourethral glands), the ductus deferens and the penis (Figure 4.1). To function effectively, the testes must be maintained at a lower temperature than the rest of the body. The difference between scrotal and rectal temperature in the boar is about 3.2°C. This temperature difference is achieved by their external location and by a vascular countercurrent mechanism in which

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Fig. 4.1  Diagrammatic representation of the mature boar reproductive tract. Redrawn with permission of Dr R. Ashdown.
arteries supplying the testes are enmeshed by testicular veins (the pampiniform plexus). This enables arterial blood entering the testis to be cooled by venous blood leaving the testis.

The testes are composed of two tissue types: the interstitial (Leydig) cells, which are responsible for the synthesis and secretion of testosterone, and the seminiferous tubules, responsible for the development of mature spermatozoa from primitive germ cells. The development of mature spermatozoa from spermatogonia takes about 34 days. Gonadotrophic hormones (principally LH from the anterior pituitary) stimulate the production of testosterone and this hormone, together with FSH, stimulates development of mature spermatozoa. Spermatozoa leave the testis by ducts that lead to the coiled duct of the epididymis and then to the straight ductus deferens. Providing that low scrotal temperatures and appropriate hormonal conditions are maintained, spermatozoa stored in the epididymis retain their fertilising ability for several weeks. Testosterone also maintains the secretory activity of the accessory glands that pour secretions into the urethra, where, at the time of ejaculation, they are mixed with the fluid suspension of sperm and ampullary secretions from the ductus deferens. The bulbourethral glands contribute the gel-like component of boar semen that forms a plug in the vagina of mated females. The size of the bulbourethral glands can be used to distinguish castrated and cryptorchid boars. In boars with retained testes the glands are of normal size, whereas they are smaller after castration.

The body of the penis lies beneath the skin of the body wall and is surrounded by cavernous vascular tissue. The apex or free part of the penis (of which the terminal 5 cm is spiralled) is covered by modified skin called the penile integument. In the resting state this is enclosed within the prepuce. There is also a large dorsal diverticulum in which urine and epithelial debris accumulate. Sexual stimulation causes dilation of the arteries supplying the cavernous tissue; the resultant increase in pressure produces considerable elongation of the penis and during erection the entire visible length of the free end of the penis becomes spiralled. Intromission lasts for up to 7 minutes, when a large volume of semen (100–500 ml) is ejaculated containing $30 \times 10^9$ to $150 \times 10^9$ sperm.

Reproduction is controlled by negative feedback hormone mechanisms involving gonadotrophin releasing hormone (GnRH) from the hypothalamus, LH and FSH from the anterior pituitary and testosterone from the testis. In general terms, hypothalamic GnRH stimulates LH and FSH from the pituitary, which in turn stimulates testosterone production by the testis. The presence of testosterone in the circulation modulates the secretion of hypothalamic hormones (the negative feedback effect), which in turn control the release of LH from the anterior pituitary.

**Success of male reproduction**

Records from pig artificial insemination (AI) centres and commercial units suggest that 20–50% of culled boars are either unable to mate or mate too infrequently. Low copulatory capacity appears more common in intensive than extensive systems
and its incidence increases with age, perhaps because of increased susceptibility to locomotor problems in such systems. Reasons for infertility in boars include reduced libido, failure to mount, impotence, poor semen quality and defects of the genitalia. Australian studies indicate that boars housed near sexually receptive females exhibit more courtship behaviour and mating activity. This suggests that the sexual behaviour of breeding boars could be optimised by housing them close to female pigs.

Reproduction in the female

Anatomy

The reproductive tract of the mature gilt or sow comprises a pair of ovaries and oviducts together with the uterus, cervix, vagina and external genitalia (Figure 4.2). The surface of each ovary is uneven, because of the many protruding ovarian follicles and/or corpora lutea. The appearance of the ovaries depends on the

Fig. 4.2 Diagrammatic representation of the mature sow reproductive tract. Redrawn with permission from Marinat-Botte, F. et al. (2000) Ultrasonography and Reproduction in Swine. INRA Editions, Paris.
physiological state of the gilt or sow. For example, prior to ovulation finely vascu-
larised pre-ovulatory follicles measuring between 0.8 and 1 cm in diameter are
visible on the surface of the ovary. By 2 days after ovulation, the outside of the ovary
is characterised by purple corpora lutea with visible follicle rupture points. After 5
days post-ovulation corpora lutea become pink and reach their final size of about
1 cm in diameter. The ovaries are composed of the medulla and the larger cortex,
surrounded by the superficial or germinal epithelium. The ovarian medulla consists
of connective tissue and extensive vascular and nervous systems, while the cortex
contains ovarian follicles and/or corpora lutea at various stages of development or
regression. Each ovary lies in an ovarian bursa or pouch attached to the upper
portion of the oviduct, which, although open, largely encloses the ovary.

The oviduct is often considered as four functional segments: the fringe-like
fimbrae, the funnel-shaped opening near the ovary called the infundibulum, the
ampulla which is dilated and accounts for about half the length of the oviduct,
and the isthmus which connects the oviduct with the uterine lumen. The junction
between the isthmus and the uterus is lined with long finger-like mucosal pro-
cesses that prevent irrigation of the lumen of the reproductive tract from the uterus
to the oviduct. Cilia lining the oviduct, combined with oviduct contractions, are
important for egg transport and to promote fertilisation by increasing sperm–egg
contact.

The pig uterus is bicornate. The two uterine horns are folded or convoluted and
may be up to 2 m long, although the uterine body is short. Both the internal mor-
phology and the tone of the uterus vary considerably during the oestrous cycle and
pregnancy under the influence of reproductive hormones produced primarily by the
ovary. The uterus consists of the internal secretory layer, the endometrium, and the
outer muscular layer, the myometrium. The cervix is a sphincter-like structure con-
necting the uterus and the vagina. The cervical canal contains a corkscrew arrange-
ment of ridges or annular rings, which, although well adapted to the spiral twisting
of the tip of the boar’s penis, provide a particular challenge for intra-uterine insemi-
nation. The cervix is tightly closed except during oestrus (when it relaxes slightly)
and parturition.

The oestrous cycle

In contrast to their wild ancestors which tended to mate in the autumn and farrow
in late winter, the domestic pig does not usually show evidence of a breeding season.
Non-pregnant post-pubertal female pigs typically exhibit oestrus every 21 days
(normal range 19–23 days) throughout the year. The oestrous cycle is usually cate-
gorised into two phases: the luteal phase (∼ days 5–16 after oestrus) and the follicu-
lar phase (day 17 of one cycle to day 4 of the following cycle). Conventionally, and
for the purposes of this chapter, the day when oestrous behaviour is first observed
is denoted day 0. The onset of oestrus is characterised by subtle changes in the pig’s
behaviour including reduced appetite, increased restlessness and lordosis response,
and physiological changes such as swelling and reddening of the vulva. Sexual recep-
tivity usually lasts from 2–3 days, although this is sometimes shorter in gilts. The mounting response of the boar appears to be stimulated primarily by the immobilisation of the sow.

Ovulation occurs spontaneously in the pig, usually after two-thirds of the oestrous period has elapsed. Estimates suggest that the interval between ovulation of the first and last follicle is between 1 and 6 hours, although there is some evidence that this interval may be shorter in the prolific Meishan pig. The number of oocytes released from the ovaries (the ovulation ‘rate’) varies depending on age, breed, parity and nutrition, but is usually between 10 and 24. Following ovulation, ova are transported to the ampulla of the oviduct by the rapid beating of cilia to await fertilisation.

The oestrous cycle is controlled by sequential interrelationships between structural and functional changes in the ovary regulated by the hypothalamic–pituitary–ovarian hormone axis. Briefly, neurosecretory neurones within the hypothalamus release GnRH into the hypothalamic–hypophysial portal system that controls the secretion of LH and FSH (collectively termed gonadotrophins) from the anterior pituitary. In turn, gonadotrophins support the development of ovarian follicles and corpora lutea. Steroid hormones (progesterone and oestradiol) produced by the ovary can exert an inhibitory effect on the GnRH neurones in the hypothalamus. Superimposed on this classic negative feedback model of the hormonal control of reproduction are intragonadal regulators (such as inhibins and activins) and other growth factors that modulate both events within the ovary and the secretion of pituitary gonadotrophic hormones. The balance between inhibitory (negative feedback) and stimulatory (positive feedback) factors changes at different stages of the oestrous cycle.

Ovarian and endocrine changes

During the luteal and early follicular phases of the pig oestrous cycle there are about 50 small (2–5 mm) follicles, of which 10–20 approach pre-ovulatory size (8–11 mm). Selection of follicles destined to ovulate is believed to occur between days 14 and 16 of the cycle. Soon after ovulation there is a rapid proliferation of primarily granulosa and a few theca cells lining the follicle wall. These become luteinised to form the corpus luteum, a process that involves rapid functional changeover from oestro
gen to progesterone production. Initially, the corpus is classified as a corpus haemorrhagicum because of the blood-filled central cavity, but within 6–8 days the corpus luteum is a solid mass of luteal cells with an overall diameter of 8–11 mm. The corpus luteum reaches its maximum weight of 350–450mg by day 6–8 and maintains its structure and secretory capability until day 16. Increased uterine release of prostaglandin F\(_{2\alpha}\) (PGF\(_{2\alpha}\)) into the utero-ovarian vein between days 12 and 16 leads to luteal regression. In cyclic animals, corpora lutea rapidly regress to form non-
secretory corpus albicans by day 16, with circulating progesterone levels declining rapidly within 1–2 days.
These ovarian changes are caused by, and respond to, circulating levels of reproductively important hormones (Figure 4.3). Towards the end of the oestrous cycle, developing pre-ovulatory ovarian follicles secrete increasing amounts of oestradiol, culminating in a peak of oestradiol around day 18. Increased circulating oestradiol is essential for sexual receptivity. During this period, oestradiol initially suppresses both LH and FSH levels, but later induces pre-ovulatory surges of both gonadotrophins. The oestradiol surge triggers the single pre-ovulatory surge of LH that initiates both the maturation of the oocyte in the pre-ovulatory follicle and the rupture of the follicle wall, culminating in ovulation. In ovulatory follicles, the oocyte begins its first meiotic division about 20 hours after the LH peak. The duration of the LH peak (43 hours) and meiotic maturation (42–44 hours) are considerably longer in the pig compared to ruminant species. Pulses of LH occur during the luteal phase; these seem to be associated with follicular atresia and maturation. LH levels are low during the remainder of the cycle.

As with LH, plasma FSH levels are low during the early follicular phase. Immediately following ovulation, the abrupt decline in circulating oestradiol concentrations allows a marked increase in the secretion of FSH which continues for 2–3 days after oestrus. This precedes a period of follicular development which results in a tenfold increase in the number of medium sized (3–6mm diameter) follicles between days 3 and 8 of the oestrous cycle.
Establishment of pregnancy

Insemination

Optimal use of boars

Both over- and under-working of boars can result in smaller than optimal litter sizes. Current guidelines suggest that one boar should serve two sows per week, assuming that each sow is mated twice around the time of ovulation. However, some studies indicate that resting boars for up to 6 days before mating increases litter size. It is clearly important to rapidly identify and remove sub-fertile boars, and hence prompt and accurate pregnancy diagnosis is essential.

Timing of insemination

The timing of insemination, by both natural mating and AI, relative to ovulation is critical for subsequent fertilisation. It is generally agreed that optimal fertilisation rates are achieved following insemination during the 24 hours preceding ovulation (Figure 4.4). Given that it is the time of onset of oestrus, rather than ovulation, that is usually known, the usual way to ensure mating at the appropriate time relative to ovulation is to mate gilts or sows every 12 hours from the onset of standing oestrus. Data using frozen semen suggest that insemination during the 4 hours preceding ovulation achieves the highest rates of fertilisation. This ensures that sperm are able to fertilise newly ovulated oocytes. In addition, boar seminal plasma interacts with the female genital tract to increase the likelihood of fertilisation.

Fig. 4.4 Sequence of events occurring at oestrus and ovulation.
Semen assessment

Assessment of the functional capacity of spermatozoa is of particular interest to the AI industry in order to select sires of good fertility. Evaluation of semen has generally been based on the microscopic examination of motility and morphology of spermatozoa. Frequently, eosin stain has been used to determine the proportion of live and dead spermatozoa, while Giemsa stain has often been used for morphological evaluation. These methods are useful, but their effectiveness and repeatability depend on the experience of the assessor. Fluorescent staining improves microscopic evaluation of spermatozoa, but its major drawback is that only 100–200 spermatozoa can be evaluated per sample. The advent of flow cytometry for spermatozoa analysis in the 1980s and the development of new stains in recent years have led to more accurate means of assessing the viability of spermatozoa. Recent data from Canada suggest that techniques associated with in vitro embryo production can be used to assess semen. Specifically, when different batches and dilutions of semen were compared, the number of sperm attached per oocyte was a major factor accounting for variation in litter size following AI. However, finding one direct test to evaluate the fertilising potential of spermatozoa continues to be elusive.

Early pregnancy (days 0–30)

Fertilisation

Fertilisation occurs in the ampulla of the oviduct, 1–3 days after the beginning of standing oestrus. Only one sperm usually enters the cytoplasm of each egg. The glycoprotein coat surrounding the egg (the zona pellucida) undergoes physiochemical changes immediately after sperm penetration, preventing penetration by other sperm. Once in the egg cytoplasm, the head of the fertilising sperm swells into a spheroidal male pronucleus containing 19 chromosomes. At fertilisation the male and female pronuclei migrate towards each other, shrink, their pronuclear envelopes disappear and the contents of the maternal and paternal pronuclei assemble into 38 chromosomes. Providing that mating or insemination is performed at the appropriate time relative to ovulation, fertilisation is very successful, usually in excess of 95%. Ovulation rate has little, if any, effect on the success of fertilisation.

Transport of the embryo in the reproductive tract

The pig embryo moves from the oviduct into the uterus at about the four-cell stage (60–72 hours after the onset of oestrus). Porcine embryos are located near the tip of the uterine horns on days 5–6 and then migrate towards the uterine body, mixing with embryos from the opposite uterine horn as early as day 9. Embryos migrate freely within the lumen of both uterine horns until about day 12, when conceptuses
undergo rapid elongation and establish their position within the uterus. Elongated blastocysts become regularly spaced within the uterine lumen, with no overlap of membranes of adjacent blastocysts.

Intra-uterine migration and spacing appear to be modulated by peristaltic contractions of the myometrium stimulated by the production of histamine, oestrogen and prostaglandins by the developing conceptus. Intra-uterine migration is essential to provide the maximum surface area of contact between the developing embryo and the uterus and to allow space for optimal development of littermate embryos.

**Embryo development**

Following fertilisation, each of the 38 chromosomes splits longitudinally and the resultant halves move to opposite sides of the zygote. The two new groups of 38 chromosomes are then isolated from one another by a membranous wall, forming two separate cells. A succession of similar mitotic cell divisions results in an increased number of cells of reduced size contained within the zona pellucida. By the 16-cell stage the embryo consists of a compact cluster of cells within the zona pellucida and is termed a morula. At this stage, the outermost cells of the morula flatten against the zona pellucida and a cavity appears within the core of the cluster, transforming the embryo into a hollow sphere called a blastocyst. Oestrogen is important for the transformation of pig morula to the cavitated blastocyst. The blastocyst consists of a cluster of cells, the inner cell mass, which will form the embryo and fetus, and a single layer of peripheral cells, the trophoblast, which forms the placental membranes. The embryo reaches the blastocyst stage by day 5 and the zona pellucida is shed (hatching) between days 6 and 7. The exposed blastocyst then undergoes an astonishingly rapid expansion accompanied by a radical change in shape. It expands from 0.5–1 mm diameter at hatching to 2 mm spheres on day 10 to 10 mm tubular shapes on day 11 or 12. Tubular conceptuses (embryos and associated membranes) rapidly (within 2–3 hours) elongate into a thin filamentous thread-like form measuring 20 cm in length. Conceptus elongation occurs by cellular reorganisation and remodelling rather than hyperplasia. After this initial elongation phase, the conceptus continues to increase in length and diameter, reaching lengths of 80–100 cm by day 16. Although the majority of littermate conceptuses are at a similar stage of morphological development, littermate spherical conceptuses can vary considerably in diameter, which, if the difference is large, can lead to a difference of 4–24 hours in the time of elongation on day 12. Such delayed embryos are believed to be at greater risk of embryo mortality.

**Interactions between developing embryos and the uterine environment**

**Conceptus signals**

Pig blastocysts secrete a range of proteins, including interferons, and steroids that change quantitatively and qualitatively as pregnancy progresses. Physiologically, the most important pig blastocyst secretory product is oestradiol. The onset of blasto-
cyst oestrogen production coincides with the initiation of blastocyst elongation. Blastocyst oestrogens promote several changes in the maternal uterus including increased folding of the surface of the endometrium, alterations in uterine secretory proteins and increased uterine vascularity and vascular permeability. Importantly, blastocyst oestrogen is responsible for preventing regression of the corpus luteum and hence ensuring maintenance of pregnancy (sometimes referred to as maternal recognition of pregnancy), whereas blastocyst-secreted proteins do not affect the lifespan of the corpus luteum.

Pig conceptuses produce oestradiol on days 11 and 12 and between days 14 and 30. Both phases are essential to extend the lifespan of the corpus luteum. Oestrogens do not appear to inhibit uterine production of the luteolysin PGF$_{2\alpha}$, but instead seem to cause PGF$_{2\alpha}$ to be sequestered into the uterine lumen. Secretion of luteolytic PGF$_{2\alpha}$ into the uterine lumen, termed exocrine secretion, results in PGF$_{2\alpha}$ being unavailable to cause luteolysis. This effect of conceptus oestrogens and modification of the direction of PGF$_{2\alpha}$ release away from the bloodstream (endocrine release) is called the endocrine–exocrine model of maternal recognition in the pig.

At least two conceptuses must be present in both uterine horns to ensure that a sufficient area of endometrium is in contact with the trophoblast for pregnancy to be maintained. This suggests that conceptus factors associated with maternal recognition of pregnancy act locally rather than systemically.

Conceptus oestrogens also increase endometrial expression of specific growth factors including insulin-like growth factor one (IGF-1) and fibroblast growth factor seven (FGF-7) which, in turn, stimulate cell proliferation and development in the conceptus.

**Uterine signals**

Porcine embryos remain unattached to the uterine wall for a relatively long period of development, and once attached, the non-invasive trophoblast does not make direct contact with the maternal blood supply. Porcine conceptuses therefore rely heavily on proteins secreted by the uterus for their growth and survival. Under the influence of ovarian steroids, particularly progesterone, the endometrium secretes a range of macromolecules with a nutrient or protective role. Among the most-studied uterine secretory proteins are uteroferrin, retinol binding protein and several plasmin inhibitors. Uteroferrin and retinol binding protein act as chaperones to transport iron and vitamin A, respectively, to the conceptus. Plasmin inhibitors may serve a role in controlling blastocyst invasiveness; although the pig embryo does not invade the uterine endometrium, it is invasive when transferred to ectopic sites, suggesting that the uterus is involved in suppressing the invasion of pig blastocysts.

**Uterine attachment**

Invasive implantation, as occurs in rodents and primates, does not occur in the pig. Rather, the attachment of the pig conceptus to the uterine wall is non-invasive and
superficial. Conceptuses begin to attach to the uterine wall on day 13, with attachment complete between days 18 and 24. Attachment occurs by the interdigitation of uterine and trophoblastic microvilli, covering the complete interface between the two layers, except where the trophoblast overlies the openings of the uterine glands. The trophoblast surface in these areas becomes modified to form specialised structures called areolae, which are the sites of absorption of nutrients secreted by the endometrium.

Placental development (Figure 4.5)

The placenta is formed from extraembryonic membranes that differentiate from the blastocyst. These include the yolk sac, amnion, allantois and chorion. During and following attachment, an outgrowth of the extraembryonic mesoderm originates from the embryoblast and migrates between the trophectoderm and endoderm. This mesodermal layer splits and combines with the trophectoderm to form the yolk sac where new red blood cells are synthesised. The mesoderm also contributes to the formation of the amnion and the allantois, which is formed from an outgrowth of the embryo hindgut. From day 19, the avascular chorion folds and fuses with the vascular allantoic membrane to form the allantochorion. This is the functional placenta in the pig. These embryonic membranes grow rapidly between days 20 and 60 and at a faster rate than the conceptus.

From about day 18 watery fluids accumulate in the amniotic and allantoic cavities and their volumes and chemical composition change throughout pregnancy. Both fluids are important to ensure that the allantochorion remains in close apposition with the endometrium throughout pregnancy, for absorbing physical shocks that may otherwise damage the developing fetus and as nutrient reservoirs for the developing fetus, with the amniotic fluids being important for enteric nutrition in late pregnancy.

Embryo mortality

Estimates of pre-natal loss suggest that up to 40% of oocytes shed at ovulation are not represented by piglets at birth. It is important to recognise that some pregnancies incur no loss, while in others, all, or the majority of, embryos die, the sow returns to oestrus and embryo mortality may not be recorded as the cause of low fertility. It is generally accepted that most pre-natal losses in the pig occur during the first month of pregnancy (Figure 4.6), with the second week of pregnancy being regarded as a particularly critical period. This is when dynamic changes including the initiation of the conceptus, oestrogen synthesis and the spacing and final placement of conceptuses are occurring and when the mother must make appropriate adjustments in her physiology if the pregnancy is to continue.

Numerous external (environment, nutrition and genetic) and internal (ovulation rate, oocyte quality, synchrony of embryo development and function, hormonal background, uterine environment) factors are associated with embryo mortality.
Fig. 4.5 Formation of the feto-placental unit. (a) Development of the primary layers (day 13); (b) formation of the yolk sac, amnion and outgrowth of the allantoic sac (day 16); (c) expanded allantois fused with the chorion to form the chorio-allantois; (d) established feto-placental unit showing amniotic and allantoic sacs and surrounding membranes (day 30).
This topic has been reviewed extensively elsewhere; however, some novel associations and/or practical opportunities are worthy of note.

**External factors**

**Environment**

Of various environmental stressors including temperature, light and season, elevated temperatures after mating are known to specifically reduce embryo survival. Exposure of gilts to high (32°C) temperatures on days 8–16 after oestrus reduces total conceptus weight and protein synthesis. This effect occurs in the absence of changes in maternal hormone levels or uterine secretory activity, suggesting that heat stress has a direct effect on embryo viability. Surprisingly, stressors such as ‘negative handling’, a brief electric shock, confinement and administration of adrenocorticotrophic hormone (ACTH) to induce circulating cortisol concentrations normally associated with stress do not appear to reduce embryo survival.

**Nutrition**

Both the composition and the quantity of the diet fed prior to mating and during early embryo development can affect embryo survival. Nutrients do not necessarily have a direct effect on embryo development and survival, but by altering circulating levels of metabolites and reproductively important hormones, they affect key organs of the reproductive tract in which oocytes and embryos develop, including the ovarian follicle, the oviduct and the uterus. Of the specific nutrients shown to improve embryo survival, the beneficial effects of increasing dietary fibre during the oestrous cycle preceding mating, dietary supplementation of riboflavin on

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Fig. 4.6  Estimates of pre-natal mortality throughout gestation. Redrawn with permission from Wiseman, J. *et al.* (eds) (1998) *Progress in Pig Science*. Nottingham University Press.
days 4–10 of pregnancy and feeding additional folic acid from weaning are all worthy of note.

While it has long been known that high plane feeding prior to mating increases ovulation rate in pigs (the so-called flushing effect), it is now evident that such nutritional regimes are also associated with increased embryo mortality, so that the potential for an increased litter size at birth is not realised. Recent studies suggest that optimum feeding regimes around the time of mating involve increased rations prior to mating, followed by low rations immediately after mating. The rationale for this approach is based on the inverse relationship between feed intake and circulating steroid (progesterone and oestrogen) concentrations in the bloodstream. The liver weight, rate of blood flow through the liver and the abundance of liver enzymes that metabolise steroids are increased in animals consuming increased rations. As a result, steroids, which are predominantly metabolised by the liver, are metabolised more rapidly and circulatory levels decrease. Animals consuming increased rations prior to mating therefore have lower circulating steroid concentrations, providing less negative feedback to the hypothalamic–pituitary axis and therefore allowing increased release of gonadotrophins (particularly LH), culminating in an increased ovulation rate and oocyte quality. After mating, progesterone is required to support embryo development, particularly in situations where the ovulation rate is high and there are more embryos to support. Reducing feed intake immediately after mating provides a means of increasing endogenous progesterone levels and thereby supporting embryo development. Studies conducted in Canada report a positive relationship between progesterone concentrations at 72 hours after the onset of oestrus and embryo survival on day 28 of the pregnancy. Although switching diets immediately after mating may be difficult to implement in a commercial situation, the use of altered feed intake to generate beneficial alterations in endogenous hormone concentrations provides a novel and acceptable means to improve reproductive outcome.

Genetic factors

Provided that gilts and sows are mated at the appropriate time relative to ovulation, as discussed earlier, the incidence of chromosomal anomalies is low (for example the incidence of triploidy is estimated to be less that 0.03) and is not considered to make a significant contribution to embryonic mortality.

The enhanced reproductive performance characteristic of cross-bred compared to pure-bred animals is at least partially attributed to greater embryonic survival in cross-bred females. However, it is not clear whether this phenomenon is attributed to direct or maternal heterosis.

Certain breeds or selected lines of pigs exhibit enhanced prolificacy. In France, selection of sows on the basis of their litter size led to the establishment of a ‘hyper-prolific’ line in which sows give birth to an average of 5.3 more piglets per litter. These pigs achieve their high litter size because of their higher ovulation rates and greater uterine capacity rather than through increased embryonic survival. Several
breeds native to the People’s Republic of China exhibit exceptional prolificacy. Of these, the Chinese Meishan pig, which typically gives birth to an average of four more live piglets per litter compared to contemporary gilts and sows from indigenous breeds, has been most studied. Prolificacy in the Meishan is a maternal trait, with the genes of the sire having no effect on litter size. The major factor associated with increased litter size in the Meishan is a higher pre-natal survival at a given ovulation rate. The Meishan pig has therefore provided a valuable model to study intrinsic factors associated with pre-natal survival in the pig.

**Internal factors**

**Ovulation rate**

Although the number of oocytes shed at ovulation determines the maximum number of potential offspring, litter size does not increase concomitantly with ovulation rate because the percentage of pre-natal survival increases with higher numbers of ovulations. Clearly, the relationship between ovulation rate and litter size varies between gilts and sows and between different breeds of pig. However, one group of researchers in the Netherlands predicted that optimal embryo survival would be obtained at an average of 18.1 ovulations.

**Oocyte quality**

It is not only the number of oocytes released at ovulation that determines how many embryos will survive, but also the quality of those oocytes. There is now increased awareness of the crucial importance of enhanced oocyte quality in promoting embryo survival, to the extent that it has been suggested that many causes of embryonic death originate during oocyte development. Several pre-mating nutritional regimes associated with improved embryo survival also increase the proportion of oocytes in the final stages of maturation, providing evidence for a direct link between oocyte competence and later embryonic survival.

**Embryo development**

Embryos carried by individual mothers vary considerably in their stage of development. This within-litter variability may itself affect embryo survival. For example, the more developed blastocysts within a litter have a better chance of survival than their less developed siblings. It is worth noting that there appears to be nothing inherently wrong with the less developed embryos in the uterus, as they survive normally when transferred to a non-pregnant recipient uterus, free from the competitive effects of the more advanced embryos. Furthermore, it is widely accepted that embryo survival is lower in gilts and sows in which within-litter embryo development is more variable, because only some embryos would be at an appropriate stage of development for changes occurring in the uterine environment. Strategies that
promote within-litter uniformity in embryo development would therefore be expected to increase embryo survival.

Late pregnancy (day 30 to term)

The transition from ‘embryonic’ to ‘fetal’ stages occurs once the cells of the embryo have differentiated into the major organs of the fetal body. Conventionally, this change is considered to occur at around day 30 of pregnancy. By this time, the major organs of the fetal body have formed, and the cardiovascular system is established and functioning and undergoes only minor changes before the end of gestation. The placenta is fully functional and effectively performs the functions of the fetal gastrointestinal tract, lung, kidney, liver and endocrine glands. The period between day 30 and term is a phase of rapid fetal and placental growth. The placental membranes grow rapidly between days 20 and 60, and at a faster rate than the fetuses they supply; subsequently their rate of growth declines and that of the fetus increases. Placental weight plateaus between days 70 and 100, while fetal weight rises exponentially between day 60 and birth (Figure 4.7).

The pig placenta is classically classified as a diffuse epitheliochorial placenta. This is because of the absence of specialised structures for nutrient exchange (such as the placentomes of ruminant placentae) and because all possible maternal and fetal layers are maintained (maternal blood vessels, connective tissue and epithelium and fetal chorionic epithelium, connective tissue and blood vessels). In early pregnancy each feto-placental unit lies end to end in the uterus and is distinct. Most fetuses face forwards and maintain toe orientation with their neighbours in the uterine horn. During the last two-thirds of pregnancy, however, some adhesion and fusion occurs between the extremities of adjacent feto-placental units, although, with the exception of freemartins, there are normally no vascular connections between the sacs.

A major role of the placenta is the transport of nutrients from mother to fetus. The efficiency with which the placenta transports nutrients and oxygen to the fetus is determined by its surface area of contact with the uterine wall (chorionic villus surface area) and by blood flow at the maternal–fetal interface, and depends on transplacental transport kinetics and transporters. Pigs have a non-invasive diffuse epitheliochorial placenta in which the maternal blood supply is well separated from the absorptive surface of the chorion. The rate of oxygen transport is limited by placental blood flow. In contrast, the abundance and activity of specific transport proteins regulate placental transport of glucose, amino acids, ions and molecules. Placental glucose transport occurs by a carrier-mediated facilitated diffusion involving several glucose transporter isoforms. Many amino acids taken up by the placenta are transported against a feto-maternal concentration gradient by energy-dependent mechanisms. These include both sodium-dependent and independent amino acid transporter systems that have different levels of activity.

Glucose and lactate, produced from anaerobic metabolism of glucose by the placenta, are the main energetic substrates used by the fetus. In normal conditions, the
oxidation of carbohydrates accounts for about 75% of oxygen uptake in the fetal pig. The majority of amino acids transferred to the fetus are used in the formation of new tissues, although some are used for energy through oxidative metabolism.

There is considerable variation in both placental and fetal weights within the same litter, with approximately one-third of litters carried by gilts and sows containing at least one piglet that is significantly smaller than its littermates. These runt or intra-uterine growth-retarded piglets have increased risk of peri- and post-mortality and morbidity and require additional investment by the producer if they are to reach market weight. Evidence that the distribution of piglet birth weights is mirrored by the distribution of fetal weights on day 30 of pregnancy suggests that the growth of inadequately grown fetuses deviates from the trajectory of their normally grown siblings early in gestation. Attempts to alleviate the consequences of low birth weight post-natally have achieved only limited success. Taken together, these observations suggest that a more fruitful route would be to develop management strategies that promote within-litter uniformity throughout gestation.

Fig. 4.7 Growth of the fetus and placenta during pregnancy. Redrawn from Marrable, A.W. (1971) The Embryonic Pig: A Chronological Account. Pitman Medical.
Uterine capacity

Uterine capacity is defined as the maximum number of fetuses that can be carried successfully to term when the number of potentially viable fetuses is not limiting. As implied in this definition, uterine capacity is about not only the physical space available to each developing fetus, but also the ability of the maternal body to provide nutrients and remove waste products. As expected, uterine capacity varies with parity and genotype, with both the ‘hyperprolific’ lines and the Meishan showing evidence of increased uterine capacity.

Hormones during pregnancy

Maternal hormones

As discussed above, during early pregnancy blastocyst oestradiol secretion maintains luteal function by overcoming luteolysis. In contrast to sheep and cattle where the placenta is the major source of progesterone in pregnancy, continued luteal secretion of progesterone throughout pregnancy is essential for pregnancy maintenance in the pig. Corpora lutea reach their maximum weight by day 8, and highest peripheral progesterone concentrations occur on day 12 and gradually decrease to term. Progesterone serves essential roles during pregnancy, including the stimulation of endometrial secretory proteins that are essential for the nutrition of the developing fetus and the suppression of oestrus, ovulation and the contractile activity in the uterus. Prolactin, produced by the anterior pituitary, may play a role in luteal support throughout pregnancy and is responsible (together with progesterone) for the development of the mammary gland in preparation for lactation. The secretion of prolactin is regulated by two hypothalamic hormones with opposing functions. In non-pregnant animals, prolactin secretion is inhibited by prolactin inhibiting hormone produced in the hypothalamus, whereas during pregnancy and lactation, prolactin secretion is stimulated, aided by prolactin-releasing hormone produced in the hypothalamus.

The polypeptide hormone relaxin is produced and stored by pig corpora lutea from days 28–105 of pregnancy and released into the circulation around the time of parturition to facilitate expansion of the pelvic ligaments and cervical dilation.

The feto-placental unit is the major source of oestrogen production during pregnancy. Levels of oestradiol increase from around 10 pg/ml before day 60 to peak values just before parturition. The role of oestrogens in late pregnancy is to prepare the uterus for dramatic contractile activity and to encourage maternal behaviours such as nest building.

Hormones produced by the fetus

The fetus’ own endocrine system matures during pregnancy, with hormones produced by the fetus increasingly taking over roles initially fulfilled by hormones produced by the maternal body and transported across the placenta. A mature
endocrine system prior to birth is essential, both because it is the fetal endocrine system that initiates the cascade of events leading to parturition and to enable the neonate to function independently after birth.

**Parturition**

The length of gestation in pigs is relatively constant, being between 112 and 116 days, depending on the breed, litter size and season. Various behavioural, endocrine and physical changes usually precede parturition. The overriding factor initiating parturition is the concentration of progesterone in the maternal circulation. Thus, farrowing occurs when progesterone concentrations fall below a certain level and, conversely, parturition does not occur when progesterone levels are maintained, despite alterations in other hormones associated with parturition. Physical signs of imminent parturition include the swelling of the vulva, milky secretions from the udder and milk let-down in response to oxytocin. Prior to farrowing, the distance walked by sows and gilts increases, nest building occurs and in the last 90 minutes before parturition the sow settles, lying on one side. The onset of nest building coincides with a pre-parturient rise in prolactin.

Provided that it is certain that day 113 of a pregnancy has been reached, injection of prostaglandin or an analogue will bring about parturition within 24–30 hours. Administration of PGF$_{2\alpha}$ results in an immediate sharp decline in plasma progesterone levels and regression of corpora lutea. Induction of parturition with PGF$_{2\alpha}$ or an analogue does not affect lactation, return to oestrus after farrowing or subsequent fertility. There are some indications that induced farrowing may be associated with a decreased incidence of metritis, mastitis and agalactia (MMA) syndrome.

Farrowing is preceded by a sequence of fetal and maternal hormonal changes beginning with fetal ACTH from the pituitary stimulating fetal adrenal glucocorticoids. These corticoids initiate uterine PGF$_{2\alpha}$ production, leading to luteal regression and a rapid fall in progesterone concentrations. There is evidence that elevated levels of PGF$_{2\alpha}$ also cause pituitary release of oxytocin and prolactin as well as ovarian release of relaxin. The release of oxytocin, which is secreted by the posterior pituitary, appears to require both PGF$_{2\alpha}$ stimulation and low circulating progesterone levels. Oxytocin is responsible for uterine contractions during labour and milk let-down. Levels of unconjugated oestrogens in maternal plasma increase during the last 2–4 weeks of pregnancy, peak before parturition and decline rapidly to basal levels soon after. The rise in oestradiol is associated with fetal maturity and is primarily of placental origin. Plasma prolactin concentrations increase markedly in late gestation and remain high during early lactation. The primary role of prolactin at this time is to initiate lactation, although it may also contribute to the parturition process. Plasma concentrations of relaxin rise in the days preceding parturition, with peak levels about 12–14 hours before the start of farrowing. Relaxin, acting together with oestradiol, is believed to remodel collagen in the cervix and hence plays an important role in cervical dilation. Maternal corticosteroid concentrations increase within 24 hours of parturition and decrease during early lactation.
Parturition occurs slightly more often in the late afternoon and at night. The entire parturition requires 2–5 hours. The time between individual births may vary from a few to 60 minutes. Piglets are delivered randomly from the two uterine horns and sometimes pass each other in the birth canal. The placentas are delivered either in part after the emptying of one uterine horn or within approximately 4 hours after the last piglet is delivered.

Although parturition in the pig is a continuous process, for descriptive purposes it is useful to divide it into three phases: (1) the preparatory stage, in which uterine contractions commence and the cervix becomes fully dilated, (2) the fetal expulsion stage, which begins when the first fetus enters the birth canal and (3) the expulsion of the fetal membranes. Parturition depends on the co-ordinated rhythmic contractions of myometrial smooth muscle, involuntary contractions of abdominal muscles and the softening of the birth canal. In late pregnancy, myometrial activity consists of irregular episodes of prolonged activity in the uterine segments containing a fetus, while the empty parts of the uterus are relatively inactive. It is only within 4–9 hours of birth of the first piglet that myometrial contractile activity extends to the whole uterus, coinciding with elevated concentrations of oxytocin in peripheral plasma. During delivery, myometrial contractions in all segments of the sow’s horn are synchronised. Contractions appear to be initiated at both ends of the uterine horn and to propagate along the entire length of the horn. Contractions moving in a cervix–oviduct direction cease when the horn is emptied. It has been suggested that this bellows effect reduces the distance travelled by succeeding piglets and prevents a ‘bottle-neck’ of piglets occurring at the cervix.

Up to 7% of fully formed pig fetuses are stillborn. Stillbirths can be classified as those occurring before parturition (pre-partum) or those occurring during parturition (intrapartum). Intrapartum deaths make up 70–90% of all stillbirths. It is believed that fetal anoxia during farrowing induced by deceased placental blood flow associated with uterine contractions, with occlusion or premature breakage of the umbilical cord or with premature detachment of the fetal membranes, is a major cause of intrapartum death.

Low birth weight and weakness at birth are responsible for further neonatal losses as they are associated with starvation, chilling, overlying and poor immunological responses. Unlike the lamb, the newborn piglet has no brown fat to provide heat and energy, but rather has to rely on glycogen as its major energy reserve. Within minutes of birth newborn piglets break the umbilical cord, find a teat and begin to suckle.

**Lactation**

**Development of the mammary gland**

From the onset of puberty, successive exposure of the mammary glands to oestrogen and progesterone induces mammary development. The post-pubertal mammary growth surge leaves 12 or 14 (or occasionally more) semi-developed mammae. At
this stage, the mammary gland has a nipple with a ring of touch-sensitive tissue. Each nipple has two main canals exiting on a flattened plane just below the tip of the nipple. The gland has a complete, though poorly developed, blood and nerve supply system, while the gland cistern, sinuses, large ducts, smaller ducts and the fine ducts are all functional. However, the majority of the mamma consists of fatty tissue together with undifferentiated cells and some structural collagen. During pregnancy the undifferentiated cells develop into active milk-secreting cells and support tissues.

Just as the hormones of the oestrous cycle prepare the uterus for pregnancy, so the hormones of pregnancy prepare the mammary gland for lactation. In the first month of pregnancy, under the influence of progesterone and prolactin, the ducts proliferate further into the undifferentiated tissue mass. During mid-pregnancy this mass begins to differentiate into lobes of alveolar tissue made up of milk-secreting cells arranged around the inside of microscopic spheres (alveoli). By the final month of pregnancy, lobes of alveolar tissue are clearly defined, alveoli are fully formed and fill with a syrupy secretion. During the last third of pregnancy most of the development occurs in the active layer of milk-manufacturing cells lying on the inner surface of the newly formed alveoli. The synthesis of antibody-rich colostrum is established in the last quarter of pregnancy and increases exponentially with mammary tissue growth. The late pregnant mammary gland is firmer, with increased mass and volume as more ducts and secretory tissue replace fat. Over the final week, secretory activity is accelerated by a rapid increase in the number of cells and their synthesis rate. Within 3 days of birth, the mammæ are full of milk, and only the fact that no milk is being withdrawn is preventing the secretory cells from continuous synthesis of milk. Milk may be expressed manually from the nipples up to 24 hours before parturition. As a result of the very rapid development of active mammary tissue in the later stages of pregnancy, the major part of the total secretory tissue present at the beginning of lactation is formed in a relatively small proportion of the total development phase.

Suckling initiates lactation. Piglets suck approximately hourly during the first 4 weeks of lactation. Subsequently the suckling frequency reduces as the young become progressively less dependent upon milk as their main nutrient source. Mammary growth continues into early lactation, and a significant increase in the amount of secretory tissue occurs. During the immediate post-natal period, tissue development proceeds in proportion to the positive stimulus received by the frequency and completeness of milk removal.

After peak milk yield has been reached during the 3rd to 4th week after farrowing, there is a gradual decline in total cell number until the end of natural lactation at 10–12 weeks, when the active secretory cells of the alveoli regress and degenerate. Withdrawal of the sucking stimulus at any time during lactation causes a rapid build-up of secretory milk products in the alveoli, severe back pressure and the termination of milk synthesis by the cells, which is quickly followed by degeneration of the active secretory layer of alveolar epithelium. The residue of the alveolar and duct structure remains intact.
In subsequent pregnancies a new layer of secretory epithelial cells is formed within the alveolar framework, 2–3 weeks pre-partum. This marks the beginning of the next acceleratory growth phase for the gland as it prepares for the next lactation.

**Milk synthesis and production**

The biosynthesis of antibody-rich colostrum (Table 4.1) gets under way in the last quarter of pregnancy and builds exponentially with mammary tissue growth (Figure 4.8). The mammary gland development will be under the general control of somatotrophin (STH), while the rise in oestrogen at the end of pregnancy is also likely to identify for the mammary gland the impending parturition and the likely presence of young whose survival will depend upon nutrients in the form of milk. The colostral milk is readily and immediately available for withdrawal by newborn piglets. Indeed, milk may be expressed manually from the nipples up to 24 hours before parturition occurs. Pressure in the mammary gland is positive, and the early milk flows easily from the mammae. Oxytocin circulating at this time as a part of parturient events also acts upon the mammary gland, helping the outward movement of milk. The first few hours of lactation involve the withdrawal of lactation products actually formed before parturition. It is parturition itself that triggers the need for a full-blown lactation involving the production at hourly intervals of some 250–500 g of milk and a total yield of some 6–12 kg (or more) daily.

Feedback from the hormonal changes at parturition (Figure 4.9) causes the secretion of the lactogenic hormonal complex comprising prolactin, STH, thyrotrophic hormone (TH), ACTH, insulin, oestrogen and progesterone. All these are impor-
tant for sustained lactation in pigs, but STH does not have the same dramatic milk production enhancement effects as is the case with dairy cows. Prolactin secretion from the anterior pituitary is normally inhibited by the presence of an inhibiting hormone secreted by the hypothalamus. The synthesis or secretion of the inhibitor is suspended, with the result that the prolactin flows uninhibited to initiate and sustain lactation. Prolactin first appears at elevated levels 1–3 days before parturition, rising dramatically in conjunction with prostaglandin, and being a contributory party to parturition itself. Prolactin present at the time of birth may also be seen as the initiator of the lactation at this time. The metabolic demands of milk production are immense, as will be shown in Chapter 11; so hormones involved in the biosynthesis of milk constituents (ACTH, STH, TH, insulin, corticosteroids and so on) are central to adequate milk yield.

Prolactin maintains the ovaries relatively dormant throughout lactation, cherishing the corpora lutea, suppressing the growth of ovarian follicles and inhibiting oestrogen secretion; taking over these roles from progesterone in pregnancy. Although gonadotrophin levels in the anterior pituitary gland itself can be quite high during lactation, little or none is released, and there is full and effective suppression of both FSH and (equally importantly) of LH. Oxytocin is released approximately hourly as a result of suckling, and circulating oxytocin is likely to have an additional feedback role in enhancing prolactin and suppressing the gonadotrophins. Prolactin levels are particularly high in early lactation, but fall gradually over the course of the lactation, especially subsequent to 6 weeks. The lactation will fail due to inadequate prolactin support at any time subsequent to 8 weeks post-partum.

Fig. 4.9 The various hormonal activities involved in parturition.
Abrupt weaning at any time will bring about a sudden and massive prolactin drop. Prolactin and oxytocin are assumed to be the main lactogenic hormones in the pig, with TH, adrenocorticoids (which also inhibit GnRH) and STH giving support. Prolactin increases rapidly during suckling, and remains enhanced for about 40 minutes post-suckling before levels fall away over the next 20 minutes prior to re-enhancement. Whilst piglets suck approximately hourly during the first 4 weeks of lactation, subsequently the suckling frequency reduces as the young become progressively less dependent upon milk as their main nutrient source.

The sucking stimulus maintains lactational anoestrus and quiescence of the ovaries by oxytocin and by prolactin inhibition of GnRH release, and thereby the withholding of FSH and LH secretions. FSH appears additionally suppressed at this time by inhibin. During lactation the positive feed to the central nervous system given by the sucking stimulus also encourages the release of opioids from the CNS, which are positive to prolactin but negative to GnRH, and thereby negative to FSH and LH. After parturition 1–14 days are required for effective uterine involution and membrane repair and refurbishment. Subsequently, however, follicles may develop, depending upon the strength of the lactation. The administration of GnRH, or of LH and FSH gonadotrophins themselves, can give rise to oestrus during lactation, but it is evident that the effectiveness of such treatment is directly and strongly related to the number of days that have passed since parturition.

During lactation there will be low-level, gradual and chronic increases in FSH and LH. At weaning, however, through the actions of hypothalamic GnRH pulses, there is a flood of pulsatile LH and a rapid rise in the FSH and LH basal levels. The pituitary gonadotrophins stimulate follicular growth, initiate ovulation and bring about oestrus through the previously described course of events (Figure 4.3) some 5 days after weaning.

The level of milk yield is in part a function of the lactational ability of the dam (her body size, her body reserves and her nutrition) and in part a function of the sucking stimulus of the young (litter size, piglet weight and piglet vigour). Lactation peaks at around 3 weeks post-partum (Figure 4.10). The yield of milk varies greatly between individual females, and there is much dispute as to the true level of milk production possible from modern hybrid sows. However, simple calculation using expected conversion efficiencies of milk by sucking pigs reveals a total lactation yield in 28 days that is unlikely to be less than 320 kg, or an average of 11.5 kg daily. The influence of the size of litter upon milk yield of the sow and the milk intake per sucking piglet is shown in Table 4.2. Milk yield also increases with parity number, as may be seen from Table 4.3, but so also does litter size – so yield per piglet tends not to increase with parity number. The intake of milk solids by sucking pigs naturally follows the lactation curve, and will peak at 3 weeks of age with a daily consumption of some 0.32 kg of solids per piglet per day. Individual piglets starting with a birth weight of 1.3 kg and a fat content of around 2% will 3 weeks later have achieved a body weight of 6 kg or more with some 15% of lipid.

Lactation finally ceases in natural circumstances around 10 weeks post-partum, as a result of progressive loss of maternal willingness to suckle and a reduction of
any need for the young to suck, as by this time they can be fully nutritionally independent of their dam. Optimum economy of production is, however, achieved at weaning much earlier than this; rarely as early as 14 days post-partum, often at 21 days post-partum, optimally at 28 days post-partum, often at 35 days post-partum, and in many countries even yet at the traditional times of 6 or 8 weeks. The major consequence of imposed weaning is that, in comparison to natural weaning, it is early and it is abrupt. Thus the sucking stimulus is lost instantaneously at a time when potential milk synthesis rate is high. Loss of the sucking stimulus and the absence of oxytocin give negative feedback to prolactin, while the failure of milk to be removed from the gland brings about resorption of biosynthesised milk constituents back into the bloodstream. This reverse flow also provides negative feedback to the hormones supporting lactational metabolism. Within 2 days the lactation is irretrievably lost and circulating levels of supporting hormone have fallen back

Table 4.2. Milk yield in relation to number of sucking young.

<table>
<thead>
<tr>
<th>Number of sucking young</th>
<th>Milk yield of sow (kg/day)</th>
<th>Milk intake of piglet (kg/suckler/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>8.5</td>
<td>1.4</td>
</tr>
<tr>
<td>8</td>
<td>10.4</td>
<td>1.3</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>1.2</td>
</tr>
<tr>
<td>12</td>
<td>13.2</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 4.3. Increase in expected milk yield with parity number.

<table>
<thead>
<tr>
<th>Lactation</th>
<th>Average daily milk yield (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>
to base. Two days may appear to be a short time for milk flow to cease and for the pig to register the need to return to the activities of the oestrous cycle, but even within the first half day after weaning the sow will have noted a dozen missed feeds. There is no need to remove either food or water from weaned sows in order to enhance cessation of milk production and the return of the oestrous cycle. The loss of sucking stimulus and the pile-up of secreted milk in the mammary glands are quite sufficient to send all the necessary signals to the hormonal and nervous systems. The mammary gland will not suffer any damage as a result of weaning, and the removal of food or water is likely to do nothing other than increase stress (rather than diminish it).

The pig is considered lactationally anoestral; that is, the presence of lactation suppresses completely the oestrous cycle. This is, however, only partly true. First, some sows may show transient oestrus early in lactation, probably due to residual levels of circulating oestrogen; but there is no ovulation. From 3 weeks post-partum there is a real possibility of providing sufficient positive stimuli to encourage both oestrus and ovulation whilst the sow is still lactating. Such stimuli include: a reduced level of sucking stimulus, reduced daily milk yield, a high level of physical activity on the part of the sow, the placing of competitive sows in groups and the presence of a boar. There is a developing interest in delaying weaning due to the benefits that accrue to the young pigs when they are left with their dam. However, for delayed weaning to be economic, pregnancy by day 40 post-partum is a requisite target. This may be realistic in some production systems. In the vast majority of circumstances, however, lactational oestrus is of academic interest only, and it is the effective presence of lactational anoestrus that brings with it the need to wean piglets before the oestrous cycle can return and the sow be made pregnant again.

Weaning before 21 days post-partum may cause a reduction in ovulation rate, and an increase in embryo loss due to the uterus not yet being returned to a state of appropriate fitness to receive a new pregnancy after the exertions of the previous one. Full uterine involution is considerably assisted by the sucking stimulus and the uterus of a sucked sow will return to normal quicker than that of a sow weaned very shortly after parturition. There will also be an increased proportion of early weaned sows that do not come into heat within 5 days of being weaned, and there may be a further proportion of sows that will return to heat, having been mated but failed to conceive. Taken together, these failures would result in an increase in the (unproductive) weaning to conception interval.

In the case of weaning after 21 days post-partum, however, the weaned sow will bounce back rapidly into an effective oestrous cycle with the rapid initiation of follicular development under FSH, and with the subsequent surge of LH release driving the sow into oestrus and ovulation.

Although the sow is not seasonally anoestrous, and may be considered as a regular breeder throughout the year, there may be seasonal effects influencing the readiness of weaned sows to rebreed. It would appear that the days between weaning and oestrus may lengthen if the temperature is high, if the temperature is low, if the atmosphere is excessively humid or if day length is shortening.
Lactation length

Natural weaning takes place over a period of 3–4 weeks, beginning around the 8th or 9th week post-partum. The switch from the dominance of the lactogenic complex to the dominance of the gonadotrophins and the hormones of the oestrous cycle is probably rather gradual, but once follicular growth is under way there will be an acceleration towards oestrus. In practical production systems natural weaning rarely, if ever, occurs because whatever lactation length is imposed upon the sow it will certainly be shorter than a grossly uneconomic 12 weeks.

The choice of lactation length is contingent upon the interests of both weaned young and weaned mother, and is resultant from the simple physiology of anovestrous in the sow. Until the sow is weaned, she may not return to oestrus and become pregnant again. Thus it can be calculated: if pregnancy is 115 days, if a sow shows oestrus and conceives in 5 days after weaning and the lactation length is 56 days, then with 10 pigs weaned per litter she will produce 21 piglets per year. If all other circumstances remain the same, a lactation length of 14 days will give 27 piglets per year.

However, all other circumstances do not remain the same. At lactation lengths of less than 14 days, the uterus of the sow has not completed involution (Figure 4.11) and such is the strength of the lactogenic hormonal complex at this time that weaning the litter imposes a trauma that takes as long to recover from in terms of the return to oestrus as would have been the case if the litter had been left sucking. From 14–18 days onward, however, weaning opportunities appear to become progressively more realistic.

Figure 4.12 shows the influence of lactation length on various aspects of reproductive performance. First (a) oestrus does not snap back post weaning quite so rapidly for 2 or 3 week weaning as when the litter is weaned at 4 weeks or subsequently. This is probably a combined effect of the state of the uterus and (most importantly) of the strength of the lactogenic complex because yield and sucking stimulus rise to their peak at 3 weeks post-partum. Second (b) conception rate is poor if the pig is weaned before 3 weeks. Some of the sows showing oestrus do not conceive, and they return to oestrus 21 days later, thus extending the weaning to conception interval. Third (c) it appears that fewer ova may be fertilised and fewer
embryos survive to term as lactation length is reduced. These failings are serious for lactation lengths below 18 days, but, as Figure 4.12 suggests, the extent of production loss is not large between 21 and 28 days of lactation length. The final number of pigs produced per sow per year does not change greatly between 21 and 32 days of lactation length (d).

The decision as to when to wean should not be based on the interests of the sow alone, however, but also on those of the sucking young. The digestive tract of the neonate, and its ancillary enzyme systems, is attuned to receiving milk as the sole nutrient source. Normally piglets would begin to eat solid food from 10 days of age at the investigatory level, and with real, if modest, nutritional purpose from 15–21 days or so. The pattern of consumption by a litter, however, will not measure that of individual piglets within the litter, some of whom will be eating by 14–21 days of age enough solid food to provide for up to 200 g of body growth daily, whereas others will be eating none at all. The capacity of the digestive tract and the ability of the enzyme system to digest non-milk sources of carbohydrate and protein appear to be critical in development terms at around 3 weeks post-partum (Figure 4.13).

The immune system of the piglet is heavily dependent upon mother’s milk; again until 3–4 weeks of age when active immunity builds up in the piglet and competency to deal with invasive disease organisms develops. There is some justification in setting a piglet weight, rather than age, as definitive of readiness to be weaned. Weights in excess of 6.5 kg have been proposed. It is possible that a litter could be

Fig. 4.12 Effect of lactation length (age at weaning) on (a) interval between weaning and oestrus, (b) conception rate, (c) litter size and (d) pigs reared per sow per year.
weaned sequentially – the larger pigs at around 21–24 days and the smaller ones at around 26–30 days, by which time they would have reached target weight. Over the latter part of this time the sow will devote a higher proportion of her yield to the smaller and weaker piglets, and so experiences a more gradual diminishment of sucking stimulus. This apparently most acceptable of management practices is, however, not often adopted due to its inconvenience and the need to split up litters upon weaning and placement into nursery pens.

Thus it is that at 21 days post-partum developments are under way that will give piglets an ability to survive on solid food and to be competent to thrive independent of their dam. Weaning at 21 days of age will accelerate these developments, but will also test them at the very time when they are at their most fragile. Sometimes the test is not survived and weaned piglets enter a phase of inappetence, slow or negative growth and susceptibility to disease, especially in the intestinal and respiratory tracts. The ability of the pig to cope with the trauma of weaning improves with age at weaning and so in consequence does the post-weaning performance of the piglets. It is usual to be able to show that piglets weaned at 28 days of age will grow to slaughter weight in fewer days overall than piglets weaned at 21 days of age; there being already some 5 kg advantage, on average, evident by 12 weeks.

Because of the relative incompetence of early weaned pigs, the degree of management care needed and the cost of feeds and equipment are directly related to the earliness of weaning. On the grounds of sow biology, weaning between 21 and 28 days appears optimal. On the grounds of piglet biology, the optimum is somewhere between 28 and 42 days. Overall, it is difficult to justify lactation lengths of less than 24 days or greater than 32 days (Figure 4.14).

**Control of lactation**

Although the nervous system is not directly involved in milk secretion or milk removal, the neuroendocrine milk ejection reflex is essential to the suckling process.
Mammary glands are densely innervated, with terminal nerve endings in the glandular tissue, the skin and around the base of the nipple that are particularly sensitive to touch, stretching and pressure. The amount of milk stored in the gland cistern is small (around 10–15% of total milk volume in the gland), and between feeds most of the milk is held in the alveoli and small ducts. While milk may be removed passively from the cistern by the sucking action of piglets, expression of the majority of milk from alveoli and ducts is under maternal control. Once the piglets are settled along the udder, each with a mammary gland nipple in its mouth, and the sow is content, the sucking stimulus transmitted from the mammae to the hypothalamus stimulates rapid release of oxytocin from the posterior pituitary. The milk ejection reflex takes place 20–40 seconds after the initial release of oxytocin, and the oxytocic effects last for only 15–30 seconds. Oxytocin causes the myoepithelial cells surrounding the alveoli to contract and the alveoli to collapse, enabling milk to be ejected into the small ducts. The ducts shorten and widen and milk rushes through the sinuses and gland cistern. Only alveolar and ductal milk is expelled by the action of oxytocin on the myoepithelium; there is no contraction of large ducts or cistern.

It is important to note that milk let-down only occurs when all the piglets are simultaneously settled and content. If they are not, oxytocin release and hence milk ejection are inhibited. There is a refractory period after each phase of suckling during which oxytocin is not released. For litter-bearing species such as the pig, it is imperative that all young are present at the udder at the same time.

Hormonal changes at parturition stimulate secretion of prolactin and oxytocin, which are regarded as the main lactogenic hormones in the pig. Prolactin concentrations increase rapidly during suckling, remain elevated for about 40 minutes after a feed and decline until the next feed. Suckling also promotes prolactin receptor gene expression and ensures the continuous production of milk. Prolactin levels are particularly high in early lactation, but fall gradually over lactation, especially after 6 weeks. Abrupt weaning at any time during lactation causes a sudden and massive drop in prolactin concentrations. During early lactation oxytocin is released approximately hourly as a result of the suckling-induced neuroendocrine milk ejection reflex. Circulating oxytocin is likely to have an additional feedback role in enhancing prolactin and suppressing gonadotrophin release.
Factors affecting the rate of milk production include the mass of tissue actively synthesising milk, the frequency and completeness of milk withdrawal and the capacity of the cisterns, sinuses, ducts and internal alveolar spaces to store secreted milk. Milk yield depends upon the lactational ability of the dam, including body size, body reserves and nutrition, and the suckling stimulus from the litter. The yield of milk varies greatly between individual females, and there is much dispute as to the true level of milk production possible from modern hybrid sows. However, simple calculation using expected conversion efficiencies of milk by sucking pig reveals a total lactation yield in 28 days that is unlikely to be less than 320kg, or an average of 11.5kg daily. The intake of milk solids by sucking pigs naturally follows the lactation curve, and will peak at 3 weeks of age with a daily consumption of some 0.32kg of solids per piglet per day. Individual piglets starting with a birth weight of 1.3kg and a fat content of around 2% will 3 weeks later have achieved a body weight of 6kg or more with some 15% of lipid.

Uterine involution is the restoration of the uterus to its normal non-pregnant size and function after parturition. The length and weight of the sow’s uterus reduce rapidly during the first 2–3 weeks after farrowing. The sequence of events during uterine involution involves shrinkage of the endometrium and resultant sloughing/discharge of tissue, which is evident from the discharge visible (lochia) during the first week after birth, a regeneration of the endometrium and the restoration of a new epithelial lining. In conventional weaning systems, this process is complete within 3–4 weeks of parturition; however, uterine involution is slower when lactation is short.

**Weaning**

Natural weaning occurs over a period of 3–4 weeks, beginning around the 8th or 9th week post-partum, and lactation ceases around 10 weeks post-partum. This occurs as a result of progressive loss of maternal willingness to suckle and a reduced need for the young to suck, as by this time they can be fully nutritionally independent of their dam. Optimum economy of production is, however, achieved at weaning much earlier than this, typically at 21–35 days post-partum. Thus the sucking stimulus is abruptly withdrawn when potential milk synthesis rate is high. Loss of the sucking stimulus and the absence of oxytocin inhibit prolactin, while the failure of milk to be removed from the gland brings about resorption of biosynthesised milk constituents back into the bloodstream. This reverse flow also provides negative feedback to the hormones supporting lactational metabolism. Circulating concentrations of lactogenic hormones return to basal levels within 2 days of weaning and thereafter lactation cannot be re-initiated.

The age at which weaning occurs affects both the subsequent reproductive performance of the sow and the viability of the piglets. For the sow, weaning before 21 days post-partum is associated with increased numbers that do not show oestrus within 5 days of weaning and fewer ovulations and surviving embryos following
mating at the first post-partum oestrus. This is due, in part, to incomplete uterine involution. In the case of weaning after 21 days post-partum, however, the weaned sow will rapidly resume oestrous cyclicity with the rapid initiation of follicular development under FSH, and with the subsequent surge of LH release driving the sow into oestrus and ovulation.

For the future viability of piglets, weaning should not occur until the capacity of their digestive tract and the enzymes that digest non-milk sources of protein and carbohydrate are established and when the piglet has acquired sufficient active immunity to thrive independently of its mother. It is generally accepted that piglets have acquired sufficient maturity in these aspects to be weaned at 21 days.

**Post-partum anoestrustr**

Sows sometimes exhibit oestrus within 48 hours after farrowing, probably due to the high levels of oestradiol at parturition, but ovulation does not occur. Provided that more than one suckling piglet is continuously present and that lactation is not unduly prolonged, sows will remain anoestrous throughout lactation. While the sow nurses her piglets, ovarian and anterior pituitary activity is suppressed, follicular growth is minimal, corpora lutea are absent and plasma progesterone and oestradiol concentrations are consistently low (Figure 4.9). The inhibition of the hypothalamic–pituitary–ovarian axis during lactation is considered to be primarily due to suckling-induced neuroendocrine reflexes, with the metabolic demands of milk production becoming increasingly important during the later half of lactation. The duration of post-partum anoestrus is affected by many environmental, genetic, physiological and metabolic factors. These include breed, strain, nutritional level, suckling, milk production, rate of uterine involution, rate of development of ovarian follicles, and pituitary and peripheral concentrations of gonadotrophins, peripheral levels of oestradiol and progesterone and changes in body weight and energy intake.

It is likely that the release of prolactin, as a result of the suckling stimulus, plays an important role in suppressing the stimulatory oestrogen feedback effect on gonadotrophin secretion. During established lactation, the release of opiates as a consequence of suckling may also suppress LH secretion. Ovarian follicular development progressively resumes during lactation, and by weaning, follicles have acquired the ability to respond to gonadotrophins.

Tissue catabolism during lactation reinforces the suckling-induced suppression of LH secretion. In first parity sows limited fat reserves during lactation and the partitioning of nutrients for lean tissue growth after weaning are believed to be major contributors to the reduced fertility often observed in first parity sows.

Removal of the litter and weaning leads to a transient increase in plasma LH levels, a gradual increase in plasma oestradiol concentrations and finally in the pre-ovulatory surge of LH that occurs at the first post-weaning oestrus, which typically occurs 3–5 days after weaning. Immediately after weaning, plasma concentrations
of oestradiol increase gradually and are terminated by the pre-ovulatory surge of LH at oestrus.

It is possible to achieve oestrus and ovulation whilst lactation is in progress, but only under particular circumstances, such as when at least 30 days have elapsed since parturition, the sows are strongly stimulated by the presence of a boar, the sows are stressed by mixed penning and multiple suckling, and the sucking stimulus from the litter is diminishing. Subsequent litters are usually slightly smaller in size.

The resumption of ovarian follicular development during lactation and after weaning is a complex process that ultimately determines the rebreeding efficiency of sows. Before weaning, ovarian development varies considerably between sows; some have relatively inactive ovaries throughout lactation, others have non-ovulatory follicular waves in which follicles grow to approximately 5 mm and regress before weaning, while some develop cystic ovaries. Weaning is therefore a random event relative to changes occurring in the ovary. This contributes to the variation in weaning to oestrus interval in sows. Most sows experience a period of rapid follicular growth after weaning and return to oestrus within 3–7 days. Delayed weaning to oestrus intervals are associated with inactive ovaries before weaning or weaning during the regression phase of a follicular wave.

**Assisted reproduction**

Among the domestic livestock species, several assisted reproductive technologies including embryo freezing, trans-cervical insemination and embryo recovery and the induction of luteolysis to synchronise oestrous cycles have proved especially challenging to develop in pigs.

**Artificial insemination**

Artificial insemination (AI) is now widely used in commercial practice and pregnancy rates in excess of 85% are frequently achieved. AI can take the form of ‘on-farm’ AI involving semen collection, dilution and insemination on the pig unit or may involve the use of fresh or frozen semen from an AI centre. Data from Thailand indicate that mixed mating, using both AI and natural mating, results in the birth of an extra 0.5 piglets per litter. The use of AI has increased dramatically during the last decade, particularly in some European countries such as Denmark, where the number of sows artificially inseminated approaches 90%. Recent estimates suggest that the use of AI accounts for 60% of all inseminations in the USA.

Current AI procedures use two inseminations during oestrus with concentrations of $2.5\times10^9$ to $4.0\times10^9$ spermatozoa in 80–100ml deposited intracervically at each insemination. This restricts the number of doses that can be prepared from one ejaculate to approximately 20; thereby limiting the contribution of AI to genetic progress in the pig industry. The number of spermatozoa per insemination can be reduced
to 60-fold if the sperm dose is deposited directly in the uterine horn. Successful non-surgical deep intra-uterine insemination using small numbers of spermatozoa has been reported in a number of domestic species. However, the cervical folds and the length and coiled nature of the pig uterine horns have hindered attempts to non-surgically introduce a catheter into the pig uterine horn through the cervix. Recent data from Spain describe the use of a flexible catheter for non-surgical deep intra-uterine insemination using fresh and thawed frozen semen in sows. Farrowing rates of 84 and 70% and litter sizes of 9.8 and 9.3 piglets have been achieved using such catheters to deposit fresh or frozen–thawed semen, respectively.

Efficient techniques for non-surgical insemination with very small numbers of spermatozoa will also increase the opportunity to use sorted semen for gender pre-selection.

**Semen storage**

The use of preserved semen for AI in pigs has increased rapidly in the last 20 years. Over 99% of inseminations conducted world-wide use semen that has been extended in the liquid state and used on the same day, or stored at 15–20°C for 1–5 days. Of these, 85% are conducted on the day of collection or the following day. Although frozen boar semen has been available commercially since 1975, less than 1% of all inseminations are made using frozen–thawed semen, most often after export from one country to another and most often for upgrading the genetic base in a particular country or herd.

Two main factors influence sperm cell function after ejaculation and during in vitro storage: the temperature at which the semen is collected and stored after dilution and the conditions of the suspension medium. Boar spermatozoa are very sensitive to cold shock. This occurs when freshly ejaculated boar spermatozoa are cooled quickly from body temperature to temperatures below 15°C, which results in a loss of viability in an increasing number of spermatozoa. Maintaining pre-diluted semen samples above 15°C for several hours appears to confer a gradual resistance to cold shock. The cold shock sensitivity of boar spermatozoa seems to change in a time- and temperature-dependent manner.

Spermatozoa are diluted with seminal fluids from the accessory glands at ejaculation and their motility is retained for a few hours. To extend their survival in vitro it is necessary to reduce the metabolic activity by chemical inhibitors or by lowering the temperature, which also necessitates dilution. Semen diluents are designed to provide protection against temperature changes and pH changes, to increase semen volume, provide a source of nutrients for the sperm and inhibit bacterial growth. Most diluents are based on sodium bicarbonate or sodium citrate buffers, although newer diluents are based on zwitterionic organic buffers that capture heavy metals and control pH.

Boar semen proved more challenging to successfully freeze and thaw than semen from other domestic species, due in part to the large volume produced at each ejaculation and its vulnerability to cold shock and sudden cooling. At present two
freezing methods developed in the mid-1970s are commercially used to freeze boar semen. In one method, the sperm-rich fractions of the ejaculate are held for 2 hours after collection in the presence of seminal plasma and then, after centrifugation, cooled for about 3 hours and pelleted on dry ice. In the second method, the semen is diluted in Hulsenberg 8 diluent and frozen in maxi-straws. Effective freezing requires the optimum combination of glycerol concentration, cooling and warming velocities. At present this appears to be 3% glycerol, a freezing rate (in the range between 0 and –50°C) of 30°C per minute and a thawing rate of 1200°C per minute.

**Sexed semen**

Currently, the only practical means of farrowing pre-sexed offspring in pigs is by sorting spermatozoa bearing X and Y chromosomes using flow cytometry. Sorted sperm can then be used for low dose transcervical AI and in conjunction with in vitro fertilisation (IVF) for the production of sexed embryos for transfer to recipients. Conventional AI techniques in the pig require about 3 billion sperm per dose of semen, making it virtually impossible to routinely use sexed semen in this way. This technology is based on the fact that the Y chromosome is smaller and carries less DNA than the larger X chromosome. Sorting sperm into separate and nearly pure X and Y populations is achieved using flow cytometry and cell sorting. Recent developments in this area include the introduction of high-speed sorting to increase sorted sperm throughput to around 6 million sperm per hour. Although 100% purity of livestock sperm X and Y populations is nearly impossible to achieve under normal sorting conditions, 95% purity is routinely achieved. Recent studies indicate that a proportion of sorted sperm will survive freezing and thawing and can be used to successfully produce piglets.

**Superovulation**

Although sows and gilts spontaneously release 10–24 oocytes during oestrus, embryo transfer procedures and the need to produce relatively large numbers of oocytes or embryos for research purposes can create a requirement for superovulation. Increased ovulation rates have been observed in post-pubertal gilts and sows following a single injection of 1000 IU pregnant mare serum gonadotropin (PMSG) at the beginning of the follicular phase (days 15 or 16). Many groups observe added precision by following the PMSG injection with an injection of 500 IU human chorionic gonadotropin (hCG) between days 16 and 19.

The regime of 1000 IU PMSG followed 48 hours later by 500 IU hCG is also effective in promoting superovulation in pre-pubertal gilts, providing they are reasonably well grown (>80 kg). Given that pre-pubertal animals do not have an oestrous cycle, this regime can be applied at any time.
Synchronisation of oestrous cycles

Synchronisation of the pig oestrous cycle has proved less straightforward than in other domestic species. This is largely because only relatively mature porcine corpora lutea (after day 9 of the cycle) respond to the luteolytic effects of prostaglandin PGF$_{2\alpha}$. The most common means of synchronising the porcine oestrous cycle involves the use of the synthetic orally active progestagen allyltrenbolone (Regumate). This is administered as a topical application to gilt or sow feed for approximately 16 days. The majority of gilts will be observed in oestrus 6 days after Regumate withdrawal. Other approaches include weaning sows at the appropriate time before oestrus and the administration of PGF$_{2\alpha}$ to gilts or sows with prolonged luteal function induced by injection of oestradiol benzoate.

In vitro fertilisation

In vitro fertilisation of porcine oocytes using both fresh and frozen semen is an established procedure in several research laboratories across the world. Porcine in vitro fertilisation is primarily a research tool, but may have application in the introduction of disease-free new genetic material and in the production of large numbers of embryos for biomedical research; for example, the possible uses of transgenic pigs to produce specific proteins and as potential xenograft donors. Production of transgenic pigs by pronuclear injection requires large numbers of early embryos which could be produced more cost-effectively by in vitro fertilisation.

Although considerable progress has been made in the in vitro production of pig embryos using improved methods for in vitro maturation and fertilisation, polyspermic penetration remains a problem for in vitro matured oocytes. The variation among boars, and even among ejaculates from the same boar, in the degree of polyspermy is a major complicating factor that needs to be resolved.

Embryo freezing

The ability to freeze pig embryos is important both for the conservation of genetic resources and as an economical and welfare-friendly way to transport pigs around the world. For many years, attempts to cryopreserve pig embryos were unsuccessful, largely because of their substantial lipid content. The birth of live piglets from frozen embryos was first reported in the 1990s and was rapidly followed by the development of more effective vitrification techniques to cryopreserve pig embryos. Three techniques to successfully freeze pig embryos have now been described: freezing, ‘normal’ vitrification and high-speed vitrification using the open pulled straw (OPS) method. Techniques to freeze pig embryos use a limited amount of glycerol as a cryoprotectant and a slow rate of cooling. However, the survival of previously frozen pig embryos after 24–48 hours of culture is extremely variable (0–50%) and the number of live births resulting from frozen embryos is low. Vitrification uses a high cryoprotectant concentration with a high cooling/warming rate to allow direct
transition between the liquid and amorphous vitreous phase and vice versa. In vitro embryo survival rates of up to 74% have been reported following such ‘normal’ vitrification using a cooling rate of around 2500°C per minute. The highest pregnancy rates following transfer of embryos cryopreserved by vitrification have been observed following pre-treatment with cytochalasin B and a post-thawing treatment to hydrolyse the zona pellucida. High-speed vitrification with the OPS uses a heated 0.25 ml insemination straw pulled to half its original diameter. Embryos in 1–2 μl drops are loaded by capillary effect and the straw is plunged directly into liquid nitrogen. The survival of embryos cryopreserved by this method is good, both during in vitro embryo culture and following transfer to recipients. The OPS method appears particularly effective for the cryopreservation of morula stage embryos.

**Embryo transfer**

Multiple ovulation and embryo transfer has not been adopted by the pig industry to the extent that it has for ruminant species. This is because pigs are spontaneous multiple ovulators with a high reproductive rate (a sow can produce as many offspring in 6 months as a cow or a ewe might in her entire reproductive lifetime), because transcervical techniques are not well developed for embryo transfer procedures in this species and because pig breeding programmes emphasise the genetic merits of certain strains or lines rather than individuals. Furthermore, pig embryo transfer usually requires full general anaesthesia and mid-ventral laparotomy for both donor and recipient animals, raising important animal welfare issues.

Pig embryo transfer is used in three primary areas: (1) for research in reproduction, (2) as a means of capitalising on superior genetic characteristics of individual sows and (3) for the movement of genetic material with a low risk of concurrent transmission of infectious disease. Embryo transfer has proved a valuable research tool to distinguish the role of the oocyte/embryo and the uterine environment on subsequent development and to gain understanding of how occupancy of the uterus affects later survival and growth. As indicated above, the use of embryo transfer for breeding improvements in the pig is limited, but it may be used, for example, when a valuable sow is unable to carry a litter to term. Possibly the most important practical application of embryo transfer in pigs is in relation to disease control. It can be used as an alternative to hysterectomy as a means of getting disease-free piglets, often representing new genetic material, into a closed or specific pathogen-free herd.

Several research groups world-wide are developing less invasive procedures for the recovery and transfer of pig embryos. A recent report described pregnancy rates of 90% following endoscopic embryo transfer in the pig, although procedural details were scant. Non-surgical embryo transfer procedures are based on the transcervical recovery and/or transfer of embryos. Several research groups have successfully transferred pig embryos to recipient females via this route, using either an AI spirette or a specially designed transfer catheter. Optimal pregnancy rates are achieved using specially designed catheters that enable embryos to be deposited in
the uterus in a small volume of fluid and when embryos are transferred to conscious, rather than sedated, recipients. Less invasive alternatives to mid-ventral laparotomy as a means to recover pig embryos have proved more difficult to develop. Alternatives include endoscopic recovery and transcervical collection from donors with surgically shortened horns. Embryos can be collected from the oviduct and uterus by endoscopy and recovery rates of 28 oocytes or embryos per donor have been reported. Although this technique is less invasive, it remains a surgical technique with the associated limitations. Surgical shortening of the uterine horns involves the connection of the tip of the uterine horns to the base of the horn, near the bifurcation of the uterine body. The large middle portion of the uterus is closed and left in the abdomen or removed. This is clearly an invasive procedure, but once in place, embryos can be collected transcervically from surgically prepared donors every 3 weeks. To date, the embryo recovery rates following this procedure have been low, but increased to acceptable numbers (18) when used in combination with superovulation.

**Pregnancy diagnosis**

*Detection of oestrous behaviour*

The traditional method to confirm pregnancy is to use a boar to determine whether the gilt or sow has returned to oestrus. This is clearly labour intensive and only an option during the 18–24 day period after mating. Alternative methods include measurement of urinary oestrogens, examination of vaginal or cervical mucus, rectal palpation to detect the strength of the pulse within the uterine artery, ultrasound techniques and oestrone sulphate assays. The more widely adopted methods are described below.

*Ultrasound techniques*

Doppler ultrasound, amplitude-depth ultrasound (A-mode) and real-time (B-mode) ultrasound have all been successfully used for pregnancy diagnosis in the pig. Doppler ultrasound is used to detect the motion of blood in the fetal heart or in the large umbilical blood vessels associated with the pig fetuses. Ultrasound waves from a transducer strike moving blood particles and are reflected back at a slightly different frequency which can be converted into audio or visual signals. Blood flow in the uterine artery can be heard as early as 21 days of pregnancy, but is not regarded as reliable until 30 days. Amplitude-depth ultrasound technology proved simpler and more reliable than Doppler ultrasound. This method detects differences in the acoustical impedance between the contents of the pregnant uterus, particularly the allantoic and amniotic fluids, and the other abdominal viscera. An easily recognised band of echoes at a depth of 15–20 cm is obtained in pregnant sows, whereas echoes from non-pregnant sows emanate from a depth of around 5 cm. Results from a thousand sows suggest that the accuracy of this technique approaches 100% for diag-
nosing pregnancy in sows between 30 and 90 days gestation. Battery-operated portable real-time scanners are now available for pregnancy diagnosis in pigs. This is an accurate method of confirming pregnancy in the pig.

**Hormone measurements**

Early pig blastocysts synthesise substantial amounts of oestrogens that pass through the wall of the uterus and are sulphoconjugated to form oestrone sulphate. Consequently, pigs show a marked increase in plasma concentrations of oestrone sulphate from about day 16 of pregnancy to a peak by days 25–30. Plasma concentrations of oestrone sulphate between days 22 and 28 of pregnancy can be used not only as a reliable pregnancy test, but also to distinguish litters carrying large numbers of fetuses from those carrying only few fetuses.

Plasma concentrations of progesterone in samples obtained on days 18–22 after mating can be useful for distinguishing pregnant and non-pregnant sows. With rapid contemporary assays, a non-pregnant sow could theoretically be presented to the boar or inseminated at her next oestrus.

**Future challenges in pig reproduction**

Reproductive efficiency remains central to the pig production industry, not only for the obvious function of perpetuating the species, but also to provide opportunities to reduce the costs of production while meeting increasingly demanding consumer expectations. In recent years the balance of pig reproduction research has shifted away from a primary objective to increase the number of piglets born per year, towards strategies that also promote piglet viability and which optimise the lifetime performance of the breeding sow. This trend is likely to continue and will require a more integrated approach in which the opportunities provided by increased understanding of reproductive processes are considered as an essential component of a co-ordinated strategy to improve pig production.

Compared to other domestic species, the refinement and uptake of assisted reproductive technologies in pigs has proved particularly challenging. Recent developments in semen sorting coupled with the ability to inseminate directly into the uterus using substantially reduced doses of semen mean that such technologies are becoming within reach of the industry. The considerable developments in embryo technologies in recent years, although partially prompted by biomedical applications, provide new opportunities for the long-term storage and global transport of pig genetic material. These technologies and their applications are particularly timely, given increasing concerns over biosecurity and the conservation of animal genetic resources.

Litter size, the interval between weaning and conception and mortality remain major areas where reproductive performance can be improved. While considerable research effort has been spent optimising mean values of these traits within specific
production systems, relatively less has been devoted to reducing the inherent vari-
ability in these traits. For example, while increased litter size and/or mean birth
weight have been major research goals, the within-litter variability in piglet weight
at birth has received less attention, despite the fact that such variation poses con-
siderable labour, welfare and management issues.

Future reproduction research should be directed towards the production of pre-
dictable numbers of healthy, uniform piglets able to cope with the challenges pre-
ated by contemporary production systems.
Chapter 5
Pig Behaviour and Welfare

Introduction

In those parts of the world where human welfare can be measured in terms of the quantity of food that people receive, the welfare of animals is usually found fairly low on the priority list of agricultural activities. First and foremost comes the need to improve the quantity of animal products available to the human population, and next to reduce the price of those animal products. However, in countries where the well-being of human society tends to be examined in terms more sophisticated than the basic provision of an adequate diet (the nutritional needs being already adequately or excessively met), society will tend to place the welfare of animals kept for the production of meat high on the list of agricultural priorities. Well-kept humans may perhaps be the more ready to consider the lot of their animals.

Animal welfare attempts to deal with both the actuality of animal health and the concept of animal well-being. Broadly, ‘well-being’ comprises two elements: the human view of the animal’s state, and the animal’s view of its own state. The first aspect falls into the purview of human sociology, the second into the discipline of various animal sciences, perhaps the most important being that of the study of animal behaviour. Animals may suffer from purposeful or accidental ill-treatment, and there is no difficulty in identifying such abuse as being contrary to both acceptable ethics (and often national laws) and production efficiency. However, well-being implies freedom from deprivation; and here there are degrees of freedom and levels of deprivation, particularly with regard to the importance of the freedom to express behavioural needs.

The science of animal behaviour not only allows a sound foundation for the assessment of welfare, but also provides the basis of good husbandry and stockmanship, and a major means of improving both the level and efficiency of pig production.

Behaviour associated with reproduction

Mating

Successful intromission requires the female to be in standing heat and receptive to the attentions of the male. In this condition the female will accept willingly indignities that would otherwise attract either an aggressive or an aversive response.
Usually the female entering oestrus will seek out (by smell, sound and sight) and approach the male for the purpose of head-to-head contact. Vocalisation, jaw-champing and frothing at the mouth will be evident from both parties, but especially the male. The female may nudge the male. In response, the boar may vigorously bunt and nudge the female and investigate the genitalia with his snout, while she will stand relatively immobile. After the niceties of courtship are completed (which, if the sow is in full oestrus, may take 1–5 minutes), the boar will mount her (Figure 5.1). More than one attempt is likely to be necessary, often accompanied by (fruitless) protrusion of the penis and pelvic thrusting. Achievement of the correct position enables insertion. Copulation takes the form of waves of thrusting followed by periods of relative quiescence. Ejaculation is usually associated with especially deep thrusts. The deeper action is associated with the ultimate locking of the spiral glans into the folds of the cervix. This element of the affair may last between 2 and 10 minutes, and its duration is highly variable. The female may move around somewhat during the course of the events. In natural circumstances, boars may mate 3 or 4 times daily over the period of the sow being in standing heat, each mating being followed by a refractory period.

The following may be surmised if optimum conception rates and fertility are to be achieved:
(1) Courtship is a necessary part of fertilisation.
(2) Females entering oestrus should be in sight, smell and sound of the male, and be able to move freely into physical nose-to-nose contact (normally through the open bars of a pen) (see Figure 5.2).
(3) Mating quarters should be of adequate size to allow (1) bunting and investigation, (2) the possibility of escape for the female from the attentions of the boar if she is not in full standing heat, and (3) effective mounting and mating. These three activities require a minimum area of 10 m², and preferably more (Figure 5.1).
(4) The floor of the mating pen should be clean and dry to give a good grip, and it may also be helpful if bedding is provided (Figure 5.1).
(5) Standing heat itself is best identified in the presence of a boar.
(6) Attention should be paid that correct intromission has taken place.
(7) Mating should not be hurried, nor interrupted at any time.
(8) Upon dismounting after successful coitus, the boar should be moved quietly away from the sow before the sow is moved to her separate quarters.
(9) Given adequate space, there is no reason why a boar should not run freely with a group of sows, provided he is not over-used. Evidence of the female having been mated is conspicuous by red abrasions and bruising behind the shoulders of the female resultant from the activity of the boar’s front legs.
(10) There is a negative effect of high temperature upon oestrus behaviour and conception in females and libido and sperm potency in males.

**Parturition**

Choice of nest site need not be immediate. Feral pigs (domestic animals allowed to run wild) will often build at the margins of woodland, constructing the nest from
tree branches, saplings, new woody shoots, and bark; but especially favoured are grasses, sedges and rushes which are carried in large mouthfuls and with great enthusiasm in the period prior to farrowing. The nest will comprise a wall of material built by rooting movements of the snout, and is likely to be asymmetrical. Pigs, of course, build nests for resting in the normal course of events by the same means. Given an area of coppice and ground vegetation, together with some form of shelter, pigs will actually clear the plant material, which may be eaten, chewed and discarded, or incorporated into the nest site (or shelter) after some degree of mastication or manipulation by the mouth. Pigs kept in groups in open straw yards will create nests and lie together in sub-groups. Nest-building may take some time, with much fetching and carrying of straw and subsequent manipulation and chewing. Sites, once chosen, may be quite long-lasting. The need to lie communally extends from a very young age, immediately after birth, through all classes of pigs as they grow, and includes adult sows and boars. Only when about to farrow will the female seek a degree of isolation from other members of the group.

In the pre-parturient female, nest-building begins about 24 hours before birth and is again associated with vigorous activity of jaw and shout. There is frequent turning around, and a deal of moving to and fro, often with the specific purpose of fetching and carrying nest-building materials. Pre-parturient sows have been observed under feral conditions to travel between 100 and 200 m in an hour and a half or so, going backwards and forwards with nesting material. Some of this frenetic activity may continue during parturition, usually within the confines of the nest area. Modern husbandry systems may frustrate nest-building activity by confining the pre-parturient sow in a farrowing crate (Figure 5.3). However, this also prevents turning and moving during parturition, which may otherwise lead to squashing of the newborn underfoot. Thwarting the nest-building drive does not appear to adversely affect the process of parturition itself. Some amelioration of the extent of nest-building thwarting may be achieved by the provision of straw at the head of the confined sow, which at least facilitates mouth manipulation of nest-building material, and also allows nest-building movements with the forelegs whereby material is raked back into a mound. There remains considerable argument as to whether sows should be allowed freedom to come and go and to turn around in the place of parturition. While some authorities point to research evidence under controlled conditions of low piglet mortality in ‘yard farrowing accommodation’, others point to the history of mortality by overlaying and crushing of 20% or more associated with open-pen pig house designs, and the progressive reduction in perinatal

Fig. 5.3 A farrowing crate which restrains the sow before and during parturition, and throughout lactation.
mortality as first farrowing rails, and next the farrowing crate itself, were introduced – the beneficiaries of the farrowing crate being not farrowing sows but neonatal piglets.

Whilst there is some benefit in terms of simplicity of management and economy of building construction in having sows in farrowing crates for the whole of the time between their entry before farrowing and their exit upon weaning, there is no evident benefit in production terms and a clear perception of disbenefit in welfare terms. It is difficult to argue (other than on convenience/building costs grounds) for the retention of sows in farrowing crates beyond the first (7) days post-parturition. The purpose of the farrowing crate in preventing piglet deaths through crushing is largely achieved in the first 3 days after farrowing. At least half of the crushing events occur during the farrowing period itself and in the course of the first full day post-farrowing. Failure to place sows into farrowing crates will result, under commercial conditions, in piglet mortality rates of between 10 and 25%. In exceptional circumstances, mortalities can be reduced below 10% even when farrowing and post-farrowing sows have freedom of movement – but it could not be said that such would be the normal expectation. A banning of farrowing crates would therefore likely be counter-productive to pig welfare, but a restriction of their use to the first week after farrowing may have some welfare benefits for the sow. It has to be also said, however, that the health and safety of persons caring for sows and young piglets is improved where the sows are retained in crates, but diminished in direct proportion to the amount of freedom given to the sow. Recent studies have re-investigated the potential for free-access farrowing quarters, with the unequivocal conclusion that they are not practicable, being associated with high pre-weaning piglet losses and difficult system management. Whilst the sow undoubtedly has her freedom of movement curtailed in a farrowing crate, the freedoms and rights of the new-born piglets (about to be crushed) are substantially more compromised in free access systems. There would seem to be some benefit, however, in considering possibilities for reducing the time spent in the confinement of the farrowing crate, and of continuing to investigate alternatives to the particularly restrictive conventional parallel bar farrowing crate constructions.

During parturition the sow will exhibit periods of passivity when awareness of extraneous activity in the environment is apparently low. This semi-comatose state is interspersed with periods of activity, when she is restless and may rise and attempt to turn. No attention is given to those of the litter that have been born, and the dam does not assist in cleaning and drying. When lying, the sow will usually be on her side, exposing the udder for frequent access by newly born piglets who will suck to obtain the benefits of colostrum as soon as possible after birth. Meanwhile abdominal and uterine muscle contractions expel fetuses, with little trauma, usually at the rate of one fetus for each deep muscle effort, and sometimes with vigorous tail movements, and over a period of 2–3 hours, with variable lengths of time between each delivery (usually around 15–20 minutes). Some placental material is voided during the course of farrowing, but most at or near the end. The umbilical cord may be broken at birth, or by the piglet struggling to make its way forward round the
rear legs of the sow to the mammary glands. The young are up, active and mobile, without assistance, within a minute or so of birth. In the natural course of events the dam will attempt consumption of placenta and piglets born dead. Cannibalism of live-born piglets is rare.

Teat-seeking behaviour by the neonate is aided little by the mother. Fore and rear leg movements, which have been interpreted as giving guidance to the young looking for the mammae, are usually counter-productive and cause more disturbance than assistance. During the first few hours post-partum milk is continuously available at the udder, and a ‘teat order’ begins to be established at this time. Within 5–10 hours of birth suckling frequency occurs approximately half-hourly, and is established at hourly intervals within the first day. The hourly frequency continues up to around 35 days of age, after which suckling bouts occur progressively less often.

**Nursing and sucking**

The establishment of the teat-order by piglets is renowned. It consists of the development of each individual piglet’s preference for a particular nipple, and that piglet’s willingness to fight for possession of its nipple, with much squealing and biting. If each suckling was to be the occasion for a litter of 10–12 piglets to squabble anew over which mammae was to be occupied by each piglet, the process of feeding would become unconscionably inefficient. The teat-order therefore represents the means by which the members of the litter may come to a general agreement over the first 2 days or so of life as to which nipple they will suck. Teat-order is usually established within 3 days of farrowing. Quarrels tend to ensue over those nipples that are placed in the middle of the udder, where mistakes are more readily made. There is also confusion when the sow changes the side that she usually lies on, for this requires the piglets to adapt to a change in their vertical position if they are to maintain their preferred teat. It is thought that the anterior mammae, which may be producing more milk, are most favoured, and won by the larger piglets; but the evidence is not particularly strong. Piglets fostered onto sows having farrowed 1–2 days previously will have little problem finding/winning a place at the udder, but after this time problems will arise as those mammae not regularly sucked will have begun to dry up, and the interloper will cause serious disruption to the established order.

Nursing may be initiated either by the sow or more commonly by the piglets. Prior to this, either or both parties are likely to be resting or sleeping. After a lapse of time from the previous suckling of about 1 hour, the sow may be roused from slumber by the attentions of one or two members of the litter who have awakened early. If the sow is willing to be sucked, she will roll on her side and expose both rows of teats. For effective and equitable feeding of the whole litter, it is necessary for co-ordination of sow and piglet behaviour to ensure all members are present, correct and ready to receive before the sow allows milk to flow from her mammary glands to the sucking young. The pattern of milk flow from the mammae of a sow
is shown in Figure 5.4. Phase 1 of suckling comprises the piglets jostling for position on the udder for purposes of identifying and retaining their own preferred nipple. This phase may last for 20–60 seconds, or more if there is quarrelling. Nosing and butting the mammarys with vigorous up and down movements of the head herald phase 2, which lasts for about 30–40 seconds. Phase 2 will not begin until the disputes amongst the piglets at the udder have been resolved and all quarrelling and squealing has ceased. This phase stimulates oxytocin release, and the piglets may get a little milk by passive withdrawal from the cistern. The piglets may then be observed to go quiet for about 20 seconds during phase 3, sucking on the teat with slow mouth movements of about one ‘draw’ of large amplitude upon the teat every second. Milk flow (phase 4) lasts for a mere 10–20 seconds, and may be recognised by the piglets’ rapid mouth movements (about 3 per second) of smaller amplitude while they stretch their necks, flatten their ears and swallow 40–80 ml of milk. After this, there may be a short period of quiet sucking, like phase 3, but often interrupted by noisy sucking and ‘smacking’ of lips (phase 5). The final phase (phase 6) returns to vigorous butting of the mammarys. This phase is usually terminated by the sow rolling onto her udder and covering her nipples. The six phases of sucking are depicted in Figure 5.5 (i–vi).

The sow herself has meanwhile been grunting in a characteristic rhythmic vocalisation pattern of about 1 grunt every second. At around the beginning of phase 3 of the suckling, this rate of grunting escalates dramatically to about 2 grunts per second, and then subsides down to 1 grunt per second by phase 4; and finally the sow will stop grunting some time during phase 5 (Figure 5.6). Sometimes two peaks in grunt rate may be heard, the second occurring around the beginning of phase 4.
Fig. 5.5  The six phases of suckling: (i) jostling for position.

Fig. 5.5(ii)  Massage of mammae.
Fig. 5.5(iii) Quiet sucking.

Fig. 5.5(iv) Milk flow.
Fig. 5.5(v)  Quiet sucking.

Fig. 5.5(vi)  Final massage.
It has been observed that not every nursing given by a sow will necessarily result in the release of milk. Unsuccessful sucklings are characterised by the absence of phase 4 from the routine, and a failure on the part of the sow to increase discernibly her rate of grunting. It would appear from the timing and characteristics of the vocalisation pattern of the sow that the increase in grunt rate is a ready external indicator of oxytocin release from the posterior pituitary. Oxytocin may be presumed to have an elapse time of about 20 seconds between release from the pituitary and action upon the gland. The duration of the effect of oxytocin upon alveolar implosion appears to be patent for a further 15–20 seconds.

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Nursing and sucking will be seen as having been disrupted or abnormal in nature if:

- piglets do not stop jostling for teats within a reasonable time from the initiation of the suckling;
- the rate of sow grunting does not increase;
- phase 4 of suckling (rapid mouth movement) is not evident.

Because of the limited amount of milk held in the cistern of the mammary gland of the sow, adequate levels of milk will only be supplied to the sucking young when the proper conditions of teat-order, increased grunt rate and phase 4 sucking behaviour prevail. With the singular and brief exception of the first hour or two post-partum, the presence of the young sucking at the mammae is not an adequate positive indication of receipt of nourishment.
Competitive and aggressive behaviour

Pigs normally live in family groups. Competition amongst them is restricted in the most part to sibling disputes in the first weeks of life, and otherwise to aggression with other families when there is an encounter, particularly if there is also competition for food or space. There is also the normal fierce, aggressive behaviour amongst competitive males. By and large, however, the family group is not a threatening but rather a comforting local environment for pigs to live in. This results from early definition of the hierarchical social (dominance) order amongst siblings, amongst less well related pigs, and amongst breeding females and also males. This hierarchy may need to be reaffirmed, or indeed altered, by occasional acts of aggression, but in the normal course of events vocal and postural threats, with the odd physical challenge, are usually adequate to maintain an ordered social structure amongst pigs living in groups. Once the dominance order has been established, however, and provided groups are not destabilised by the addition of strange pigs, the vast majority of aggressive acts between pigs take place at the time of feeding, or at other times when there is real competition for a scarce resource – such as newly provided straw.

This relatively harmonious state of affairs does not pertain in many domestic pig-keeping situations. Aggression arises in modern pig husbandry systems as a result of:

- Lack of adequate space to respond submissively to a threat, and to achieve full avoidance action and movement away. A situation that would otherwise have been averted is thus caused to develop into the need to defend and fight.
- Competition for food which creates a situation of constant reassessment of the hierarchical order in the face of hunger, and unwillingness of low-ranking animals to comply readily with their more lowly position when to do so would be, effectively, to fail to eat.
- Frequent disturbance of social hierarchies occasioned by the mixing of pigs of different social groups. This occurs at weaning, often again on one or two occasions while growing, on despatch for slaughter and in the slaughterhouse lairage. Adult sows kept in groups are mixed into disturbed social structures at least once every parity while awaiting mating or while pregnant.

Threats usually take the form of vocalisations or movements of the head, and may be followed by head-butting and shoulder-pushing, although lesser body positions and the mere physical presence of a dominant pig may elicit the necessary avoidance reaction on the part of submissive pigs of lower rank. Most fighting amongst pigs is with the mouth open and teeth bared. Upward thrusting movements and bites inflict elongated bruising, grazes and gashes, mostly to the flanks, shoulders and face. A pig may charge at another, usually targeting the head (if head-on) or the flank and belly. Bunting and rooting is common, especially at the underside and between the hind legs.
The consequences of fighting amongst pigs are severe. Scarring to the faces of sucking pigs due to fighting at the udder may facilitate entry of bacteria and the development of exudative dermatitis. Aggression amongst newly weaned pigs mixed together into broken family groups can reduce the growth of all the pigs in the pen for a period of up to 2 weeks while the new social order is established. If pigs of equal strength and dominance meet repeatedly, individual animals can be severely damaged. Pigs pushed down the social order by fighting may subsequently fare less well, be denied full access to feeding possibilities and fail to thrive. Not only are these pigs inefficient in their growth, they are also soft targets for disease organisms and therefore a threat to the whole group.

Because much aggression starts with competitive feeding, and its consequences are often most severe when expressed in terms of diminished food intake, it is essential that adequate trough space is available for all pigs to eat as frequently as they may wish from ad libitum hopper systems. If meal fed, the trough length must be adequate for all pigs to eat at the same time and avoid aggressive interactions while doing so. This will require a trough space allowance per pig that is greater than the width of the pig across its shoulders. Optimally two times shoulder width is an appropriate guide to trough space allowance per pig if a competitive group is to be fed from the same trough simultaneously, and if pigs of lower social rank are to receive their full and fair share of food provision. Divisions also help considerably, even just between the pigs’ heads.

Adult sows may fight vigorously when placed into novel social groups, as may often be the case after weaning for group-housed sows. As such fighting may occur around the time of oestrus and during the first 3 weeks of the next pregnancy, losses of embryos can result as a consequence. Sow groups will often form with one dominant animal which eats greedily and may become large and fat. There are also likely to be one or two subservient animals which actively avoid competitive feeding situations and, in addition to being wounded and bruised, may become emaciated. This unacceptable behaviour in group-housed sows can be ameliorated by individual feeding. Placing pelleted food scattered amongst the bedding, or on the ground in piles, separated by a substantial distance, is helpful in allowing all sows equality of access, and is often practised in large straw yards or in outdoor pig units. For smaller pens, however, it is necessary to feed each member of the group individually. This is best done with an individual crate into which each pig can be shut and protected from others while feeding takes place (Figure 5.7). Electronic feeding systems are also available (Figure 5.8) where the feeding station is continuously accessible to pigs wearing electronic identification tags. One stall is adequate for 15–20 sows, but is often used for twice that number. Ad libitum feeding of sows is unusual in pregnancy as consumption is likely to be considerably in excess of both need and an economic allowance. In any event, it should not be assumed that the presence of an ad libitum feed hopper will ensure freedom of access by all pigs in a group. Dominant animals may well guard the feeding station and prevent access to pigs of lower social rank. This can also happen with electronic feeding stations where, in practice,
Fig. 5.7  Individual feeding facilities for group-housed sows.

Fig. 5.8  A continuously available electronic feeding station for use by group-housed sows in straw yards.
pregnant sows tend to take all of their daily allowance in their first-and-only visit of the day to the station.

Tail- and ear-biting amongst growing pigs should not properly be considered as aggressive or competitive behaviour; this phenomenon is abnormal, and the behaviour aberrant. A pig may bite another’s tail or ear, which will first be bruised and then bleed. The troubled pig will often be passive to these proceedings. The bleeding may then attract further attacks over the next hours or days. At this time significant amounts of tissue will be lost and there will be copious bleeding. The bitten pig will lose condition rapidly and become distressed. A more general outbreak can occur. Frequent observation of growing pigs is necessary in order to control the problem. The pig attacked and the pig attacking should be removed from the pen at the first sign of disturbance, and placed alone in individual accommodations. It can now be safely asserted that although some strains of pig might be more prone to tail- and ear-biting than others, the cause of this problem is environmental and managemental. Predisposing factors may be:

- insufficient environmental stimulation;
- inadequate space allowance;
- inadequate temperature control;
- inadequate air movement;
- imbalanced nutrient composition of the diet;
- inadequate amounts of feed provided;
- unpalatable feed;
- inadequate trough space and access to feed;
- inadequate water supply.

Dr Peter English of Aberdeen University makes the point that there is an interaction between the importance of social rank in aggressive and competitive situations and the general standards of management on the production unit. Thus pigs of low social rank, submitting to aggressive pen mates in competitive situations, will suffer greatly in circumstances where, for example, there is limited living space or limited trough space. This concept is a vital part of good husbandry and adequate welfare.

**Locomotion, ingestion and elimination**

The notions that pigs (1) spend most of the time sleeping, (2) eat greedily and (3) have dirty habits are misconceptions (at least in part) arising from modern husbandry systems.

In the semi-natural environment of the Edinburgh Pig Park, domestic pigs were kept in groups of about six adults, together with young offspring, in areas of 1.2 ha. Feed was provided to a level adequate for a protected environment, and therefore likely to have been somewhat inadequate to provide fully for dietary needs in the semi-natural environment. During the day, the pigs spent half their time grazing and
rooting, and a further third walking about and generally manipulating, working over and interacting physically with their environment (Table 5.1); only 6% of the time was spent lying. The males spent 4% of their time in competitive behaviour, young adults rather more (6%), but the sows hardly any (1%).

In the Edinburgh Family Pen system of pig production four sows and their litters had access to defaecation areas, rooting areas (peat), activity areas (straw) and nesting areas (straw). The growing pigs – which were housed together with the adults – were fed *ad libitum*, while the sows were individually fed to ensure that the full feed allowance was available to each. The overall space available for some 4–5 adults and 40 young (through to finish) was generous at 110 m². Despite opportunities for ranging more widely, the pigs spent more than three quarters of their time in the nest area, being found in the activity area for only 10% of their time, and of the remaining time more was spent in the feeding area than in the rooting area. Pigs spent more than half of their day-time sleeping, a further quarter in general activities, 5% eating and one tenth of their time rooting (mostly in the nest area). Table 5.1 shows clearly the dramatic reduction in foraging activities (50–15%), and a dramatic increase in time spent lying (6–60%) compared to the Pig Park.

In stalls or tethers, pregnant sows will spend about one fifth to a quarter of the daylight hours standing, and over three quarters lying. Eating only takes 10–15 minutes per day (see Table 5.1). Some of the time spent standing will be used for repetitive activities such as bar-biting and chain-chewing. There appears to be an inverse relationship among pigs between the incidence of such repetitive activities and the time spent lying. It is not surprising that standing usually occurs before, during and after meals and drinking, and whilst other activities (mating and human-related) are going on in the house.

**Table 5.1.** Comparative day-time activities of pigs in extensive, semi-intensive and intensive production systems (percentage of total daylight hours).

<table>
<thead>
<tr>
<th>Activity</th>
<th>Pig Park</th>
<th>Family Pen</th>
<th>Sow tethers/stalls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eating-related and rooting</td>
<td>50</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>Moving and interacting physically with the environment</td>
<td>30</td>
<td>25</td>
<td>—</td>
</tr>
<tr>
<td>Lying recumbent</td>
<td>6</td>
<td>60</td>
<td>76</td>
</tr>
<tr>
<td>Standing still</td>
<td>—</td>
<td>—</td>
<td>22</td>
</tr>
</tbody>
</table>

**Locomotion**

As has been seen, feral pigs spend a significant amount of time active and moving about the range area (more than three quarters of the daylight hours; Table 5.1). Much of this movement is in association with foraging. Pigs also rapidly explore new territory to a wide extent. They will wander, walk purposefully, trot significant distances (hundreds of metres) and scamper (tens of metres). Very rapid movement may be accompanied by sharp, excited grunts and barks. It would appear that young
pigs especially enjoy rapid movement, and will leap with agility when startled. Chasing behaviour is an important part of play – and aggression. Healthy pigs play more often and more vigorously than sick ones. This general description is not a familiar pattern in intensive production systems, where there is little need for locomotor activity; and indeed, little opportunity. Undue degrees of restraint on movement may exacerbate locomotor problems in joints, and may also predispose to frustration. However, when given freedom to move widely, but where the need to do so is absent, pigs will usually volunteer to spend a high proportion of the day inactive. This was clearly observed in the Edinburgh Family Pen system of pig production (Table 5.1) where, despite ample opportunity for activity and exercise, the pigs spent some 60% of their time lying. Well-fed young pigs when not eating or eliminating will usually be found sleeping. The lactating sow with a ready provision of ample food will lie with equanimity in the nest with her piglets. It is self-evident that sows in tethers, stalls or crates are denied locomotor activity other than moving to and from the lying position, and moving backwards and forwards one or two steps. Such pigs spend rather more time lying, even more than in the Family Pen. However, evidence for the need to do something other than sleep is provided by the significant amount of time that pregnant sows in tethers and stalls will spend standing (Table 5.1).

In intensive production systems, movement between houses and at the time of despatch can be a stressful event for the animals. Pigs are best moved in limited file down a race with solid sides and an open top (Figure 5.9). Contrasts between intense light and dark should be minimised. Pigs readily accept a change of slope, but not more than 15°.

**Ingestion**

Feral pigs will spend more than 50% of their day foraging; this they tend to do in groups. Foraging involves rooting up and eating pasture grasses, small trees and shrubs, and seeking other food such as plant seeds, fruits, berries, and leaves and shoots of larger trees. Insects and small animals, such as beetles, worms and grubs, are commonly consumed, whilst larger animals, and the young of larger animals which are not swift enough to avoid capture, may also be killed by pigs. Pigs will eat available carcasses of animals that have died or been killed by other predators. The pig is an omnivorous and opportunistic feeder. Having such a wide variety of feeding opportunities, it is not surprising that they have both efficient fore-gut and hind-gut digestive systems. The ‘monogastric’ digestive system operates in the stomach and small intestine, which is well-adapted to dealing with lipids, sugars, starches and proteins. The highly efficient caecal and large intestinal digestive system operates through the help of a substantial bacterial population, which will deal with nutrients in plant tissues high in non-starch polysaccharides. Neither is it surprising that the pig can readily discriminate the different nutritive values of a wide variety of feedstuffs which enable self-choice feeding and the automatic balancing of the diet (see below). The pig derives satisfaction from seeking food and is well-equipped to
do so with a high sense of taste and smell and a sensitive snout. The pig’s snout offers a capability for rooting and moving substantial quantities of inert material in search of food. Many of the food sources sought in nature require substantial manipulation and mastication before swallowing.

The pig therefore possesses considerable drives both to forage for food over long periods of time (and distances) and to manipulate thoroughly what it finds in its jaws. The natural situation can be contrasted with modern systems of production where the full day’s nutrient requirement is provided in a trough and can be consumed in a feeding time of around 20 minutes. Being comminuted already, the need for food mastication is minimal. Competition at the trough creates a positive relationship between the rate of eating and individual success in terms of growth. It is also noticeable that the less pigs are allowed to eat in the day, the more rapidly they will eat (the more greedy they will appear). The digestive processes also differ.
greatly between foods that may be ingested in feral situations (these are high in structural non-starch polysaccharides) and the nutrient-dense starch/oil/protein mixes which form the major part of an intensive compound diet. The latter of these diets is digested for the most part in the stomach and small intestine and fills a much lesser volume within the gut. Concentrated feeds may frequently fail to satisfy hunger while fulfilling nutrient requirement. Hunger will lead to anticipation as the time of the next feed approaches. It is evident that the strong and inherent drives to select feedstuffs amongst alternatives, to forage for food and to manipulate food and non-food matter with the jaw are all left entirely unsatisfied in modern production systems. However, the need for eating-related activities appears to be influenced by individual environmental circumstances, and it must not be assumed that the time spent in feral conditions foraging for food is necessarily a behavioural need in circumstances where ample food is readily available. Where there is both ample straw for manipulation and a rooting area, pigs spend only 15% of their time in eating-related and rooting activities. Nevertheless, this is considerably more than the 2% time spent eating by sows in stalls and tethers, and pigs in richer environments with bedding and rooting areas available will spend a quarter of their time moving and interacting physically with the environment, much of which will involve work with snout and jaws.

**Elimination**

Pigs are fastidious in their elimination patterns. Defaecation is usually in special chosen places in the pen, often in corners or alongside walls or other barriers. In the Pig Park defaecation places were selected and used with care, there being little or no random elimination over the area. Only when this (clean) behaviour is prevented or confused will pigs soil lying areas and defaecate without consideration for location. Purposeful soiling may occur at high temperatures, either indoors or outdoors, when pigs will wallow in faeces and urine or (preferably) in mud. This is entirely logical behaviour as the pig has a very limited ability to sweat and a predisposition to heat stress and sunstroke.

Choice of lying area and dunging area may differ between the designer of the pig house and the occupant. This difference of opinion will lead to pen soiling. At lower stocking densities, ‘lying areas’ may become used for elimination. In the Family Pen system the peat rooting area and the straw-bedded activity areas were frequently used for defaecation and urination, despite the provision of areas designed specifically for elimination. This may have been because the pigs did not recognise the defaecation area designed for them, or they found the need for the rooting and activity areas superfluous and therefore utilised them for elimination. The frequent inability of the pig and the pen designer to fully agree about the ‘correct’ defaecation area as well as the need to keep pens clean of accumulation of excreta have led to pen designs with fully slatted floors. Faeces will fall through the slats to the slurry chamber below wherever in the pen the defaecation has occurred. Unfortunately, although solving one problem, the full-slatted pen is a
barren environment which does not allow the use of bedding materials. It is questionable whether such pens are satisfactory for adequate pig welfare.

**Feeding behaviour**

One of the basic rights of an animal is the provision of adequate amounts of food of proper nutrient content. It is often taken for granted that a pig should be fed a mixed diet, balanced for nutrients by control of ingredient content, and that the decisions regarding appropriate feedstuff mixtures and nutrient contents are best made by nutritionists, feed compounders and production managers. This, however, is rather a recent idea and pigs must have balanced their own diets quite satisfactorily for many thousands of years of evolution by choosing from their environment those feedstuffs that were best suited to their needs. There is no reason to presume that the modern pig has not retained the abilities of its ancestors to choose a satisfactory diet from a range of ingredients.

In order to satisfy its nutrient needs by self-choice feeding, the pig must be broadly aware of the following precepts:

1. The pig must have some mechanism for identifying – in quantitative terms – its needs for maintenance, for growth of lean and fat and for lactation, and for the relative balances between those needs. The pig must have some means to recognise that different needs can be satisfied only by different nutrients; energy for maintenance, protein for lean growth, calcium and phosphorus for bone growth, trace minerals and vitamins for metabolic processes, and so on. These different nutrients must be differentially distinguishable in the feedstuffs on offer.

2. Choices must be made within the boundaries of appetite, and within the ability of the pig to excrete unwanted nutrients and detoxify food toxins unavoidably ingested.

3. Choices should not be limited by narrowness of range of ingredient supply, or obscured by the confounding of needs. Problems of choice will occur when a wanted nutrient is only to be found in a feed ingredient that already contains an excess of an unwanted nutrient, or in a feed ingredient that is unpalatable. Pigs will discriminate with considerable precision against feedstuffs they find unpleasant to eat. They will also avoid fungal toxins, some plant toxins (such as those in cruciferous and leguminous plant seeds) and extraneous non-food solid particles such as stones, glass and metal. There can be aversion to specific tastes, such as bitterness or unpleasantness which may be associated with plants with toxic or anti-nutritional factors.

4. The pig should be granted an opportunity to learn; to experience the metabolic consequences of different ingestion choices, to remember which feedstuffs were associated with the various possible consequences, and to recognise either the feedstuff or the feedstuff component (or nutrient) in terms of its metabolic consequences.
Despite long standing evidence to the contrary, the idea that pigs could select and balance their own diet is often met with scepticism; not least because (a) it was assumed, contrary to the market demand for lean pork, that the pig’s idea of bodily perfection was obesity, and (b) many experiments testing the possibility of effective self-choice feeding have been inconclusive. With recent improvements to genotype the first assumption is no longer universal. The second may have been due to the experimental design being directed to testing for principle (1) above, but failing to accommodate principles (2), (3) and (4). Indeed, while principles (2) and (3) may have been denied unwittingly through poor experimental design, principle (4) – the opportunity to learn – was in some experiments purposely obfuscated by devices such as frequent alteration of the location in the pen of the different diet types.

Self-choice feeding with the possibility of effective energy and protein balance is of paramount interest not only because this is an important economic aspect of nutrient supply, but also because discrimination in this particular aspect of diet formulation may be presumed to be of special concern to the pig. Successful self-choice amongst pigs with regard to optimum energy and protein balance would have the following benefits:

1. Determination of the optimum balance of diet energy and protein by the nutritional wisdom of the pig rather than the nutritional wisdom of the human diet compounder. If the pig is able to follow the four principles outlined above (intrinsic knowledge of nutrient need and recognition of nutrients in feedstuffs, adequate appetite, absence of confounding factors and the opportunity to learn), then it may be that the pig is more skilled in determining its individual optimum than the human.

2. Achievement of maximum growth rate unrestrained by nutrient limitation imposed by inadequacy or imbalance of the nutrient supply. If the pig can balance its own diet, then it can adjust that balance on a daily basis throughout growth, thus optimising nutrient provision.

3. Allowance for individual variation in nutrient requirement. In this way the requirement of all pigs is exactly satisfied, and the diseconomies are avoided of over-providing for some members of the population, under-providing for others and optimally providing for only few. This is the inevitable consequence of compounding a single diet to the average requirement of a variable pig population. This benefit prevails with regard to both the use of a diet by a group of pigs at any one time, and the change in diet specification that occurs for every individual pig over time as it grows. Not only do pigs of similar age or weight differ in their rates of protein and lipid growth, but also the ratio of diet protein needs to diet energy needs changes as the pig grows. This is because the need for energy becomes increasingly important in comparison to protein as maintenance costs and lipid growth become progressively greater relative to protein accretion.

There is also the possibility of disbenefits:
(1) The pig cannot be forced to eat what it may not wish to eat because of factors relating to unpalatability or (human-imposed) imbalance. Often a production manager may wish the pigs to grow at a different rate or with a different lipid:protein ratio in the growth than the pig might consider optimum. Also, it may be necessary for the pig to consume ingredients less than optimally palatable. These things can only be achieved if the pig is given a simple compounded diet with no choice of ingredients.

(2) A period of learning or training may be required and this takes time and management effort, especially in modern management systems.

(3) At least two sources of feed must be available to the pig in order for choice to be exercised. This doubles the feeder equipment requirement.

Nonetheless, experiments at Edinburgh conducted over many years have shown that if pigs are given at the same time both a high protein and a low protein feed, and allowed to choose freely between them, and if the feeds are of ingredients all of which are similarly acceptable to the pig, and if a short period of accustomisation to both feeds by alternative provision is allowed, then:

- the pig demonstrates ‘nutritional wisdom’ and can recognise the relative protein concentrations of the feed;
- the pig can balance its diet with respect to protein and energy;
- optimum growth rate can be consistently achieved.

Table 5.2 shows responses of young pigs given single diets of various protein content from 12 to 30 kg live weight. Daily live weight gain is seen to increase with crude protein (CP) content to a peak at 217 g CP/kg diet, but then at 265 g CP/kg diet the growth rate slightly diminishes, showing (1) the classical response to diet protein and (2) the optimum diet crude protein content. In the second part of the experiment pigs of similar weight were offered choices between pairs of these diets, and the results are shown in Table 5.3. The pigs offered a choice between two diets of differing crude protein content appeared able to discriminate between them and select sufficient of each to create a balanced diet, which in this event appears to be between 202 and 208 g CP/kg. The precision with which this final diet was independently chosen despite widely different source feed pairs is quite remarkable. Pigs offered the two lowest and the two highest crude protein concentration diet pairs were, of course, prevented from achieving the preferred balance, the optimum

Table 5.2. Influence of diet content of crude protein upon daily live weight gain of pigs given a single diet (from Kyriazakis et al. (1990) Animal Production, 51, 189).

<table>
<thead>
<tr>
<th>Crude protein content of the diet (g/kg)</th>
<th>125</th>
<th>171</th>
<th>217</th>
<th>265</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth rate (g/day)</td>
<td>492</td>
<td>627</td>
<td>743</td>
<td>693</td>
</tr>
</tbody>
</table>
solution being unfeasible. Table 5.3 demonstrates that diet selection was indeed optimum, achieving rates of daily gain rather superior to that determined with the best single diet in the first part of the experiment. This experiment also showed that pigs chose to reduce the protein level in the diet that they selected as they grew. This is consistent with expected changes in the balance of nutrient demand. The crude protein content of the final diet voluntarily chosen from pairs of feeds with adequately widely differing crude protein content diminished smoothly from 230 g CP/kg at the beginning, to 210 g CP/kg in the middle, to 190 g CP/kg at the end. The Edinburgh group have also demonstrated the latter phenomenon with older pigs offered a choice of a pair of feeds at 119 and 222 g CP/kg when grown from 45 to 105 kg live weight. Gains in excess of 1 kg daily were achieved, while the diet selected by self-choice began at 195 g CP/kg and then diminished smoothly over time to 170 g CP/kg when pigs were 60 kg, and 155 g CP/kg toward the experiment’s end. In further experiments it was found that pigs artificially grown to be fat (by being previously given a low protein diet) selected a higher protein diet subsequently than pigs grown to be lean; thus correcting the deficiency, maximising growth and readjusting body composition toward their preferred lipid:protein ratio. There is also a strong (and logical) genetic component to choice of protein:energy ratio; pigs of higher lean growth potential identifying and satisfying their need for a greater protein intake.

In all the above experiments and many others reported in the literature pigs have shown an unerring precision in regulating their food intake and selecting a diet that meets their needs. The expression that one ‘eats like a pig’ may not be considered anymore as having negative connotations!

### Injuries and mutilations

Damage to the body can be inflicted through pigs fighting each other at any stage of life. Damage may be particularly serious in newly grouped weaned pigs, and growing pigs and adult sows upon regrouping; all in consequence of the need to re-establish a dominance order and the unwillingness of one or other of two equally

<table>
<thead>
<tr>
<th>Crude protein contents of diet pairs (g/kg)</th>
<th>Crude protein content of final diet chosen (g/kg)</th>
<th>Live weight gain (g/day, from 15–30 kg live weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125 and 171</td>
<td>160</td>
<td>682</td>
</tr>
<tr>
<td>125 and 217</td>
<td>208</td>
<td>752</td>
</tr>
<tr>
<td>125 and 265</td>
<td>204</td>
<td>768</td>
</tr>
<tr>
<td>171 and 217</td>
<td>202</td>
<td>769</td>
</tr>
<tr>
<td>171 and 265</td>
<td>205</td>
<td>763</td>
</tr>
<tr>
<td>217 and 265</td>
<td>218</td>
<td>764</td>
</tr>
</tbody>
</table>

Table 5.3. Daily live weight gain of pigs given a choice of two diets of different crude protein content (from Kyriazakis et al. (1990) Animal Production, 51, 189).
matched aggressors to submit. Occasionally the introduction of a single animal into an otherwise stable group will elicit multiple attack, to the severe detriment of the interloper. Pigs’ teeth can inflict cuts and slashes, but equally as damaging can be rooting and thrusting movements of the head which will bruise deeply, damage limbs and cause internal injury. Second only to abrasions from fighting, the most common damage to growing pigs results from tail- and ear-biting.

The third most common mutilation is damage to legs, which occurs especially in growing pigs on slatted floors and in pens without bedding. Here, although removal of the skin and physical injury to limbs and joints may cause locomotor problems, more significant perhaps is the high frequency of swollen joints, the presence of lumps and bumps around the legs, and especially swellings on knees and hocks. The same floor types can also predispose to damage to the sole of the foot through abrasions, to infections between the toes, to cracked and damaged toes, and to uneven or aberrant toe growth. Where the skin is broken, and where there is any limb injury, there is the added likelihood of the incursion of infective agents which will cause further local inflammation, and occasionally systemic toxicity and disease. Secondary infections may spread through any damaged limb to cause a general septicemia.

Damage to leg joints and other locomotor problems may also commonly be found in sows as a result of fighting when straw yards are used for loose-housing. However, more frequent damage to bones, joints, muscles and tendons arises in tether and stall systems where pregnant and lactating sows may have difficulty in rising and lying down, and may lose their footing on slippery surfaces. Sows in stalls or tethers are also prone to swellings, abrasions and other injuries to the feet, ankles, hocks, knees and also to the shoulders and thighs resultant from concrete floor surfaces and slats. Such surfaces are often also dirty and a ready source of secondary infection.

Tethered sows are susceptible to damage from the tether, especially neck tethers, but also those used around the girth. Metal-bar and chain neck tethers, even when protected with plastic coating, can on occasion rub, inflame and cut into the flesh, creating a deep wound. Only by substantial modification of production systems, and by constant observation and monitoring of young pigs and sows can the consequences of these injuries be lessened.

At least four categories of mutilation are inflicted by man in the normal course of husbandry practice and common custom. These are as follows:

1. The sharp baby teeth of piglets are clipped, usually within 1 or 2 days of birth at the same time as iron is administered. Piglets’ teeth are clipped in order to avoid (a) damage to each other while fighting for position at the udder, (b) damage to the nipples of the sow and (c) reduction of sow milk yield through udder irritation. There is some dispute about the need for this procedure, and in many cases neither (a) nor (b) may occur if piglets’ teeth are left unclipped. However, the consequences of either when the piglets are older, when the damage is already done and the task of cutting the teeth so much more diffi-
cult are so considerable that most managers opt for routine teeth clipping. The clippers used should be sharp and the teeth clipped, not crushed, to the level of the gum.

(2) In production systems where tail-biting is a problem, the tail may be removed, again within 2 days of birth. Often the teeth-clippers are used. Perhaps more satisfactory may be the use of a high-temperature blade, such as developed for beak trimming in poultry. The tail may be removed in its entirety, half may be removed or just the last quarter at the tip. The removal of the major part of the tail is on the assumption that aberrant tail-biting behaviour cannot occur if there is no tail. The removal of a smaller part creates a more sensitive tail-tip; thus encouraging bitten pigs to move rapidly away before the damage is done, rather than to remain passive to the attentions of a tail-biting aggressor. The appropriate solution to tail biting is, of course, the removal of its original cause (see above), not the removal of the pig’s tail – either in whole or in part. However, where tail-biting is a real problem on a unit, it is in the best short-term interests of the animals to dock all tails, not to await trauma in the knowledge of its likelihood.

(3) Pig identification through ear-notching is a part of good husbandry. Plastic coloured and numbered identification tags can be inserted into the ear by the creation of a single hole with a sharp instrument in a part of the ear where there is some presence of cartilage but few or no blood vessels. The blood vessel of the ear will if severed bleed copiously, and this is to be avoided. Such ear tags have an adequate record of security, but some will be lost. Many traditional pig identification systems rely on removing notches from the periphery of the ear, and this can be done at the same time as iron is given, the teeth are clipped and the tails are docked. Up to four notches can be accommodated on each ear, allowing ambitious systems of numbering or coding according to week of birth, litter of origin and ultimate destination, or whatever. The system is fail-safe unless the ear becomes further mutilated by the attentions of other pigs, or by being caught and torn. In general, the more comprehensive the numbering system the more mutilated the ear, and the more tattered its appearance. The ear may also be used as the site of a permanent tattoo mark; this may often be of 4 or 5 letters and/or numbers, and requires the use of a punch made up of many needles and blacked with paste. The area of damage is extensive in a small ear but the discomfort appears to be short-lived, and the mutilation is not evident. Tattoos on the inside of the ear cannot, of course, be read from a distance in the same way as a large plastic tag or notched ear.

(4) The removal of the male’s testicles serves a number of purposes:
(a) Those males not considered of good type and fit to sire the next generation are prevented from mating and producing offspring.
(b) Pigs that would otherwise be lean will be more fat.
(c) The flesh of the castrate will not be subject to tainting, as can occur with entire boars as they mature.
These evident benefits, amongst others, have created in some countries a need to castrate male animals if they are to be used for meat.

Castration is best completed before 21 days of age, and preferably before 10 days of age. Castration is achieved by the use of a sharp knife to make two incisions in the scrotum through which the testicles can be drawn and the attaching cords broken or severed. The area should be cleaned with antiseptic before and after treatment. Piglets being castrated complain vociferously, but this is probably due mostly to being held upside down while the operation is carried out. There is clearly discomfort after the event as a result of the breaking of the cord joining the testicles to the body, the general trauma in the scrotal and groin areas, and, of course, the incisions. There should only be slight risk of subsequent infections.

Although a universal practice only a few years ago, many production systems have now dispensed with this mutilation. There are adequate alternative ways of preventing unwanted breeding (for example, separate penning). The higher growth rates, leanness and efficiencies of the entire male over the castrate are of great benefit to the economy of the production system, and provided the entire male is slaughtered at a young age (less than 160 days) the likelihood of taint is low. Besides, tests for tainted meat may now be incorporated into the quality control system on the slaughterhouse line to ensure ‘rogue’ carcasses are identified and withdrawn from use for meat.

**Behavioural response to stress**

The major stressors are disease, injury and subjection to aggression. These may be addressed by an effective health programme, sound housing, good management and avoidance of placement of the pig in situations where it will be subject to aggressive interactions which result in the deprivation of food, water or lying facilities.

Stress may also occur as a result of other, specific environmental problems, for example on moving pigs from place to place, whenever they are goaded, during transportation, under conditions of heat (or cold), in slaughterhouse lairage and at the point of slaughter. Such stress may be manifest as porcine stress syndrome (PSS) and pale, soft, exudative meat. Susceptibility appears to be affected by genetics, since some strains are more prone than others. Some of this effect is due to the occurrence of the halothane gene, since pigs that are halothane-positive (nn) are susceptible to stress and the occurrence of this trait varies between strains (Chapter 2). A level of stress-related sudden death between weaning and final slaughter of around 1% can be expected on production units. At levels of above 2% there should be investigation as to the cause.

In behaviour and welfare terms, stress is often perceived as the consequence of the restraint that occurs in intensive production units. Particular restraints are seen (1) with tethered and stall-housed pregnant sows which cannot turn around, and have limited (less than 1 m) forward and backward movement (Figure 5.10), (2) with
lactating sows similarly restrained in farrowing crates and (3) with common stocking densities among growing pigs (Figure 5.11) where there may be both many pigs in a group (more than 10) and limited space per pig (less than 1 m² per 100 kg of pig). The outward expressions of these stressors may be seen as stereotypic behaviours, extremes of placidity and apathy and aberrant behaviours such as tail-biting. All types of stress, disease and injury represent an inability to cope with the environment, or other pigs, or the frustration of desired behaviours. Stress will bring about a depression of the immune system and an increased likelihood of disease. There will be reduced appetite and growth, and decreased breeding efficiency. The degree of stress required to bring about any given and quantified reduction in performance, however, is complex and not yet clear.

Stereotypic (repetitive) behaviour may typically take the form of one or other, or a combination, of repetitive tongue-sucking, bar-biting (Figure 5.12), bar-sucking,
chain-chewing, head-waving or excessive water-drinking. The presence of stereotypic behaviour has sometimes been suggested to indicate that the pig is coping with the stress, but is now more generally accepted as showing that normal control mechanisms for behaviour have been disrupted, and is usually accepted as indicative of a low level of welfare.

Investigations by Dr Mike Appleby, Dr Alastair Lawrence and colleagues at Edinburgh have challenged the presumption that stereotypic behaviour is a response only, or even mainly, to restraint. It is true that it is seen most commonly in pregnant sows in stalls/tethers on intensive units; but there is a strong relationship between feed level and stereotypic behaviour (Figure 5.13), and this may be found in both restrained and loose-housed sows. At high-level feeding, stereotypic chain-chewing has been found to be virtually absent from sows in tethers and in loose-housing provided with chains for pigs to chew on. In both systems generously
fed sows spent 80% of their time resting. At low-level feeding, however, resting behaviour was reduced to 70% of day-time hours for tethered sows and only 40% for loose-housed sows. The incidence of stereotypic chain-chewing was found to occupy 10–20% of the day-time hours of both tethered and loose-housed sows. It appears here that the frustration resulting in stereotypic behaviours is that of a desire to forage, and to use the manipulative potential of snout and jaws. Also, there may be a frank hunger problem describable not in terms of nutrient shortage but of inadequacy of food bulk.

Care is needed, therefore, in the interpretation of the causes of stereotypic behaviour. It is further the case that increased freedom levels may themselves bring stress, particularly when adult sows are placed into groups which leads to competition for...
food and to the aggression that comes from the establishment and maintenance of the dominance hierarchy. Individual sows in group-housed conditions may become heavily stressed, and this may be ameliorated by separation from the group and individual penning and feeding (which implies an increased degree of restraint).

Outdoor sow-breeding pig-keeping systems are rated highly in terms of reduction of stressors associated with extremes of confinement, but these same systems bring with them different stressors related to group living: variable feed intakes; wetness, coldness and hotness; poor ground conditions; and an increased possibility of inadequate housing. There is reason to accept the view that it was the inadequacies of outdoor and loose-housed systems that encouraged first the introduction of the individual sow feeder, then the indoor farrowing crate, then the sow stall, and finally the various attempts that have been made to provide housing with a fully controlled environment.

There is much present interest in the possibilities for systems of production that increase potential movement and space whilst avoiding some of the new stressors that may be associated with it. Such systems will usually need to include:

- avoidance of injury and disease;
- generous provision of food and water;
- small group size;
- solid flooring for at least a part of the pen;
- use of bedding (for example, straw);
- provision of material for oral manipulation;
- low density stocking;
- provision of ample trough space for growing pigs;
- individual feeding for breeding sows;
- stability of animal groups by obtaining constancy of individuals in the group;
- maintenance of growing pigs in family (litter) groups through to the point of slaughter.

**Transportation**

Animals in transport should probably be rested and watered about every 8 hours. However, unloading itself or even resting in a loaded vehicle can themselves be the cause of distress – especially in warm climates. There may be more logic in setting a maximum transport time for slaughter pigs of 8 hours, and obviating any need to recommend periodic resting. The shorter the transportation time between farm and abattoir the lower the stress and the better will be the ensuing quality of the meat. The average transportation time to slaughter houses in the UK is 3 hours, but even shorter times would give benefit. In many other countries transportation times to the slaughter house can range between a few minutes to many hours. For the transportation of breeding pigs over larger distances, special arrangements are required for feeding and watering in the lorry, and animals should travel at a lower stocking
density and in greater bedded comfort than would be considered appropriate for slaughter pigs.

Space required for the transportation of slaughter pigs is usually between 250 and 300 kg/m² (compared with 100 kg/m² for housed growing pigs), and there are suggestions that the higher levels of stocking are contra-indicated, and stocking density should be reduced below 250 kg/m². Unless special provision is made, such as that for the transportation of breeding pigs over long distances (low stocking density, provision of ample bedding, etc.), then excessively low stocking density may actually increase the discomfort of the ride and thereby increase stress, reduce welfare and prejudice the quality of the end-product meat.

Under all circumstances of animal movement (between pens, to and from lorries and in slaughterhouse lairages and handling pens) and animal transportation, animals should be moved without goading (of any sort), stress or injury.

Welfare

Welfare is best examined from two perspectives. The first is the human perception of pig welfare; the second is the pig’s perception. The first is likely to be variable, shifting as the precepts of society change. It will be geographical in its interpretation, depending upon local custom and culture. It will be motivated through a political will and may be enforced by legislation. The second perspective may accord in some or many respects with the first, but has a different base. The pig’s perception of welfare will tend to relate to its state of health and well-being, freedom from injury, adequacy of supply of food and water, freedom from unacceptable acts of aggression, freedom from stress, and the ability to pursue those behaviours necessary to create an agreeable life within the context of the environment in which the pig finds itself. These elements have been discussed in the preceding sections of this chapter.

Some environments are irredeemably disagreeable and the behaviours performed in them therefore tend toward the aberrant. Early weaning, before 21 days of age, cannot be readily coped with by piglets because of the abnormal and traumatic nature of this situation, and the degree of deprivation caused by it. The negative consequences are legion in terms of production inefficiencies, but also included must be behavioural depression, aberrant fighting, belly-nosing and bullying. Again, it is true that the behavioural needs of a tethered sow are different to those of a free-ranging one, and in the former case many behaviours shown under free-range are not needed. However, if that tethered sow is inadequately fed, on a low grade of flooring and also cold, then there is no behavioural repertoire that could make the position agreeable to her. It is not logical to say that such a sow, having been rendered negatively apathetic to her plight, has no behavioural needs because she has given up trying to show any.

It is perhaps important that scientific investigation should bring together the human and the pig perceptions of welfare, and ensure that legislation or guidance through the former does indeed enable improvement in the latter. It would be mis-
guided to assume that reduced welfare is present when (1) a situation arises that is unacceptable to humankind but not necessarily also to the pig, or (2) there is absence from one environment of the behaviour seen in another, which latter environment is perceived by the human to be ‘better’. Thus pig welfare in some conditions of restraint may be improved on that in some conditions of freedom; for example, when the former allows adequate provision of food but the latter allows only competition and aggression. In outdoor and feral conditions, pigs spend much time in rooting activities, but this is not the case when there is adequate food supply and straw in a more protected environment. This was noticed when pigs maintained in the high welfare and spacious Edinburgh Family Pen system of pig production failed to use the area provided for rooting in peat and soil, but rather abused it as a place for defaecation and urination.

Insofar as welfare reflects the human idea of optimum animal care, generalisations about the circumstances that should prevail on pig units are impossible. Legislative guidance may be given in terms of:

1. Codes of conduct describing housing systems, environmental control, feeding, management, health and disease control.
2. Approval of particular pieces of equipment, pen and house construction.
3. Approval of premises for holding pigs and of persons to keep pigs.
4. Prescription of breed type and genetic selection policies.

All would require an Inspectorate (who may or may not have powers in law), while the last implies also education and demonstration of a given level of knowledge and competence. Licensing may override the need for welfare codes and for approvals of equipment if it is considered that the degree of satisfaction of the welfare needs of the animal may best be judged by a trained inspector. The ability of the pig-keeper to maintain a high level of welfare on a pig unit is probably more dependent upon his or her own knowledge, skill and degree of caring than upon a strict interpretation of codes, or the use of (or avoidance of the use of) particular approved systems or pieces of equipment. There is the added dimension that the desire to legislate against given equipment and systems of production may exceed the strength of the information that the enactment of the law would require. In the wish to remove the use of one piece of equipment, inadequate consideration may have been given to the welfare implications of the (often relatively untried) alternatives.

Overriding in the interests of pig welfare is the quality of stockmanship – the knowledge, ability and willingness of the person in charge of the stock to care fully for their needs. From the point of view of the pig, the quality of the person looking after it must take first priority over and above the quality of production systems, housing and equipment.

Some authorities would wish to base their requirements for adequate welfare on the extent to which the pig can express basic rights. These include:

- the provision of water, adequate amounts of food and food of proper nutrient content;
- freedom from disease and injury;
• a comfortable environment;
• freedom from aggression and fear;
• ability to express normal behaviours and satisfy normal behavioural needs.

Such a list is laudable, but its enactment in laws or guidelines for practical pig production is fraught with difficulty. Nutrient supply for what purpose? What if a pig desires to be grossly fat? How free from disease? Health itself requires a degree of subjection to organisms causing disease, and therefore contains the possibility of disease. Sometimes one freedom denies another: freedom to express the normal behaviour of the creation of a dominance order requires a degree of aggression and fear. The definition of a normal behavioural need is greatly dependent upon circumstances; a normal behaviour on free-range may not be required in a protected environment.

In many countries three levels of formal activity relating to welfare can pertain: first, laws relating to the prosecution of persons who cruelly ill-treat or abuse animals; second, laws relating to the banning of certain production systems that are considered inappropriate on grounds of the distress caused being excessive in terms of both human and animal perceptions (such as, perhaps, stalls and tethers for pregnant sows, and very early weaning of piglets at less than 3 weeks of age); third, guides or codes that are not themselves law but failure to observe that may be used as evidence to support convictions under the first two activities. A fourth possibility, the licensing of stock premises and stock-keepers for pig production enterprises, has not yet been invoked. In the UK there are Codes of Recommendations for the Welfare of Livestock: Pigs, published by the Ministry of Agriculture, Fisheries and Food (now DEFRA). The 1988 edition includes the following in its preface:

‘The basic requirements for the welfare of livestock are a husbandry system appropriate to the health and, so far as practicable, the behavioural needs of the animals and a high standard of stockmanship.

Stockmanship is a key factor because, no matter how otherwise acceptable a system may be in principle, without competent, diligent stockmanship, the welfare of the animals cannot be adequately catered for. The recommendations which follow are designed to help stockmen, particularly those who are young or inexperienced, to attain the required standards. The part that training has to play in the development of the stockman’s awareness of welfare requirements cannot be overstressed. Detailed advice on the application of the Code in individual circumstances is readily available through the official advisory services and in advisory publications of which a selection is listed at the end of the Code.

Nearly all livestock husbandry systems impose restrictions on the stock and some of these can cause an unacceptable degree of discomfort or distress by preventing the animals from fulfilling their basic needs. Provisions meeting these needs, and others which must be considered, include:

• comfort and shelter;
• readily accessible fresh water and a diet to maintain the animals in full health and vigour;
freedom of movement;
the company of other animals, particularly of like kind;
the opportunity to exercise most normal patterns of behaviour;
light during the hours of daylight, and lighting readily available to enable the animals to be inspected at any time;
flooring which neither harms the animals, nor causes undue strain;
the prevention, or rapid diagnosis and treatment, of vice, injury, parasitic infestation and disease;
the avoidance of unnecessary mutilation; and
emergency arrangements to cover outbreaks of fire, the breakdown of essential mechanical services and the disruption of supplies.

Pig husbandry systems in current use do not equally meet the physiological and behavioural needs of the animals. Nevertheless, within the framework of the statutory powers under which the Code has been prepared, an attempt has been made, on the basis of the latest scientific knowledge and the soundest current practices, to identify those features where the pig’s welfare could be at risk unless precautions are taken. The Code sets out what these precautions should be, bearing in mind the importance to the pigs of their total environment and the fact that there is often more than one way in which their welfare can be safeguarded.’

The Codes of Recommendations themselves then spell out, in 56 paragraphs, particular aspects of housing, equipment, feeding and management; including different provisions for indoor and outdoor pigs. The Recommendations aim to enhance welfare by guiding toward, amongst others:

(1) provision of proper housing and effective equipment;
(2) avoidance of injurious structures and surfaces;
(3) provision of a clean, dry bed and provision of bedding materials and proper flooring;
(4) protection against fire and power failures;
(5) proper environmental temperature, humidity, air movements and lighting for all classes of pigs;
(6) adequate provision of water and food at proper levels and of proper nutrient composition, and proper feeding arrangements whereby competition amongst pigs for food and aggression during eating can be avoided;
(7) a high level of animal care and individual attention, especially at critical times, and including frequent animal inspection;
(8) avoidance of the creation of unstable pig groups;
(9) proper conduct of mutilations, such as ear-marking (where necessary), castration (to be avoided where possible), tail-docking (to be avoided where possible) and tooth-clipping (to be avoided where possible);
(10) the protection of newly born piglets from crushing by the sow and the special provision required for the comfort and cleanliness of farrowing sows;
(11) the age of weaning (not less than 3 weeks in normal circumstances);
(12) proper allowances for floor space and the provision of feeding, sleeping, exercise and dunging areas;

(13) prevention of aggression amongst pigs, especially sows in groups, and adequate provision of individual sow feeding facilities;

(14) avoidance of stalls and tethers for pregnant sows, but the use rather of open-pen yard systems with straw which allow a greater degree of exercise and expression of behavioural needs;

(15) proper boar accommodation and mating areas, together with needs for bedding and dry and suitable floor surfaces.

These Codes are helpful in that responsible persons could not find them in any way negative to pig welfare, but strict adherence to the Codes does not itself ensure welfare. There remain vexed questions: for example, that of the relative extent of welfare of sows in or out of sow stalls, which depends much on the circumstances prevailing for the sow kept in an alternative. Nevertheless few would suggest that current systems for keeping pigs, either intensively, semi-intensively or outdoors, are in any way ideal. Any steps toward the improvement of pig welfare should be welcomed, not only by the pig but also by the pig manager, who will be aware that a high welfare system is likely to be efficient and productive and also creates a more pleasant environment in which people may work rewardingly with pigs.

**Improvement of welfare**

Prior to the publication in 1964 of *Animal Machines* by Ruth Harrison, animal welfare was entrusted to pig producers. Good husbandry was considered to be synonymous with animal care and also with profitability. *Animal Machines* implanted the notion that a cheap food policy and a drive to increase output created an intensive farming system for pigs contrary to the interests of the animals. Nevertheless, the intensification and close confinement of pigs led to a most welcome increase in the availability of low-priced pork products. It was the Brambell Report, published in 1965, that paved the way for the formation in the UK of the Farm Animal Welfare Council, and the publication of Welfare Codes of Practice. The positive position for pig welfare which now exists in many countries seems due mostly to three factors:

(1) concern that total sales of pig products may fall if the buying public becomes unhappy with the way in which the animals are cared for on the farms;

(2) the possibility that pig products identified as having come from livestock farms with especially high welfare attributes (outdoor production, straw-based systems, loose housing, low density stocking etc.) may command higher prices;

(3) legislation.

Enhancement of the image of livestock production methods towards a greater degree of greenness has often taken the form of de-intensification of modern close confinement pig-keeping systems. In this case conflict can develop as de-intensified systems may well be of lower welfare than high quality ‘intensive systems’; there
should be no illusion that outdoor systems for keeping pigs are necessarily always in the animals’ best welfare interests as it predisposes them to aggression, variable feed supply, lack of environmental control, exposure to harsh weather conditions and difficulties in the administration of health care. Even the perceived wisdom that it is restraint that causes pregnant sows in tethers and in stalls to show stereotypic bar-biting and chain-chewing behaviour has been challenged, with the amount of feed supplied being as important a factor in stereotypic behaviour as the extent of confinement. Notwithstanding, it would seem proper to identify some middle-ground between unacceptable restraint on the one hand and inappropriate extension on the other. It may be the case that semi-intensive loose-housing systems fulfil this role, although it remains difficult to see how the farrowing crate can be readily replaced for periparturient sow restraint.

Recent interest has increased in meat from farms that assure that they fulfil the highest welfare standards, including low density stocking, ample use of straw bedding, extensive production systems, freedom from the use of feed additives and so on. Assurance schemes of this nature, together with the appropriate mark, may be associated with particular brands, supermarket chains and pricing policies. A substantial proportion of the pig meat market is now moving in this direction and the most effective safeguard for animal welfare is now coming to be not legislation, but the customer base. Supermarket buyers lay down codes of welfare conduct covering aspects of housing, management and transportation, as well as breeding and feeding, upon which purchase of the pigs is predicated. Public requirement for reassurance regarding the welfare of pigs on farms is thus taken care of by those who supply them, and who in turn demand from pig producers adherence to strict conditions of production if their pigs are to be purchased.
Chapter 6
Development and Improvement of Pigs by Genetic Selection

The early years

Where the Englishman Robert Bakewell of Dishley Grange succeeded in the creation of the improved Leicester sheep, he failed with pigs. However, the principles applied by Bakewell are germane to all the farm animals, including pigs, and he was conspicuous in having made farm animal breeding commercially successful through the sale of the stock he improved.

Bakewell farmed in the latter half of the eighteenth century, during which time the number of people in the British Isles doubled, to about 10 million by around 1800. The Industrial Revolution created a population of town-dwellers and factory workers separated from their agricultural origins, and requiring to be provisioned from an agricultural industry that was itself being revolutionised to cope with the new social environment. Slaughtered pigs were able to provide lard, meat, leather and bristle. Some 200 years on, it appears that both the Industrial and Agricultural revolutions have run their course. Having created for the industrial nations a society where much of the physical toil has been taken out of factory work, the plentiful nature of food has become an embarrassment and not a comfort; rather than simply assuaging the hunger of the people, agriculture in northern Europe and the USA must now satisfy strident demands for quality in food, and also accommodate such additional diverse sociological aspirations as animal rights and environmental care.

At the start of the eighteenth century, Townsend’s and Tull’s development of root, brassica and potato crops for winter keep, together with the more plentiful availability of dairy by-products, millers’ offals and waste from butter, cheese, bread and beer manufacture, had allowed a higher proportion of stock to be over-wintered rather than slaughtered in the late autumn. Prior to the 1700s most meat was either from castrated males surplus to breeding herd needs, from pigs slaughtered and salted down at the year’s end because of lack of winter keep, or from sows that had served their time breeding. Year on year continuity greatly increased the potential size of breeding herds and encouraged the development of breeds of livestock with the sole purpose of providing meat. Successive years of breeding life enabled individual dams and sires to be maintained long enough for their offspring to be assessed, and a breeding value for the parents to be quantified. Selection of parents shown to have produced offspring with beneficial characteristics (or traits) enabled the pursuit of positive and directional selection, through the use of proven parents
in the breeding herd nucleus over subsequent years. The nineteenth century saw the setting up of Agricultural Societies (the Highland in 1822 and the Royal Agricultural Society of England in 1838), and the opening of pedigree stud books. Such activities helped the planned promulgation of proven sires. It was also at around this time that agriculture was forwarded as a worthy topic for research and academic study, Edinburgh being the first university to appoint a Professor of Agriculture (Andrew Coventry) in 1790.

David Low, FRSE, second professor of Agriculture in the University of Edinburgh, contributed substantially to the science of pig breeding by preparing for publication by Longman, London, in 1842 *The Breeds of the Domestic Animals of the British Islands*. Low points to the many and varied genera of hog, all ‘feeding on plants, but especially on roots, which their strong and flexible trunk enables them to grub up from the earth. They devour animal substances, but they do not seek to capture other animals by pursuit . . . they delight in humid and shadowy places’. Low describes three genera of the species *Sus*: hogs, wart-hogs and peccaries. The hogs include (1) the wild boar of Europe – considered to be the progenitor of the domesticated pig, (2) the Babirousa pig of the East Indies and (3) the smaller Asian or Siamese Pig. The admixture of the Chinese pig, assumed to be derived from the Asian and Siamese roots, with the European domestic breeds throughout the nineteenth century has been identified as the primary means by which the indigenous European breeds received the perceived benefits of reduced age and size at maturity, and increased fatness. Indigenous breeds (such as the Old English) throughout much of northern Europe were considered as being too large and too lean. Only a few of the European domestic breeds present at that time escaped importation of Chinese genes. When David Low wrote, it was clear that Europe contained many domesticated breeds of various sizes, colours, shapes, ear position and degrees of prolificacy and fatness. Low’s illustrator depicts two, the Neapolitan and the Berkshire. Although both of these are coloured, it is evident that saddleback and wholly white breeds were also common-place, especially the Yorkshire (to be subsequently called the Large White), the Lincolnshire, the Norfolk and the Suffolk. These same counties still espouse by far the greater part of British pig production. White pigs with lop ears (Landraces) were also evident at that time in France, the Netherlands, Belgium and Germany, while in the former USSR it is asserted that pigs were wilder and more akin to the wild boar type than to the European domestic types. The American breeds are supposed to be derived from mixtures of all types, that continent being subject to immigrants (and their livestock) from most other continents of the world, including Africa, Asia and Europe.

Despite the fatness of the wild boar, and its influence at that time on some of the European breeds – especially those in the East – the European indigenous breeds tended on the whole to be large, late maturing and rangy. Those breeds receiving substantial quantities of genes from pigs of Asian origin became, by contrast, small, fatty and early maturing. Intermediate types were evident, depending upon the extent of influence of the Chinese pig. However, apparently unique amongst the farmed pigs of the nineteenth century appears to have been those of the Duchy of...
Parma in Italy, which combined characters otherwise seen as incompatible – large size together with an aptitude to fatten. These characteristics still remain the essential prime requirement for the creation of top quality Parma ham.

Robert Bakewell’s idea that animal could be bred especially for the improved production of meat followed from the acceptance that a given animal genotype was not, as had been previously assumed, fixed, but could be changed by the imposition of a selection programme through the hand of the animal breeder. Characters such as size, fatness, rate of growth, prolificacy and efficiency could be assessed and progressively improved generation by generation, to create a new type of farm animal, one whose specific and primary purpose was the production of meat. The notion of artificial selection in farm animals predated that of natural selection forwarded by Darwin (*The Origin of Species* was published by John Murray, London, in 1858), who learned much from the agricultural practices of the times. The ‘wrong’ assumption of a static animal type has the corollary that individual animal size, fatness and rate of growth are only affected by health, nutrition and the environment, and that the choice of breeding sire and dam does not imply the possibility of progressive changes in the characteristics of the next generation. The basic ‘correct’ principles of selection for improvement of type, as perceived and practised by Bakewell, were, in contrast as follows:

- Breed type can be improved by the progressive selection and fixing of characters.
- Animal populations show variation in their characteristics, and this phenotypic variation can be observed and quantified. The phenotype is what is observable and measurable, and is a consequence of both the genetic make-up of the animal and the influence of the environment upon the animal.
- Although much of the variation will be due to health and nutrition (environment), some will be passed on to (inherited by) the next generation (genotype). The genetic quality of the parent can thus be judged by assessment of the progeny, and potential sires can be ranked on the performance of their offspring.
- If selection for improved characters is made in a single place under a single set of conditions, then the chance of the improvement appearing in the offspring is higher. This is because what can be seen and measured (the phenotype) is the sum of genotype and the environmental variations, and wherever the environmental variation can be reduced, then the relationship between the phenotype and the genotype strengthens.
- Beneficial characters can be fixed into a line of animals if particular individual (or families of individuals) are used frequently within the development of that line (line breeding). Especially, an individual parent of high quality was frequently used in the 1800s in both the maternal and paternal side of the family in order to fix some special quality into subsequent generations. In the classic case of the famous Shorthorn bull, Comet, his sire, Favourite, was mated to his own (Favourite’s) mother, to sire Comet’s dam. These principles of in-breeding had been learned from thoroughbred racehorse studs after the introduction of
Arab blood primarily from only three sires. It was also noted, however, that inbreeding could lead to a lessening of reproductive ability.

• The choosing from the population of few male animals of extreme beneficial type, that is to say a high intensity of selection, followed by their concentrated use as sires in a nucleus breeding herd, will bring about the most rapid rate of change. For females, such a high intensity of selection is not possible due both to a breeding herd needing many more females than males, and to the large percentage of females required for retention in the herd as replacements. Because of imposed selection of less desirable types on the female side, progress is unavoidably slower than in the male, where only the best types can be selected. There is, however, benefit from at least minimal selection amongst the females so that all animals showing adverse characteristics contrary to the direction of selection can be removed: in effect, the rejection of females not true to type.

• Having created an improved animal type in the breeding herd, and fixed that type so that it breeds true generation upon generation, the male offspring from the herd can be considered as appropriate for sale as top-crossing sires to commercial meat producers for use on their female stocks. In this way the improved character (or characters) now secured in the nucleus may be spread through the rest of the population by the sale of males. Bakewell demonstrated particular entrepreneurial skills in this direction. To facilitate the marketing exercise the new improved type requires to be named, and to be readily identified both by eye and by subsequent performance. The potential purchaser must be able to see that he or she is buying the new improved product and, having bought it, the improvement must be demonstrable in added value terms which, at the time of Bakewell, was seen as reaching market at a younger age and a higher degree of fat cover.

The term ‘improvement’ from 1750 through to 1900 was associated with the creation of special breeds of pig with an increased penchant for fatness. In pigs, fat was seen as a beneficial character. Fat was a healthy provider of energy to a population of manual workers, and also provided an effective cooking lard for both meat itself and other foods in the absence of readily available vegetable oils. If there was a tradition of British livestock breeding to increase fatness, then this was less the case for Continental breeds, where lean meat remained a primary interest of the consumer and where vegetable oils were more readily available for cooking. In general, while Continental breeds of meat-producing animals remained relatively lean and of large size, many British breeds became smaller and fatter.

Prior to the creation of the new ‘improved’ breeds, the incorporation of fat into meat had been achieved by the fattening of animals that had reached their mature size, and were ready to partition nutrients away from lean growth and toward storage fat. It is evident from records relating to the unimproved breeds that adult size was considerably greater than that of the subsequently ‘improved’ types which superseded them. The original Yorkshire breed of pig was so large that some could reach the height of a pony and half a ton in weight (at least double the size and
weight of the improved Large White). The most notable character common to all ‘improved’ meat-producing livestock was that of earlier maturity, which was defined as adequate fatness and finish at a younger age and lighter weight. This was achieved by selection of types that incorporated high levels of fat into the body tissues during growth and reached lean mass maturity at a smaller size – both relatively highly inherited characters. In the pig population, selection for early maturity and fatness was certainly closely associated with reduced final size. It appears that these ‘improvements’ were also negatively correlated with reproductive characteristics. The reproductive problems were likely to have been caused by the incorporation of new genes from Asian pigs. These pigs (including some Chinese types) were small, chunky and often coloured. They were chosen to cross with the indigenous European breeds because of their propensity to reach both sexual and size maturity at a younger age, and to be fat. [It is well to remember that in the nineteenth century (as now) there were very many breeds and types of Chinese pig, and it may not be presumed that they were the same ‘Chinese pigs’ that are presently of interest for their possession of genes for especially high prolificacy.] The problem of the creation of a sire with excellent characteristics and meat, but with less excellent characteristics for reproduction, is readily solved by a crossing programme following the differentiation of sire and dam lines. This simple expedient appears to have been rejected through the nineteenth and early twentieth century for the pig breeds. During this time there was much pressure to create pedigree breeds that were complete in themselves, the male and the female lines being of the same type and breeding true.

The creation of particular pedigree breeds, and the hope that they would excel both in meat and reproduction characteristics, was a common attribute (failing) of pig farming practice through the nineteenth and twentieth centuries, but it was not any part of Robert Bakewell’s breeding plans. Bakewell was quick to exploit the separate development of sire lines with specially excellent carcass and growth characters, and of dam lines with specially excellent reproductive characters. Most rapid genetic progress was made overall when these different sorts of qualities were single-mindedly pursued in quite separate populations which were only brought together at the point of creation of the slaughter generation.

Robert Bakewell counteracted reproductive shortcomings in his improved meat line of Leicester sheep by the use of the improved breed only as a top-crossing sire upon highly prolific dams of a different breed (or cross-bred) for the production of the slaughter generation. The sheep industry of England utilised, two centuries ago, commercial cross-bred breeding flocks showing the added benefits of hybrid vigour in the reproductive traits. Thus, while the sire line was formed through the use of in-breeding and type-fixing techniques, the dam line was formed by a two-step programme: pedigree selection in the nucleus, followed by a stratification programme involving out-crossing of prolific breeds. This lesson was to be well learned – or rather re-learned – by the modern pig breeding companies only relatively recently. In the early years, no such sire-line or cross-bred dam line breeding schemes had appeared to the pundits of the day to be necessary for the pig, breeds being devel-
oped from the same root for both meat and reproductive efficiency. Thus the same pedigree breed was assumed to be proper to provide sire, dam and slaughter generation. This assumption was, of course, unhelpful.

The desire to make ‘coarse’ indigenous pigs more obese seems to have run amok in the late nineteenth century with show-ring exhibitors priding themselves on grossly over-fat breed types. These, it appears, were simultaneously being rejected by the purchasing populace who looked for their pork and bacon from unimproved breed types such as the Yorkshire (Large White) and the Tamworth, these latter having apparently escaped the more serious of the ravages of the ‘improvers’. The Tamworth had previously been expressly criticised for its over-leanness! In the event, the market for pork and bacon products exceeded the remaining availability of reasonably lean pig types to provide for it. The fancy breeders had failed to listen to the messages from the market-place. There arose, in consequence, a market for leaner bacon and ham imported into Britain from the Continent. Importations of pig meat to Britain rose from 300 to 300 000 tons in the latter part of the nineteenth century. Continental pigs, however, were not only of leaner genotype; it is likely that they were also grown with superior production skills.

The breeds that majored in the early twentieth century in Britain were the Large White, the Tamworth and the Saddleback. The Danish pig industry developed at the same time a base population from European Large White and local Danish Landrace pigs. The Danes created a white breed, the Danish Landrace, with lop ears (as opposed to the prick ears of the Large White) whose success was resultant not from the genetic base itself so much as from the logical improvement of that base in the direction of customer requirements for lean bacon. The improvement programme for the Danish pig was driven through the medium of the central progeny test – classical Robert Bakewell breeding theory and entrepreneurship! By the 1920s half the pig meat consumed in Britain (the presumed cradle of the science of livestock improvement) was imported, mostly from Denmark.

Thus the great opportunity afforded to the British to apply the teachings of Bakewell was, for the pig, largely missed in this country. It was, however, relentlessly pursued on the Continent with beneficial consequences especially for the Danish, German and Dutch pig industries.

The creation an improvement of the twentieth century breed types

The century through to 1950 saw the consolidation of the breed types that had been originated in the 1800s. The agricultural industry producing meat from beef and lamb developed stratification schemes, with the use of specialist meaty sire lines on cross-bred dam lines strong in reproductive traits. Meanwhile, in stark contrast, the production of milk from dairy cows and pork from pigs pursued the use of the same breeds for both parents of commercial stock. During the latter half of this period the extreme Middle White type of pig, which produced a small fatty carcass seen as
ideal for the pork trade of the nineteenth century, was supplanted by the Large White and the Scandinavian Landrace types, more suited to cured bacon production. By the middle of the twentieth century production efficiency required faster growth rates, while consumer preference demanded not just less fat, but almost its absence.

Perhaps because there was evidently so much to be done in the case of the fatty pig, it is the pig industry that has championed the breeding of contemporary lean meat strains of farm livestock. Two hundred years on, the pig industry leads in the application of the science of genetics to the production of the commodity demanded by the market, and it is the sheep industry (the pioneer of two centuries ago) that has this time been tardy to understand either the elements of the application of genetics or the basic rules of market demand and customer satisfaction.

In the creation of lean growth and the avoidance of fat, the propensity to fatten at a lighter weight and a younger age becomes a negative and defunct character. Selection for lean growth brings with it an increase in final adult lean body mass and final body size dimensions, such as used to be shown by some of the unimproved pig types, and indeed as preserved in some of the Continental breeds of cattle.

Although selection for growth, meat and reproductive characteristics created improved breed types also in the former USSR and Asia, little if any progress that may have been made early in the twentieth century now remains, perhaps with the singular exception of the Chinese Meishan pig type. This is small, slow growing and extremely fat, like other Asian types; sexual maturity is early and litter size is up to 25% greater than for the European white breeds.

Presently, the world pig population is of two distinct kinds. First, there remain indigenous Asian types in village communities and on traditional farms throughout China, South-East Asia and parts of Africa. However, for commercial pig meat production as a business-based farm enterprise, the pigs of Europe and North America predominate. Pig breeding companies based in the European Community and the USA are presently exporting genes to every part of the world where pig meat is eaten – to the exclusion of the indigenous types.

The genetic base for the contemporary pig breeding businesses around the world has been derived from relatively few breeds. Most of these have emerged in Europe and North America as populations breeding reasonably true to type in the early 1900s. The pig populations of Australia, New Zealand, South America, South East Asia and Japan have developed significantly toward the European and North American patterns over the last two decades. These countries have been able to accept the advantage of the developed European pig base of the 1960s and 1970s, and with it have recently achieved some remarkable rates of further genetic improvement.

The **Large White** or **Yorkshire** breed (Figure 6.1) is, world-wide, the most widespread of modern pigs. Easily recognised as wholly white and with prick ears, the breed is renowned for being superior to all other types in its growth rate, and beaten only by the Meishan for its litter size. Modern strains are of large size, the females maturing above 300kg live weight. Growth rate may readily exceed 750g daily from birth to 100kg, producing a carcass with 55–60% lean meat. Puberty is at around
180 days, and litter size will be around 11–13 piglets with an average birth weight of about 1.25 kg. Now accepted as a lean and meaty pig, it was at one time rather fatter. The Large White has, however, been subjected to intensive selection against fat over the last 30 years, and is now one of the leanest of all pig types. The breed is seminal to the foundation of most white pig stocks, and as a pure-bred line is fundamental to most crossing programmes involved in the production of the present-day hybrid female. In many countries of the world, including northern Europe, it is also widely used as a top-crossing sire.

The **Landrace** is a general description of a white lop-eared type, in effect ‘the race found most abundant nationally’. It is helpful if this large and variable group of pigs is considered as falling broadly into two quite different varieties. The original Scandinavian Landrace types (Figure 6.2) are long, quite lean, and acceptably prolific, but not especially muscular. Selected for bacon production and farmed as a single pure breed for many years in Denmark, the Danish Landrace is perhaps the most famous of all breeds as an exemplar of the success of progeny testing and selective breeding. Now, however, its main use world-wide is in crossing with the Large White. Nevertheless, given its dominance of the quality pig meat market for more than half of the twentieth century, it is not surprising that the Danish industry showed some reluctance in accepting that the pure breed could indeed be improved upon. Such acceptance has, however, now resulted in the Danes since the 1990s pursuing cross-breeding and top-crossing programmes with characteristic
vigour. In addition to Denmark, this Landrace type is found in, and holds the name of, Norway, Sweden, France and many other nations. The size and performance of the Scandinavian Landrace approaches that of the Large White, some strains bettering the latter.

The other Landrace variety is typified by the Belgian (Figure 6.3), Dutch and German Landrace breeds. Also white and lop-eared, these are, however, slightly less prolific, but are specially noted for being muscular. The depth of muscle in ham and loin, the lightness of bone, the high percentage of lean carcass meat and the full and rounded shape of the hams and eye muscles characterise these breeds as popular for use as a top-crossing sire, and indeed they are used widely as such throughout Europe. The meat is, however, relatively more prone to PSE. They are also sometimes used as commercial females in their native countries, producing in the progeny an extremely muscular carcass, but a slaughter generation that tends to be stress susceptible, to grow rather slowly and to have arisen from a modestly sized litter. In some European pig keeping systems the Scandinavian Landrace type is used in the female line, whilst the blockier Belgian, Dutch or German Landrace type is used as the top-crossing sire.

The Duroc pig (Figure 6.4) is coloured, ranging from gold through red to dark brown, and probably stems from the Berkshire. A white strain has now been bred by capitalising on the dominance of the white gene in coat colour, and the presence of a DNA test to distinguish between the heterozygote and homozygote white types.
Fig. 6.3 Improved pig of the Belgian Landrace breed type. Contemporary (courtesy: Pig Improvement Company).

Fig. 6.4 Improved pig of the Duroc breed type. Contemporary (courtesy: Cotswold Pig Development Company).
This robust and heavy-boned breed is as numerous in the USA as the Large White or Yorkshire. Whilst neither especially prolific nor lean, it is deeper-muscled (but fatter) and faster growing than the Scandinavian Landrace. Its popularity in the USA is said to stem from its ability to thrive in a simple farming system. It is germane that the European white hybrid females found it difficult at first to make their mark in conventional North American farming systems until they were crossed with a Duroc. The use of the Duroc has increased in Europe over recent years. It has found favour as a top-crossing sire in Denmark (amongst other countries), being said to impart improved meat quality to the Danish Landrace (by having 4% rather than 2% intramuscular fat in the eye muscle and having a deeper red colour to the meat). Intramuscular fat is considered positive for eating quality in fresh pork joints, although negative for processing. The Duroc, of course, unless of the newly developed all-white strain, has strongly coloured skin and hair, both of which are disliked by processors. Used in the female line the Duroc is purported to offer robustness to the hybrid mother, particularly in the context of outdoor and extensive pig keeping systems. These last qualities may be important in the light of welfare agendas, but Duroc genes may also impart slower growth, greater fatness and smaller litter size. On balance there may be benefit in using Duroc blood to strengthen female breeding lines by infiltrating Duroc genes at low level into the female line.

**Hampshire** pigs are black with a white belt. Commonplace in the USA, Hampshires were derived originally from the Essex and Wessex saddlebacks of England. Now with a reputation for meatiness rather than reproductive performance, the Hampshire has been used in the creation of some hybrid sire-lines. The **British Saddleback**, of the same root as the Hampshire, is perceived to have rather different qualities: good mothering ability and adaptability to outdoor and extensive pig keeping systems. The progeny tend, however, to be rather fatter and slower growers than white pigs. It remains to be seen whether the Duroc cross will ultimately oust the Saddleback cross as the main source of females for outdoor pig keeping systems.

**Pietrain** pigs from Belgium are piebald (white and black spotted), rather small and stocky, and of extreme blocky shape with large hams, large loin muscles, a high percentage of lean meat in the carcass, light bones and high carcass yield. Nervous in disposition, they are readily stressed and prone to sudden death (PSS), and their meat has a high tendency to PSE. Their reproductive efficiency is low. In comparison with the Large White, the Pietrain produces two fewer piglets per litter, but can have 10 cm$^2$ greater eye muscle area (54 versus 44 cm$^2$) at 100 kg live weight. Whilst relatively few in numbers of pure-breeding herds, these pigs have had a dramatic effect on the muscling qualities of many European pigs, and their genes have been used to improve the shape of many of the leaner white types, especially the Landraces. Pietrain blood is considered by many to be highly useful in top-crossing sires, but it is counter-productive in the female lines.

The European and North American axis to modern pig breeding initiatives has created a narrow breeding base which emphasises growth rate, efficiency and lean-ness, while maintaining prolificacy, often by the expedient of hybrid vigour rather
than by positive selection. There are many and various Chinese breed types, commonly characterised by small mature size, precocious sexual maturity, black coloration and fatness. The **Meishan** (Figure 6.5) may offer increased litter size, but has the severe shortcomings of extreme fatness and slowness of growth. A Meishan pig has an adult weight of no more than 150 kg, and grows at a rate of 400 g daily to produce a carcass with only 45% lean meat, but it also reaches puberty at less than 100 days of age, has 16 nipples and an average litter size of around 14 piglets with a birth weight of about 800 g. The ‘extra’ 3–4 piglets born are a result of both a greater ovulation rate (20, versus 17 for the Large White), and better embryo survival (70, versus 65 for the Large White). Use of the Meishan to produce cross-bred breeding females (12.5 or 25% Meishan) has attracted much attention, but has been less notable in its success. The animals have turned out to be rather difficult to manage, and the slaughter generation is not particularly appropriate for European and North American requirements, the one-eighth Meishan having smaller muscle size, more fat, lower killing out percentage and a tendency to androstenone/skatole taints. Also important is the genetic diversity to be found in the many other varieties of Chinese and Asian pigs which comprise the indigenous populations of many countries, and still provide a significant part of the world’s pig meat supply. Such genes might not be useful now, but may well have unforeseen qualities that could be needed in the future, particularly where advances in genetic engineering allow the extraction of beneficial genes while avoiding transfer of negative traits.

Many old European and North American breed types have fallen by the wayside along the road of the creation of the modern pig. These may, with care, be preserved
as rare breeds. While many of the British breeds – too numerous to catalogue – are already extinct, others survive as small breeding groups, including the Berkshire, Lop, Gloucester Old Spot, Large Black, Middle White and Tamworth. American breeds being left aside of today’s mainstream breeding programmes include the Poland China and Spotted, the Lacombe and the Chester White, although each of these may yet be found in substantial numbers. The classic nineteenth century European breed types of France, Italy and Iberia are now, sadly, largely lost.

A substantial proportion of the world’s pigs now come from breeding companies. Breeding companies’ breeding programmes have rendered the concept of breed somewhat redundant. Thus, female breeding lines, pure-breeding in nucleus pedigree herds, may have arisen from mixtures of Large White, Landrace, Duroc, or whatever. These lines are just as legitimate ‘breeds’ as the more conventional expectation of the words used above. Equally, the male breeding lines, pure-breeding in nucleus pedigree herds, may possibly have arisen from mixtures of Large White, Pietrain, Belgian Landrace, or whatever. Nucleus breeding company stock can really only be identified by the names given them by the breeding company itself, although it is always going to be helpful to learn of the origins of the breeds.

Introduction to pig improvement strategies

The three ways of altering the genetic make-up of pigs, and thereby affecting their improvement in a given direction, are well known and simple:

1. the use of hybrid vigour;
2. the incorporation or introgression of new genes from pigs of different breeds;
3. positive selection for a given character (or character) within a breeding population.

While the strategies themselves may be well accepted, the methodologies employed to pursue them are many and various, and the subject of differences in both scientific and practical opinion.

Animals in a given population vary in the degree to which any particular character is expressed. Usually the variation is normally distributed so that most animals appear to be about average, but a few are really exceptional (Figure 6.6). Conventional breed improvement relies upon the notion that use of exceptional individuals as parents of the next generation will bring about a positive change in the population mean (Fig. 6.7).

A pig’s phenotype (P) is the combination of its genetic make-up (G) and the environment (E):

\[ P = G + E \]  

(6.1)

The variance seen amongst individuals in a population \( \sigma_P^2 \) is caused through variance in genetic make-up \( \sigma_G^2 \), variance in the environment \( \sigma_E^2 \) and \( \sigma_{GE}^2 \), the interaction between genotype and environment:
The degree to which $\sigma^2_P$ (what is seen and measurable) is influenced by $\sigma^2_G$ (that part of $\sigma^2_P$ which is genetic in origin) will be increased if $\sigma^2_E$ (the influence of the environment) is minimised.

The genotype (G) is the combination of additive genes (A). Dominance (D) and interaction effects (I):

$$G = A + D + I$$  \hspace{1cm} (6.3)

The genetic variance ($\sigma^2_G$) is the sum of the additive ($\sigma^2_A$) and non-additive gene action [dominance and interaction ($\sigma^2_D, \sigma^2_I$)]:

$$\sigma^2_G = \sigma^2_A + \sigma^2_D + \sigma^2_I$$  \hspace{1cm} (6.4)

The proportion of $\sigma^2_P$ represented by $\sigma^2_A$ (that part of total variance which is due to the additive genetic variance) is the heritability ($h^2$). Heritability ($\sigma^2_A/\sigma^2_P$) values range between 0 and 1. The additive genetic make-up expresses the breeding value (BV) of a parent, and is passed on to the offspring in a simple and additive way. An individual’s breeding value can be expressed as deviation of that individual’s performance from the mean of the population:

$$BV = h^2(C - \bar{C})$$  \hspace{1cm} (6.5)
where \( C \) is the performance of the individual and \( \bar{C} \) the population mean. The accuracy of predicting breeding value is tied directly to heritability, and expressed as \( \sqrt{h^2} \).

Heritability (\( h^2 \)) can be estimated by quantification of a character in the parents and in their progeny and siblings, and calculating the relationship that exists between the two in the expression of that character; that is, the regression of offspring on parent. By definition, measurements of a character can only be of the phenotype which – depending on \( h^2 \) – may or may not bear a close relationship to the genetic constitution or genotype.

Phenotypic selection for inherited characters within a single population of animals allows generation by generation improvement. The amount of change of the population (the response, \( R \)) depends upon the heritability and the extent of the superiority of selected parents over the population mean (\( S \)). The heritability for fat depth in pigs is about 0.5. If the population mean fat depth is 14 mm, and the phenotype of the two parents is 10 mm and 12 mm, then the parental superiority is 3 mm and the expected genetically determined fat depth of the offspring would be

\[
R = h^2S
\]

(6.6)

The possibilities for parental superiority relate to the amount of variation available in the population. A character without much variation in the population will be difficult to improve due to the similarity between the population mean and the value shown by the superior few. On the other hand, selecting the best few from a population showing great variation will produce rapid positive change in the population. This point is elaborated in Figure 6.8. In population (a) the best few pigs are far distant from the mean in terms of their leanness, but in population (c) the best few pigs are only slightly superior to the population mean.

To select only the fewest possible of the most excellent of individuals and to spread their genes through the maximum number of less excellent animals is fundamental to any animal breeding programme. The fewer of those chosen, the higher will be the intensity of selection (\( i \)), the greater the extent of parental superiority, and the greater will be the response:

\[
S = i\sigma_p
\]

(6.7)

where \( \sigma_p \) is the phenotypic standard deviation, and the coefficient of variation for the character is \( \sigma_p/\text{population mean} \).

The amount of genetic improvement per generation (\( R \)) can now be expressed as the product of the variance of the character in the population, its heritability and the intensity of selection employed:

\[
R = ih^2\sigma_p
\]

(6.8)

The rate of genetic improvement per year (\( \Delta G \)) depends upon the generation interval (\( GI \)); the quicker the turnover of each generation, and the shorter the interval, the more rapid will be the annual rate of genetic change:
\[ \Delta G = i h^2 \sigma_p / GI \]  

(6.9)

The maximum rate of genetic improvement will usually be more rapid in larger breeding populations than smaller ones because of the influence of \( i \). Increase in the population size will:

1. increase the variation available from which to select;
2. allow a greater intensity of selection without increasing the degree of in-breeding;
3. allow improved genes to be spread through a greater number of prospective parents.

Large populations are self-evidently found as breeding herds with many females, but modern biotechnology may extend the role of a single female of high quality by multiple ovulation and embryo transfer. Gene distribution from excellent males is also extendible by use of artificial insemination. Continued selection of one par-
ticular sub-group of individuals showing the character(s) needed may lead to in-breeding depression. In-breeding brings a loss of vigour, a reduction in breeding ability and a loss of biodiversity. The in-breeding rate per generation can be estimated as the reciprocal of \(2(4m/f + f)\) or \((1/8f + 1/8m)\), where \(m\) is the number of males and \(f\) the number of females in a breeding population.

Correct identification of ‘better’ parents for the next generation from amongst a number of candidates is obviously crucial to realising a high value for the intensity of selection \((i)\). This is not so easy as may appear. Some characters are not available for direct measurement, such as litter size or milk yield in a male, or weight of lean tissue mass in a pig that must remain alive if it is subsequently to breed. In these cases measurements must be made in relatives, or predicted from a correlated character that can be measured in the live animal. Even measurements made on the candidate itself may not be all that they seem. A fat pig with a big appetite is not the same sort of fat pig as one with a small appetite. The character measured and the environment in which the character is assessed are importantly related, so the method of testing chosen and the character to be selected are interdependent.

The assessment of an individual’s worth or breeding value by progeny test (measurement of the performance of the offspring) is an implicit requirement for assessment of characteristics such as milk yield or prolificacy in a male. It was used with great success in the early years of the rise of the Danish pig industry to select against fatness. Although accurate, it is expensive. For traits of low heritability such as reproductive performance, it is accepted that information on any individual requires to be derived from as many close relatives as possible, especially the progeny. The assessment of an individual’s worth by its own performance is most effective for use with more highly heritable traits such as growth rate and carcass quality. In characters that can only be measured post mortem, this is predicted from correlated measurements such as fat depth in the live candidate, and from direct measurements made in siblings sacrificed for the purpose.

The performance test and the progeny test are not, of course, mutually exclusive. One candidate’s performance test is its parents’ progeny test! The breeding value of an individual can therefore be best predicted from a combination of information from its own performance test, from the performance of its siblings and progeny, and with information from ancestors and a wider forum of relatives. All such information naturally accumulates as a breeding programme progresses generation by generation. If all these data are put together (an ‘animal model’), and appropriate adjustments are made for differences in time and place, then an enhanced accuracy of prediction is possible. This is especially useful for traits of low heritability, such as milk yield or litter size selected for in the female lines. Considerable computer power is essential to deal with the huge mass of quantitative data that may usefully pertain to a single candidate for selection. The ‘animal model’ technique of using all available data on all available relatives is now accepted practice in large breeding companies and is used together with best linear unbiased prediction (BLUP) which separates out the management effects such as time and place (fixed effects) from random effects (genetic effects).
It is invariably the case that selection must be based on more than one character. Each additional character slows down the rate of progress in any one, but maintains a fitter overall population. Thus selection may need to be for growth rate and carcass quality, or feed conversion efficiency and litter size. To select simultaneously for more than one character, an index is required. The index will include, and also ‘weight’, the various elements according to their relative importance. However, problems can arise if two desired characters are highly negatively correlated, such that positive change in one causes deep negative change in the other. In this case the usual solution is to choose separate selection lines for each character.

Non-additive genetic variance ($\sigma^2_D$ and $\sigma^2_I$) represents contributions from parents that do not add together simply. Characters showing non-additive genetic variance cannot be selected for progressively within a breeding population. However, such variation is responsible for heterosis, and is extremely valuable in breeding plans. Heterosis is usually shown most strongly when two pure-bred breeding populations are crossed. The causes of non-additive genetic variation are generally understood to be dominance ($\sigma^2_D$) and interaction ($\sigma^2_I$). Dominance relates to interactions at a given locus (A over a), while interaction relates to interactions across loci (A or a alleles with B or b, or with C or c, etc.). Dominance is seen to occur when the gene complement of one parent suppresses that of the other, as would be the case when a homozygous halothane positive pig (nn) is mated to a homozygous halothane negative pig (NN) and the resultant heterozygous offspring (Nn) is halothane negative (i.e. behaves as if it were NN). Were there to be no dominance and the genetic variation was additive, the heterozygote would be expected to show an intermediate value of halothane response. Often dominance is not complete, as is the case for halothane-gene-associated porcine stress syndrome (PSS), and the heterozygote may continue to show a tendency toward PSS-linked characters such as PSE associated with the halothane gene. The heterosis that results from dominance effects is best seen when individuals, homozygous for different characters, some positive and some negative, are crossed and as a result show in the heterozygous offspring all characters positive. Where traits A and B both show dominance, the homozygote AAbb (showing excellence for A, but poor quality in b), crossed with the homozygote aaBB (showing excellence for B, but poor quality in a), will give progeny AaBb, which because A and B are dominant show excellence for both A and B.

Interactions ($\sigma^2_I$) occur where the genes from the two parents complement each other and build together a whole that is greater than the sum of its parts. This would be the case where A, B, C, etc. were all contributing elements of a complex productive trait, and had the opportunity of positively interacting the one with the other. Such a situation might readily be envisaged for litter size where ovulation rate, fertilisation rate, uterine capacity and embryo survival all contribute to the number of piglets born. Sometimes non-additive gene action of this sort results in heterozygote performance that is superior to either of the parent homozygotes.
Hybrid vigour in pig improvement strategies

Non-additive genetic change, demonstrated as heterotic effects and brought about by dominance and interaction, is by nature once-and-for-all. Progressive improvements are not possible, and the phenomenon must be recreated at each generation when two particular pig strains are crossed. It occurs neither for all crosses, nor in all characters. The consequence of a particular crossing regime for a heterotic effect in a given trait cannot be predicted – other than by use of genetic markers – before it has been tried out. However, once heterosis is found it will reappear for the particular character each time those two particular pig strains are crossed. Heterotic phenomena in pigs are primarily – but not exclusively – observed in the reproductive traits, which are of low heritability and difficult to improve by conventional selection amongst additive genetic variation within a breeding population. The inverse relationship between heterotic effects and the extent of additive genetic variance follows in part from Equation 6.4; the genetic variation ($\sigma^2_G$) being the sum of the additive genetic variance ($\sigma^2_A$) and the heterotic ($\sigma^2_D$) and interaction ($\sigma^2_I$) effects.

Table 6.1 considers the case of three breeds and two crosses between them. For growth rate, the crosses may be seen to perform exactly at mid-parent values. For example, \((650 + 750)/2 = 700\). This is the conventional expectation for additive genetic variance. However, for litter size there is heterosis. The mid-parent value for case 4 (Large White $\times$ Landrace B) would be 10 piglets born, but performance levels of 10.75 are noted. One may question the benefit of such a cross, as the performance of the Large White breed (case 3) is already better with respect to both growth rate and litter size.

Table 6.1. Performance of three pure-breds and two cross-breds showing the presence and absence of heterosis (hybrid vigour) in the cross-bred: (a) progeny superior to average of the parents, (b) progeny superior even to the better parent.

| Case 1: Pure-bred (Landrace type A) | 650 | 10 | 3 |
| Case 2: Pure-bred (Landrace type B) | 700 | 9  | 4 |
| Case 3: Pure-bred (Large White)     | 750 | 11 | 3.5 |
| Case 4: Cross-bred (Large White $\times$ Landrace B) | 725 | 10.75$^{(a)}$ | 3.75 |
| Case 5: Cross-bred (Large White $\times$ Landrace A) | 700 | 12$^{(b)}$ | 3.25 |

Although this example shows no heterosis and mid-parent values for growth rate, this is not always the case. There is often some heterosis [type (a)] shown for growth rate in crosses between the Pietrain and Large White, and between the Duroc and Large White.
and litter size. However, a third character such as lean meat percentage or ham shape score may be superior for the Landrace B, and the mid-parent value for this quality, together with the mid-parent value for growth rate and the above mid-parent value for litter size, may make a worthy cross-bred generation. Case 5 (Large White × Landrace A) shows the best hybrid vigour response, producing a litter size of 12, one whole piglet above the best parent (the Large White). The case 5 cross certainly maximises litter size, although not growth rate or ham shape, which will have to be handled by a different stratagem.

True heterosis had, of course, been early demonstrated by maize breeders, upon out-crossing two in-bred, low yield, homozygous lines. The resultant F1 heterozygote produced a yield of maize that was greater than either of the two original lines even before the in-breeding regime commenced. To create hybrid vigour in pig populations it was at first thought that performance depression by in-breeding might also be necessary. This, however, is not the case, and there is no such prerequisite. Nevertheless, to show hybrid vigour it is necessary that the two breeding lines used should be distinct from each other.

Heterosis in the reproductive traits was noted in the early 1960s. The Large White and Scandinavian Landrace remain the two breeds most often used in cross-breeding schemes to enhance reproductive traits in pigs. Heterosis is, however, also evident in crosses between the Duroc and the Landrace and Large White breeds. It has been consistently demonstrated that there is heterosis at two levels. First, the cross-bred litter out of the pure-bred dam is of greater size and vigour, resulting in higher numbers weaned and a greater weaning weight; cross-bred progeny may have at least a 5% lift in litter size and a 10% lift in litter weight at weaning. Second, the use of the first generation F1 hybrid females as mothers for the next generation gives a further boost (5% at least) to performance, due to the greater reproductive vigour of the dam (Table 6.2). Litters from F1 mothers may confidently be expected to show 1.0–1.5 more piglets weaned as a result of greater numbers born and subsequent piglet viability. Due to improved milk production and piglet vigour there is also likely to be an enhancement of up to 1 kg in individual piglet 28-day weaning weight.

It will be recalled, however, that these gains are not progressive. They have been of this same order for 30 years and only occur upon the recreation of the F1 by the out-crossing of pure-bred lines. The pure-bred lines must therefore be maintained as independent pure-breeding populations for the specific purpose of creating

<table>
<thead>
<tr>
<th>Table 6.2. Effect of cross-breeding upon reproductive performance.</th>
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<tbody>
<tr>
<td>Percentage improvement over pure-bred for pigs weaned/dam/year</td>
</tr>
<tr>
<td>First cross</td>
</tr>
<tr>
<td>Back-cross or three-way cross¹</td>
</tr>
</tbody>
</table>

¹ Using the F1 as the dam and a third breed as the sire.
generation after generation of new heterozygous F1 progeny. In the meantime progressive selection can also be made in the pure-bred populations as exampled in Table 6.3.

One of the characteristics of the F1 generation, in addition to heterosis in the reproductive traits, is the uniformity of the heterozygote, which is particularly standardised in physical appearance and performance. This has considerable commercial advantage in itself. If, however, F1 heterozygotes from the same parental sources are themselves crossed to create an F2 generation, there is a disassociation of the genes that had previously complemented each other so beneficially. The result of crossing heterozygotes is unfortunate in two respects: first, half the hybrid vigour will be lost, and second, the progeny may be more variable. Variability may show in form, function and all aspects of performance. Such variability is strongly disadvantageous at production level (although the creation of F2 generations is the stock-in-trade of breeders wishing to create variation from which to select).

There is therefore disbenefit in choosing either:

(1) to use the same F1 construction for both the sire and the dam of the slaughter generation; or
(2) to use the slaughter generation as a source of replacement breeding females.

It is important that the male used on an F1 parent female should be either pure-bred (one of the pure lines that created the F1 is satisfactory) or a cross-bred of different origin that includes at least 50% of novel genes. In general, producers should resist the temptation to draw replacement female stock from out of their finishing pens of slaughter pigs; female breeding stock is probably best recreated at each and every generation, from crossing the pure-bred lines.

Hybrid vigour in the reproductive traits of pigs is also evidenced in the male side. In this event the phenomenon shows itself through hardiness, earlier sexual maturity, longevity, increased libido and improved sperm concentration and viability. As a result, cross-bred boars can be easier to use, are more ready to mate, will improve conception rates and will produce litters of greater size in consequence of enhanced semen characteristics and libido. Between 0.25 and 0.75 piglets more per litter have

### Table 6.3. An example of improvement made in the pure-breeding populations by selection, together with exploitation of heterosis in the cross-bred offspring.

<table>
<thead>
<tr>
<th>Litter size (numbers born)</th>
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<tr>
<td>Pure-bred line A</td>
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<tr>
<td>Pure-bred line B</td>
</tr>
<tr>
<td>Cross-bred (A x B)</td>
</tr>
</tbody>
</table>

**After n generations of selection including litter size**

| Pure-bred line A          | 10.5 |
| Pure-bred line B          | 11.5 |
| Cross-bred (A x B)        | 12.0 |
been claimed from the use of hybrid boars. However, producers value particularly their increased libido as compared to the pure-bred types.

Breeding regimes planning to utilise hybrid vigour in the female line tend to take one or other of the forms in Table 6.4. Option 1 is a typical two-way cross which may be handled with either line as male or female (i.e. a variant on the scheme would be for L to take the place of LW and vice versa). Sometimes the same breed may be used in the male and female line, but a different strain is chosen for those different purposes. Option 2 is a three-way cross where P is always the top-crossing sire, but LW and L may be reciprocated. Option 3 utilises a cross-bred male line from sources different to the female line, thus maximising hybrid vigour in both sire and dam, as well as offspring. A further option is a variant continuing on from option 1 where females from the slaughter generation are drawn out for replacements in the breeding herd. This scheme is called criss-crossing and some heterosis is preserved by alternate use of the two source breeds for the sire of the next generation. Such a plan fails to optimise heterosis, and requires both growth and reproductive traits to be dealt with by use of an index, and simultaneously selected for in both populations. Once popular, it is now largely discredited. In the third option, breed ‘D’ may be any suitable sire-line sire, as indeed may breed ‘LW’. Crosses between the Large White or Landrace, and the Duroc, the Hampshire, the Pietrain and Landraces of the Belgian and German type are all feasible, as are other possibilities.

**Improvement of pigs by importation of new genes**

Importation of genes for specifically required characters into an otherwise satisfactory population is second only to complete population replacement as the simplest form of genetic improvement.
Where the alternative gene source is better overall than the existing population, then the latter’s complete replacement is indicated. This could be done either at a single stroke or by ‘grading up’. The one-step option for breed replacement is usually employed in pig production, rather than the more tedious grading up process. Either a unit is requiring stocking *de novo* or the opportunity is taken to depopulate an existing unit, disinfect and rest, and restock with a replacement pig type of improved quality and higher health status.

Examples of instantaneous replacement therapies would be the substitution of the modern white hybrid female for local indigenous pig stocks, a decision to change breeding company or a policy change in choice of top-crossing sire.

Grading up is a tiresome process by which the replacement breed is used upon the base population to sire five generations, until the population base has 97% of the genes of the sire breed, and may therefore be considered to be that breed. The appropriateness of grading up would be limited to where the availability of the new breed is restricted to few individuals but is required to create a new nucleus herd. A typical possibility would be the use of semen from a muscular breed to create, from indigenous stocks, a particularly meaty sire-line population.

Often, the alternative gene source is not better overall than the existing population, but holds within it one or two specific characters of value. Wholesale breed replacement is therefore uncalled for. The incorporation of imported genes is required to augment rather than replace the existing population, and to create an amended breed. The injection of genes is achieved by one or more initial crosses followed by subsequent selection to retain the wanted genes, but to exclude the unwanted ones. In this way the Meishan has been used to introgress genes associated with prolificacy into the lean and fast growing Large White and Landrace types. The first cross shows heterosis above mid-parent in prolificacy, giving about two or three extra piglets per litter, but it is also painfully fat and slow growing. By subsequent back-crossing with the White breed and appropriate selection, prolificacy may be held in the genome while slow growth and fatness are reduced. The achievement of one extra piglet per litter with no loss of growth rate or meatiness would be considered as a highly beneficial breeding programme. In the event, the Meishan crossing programme has been slow to deliver, but tangible benefit may be upon the horizon.

The Belgian Landrace is a meaty breed, but also halothane positive, with lowered breeding efficiency, easily stressed, and whose carcass meat is liable to loss of quality through PSE. For this reason it is usually used only as a top-crossing sire, the normal halothane negative (NN) gene being dominant and the heterozygote being stress resistant (Nn) when produced from a normal (NN) mother. It is an important point of principle in the use of the heterozygote (Nn) type that while the normal type (N) is dominant for predisposition to stress (and mortality) and this problem is therefore largely absent from the Nn heterozygote, the inheritance of lean meat percentage is additive, the Nn heterozygote showing values intermediate between the two parents (about +2.5% of lean meat). However, the carcass would be even more valuable if the mother were also to carry the gene for meatiness whilst avoiding all the
problems of the associated halothane gene; in effect, a new breed of meaty Large White created by the introgression of genes for meatiness, but the exclusion of genes for stress. The disassociation of blocky muscling and stress susceptibility is, however, proving difficult, and ‘Meaty Large Whites’ tend to be heterozygous (Nn) for halothane and suitable only for use in the sire line. When used also in the female line the dominance effects are lost, and PSS reappears in a proportion of the (nn) offspring (Table 6.5). It remains an important goal for animal breeders to achieve separation of meat characteristics from stress characteristics in breeds such as the Belgian Landrace and Pietrain. However, it may be that meat-line qualities could be achieved equally well by selection within a population of halothane negative (NN) pigs. Transgenic techniques with marker-assisted confirmation of gene transfer may have something to offer the introgression of single or few genes into a population.

If the animal breeder perceives that a mixture of genes from both breeds, or equally as often from three or four breeds, could be of benefit, then a completely new breed could be manufactured. This idea was responsible for the Minnesota and Lacombe breeds, and forms the basis of most of the ‘breeds’ now standing in nucleus pure-breeding herds at breeding companies. First, the source populations are crossed, giving a mixed heterozygous population which is then mated back to itself. The next generation has within it the genes from all the source breeds, and a greater amount of genetic variation than was ever available to select from within any of the founding populations. The gene mix can now be exploited by the selection of animals showing wanted characters and rejection of those that do not. Matings amongst selected animals bring about concentration of wanted genes until the population is pure-breeding. It is a common difficulty with such schemes that variability in the offspring may continue for many generations after the original admixture has taken place. Importantly, gene importation and breed mixing have created the majority of the pure-breeding nucleus dam and sire-line populations of today’s breeding organisations, which are new or amended breeds created by both gene importation and selection. The original concept of ‘breed’ is now therefore lost at breeding company level. Specialised sire lines are invariably made from admixtures of some or all of Hampshire, Pietrain, Belgian Landrace, Duroc and Large White breeds. The success of the method depends upon the quality of the source populations used and the efficiency of the subsequent selection programme.

Although the construction of a pure-breeding population of perfect pigs showing all beneficial characters at levels of excellence seems a laudable and tidy objective,
it is by no means the most efficacious route to combining characters of different type. Breed crossing programmes can be justified without the need to invoke the benefits of hybrid vigour. Achieving mid-parent values can be ample reward in itself. The genes of the Duroc and Large White are well combined by the simple expedient of using the cross-bred (D × LW). Such a cross has found favour both in the sire line when mid-parent values for meat quality characteristics are appreciated and in the dam line when better than mid-parent values for prolificacy and for hardiness are useful in extensive pig keeping systems.

Modern breed improvers make frequent use of gene importation to introduce new characters and to produce a greater pool of variation from which to select. All three techniques, breed amendment, new breed creation and continuous cross-bred production, are commonplace tools of the trade for national and international breeding companies. Gene addition and use of heterosis are complementary: lines that have been the subject of gene importation can be used in hybrid breeding programmes in both the male and female lines.

Breed mixing has sometimes, most unfortunately, been used in substitution for a progressive breeding programme. This dubious practice involves the maintenance of four or five small herds, one for each breed, within which no selection takes place, but whose sole purpose is to maintain various different breed types. (For example, one prolific breed, one coloured breed, one fast growing breed, one lean breed, one meaty breed and so forth.) Market needs are then satisfied on the basis of mixing and matching the nucleus breeds. This strategy promises much but delivers little, because there is no genetic improvement taking place in the source breeds.

So the third and equally complementary leg of breed improvement strategies is the achievement of positive change by genetic selection within pure-breeding populations. The continued effectiveness of hybrid breeding and gene importation programmes is dependent upon progressive improvement in the source populations by selection. It is explicit that no breeding programme is sustainable by cross-breeding and gene importation techniques alone.

**Pig improvement by selection within a breeding population**

Improvement by selection within a population depends upon the presence of additive genetic variance ($\sigma^2_A$) and the shifting of the population mean in the favoured direction by the use of sires and, to a lesser extent, dams of excellence. Proof of a candidate’s superiority depends upon measurement, but only the phenotype can be measured. The phenotypic variation for a trait is the sum of the additive genetic effects and the environmental variation, providing the influences of dominance and interactions (heterosis, $\sigma^2_D$ and $\sigma^2_I$) are taken to be small. Where $\sigma^2_G = \sigma^2_A + \sigma^2_D + \sigma^2_I$:

$$\sigma^2_P = \sigma^2_G + \sigma^2_E$$

(6.10)

(see also Equation 6.2).
As will be recalled from Equation 6.8, response to selection (R) depends on the heritability ($h^2$), the intensity of selection (i) and the extent of variation existing within the population as measured by the standard deviation ($\sigma$). While adequate population size facilitates i, a short generation interval (achieved by very frequent replacement of nucleus sires and quite frequent replacement of nucleus dams) maximises the rate of response (see Equation 6.9).

**Heritability ($h^2$)**

Heritability relates to that part of $\sigma^2_p$ which is accountable by $\sigma^2_G$:

$$h^2 = \frac{\sigma^2_A}{\sigma^2_p} \tag{6.11}$$

and is demonstrated by the influence of the parent upon the genetic composition of the offspring. $h^2$ can be determined as the regression of the performance of the offspring on the performance of the parents (mid-parent), but can also be built up from knowledge of resemblances between other relatives – especially siblings. Figure 6.9 shows the estimation of $h^2$ for growth rate from a population of pigs. Each dot is the value for the mean performance of one pair of parents against the performance of their offspring. Thus, for the open circle, the growth rate of the sire was 900 g daily and that of the dam 700 g daily. The mean growth rate of all the parents was 600 g, so the mid-parent value was $(900 + 700)/2 = 800 - 600 = +200$ g. The growth rates of four offspring that were measured were 650, 600, 750 and 700 g daily. The mean growth rate was $(650 + 600 + 750 + 700)/4 = 675 - 600 = +75$ g. Over all parents and offspring, the regression has a slope of 0.5.

Heritability values for some important pig production traits are given in Table 6.6.

Characters such as carcass quality, which are influenced little by environment, are highly heritable (as $\sigma^2_E$ becomes smaller, then $\sigma^2_G$ becomes a higher proportion of $\sigma^2_p$). Conversely, characters such as reproduction, which are much influenced by
environmental effect, are lowly heritable. Heritability \( h^2 \) is an estimate and may therefore vary. If \( \sigma^2_E \) is great, \( h^2 \) values for reproduction and growth can be less than 0.1 and 0.3, respectively. However, where the environment is controlled more closely, \( h^2 \) for these characters can readily double. It follows that control of \( \sigma^2_E \) will maximise the efficiency of identification of true genotype and thereby increase \( h^2 \). The greater \( h^2 \) is, the faster will be the rate of genetic improvement made by selection of best parent.

### The selection differential (S) and the intensity of selection (i)

The selection differential (the extent of the superiority of selected parents over the population mean) relates to the intensity of selection (i) and the variation (\( \sigma \)). Response to selection is the product of the heritability and the selection differential, as shown in Equations 6.6, 6.7 and 6.8.

The more exceptional the selected parents, in comparison to the population mean, the more exceptional will be their offspring, and the faster will be the rate of positive change in the population as each generation passes. Given the regression of offspring on mid-parent shown in Figure 6.9 for growth rate, it is self-evident that the further to the right hand side of the x axis are the parents, the higher up the y axis will be the progeny. It is also evident that the steeper the slope of b, the better will be the progeny response and the closer the progeny performance to (superior) selected parent levels. Breeding plans should aim to maximise movement in the direction shown by the arrows in Figure 6.10.

Where some 40% of the population has to be selected as parents for the next generation, then the selection differential will not be great. A low differential and

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**Table 6.6.** Heritability estimates for pigs.

<table>
<thead>
<tr>
<th>Reproductive characters (lowly heritable)</th>
<th>( h^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ovulation rate</td>
<td>0.10–0.25</td>
</tr>
<tr>
<td>Embryo survival</td>
<td>0.10–0.25</td>
</tr>
<tr>
<td>Numbers born</td>
<td>0.10–0.20</td>
</tr>
<tr>
<td>Survivability of the young</td>
<td>0.05–0.10</td>
</tr>
<tr>
<td>Readiness to rebreed</td>
<td>0.05–0.10</td>
</tr>
<tr>
<td>Milk yield</td>
<td>0.15–0.25</td>
</tr>
<tr>
<td>Milk quality</td>
<td>0.30–0.50</td>
</tr>
<tr>
<td>Longevity</td>
<td>0.10–0.20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Growth and carcass quality characters (moderately heritable)</th>
<th>( h^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily live weight gain</td>
<td>0.30–0.60</td>
</tr>
<tr>
<td>Lean tissue growth rate</td>
<td>0.40–0.60</td>
</tr>
<tr>
<td>Appetite</td>
<td>0.30–0.60</td>
</tr>
<tr>
<td>Backfat depth</td>
<td>0.40–0.70</td>
</tr>
<tr>
<td>Carcass length</td>
<td>0.40–0.60</td>
</tr>
<tr>
<td>Eye muscle area</td>
<td>0.40–0.60</td>
</tr>
<tr>
<td>Ham shape</td>
<td>0.40–0.60</td>
</tr>
<tr>
<td>Meat quality</td>
<td>0.30–0.50</td>
</tr>
<tr>
<td>Flavour</td>
<td>0.10–0.30</td>
</tr>
</tbody>
</table>
a high proportion selected will be typical for selection of breeding females. A high selection differential, with usually less than 10% and often less than 1% selected, would be typical for sire selection; especially if artificial insemination is utilised to facilitate maximum coverage of females by the minimum number of quite exceptional males. The influence of the proportion selected upon degree of excellence of selected parents is illustrated in Figure 6.11.

The selection differential is dependent upon both $i$ and $\sigma$:

$$S = i \sigma$$  \hspace{1cm} (6.12)

Selecting the top 10% of animals for a character with low variation in the population gives a lower value for $S$ than selecting the top 10% for a character with high variation, as is shown in Figure 6.12, for characters of (a) low and (b) high variation. The influence of heritability and selection differential upon the extent of improvement in three characters is depicted in Figure 6.13.

It has often been wrongly assumed that as a selection programme progresses the extent of variation available to select from must diminish, and the response must slow ultimately to a plateau, although it is reasonable to expect some limit to exploitable variation for characters that threaten health. For traits being selected
downwards, such as backfat depth, it is unavoidable that variation must lessen as
the population mean approaches zero (Figure 6.8), but for traits selected upwards,
such as reproductive characters and lean tissue growth rate, no limit is evident.
Common sense suggests that litter size must be limited by uterine capacity at some
point, but even this expectation will not be met if there is a correlated positive
response in maternal size. There is no reason to suppose that a plateau to response
is likely to be reached in the foreseeable future for characters associated with lean
growth and reproduction.

The extent of genetic variation in meat quality traits is the subject of present dis-
cussion; it could be that whilst some aspects of meat quality such as flavour and
tenderness might be reasonably heritable, there could be little additive genetic vari-
ation ($\sigma^2_A$) available from which to select, because $\sigma^2_P$ is small.

**Generation interval (GI)**

For the animal breeder, it is the annual rate of response that counts, not simply
response per generation (as was shown in Equation 6.9):

$$\Delta G = h^2\sigma_p/GI$$  \hspace{1cm} (6.13)

The fewer years per generation the faster the rate of response. Pigs become sexu-
ally mature between 6 and 9 months of age, and pregnancy takes a further 4 months.
A pig generation can therefore be turned around in about 1 year. In practice, it may
not always be economical to use a sow for only one litter; she may remain in the
herd for up to 4 years, which considerably lengthens the generation interval. There
is benefit in keeping to a rigorous regime of culling sows out of the nucleus herd –
perhaps to a multiplier herd – after a given number of litters (often two). However,
if reproductive traits are a part of the selection programme, it is impossible to accu-
rately predict breeding value for reproductive characters in only a few litters. This
is where information from relatives becomes so useful.
Fig. 6.13  Influence of heritability and selection differential upon rate of improvement following use of a selected parent. In the first example the selected male has a carcass length 10% better than the average of the breeding herd. If the heritability for carcass length is 0.5, a 2.5% improvement would be found in the offspring. Some 12 months are likely to elapse between the birth of the selected male and the birth of his offspring. In a less variable population of pigs a male with a carcass length of 880 mm might not exist and the longest animal be only 5% above average (840 mm), so the offspring would only be improved by 1.25%. In the second example a breeding female has been selected consequent upon her producing litters with 10% higher than average number of pigs. With a heritability of 0.1, the offspring are likely to show an improvement of only about 0.5%. In this case 24 months or more elapsed between the birth of the selected female and the birth of her offspring. In the third example a male with P2 10 mm, used on a population with average P2 20 mm, will produce offspring whose P2 measurement will be about 17.5 mm (heritability assumed to be 0.5). A male with P2 measurement of 14 mm, by the same calculation as example 3, produce offspring P2 measurements of around 18.5 mm. The size of difference between the average of the selected parent and the averages of the population will depend upon the number of animals that have to be selected from amongst the candidates. It is, for example, much more probable that the mean P2 of those selected will be 10 mm if one is selecting only five individuals from 100 candidates; conversely, it is more probable that the mean P2 will be 14 mm if one was selecting 25 individuals from 100 candidates (Fig. 6.11).
The same argument pertains even more strongly to the male. The most accurate assessment of the breeding value of a sire can be made by study of his progeny, but there is a necessary delay while the progeny demonstrate their qualities. Measurement of the performance of the sire himself may be a less accurate determinant of breeding value than measurement of the progeny, but it reduces generation interval, performance test data being available even while sexual maturity is yet being attained. The shorter generation interval allowed by performance test far outweighs any loss of precision in breeding value determination. Where the character is sex-limited, such as litter size, the progeny test might be considered obligatory to assess the breeding value of a candidate male; but information from relatives, if they be numerous enough, can do much to allow the allocation of a breeding value for reproductive traits to a potential sire even before he is sexually mature.

There is a temptation to keep an especially good sire or dam in the breeding nucleus. In the time when line breeding techniques were used to fix a particularly desirable quality, the use of one particular individual, or family, over many generations was an essential part of pedigree breeding strategy. Individuals of outstanding merit were sought and could remain in a herd for 4 years or even more and set in place the future destiny of that population (and its owner). However, this practice fails to maximise rate of genetic change. The advances in growth rate and leanness over modern times have only come about since breeders have been willing to rapidly replace their herd boars, maintain a high rate of turnover of breeding stock and reduce generation interval to the minimum. The realised generation interval for pigs in breeding companies is presently about 400–450 days. The effective lifespan for the use of a dam in a pure-breeding nucleus which is the subject of intensive genetic selection should normally be 2–4 litters, and the effective working life of boars in a nucleus should be measured in weeks or months rather than in years.

**Pure-breeding (nucleus) herd size**

Pedigree breeders used to have relatively small breeding herds, and relied heavily upon few (championship) stock boars and often also upon their close relatives. Effective herd size is increased by provision of a testing facility to which can be sent candidates from many herds, followed by the willingness of individual breeders to use only tested sires of the most exceptional quality. Such was the basis of many national pig improvement schemes, but these have mostly fallen into low usage or disuse since breed improvement responsibilities have passed to the independent breeding companies.

There are many reasons for the demise of the small pedigree breeder, even with access to central testing. Amongst these have been unwillingness to co-operate to create a genuinely operational nucleus of significant size. However, equally important was the fear that central testing might spread disease. Candidates could bring to the central testing facility disease organisms resident on the various breeders’ independent units, exchange those organisms in the course of the testing pro-
gramme, and then redistribute them to the pedigree breeders through the medium of those candidate boars that were selected. The rise of interest in high health status stock demanded by commercial buyers of improved pigs compromised central testing as a means of increasing effective nucleus herd size.

Response to selection has been shown to be positively influenced by the accuracy of measurement, the intensity of selection (i) and the amount of variation available (σ). All these are facilitated by large population size. In large herds it is also easier to minimise generation interval.

Where heritabilities are high, nucleus herd sizes of 250–500 pure-breeding females may be acceptable, as with the male side of a sire-line population which may need to be open to importation. For moderate heritabilities a nucleus of 500–1000 breeding females is required, whilst for low heritability traits, herd sizes in excess of 1000 are a prerequisite for acceptable rates of genetic change. It is unusual (but not infeasible) to consider single-site pure-breeding herds of such size; 250–600 breeding sows on a single site would usually be the effective herd size for proper management and recording of elite animals which are the subject of intensive genetic selection programmes. The whole of the nucleus could, with benefit, be spread over a number of separate units; in effect, the nucleus is made up from a group of herds. This is not a significant complication given computer recording (BLUP) and the relative ease with which the genes of a boar can be spread across sites by the use of artificial insemination.

**Accuracy of measurement and effectiveness of candidate comparison**

The selection of parents of special worth assumes that those selected do indeed possess it; the measurement taken must reflect the character measured. However, misrepresentation of the facts can be a significant contributor to environmental variation; many elements conspire towards this:

1. human error at the point of measurement;
2. recording and computer entry error;
3. measurements being of necessity indirect, such as ultrasonic measurements for fat depth and the need to predict lean mass in the live animal from associated fat depths and body weights;
4. measurements being possible only upon relatives rather than the candidate itself, such as those for litter size or meat quality.

In addition to the type of errors in effective measurement identified above, other errors are directly attributable to the way the nucleus herd is managed. They are built into the system itself. It is essential than management variations are obviated or assiduously recorded for removal of fixed effects by BLUP analysis. Examples would be: candidates measured for lean gain having different body composition and/or age at the start of a performance test; candidates measured for growth and efficiency having eaten different amounts of feed over the duration of test; candidates measured for litter size having different management routines at the time of...
mating; candidates measured for susceptibility to PSE having relatives slaughtered
at different processing plants, and so on.

Improving the accuracy of measurement is part of reducing environmental vari-
ation ($\sigma^2_E$). Many failures are the result of management convenience, and it is
axiomatic that a genetic selection programme is managementally inconvenient. The
approach of staff and management to a nucleus breeding herd requires to be
radically different from that of a commercial production unit.

**Genotype–environment interaction**

Genes are, perforce, expressed in the environment. A pig cannot grow in the absence
of an environment containing feed. An inherited resistance to a disease cannot be
expressed in the absence of the disease organism (Table 6.7). This might be thought
to mean that candidate testing must take place in the environment to which the
genes of the progeny will be exposed.

One problem arising from this analysis is that the commercial environment (the
environment of the progeny) may be more variable and unstable than that of a
nucleus herd where the intensive testing and selection must take place (the envi-
ronment of the parent). There is disadvantage in a variable environment because
where environmental effects ($\sigma^2_E$) are large, effective heritability will be low due to
$\sigma^2_A$ being a small proportion of $\sigma^2_P$.

$$\sigma^2_P = \sigma^2_A + \sigma^2_E \quad (6.14)$$

and

$$h^2 = \frac{\sigma^2_A}{\sigma^2_P} \quad (6.15)$$

as will be recalled from Equation 6.11.

Genotype:environment interaction impacts heavily upon choice of nutritional
environment for a programme of selection for lean tissue growth rate and fatness.
The commercial environment may favour restricted feeding of a diet of average
nutrient quality, but under these conditions differences between individuals for lean
tissue growth rate may not be readily apparent. It is only at higher levels of energy
and protein that differences in lean growth and fatness become evident, as demon-
strated in Figure 6.14.

<table>
<thead>
<tr>
<th>Litters from sire A</th>
<th>Without K88</th>
<th>With K88</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td>Litters from sire B</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 6.7. Interaction between genetic competence for resistance to *Escherichia coli* K88 and the
presence of the organism in the environment.
Inasmuch as it appeared evident earlier that candidate testing must take place in the environment of subsequent gene exposure and expression, it is now equally evident that candidate testing must also take place in the environment that best distinguishes between the genotypes.

For the breeder, priority goes to the selection of candidates in an environment that reduces variation and increases the likelihood of successfully distinguishing between candidates of different merit. This will inevitably mean a test regime different from the circumstances of production. It is necessary in this event that there is no severe genotype–environment interaction of the sort where a candidate chosen as better on the test regime may turn out to be worse on a commercial farm (Figure 6.15).

More usually, the quality of the commercial environment simply fails to allow the full expression of selected characters. Producers with previous experience of pig strains of moderate quality who have upgraded their genetic base by the purchase of improved stocks also require to upgrade their environment (especially the nutri-
The presence of genotype–environment interactions casts doubt upon the wisdom of making comparisons of different genotypes in a common environment. To compare various breed types and breeding company products and identify which is the best appears sensible at first sight. However, if each type is tested under a different regime the comparison is confounded, while if each type is compared under the same regime, that identified as ‘best’ will merely be the one that most closely fits that particular regime. Regardless of the inconvenience or difficulty of the interpretation, it is often the case that different pig types can only be properly compared when each is tested in the environment best suited to that type. The corollary is that such comparisons perhaps should not be attempted, and assessments of commercial products are probably best made by the marketplace. Pig purchasers should opt for the pig type most likely to perform best in the individual conditions of that purchaser. This will relate to the test environment chosen for selection of parents in the nucleus breed improvement programme. Breeding companies should therefore expect customers for their stock to be interested not only in selection objectives and selection intensities, but also in methods of testing.

Index selection

Selection strategies rarely, if ever, result from only one selection objective, and selection objectives rarely, if ever, result from only one measurement. The combination of measurements and objectives requires the construction of an index that converts many numerical values for various traits into a single value, and allows candidates to be ranked for excellence by use of one single numerical value – or index. Lean tissue growth rate alone is not adequate to ensure a high quality carcass; minimally, fat depth should also be included in the selection programme. Reproductive traits, as well as carcass and growth characteristics, may require active positive selection.

Thus selection strategies require indices to handle both the simultaneous pursuit of two traits of importance which may or may not be positively or negatively correlated (such as growth rate and reproductive performance), and the pursuit of a single trait approached through more than one measurement (such as lean tissue growth rate which requires, together with daily gain, at least measurement of fatness and, helpfully, also lean mass – perhaps on relatives). Usually breeding indices need to combine both of these requirements. Weightings for each of the measurements used in the index are needed not only to achieve numerical sense from measurements that will have different magnitudes of value quite unassociated with their importance, but also to give appropriate value (weight) to information of different quality (direct versus indirect measurements, for example), and similarly to give appropriate weight to traits of differing economic importance (the breeding objective in a sire-line might wish to value lean percentage above growth rate, while the breeding objective in a dam-line might wish to economically value litter size above leanness).
Notwithstanding the need to pursue more than one objective if a realistic selection programme is to be maintained, there are negative consequences to overly complex and excessively broad-based selection objectives containing many diverse elements, some of which may not be directly germane to production efficiency. Most rapid progress is made if one objective only is pursued single-mindedly. However, optimum progress in efficiency and economy of the pig production process can equally only occur where more than one trait is the subject of selection pressure. As each additional objective is included in the index then the rate of progress in any one is progressively slowed unless the traits are positively correlated. Simultaneous pursuit of negatively correlated traits will ensure slower progress, as will a larger number of traits, and also the inclusion of unneeded traits. Only those characters crucial to performance should be the subject of improvement by selection.

Where two traits are negatively correlated (such as is probably the case for reproduction and carcass quality) it may be helpful to avoid their inclusion in a single index by dividing the population into two lines, a dam line and a sire line. The two lines may then be crossed at the point of creation of the commercial F1 generation. The rationale behind such a scheme is described in Figure 6.16.

Some threshold characters may best not be included in an index, but dealt with by simply culling all individuals not reaching the required minimum level (the independent culling level). These would apply regardless of the ultimate objective of the breeding scheme. Meat quality may be adjudged as one; leanness is only beneficial if the muscle is free from PSE. Good legs are a prerequisite for boars and sows, regardless of potential litter size. All sows must have at least 12 nipples, and all boars must be willing to mate. Only when all the threshold levels have been passed would candidates go forward for calculation of their merit on the basis of an index.

The construction of an index to allow multi-trait selection is complex.

(1) Even when only a single character is the subject of the improvement programme, the efficiency of selection of that character can be improved if associated characters are included in the criterion of assessment. The measurement

<table>
<thead>
<tr>
<th>Dam line</th>
<th>Sire line</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial position</strong></td>
<td><strong>Initial position</strong></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td><strong>Select for 10 years</strong></td>
<td><strong>Select for 10 years</strong></td>
</tr>
<tr>
<td>Litter size and lean percentage</td>
<td>Litter size and lean percentage</td>
</tr>
<tr>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>55</td>
<td>65</td>
</tr>
<tr>
<td><strong>Litter size</strong></td>
<td><strong>Litter size</strong></td>
</tr>
<tr>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Lean percentage</td>
<td>Lean percentage</td>
</tr>
<tr>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

*Fig. 6.16* Use of specialised sire and dam lines with differently weighted indexes for each line.
of percentage lean tissue in a live candidate boar is improved if information is also included from measurement of ultrasonic backfat depth, muscle depth, ham shape and feed conversion efficiency, as well as with use of dissected lean content obtained from slaughtered siblings.

(2) When multiple characters are required to be improved in the selected population they may be strongly or weakly positively related. The daily rates of total gain and of lean tissue gain are closely related, but daily lean tissue growth rate and fatness are not necessarily so. Under ad libitum feeding conditions the relationship between lean tissue growth and fatness may be positive, whereas under restricted feeding conditions the relationship may be negative. Such positive and negative relationships require to be understood and statistically accounted for in the index.

(3) Some characters are more important than others, and it is sensible to weight the important ones so that improvement is more rapid in those elements than in the less important ones. Fat depth would be considered of great importance in a country with fat pigs and a human population discriminating against fat. However, fat depth would be of less importance in a country that already had thin pigs, and a human population concerned more with flavour and cookability than with the ultimate in leanness.

Weightings are sometimes dealt with by attaching financial values to each character. If it is obvious that a selection objective must have economic benefit, then the index is an ideal means of apportioning more weight to those characters of greater economic benefit. However, even in the context of a single market, economic benefits can be transient and liable to fluctuation. If each fluctuation is accommodated into the index as price changes occur, there is a danger that the index merely ensures a limited rate of progress due to constant direction changes. If, however, fluctuations are ignored, the market situation may drift to a position where the weightings of characters in the index no longer reflect reality. For breeding companies trading internationally, the situation is even more complex as there are large differences in the economic ranking of various characters between countries. Ham shape, for example, is economically vital in Spain, but smaller in the UK. It follows that economic weightings placed into indices should be viewed with suspicion. It is perhaps best to decide selection priorities, settle on their relative importances, consider likely rates of progress and then weight the index. The weightings will thus reflect clear management decisions and be expressed biologically, rather than being open to the caprice of changing financial circumstance.

The National Swine Improvement Federation of the USA offered, amongst others, the following examples of simple indices (I).

For sows:

\[ I = 100 + 7(N - \bar{N}) + 0.4(W - \bar{W}) - 1.4(D - \bar{D}) - 53(B - \bar{B}) \]  

(6.16)

where \( N \) is the number of piglets born alive, \( W \) is the weight of the litter (in pounds) at 21 days of age, \( D \) is days to 230lb live weight and \( B \) is backfat depth (in inches).
If \( N = 10, W = 130, D = 160 \) and \( B = 1.0 \), and for two candidates \( N = 11 \) and \( 12, W = 150 \) and \( 140, D = 130 \) and \( 135 \) and \( B = 0.7 \) and \( 0.8 \), then \( I = 166 \) and \( 160 \), respectively. The index, upon use, showed itself to be weighted in favour of numbers born and maternal growth rate, which was not unreasonable.

For males:

\[
I = 100 + 112(DG - \bar{DG}) - 120(B - \bar{B}) \tag{6.17}
\]

where \( DG \) is daily gain (in pounds) and \( B \) is backfat depth (in inches). If \( \bar{DG} \) is 1.5 and \( \bar{B} \) is 0.6, and for two candidates \( DG = 1.7 \) and \( 1.6 \) and \( B = 0.5 \) and \( 0.4 \), then \( I = 34 \) and \( 35 \), respectively. This index appears weighted approximately equally for gain and fatness.

A simple index used for the selection of gilts from group feeding pens might be:

\[
I = (100 \times DLWG) - (2 \times P2) + (0.02 \times W) \tag{6.18}
\]

where DLWG would be measured from birth (in kilograms), \( P2 \) is the depth of fat over the eye muscle (in millimetres) and \( W \) is weight (in kilograms) at the point of measurement. All animals would be weighed and ultrasonic backfat determined at the \( P2 \) site at an age reasonably close to 150 days. Two candidate gilts reaching 89 and 95 kg live weight at 150 days of age with respective \( P2 \) measurements of 10 and 12 mm would have similar index scores.

The simple boar index:

\[
I = (0.08 \times DG) + (50 - P2) \tag{6.19}
\]

is weighted more favourably towards growth rate than the index:

\[
I = (0.04 \times DG) + (100 - 2P2) \tag{6.20}
\]

Two candidates A and B, with daily gains of 800 and 900 g, respectively, and \( P2 \) backfat measurements of 15 and 20 mm, respectively, will score on the first index 99 and 102, but on the second index 102 and 96. Thus candidate B is perceived to be better (being faster growing) when the first index is used, but candidate A is better (being less fat) when the second index is used.

The purpose of the indices examined so far has been primarily (1) create balance amongst numerical values of different order so that \( I \) is meaningful (daily live weight gain might be 1000 g and backfat depth 10 mm, but the former is not 100 times more important than the latter), and (2) to give due weighting to those elements of the index that are more important because they are more economically valuable, or because they are more dependable (numbers born versus piglet birth weight). The addition of genetic parameters allows a more complete approach by accommodating relative heritabilities, correlations and variances for each of the measurements.

Suppose the objective of the index is to improve lean tissue growth rate (LTGR), estimated through measurement of daily gain (DG) and backfat depth (BF), then the index requires weighting (b):

\[
I = b_{DG} \times DG + b_{BF} \times BF \tag{6.21}
\]
Calculation of values for $b$ needs:

1. the phenotypic variances of DG ($\sigma^2_P(DG)$) and BF ($\sigma^2_P(BF)$), and the covariance relationship between them ($\text{cov}_P(DG,BF)$);
2. the genetic covariance between DG and LTGR ($\text{cov}_A(DG,LTGR)$) (the relationship between what is being selected for and what is being measured);
3. the genetic covariance between BF and LTGR ($\text{cov}_A(BF,LTGR)$).

The value calculable from the solution of simultaneous equations for $b_{DG}$ is:

$$\frac{\text{cov}_A(DG,LTGR)/\sigma^2_P(DG) - \text{cov}_P(DG,BF) \times \text{cov}_A(BF,LTGR)/\sigma^2_P(BF)}}{(1 - r^2_P)}$$

(6.22)

and that for $b_{BF}$ is:

$$\frac{\text{cov}_A(BF,LTGR)/\sigma^2_P(BF) - \text{cov}_P(DG,BF) \times \text{cov}_A(DG,LTGR)/\sigma^2_P(DG) \times \sigma^2_P(BF))}{(1 - r^2_P)}$$

(6.23)

where $r^2_P$ is the important phenotypic correlation between the two elements in the index, DG and BF.

These example indices are, of course, simple, although they are of use; one limitation is that they only include information from the candidate. It can readily be understood that when an index must include multiple measurements and multiple traits in its objective, when economic values may be as important as the genetic parameters, and when information is coming in from many different sources, then the indices used in practice can become extraordinarily sophisticated, and handleable only by computer techniques.

**Selection objectives**

It is established that the fewer the selection objectives the faster the rate of improvement in those chosen. Priorities must therefore be set at the outset of the breeding programme.

There are three broad areas:

- reproductive traits;
- meat quality;
- efficiency of growth;

and two broad criteria:

- monetary worth;
- potential rate of progress.

Taken separately, the same unit of additional financial return can be obtained by about 20% improvement in daily live weight gain, 4% improvement in feed conversion efficiency, 3% improvement in carcass lean percentage or 7% improvement in litter size. For growth rate, a rate of improvement of around 20g daily live weight gain annually appears to be readily achievable by breeders and shows no diminu-
Concentrated selection for carcass lean percentage appears to be able to accumulate up to 1% unit of lean annually in fat pig stocks. Limits to the amount of improvement possible for reproductive traits remain to be explored. Litter size may be increaseable by 0.1–0.2 piglets annually with the help of BLUP, and it has been shown that faster rates may be possible.

Achievement of improved carcass lean percentage by reduction in appetite and growth rate with no change in feed conversion efficiency is clearly less beneficial than improvement of carcass lean percentage by increase in lean tissue growth rate which is also positively associated with feed conversion efficiency and daily gain. The rate of change in one character as a result of selection for another character relates to the intensity of selection, the heritabilities of the two characters, and phenotypic variance and the genetic correlations. Where there is a positive correlation between traits selected for, then parallel or mutually enhancing progress is obtainable. However, when there is negative correlation, progress in one set of traits can adversely affect another set of traits such as, for example, where selection for carcass characteristics may be negatively correlated to reproduction traits. Selection for leanness and against backfat, bringing with it the correlated response in appetite reduction, will result in a negative association with reproductive traits. This may be due to a predisposition to inadequate body condition on the part of such pigs, or to more complex hormonal interrelationships. Whatever the cause, if breeding performance is to be maintained in such strains, substantial improvements in management, nutritional and health practices are a minimum requirement. Where selection has, on the other hand, been for lean tissue growth rate, and there has been no negative correlated response in appetite (indeed, often the reverse as lean tissue growth rate and feed intake tend to be positively correlated), and where severe reductions in body fatness have not been sought in the selection regime, then correlations with reproductive traits (litter size, birth weight, lactation yield) appear to be either absent or positive – the latter being unsurprising in the event of an increase in growth rate, appetite and mature size.

Table 6.8 shows responses to selection for four characters each selected alone under *ad libitum* feeding conditions. The table shows that selection for daily gain

<table>
<thead>
<tr>
<th>Character responding</th>
<th>Daily live weight gain alone</th>
<th>Reduced backfat depth alone</th>
<th>Feed efficiency alone</th>
<th>Lean tissue growth rate alone</th>
<th>Increased appetite alone</th>
<th>Index 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily live weight gain</td>
<td>++++</td>
<td>--</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Lean tissue growth rate</td>
<td>++++</td>
<td>+</td>
<td>++</td>
<td>++++</td>
<td>+++</td>
<td>++++</td>
</tr>
<tr>
<td>Reduced backfat depth</td>
<td>--</td>
<td>++++</td>
<td>++</td>
<td>+</td>
<td>--</td>
<td>++</td>
</tr>
<tr>
<td>Increased appetite</td>
<td>+++</td>
<td>--</td>
<td>--</td>
<td>++</td>
<td>+++</td>
<td>++</td>
</tr>
</tbody>
</table>

1 Index including values for live weight gain, lean tissue growth rate and backfat depth.
alone will have positive responses in terms of lean tissue growth rate and appetite, but the pigs will get fatter. Selection for reduced backfat alone will bring about reduced daily live weight gain, reduced appetite and have only a small positive effect on lean tissue growth rate. Selection for feed efficiency alone has only slight consequences for each of the characters, on account of the conflicting influence of gain, appetite and fatness on efficiency – but appetite is reduced. Selection for lean tissue growth rate alone has similar effects to selecting for daily live weight gain alone. Selection for increased appetite alone will produce fast growing but fat pigs. It will be noted that only by use of a properly constructed index can optimum gains be ensured in the overall breeding objective.

It is entirely sensible that most genetic improvement over recent years has been made in reduction of fat, as this was clearly the most immediately cost beneficial change. The position is augmented by the high heritability of this trait which has allowed a rate of change of about 0.5 mm P2 (or 2.5%) backfat reduction annually. Potential progress for further backfat reduction in some pig populations is now greatly diminished, however; present levels having been reduced to 8–10 mm P2 are now approaching the minimum necessary for adequate meat quality. Further improvements in carcass leanness in the future are likely to be made through positive change in carcass yield and negative change in carcass bone content.

Although the potential for further progress in fat reduction is somewhat limited in many north European pig stocks, there remain large improvements possible for most other pig types world-wide. There is no evidence yet of any diminution in rate of change possible for traits associated with increased lean tissue gain, and as these are being selected upwards there is no reason to suppose any immediate limit, provided, of course, that restraints are not placed on positively correlated traits; if appetite were restrained, then further improvement in growth rate would be limited.

For optimum production of meat the selection index is likely to take into account:

- daily live weight gain;
- fat depth;
- percentage lean;
- daily lean tissue growth rate;
- eye muscle area;
- ham shape;
- muscle quality;
- fat quality.

The relative importance of meat quality (eye muscle area, ham shape, muscle quality and fat quality) in comparison to lean growth (daily live weight gain, percentage lean and daily lean tissue growth rate) varies greatly. In some countries the former group of qualities are unrewarded at the point of slaughter and therefore considered unimportant to the producer. In other cases meat quality is prerequisite in a slaughter pig to the extent of these characters being handled as criteria for independent culling. There is reason to believe that the shape of pig types such as the Large White and Scandinavian Landrace can be improved by selection, and some
such types are now coming forward without having had gene importations. Most well-shaped White breeds have, however, been created through gene importations from Pietrain or Belgian Landrace types.

The accumulation of all these various production characters together need not always seriously detract from progress in any one. Rather they may be supportive of each other when positively correlated, as are live weight gain, lean tissue growth and lean percentage, and also as are eye muscle area and ham shape. The proposition, as has been shown in Table 6.8, that selection for fat depth alone may bring with it the negatively associated traits of reduced daily gain and appetite supports the view that these characters should be included in the index in order to stop reversion. Some indices also include feed conversion efficiency, but this can be a complicating factor as it is itself a compounded value which is liable to be influenced by a number of disparate characters.

Meat quality is only now receiving a measure of attention as a selection objective. As usual, the first response of breeders to consumer interest in meat quality has been to look for quick solutions through the importation of genes from other breeds. The use of the Duroc in the sire line has been considered as a way toward rapid improvement of the eating quality of fresh pork products from the Large White and Landrace breeds.

For many years halothane positive pigs (nn) were used in the male line to impart qualities of muscle mass and carcass yield to a heterozygote (Nn) slaughter generation. It was thought that the Nn type not only had lost the propensity to PSS, but was also clear of PSE meat quality problems. Unfortunately, the latter was found not to be the case. Nn types were intermediate for meat quality traits between NN and nn. PSE and PSS are linked with the ‘halothane gene’ to high lean percentage, large muscles and improved killing-out percentage. It would appear that only about one third of the positive characteristics (but probably more than two thirds of the negative characteristics) are directly linked to the gene. DNA fingerprinting to identify the HAL 1843 gene will permit removal of the halothane gene and therefore resolve genetically associated PSE and PSS problems, but will leave more than half of the benefit to carcass quality in terms of muscle mass.

Within-population selection for intramuscular fat may be worthwhile, and although there is close association between intramuscular fat (a possibly positive attribute) and subcutaneous fat (a definitely negative attribute), some strains of the Duroc breed do suggest that this association can be weakened. Many types of Duroc carry almost twice as much intramuscular fat as many modern populations of Large White and Landrace, but only around 25% more subcutaneous fat. The cost in terms of other selection objectives foregone while intensive selection is made simultaneously for intramuscular fat and against subcutaneous fat might, however, be extortionate. Beyond fatness, it is possible that in the future there may be successful selection for other aspects of meat quality, given the present levels of improvement in knowledge about the causes of tenderness and flavour. Besides, there is ample evidence to suggest that tenderness and flavour could be readily and greatly improved by attention to the pre-slaughter, slaughter, meat packing, meat retail and
household cooking aspects. Until these standards are improved, perhaps there is little merit in creating a superior genotype for tenderness and flavour.

Genetic improvement in meat quality is likely to remain for a little while yet at the level of a search for breeds possessing particular attributes of flavour and tenderness, and the incorporation of these into the male lines. However, in the long term it is possible to envisage a programme for the improvement of meat quality by within-population selection. There is some evidence that susceptibility to androstenone and (more seriously) skatole taints is a heritable trait. Selecting for ability to clear skatole from the system, or for a resistance to creating or absorbing skatole, would appear beneficial.

Improvement in reproductive performance has a remarkably high pay-off, but until 1980 or so had been avoided as a selection objective by managers of breed improvement programmes. Not only is heritability low, but also the trait is sex limited. Because measurement of the breeding value of a boar for reproductive characteristics can necessarily only be made by measurement of relatives and progeny, many litters are required before a dependable view of a candidate can be obtained. These problems are exacerbated by a long generation interval. In the past within-population selection programmes for reproductive traits at nucleus level had been side-lined, and the need to incorporate litter size and number of litters per year into a selection index had been given low priority. Instead:

1. New genes have been sought and incorporated from renowned prolific breeds such as the Large White and some Chinese types.
2. Heterosis is employed in breeding programmes by the crossing of White breeds, and use of these F1 hybrid crosses as parents for the slaughter generation.
3. Special herds of super-prolific sows have been created from the results of searches through many thousands of pigs for individuals showing quite exceptional reproductive performance, such as four litters with more than 14 piglets born (and now presumed to carry a gene of large effect for ovulation rate or embryo survival). The outstanding individuals are bred together by back-crossing to form the core of a hyperprolific dam line which may have up to two piglets more born per litter. To maintain health status the genes from this line are then moved into the conventional nucleus herds through the medium of artificial insemination and hysterectomy. The down-line expectation from this tactic is around 0.25–0.75 more piglets per litter at final parent level. Theoretically, this procedure could be handled continuously, but it takes about 6 years of back-crossing and testing to secure hyperprolificacy in the genome for a benefit of about one piglet per litter, which is somewhat slower than conventional selection using modern techniques.

All these policies have been, to some degree, useful, but equally all suffer from failing to achieve year-on-year progress. For further improvements in reproductive capacity there is no avoidance of within-population selection (with the possible exception of genetic engineering techniques which are not yet available), and now
all the leading breeding companies are making strong selection for reproductive efficacy by generation-upon-generation improvements from the additive genetic variance available in this trait.

The most appropriate reproductive trait for selection is probably litter size, as this at least is relatively easily measured. Modern breeding programmes can now incorporate litter size, and other reproductive traits if required, into indices used for selection in the female line. The present acceptance of reproductive characters into the suite of selection objectives by contemporary breeders is due to two recent advances. First, better environmental and management control procedures are allowing a significant reduction to be made in the size of $\sigma^2_E$ and a consequent lift in heritability from around 0.10 to above 0.20. Second, the use of the computer and best linear unbiased prediction (BLUP) statistics, by incorporating additional information from many relatives, times and places, avoids the need for lengthy generation intervals and tedious progeny tests of the prolificacy of a sire’s daughters. Together with BLUP, the restricted maximum likelihood (REML) statistical method for estimating parameters raises accuracy of determination ofheritabilities and covariances, and effective $h^2$ values under REML procedures may rise above 0.25. BLUP is likely to realise significant improvements in litter size and other fertility rates over future years. BLUP and REML technology may allow a rate of improvement of 0.2–0.3 piglets per litter per year if litter size is the only selection objective in a population of 1000 breeding sows or more. With a mixed model in which fixed management effects and random genetic effects are estimated at the same time, and where selection for traits other than litter size also must be accommodated, rates of improvement of 0.20 piglets per litter per year have been predicted, but are yet to be proven. It is conceivable that selection for ovulation rate alone would result in an early loss of response and a plateau in litter size improvement due to the countering forces of embryonic losses and limited uterine capacity. Litter size is a compound trait which requires at least four separate elements to be simultaneously improved (ovulation, fertility, embryo survival, uterine capacity). Selection for litter size (rather than its component parts) should ensure progress in all the associated traits required and there is no reason to believe that litter size response will plateau in the near future. Fourteen rather than twelve functioning mammary glands may become an essential component of a breeding sow.

The progeny and performance test

The progeny test post-Bakewell was reinvented by the Danes in the early years of the twentieth century. Central progeny testing, being expensive but accurate where the effects of environment must be minimised, is most preferred for traits that are sex-limited and lowly heritable, such as litter size and milk yield. The progeny test using central testing station facilities for identification of superior sires with regard to growth and carcass quality traits was used with great success in Denmark through the middle decades of the twentieth century, and was responsible for creating the Danish Landrace pig type and the excellent lean Danish bacon by Wiltshire cure
which was derived from it. The progeny of candidate sires were sent for central testing where, in one common environment, growth and carcass characters were assessed, primarily through an index of feed efficiency and leanness. One of the attributes of the scheme was the large population size made available on account of all nucleus breeders contributing to the scheme and being ready to use the proven boars provided from the scheme.

The exorbitant costs of central progeny testing have necessitated a more realistic approach and the evaluation of progeny in their herds of origin. This requires:

1. an effective artificial insemination service to use improved males across a multi-site nucleus;
2. genetic connection between different geographical locations by the wide-ranging use of sires being evaluated;
3. sophisticated computer techniques to handle the records; and
4. BLUP evaluation techniques to cope with the statistical methods required to generate a sire breeding value from as many relatives as can possibly be accommodated, and also to take into account the differences between farms, seasons, generations and times.

The availability of these facilities has now led to the demise of central progeny testing and of contemporary comparison testing for the selection of reproductive traits in pigs. Now combinations of performance and progeny testing are in use in nucleus herds of female lines for purposes of the improvement of reproductive traits especially through the use of REML and BLUP procedures.

Performance testing of the modern era probably originated in the USA amongst Duroc breeders. Certainly it was the North American pioneers of the application of genetics to pig breeding – Hazel, Lush and Dickerson – who clarified the potential of performance testing. They saw the possibility of examining more individuals and reducing the generation interval. More rapid progress can be made in the growth and carcass traits of moderate/high heritability by performance test than by progeny test. The American breeding plans were developed further by Dickerson, by Fredeen of Canada and by European geneticists such as Clausen, Jonsson, Johansson and Skjervold in Scandinavia, and Falconer, Robertson, Smith and King in the UK, and by the disciples of these latter, such as Brascamp, Bichard and Webb.

During the 1950s and 1960s, central testing stations were set up throughout Europe and also in North America on the Danish pattern. None of these schemes was as successful as that of the Danes. The Danish scheme was centrally controlled by Danish Slaughterhouses, a single autocratic organisation with a clear view of a limited goal (Danish bacon for exports) and with the ability to organise the distribution of improved genes through a breeding pyramid which concentrated the best genes in the nucleus herds.

A typical performance (and sibling) testing operation on a national scale would involve the setting up of a number of central test stations to which were sent (usually) four siblings: two entire boars (the candidates), a castrated male and a female. The candidates joined as large as possible a population of contemporaries,
all to be tested and compared under the same conditions of place, time, environment, nutrition, health and management. Pigs would be entered at around 25 kg and a test begun at a given set weight (30 kg). After being grown to a second given set weight (100 kg) individual daily live weight gain and ultrasonic backfat depth (and muscle depth) would be determined for individual pigs, and feed consumption and feed conversion efficiency measured for individual candidates or for a sibling group. The candidates would be assessed for physical competence, including type, legs, feet, number of nipples and so on. The castrated male and female would be similarly measured for their performance, but would then be slaughtered to yield sibling data on killing-out percentage, lean meat percentage, fat content, muscle quality, eye muscle depth, shape of ham and other associated carcass and meat quality characters. Breeding value is estimated from the index score, which would be constructed for each candidate male, built up from all of the information available from the quartet, and expressed as a deviation from the mean of contemporaries on test.

Boars of proven excellence are then available for return to their original owners and use in pure-breeding nucleus herds or sold for use in other pure-breeding nucleus herds. Boars proven to be good but not outstanding would be sold to commercial producers for siring cross-bred slaughter pigs. Boars shown to be of less than average quality would be slaughtered.

Alongside the central test for males, the females would be performance tested on the nucleus unit of their origin. Selection rates would not be high, and this element of the scheme would contribute only a small proportion of the genetic gain. After an initial sorting based on conformation, legs, feet and nipples, females would be evaluated for their weight for age and ultrasonic backfat depth, and ranked according to a simple index. If required, the index could include litter size of origin and some assessment of the dam’s general prolificacy.

Such a scheme (but without litter trains) operated in the UK through the second half of this century under the Pig Industry Development Authority and later the Meat and Livestock Commission. It was instrumental in creating the rapidly developing nucleus pure-bred herds which later became seminal to the UK breeding company structure. From 1980 onwards it has had to be realistically accepted that the scheme foundered due to the lack of candidate sires coming forward. The scheme has been the victim of its own success. The breeding companies have themselves adopted similar schemes for use in-house and the performance test (especially for growth and carcass quality traits) remains central to company progress by genetic selection.

The withdrawal of progressive pig breed improvers from the UK national scheme and the setting up of their own schemes in the context of independent and competitive trading was hastened by four further issues:

1. The testing regime was particularly targeted to the improvement of carcass quality and was having no beneficial effect upon daily lean tissue growth rate. The breeding companies, on the other hand, were already beginning to iden-
tify that their grandparent stocks were approaching the minimum levels of backfat depth that could be acceptable within the constraints of carcass quality, and their main interest was now turning away from lean percentage and toward lean tissue growth rate, conformation, meat quality and reproduction.

(2) The national scheme was naturally biased towards general national needs. However, the breeding companies were already embarking on individual objectives. The export market, for example, requires particular qualities not always recognised as priorities nationally; for example, ham shape and muscle size were peripheral to UK requirements, but seminal to those of Europe.

(3) Central testing represented a real health hazard due to the mixing of animals on test from many farms of origin. As health in their stock is prerequisite to breeding companies selling on to other producers a live pig product, the notion of bringing into nucleus herds sires that had been exposed to a range of diseases during test was an anathema.

(4) Breeders recognised that the test regime used was not best placed to make effective selection of characters now of primary interest. A genotype–environment interaction effect had arisen between the national test and the customer base. BLUP with ‘on-farm’ testing was shown to give faster rates of gain than the central test.

There may be a realistic continuing role for a national central facility for carcass evaluation. It is true that ultrasonic techniques can measure fat and eye muscle depth, and even assess muscling of the ham. With ultrasonics, an excellent prediction of lean tissue mass (and hence lean tissue growth rate) can be provided from measurements on the live animal; the need to slaughter in order to determine body composition is now much reduced. However, these predictions are themselves dependent on regression equations, and these equations must be determined from data sets including information from both live and slaughtered animals. Not only is a central carcass analysis service highly effective at providing data for building these regression relationships, but also these relationships are themselves:

- breed type specific;
- company specific;
- liable to change over time as genetic progress is made.

Therefore a forward-looking breeding company needs to maintain a continuous flow of sample animals for full carcass analysis so that (1) the prediction equations that are used in indices for assessing sire candidates can be kept up to date and accurate, and (2) carcass and meat quality characters determinable only on the dead animal can be measured and monitored.

If ultrasonic technology has allowed good prediction of body composition of live animals, technology to assess killing-out percentage, cut-out values, shape, balance of high-price cuts, proportion of bone and so on is less well advanced. Slaughter of sample animals from candidate sires is prerequisite if any assessment is to be attempted of breeding value for such characters as fat quality, muscle colour, muscle
tenderness, water-holding capacity, intramuscular fat levels, absence of taints and the like.

National schemes for performance testing at central facilities would only have a continuing place in breed improvement where:

- there is a clear need to change the whole population of a nation’s pigs in an agreed direction, and where the selection objectives are few;
- a scheme is needed to encourage new entrants into the breeding business;
- there is a wish to attempt to rank and compare different nucleus units within a breeding company, or different breeding companies within a given market environment;
- a carcass dissection and meat quality facility is needed to service pig breeders;
- there is a national structure that promulgates improved genes in such a way as to ensure unidirectional movement which avoids dissipation of excellent genes to non-nucleus breeding stock; in effect, where there is a determined and controlled breeding pyramid.

A pyramidal breeding structure (Figure 6.17) is needed for both national and company schemes. The notion rests on the simple premise that the most excellent genes should be maintained in the nucleus for improving that nucleus. The improved genes are then multiplied up and moved down to commercial level. This does create a degree of genetic lag, as it takes time for improvements to filter down from great grandparent nucleus level to parent level and the slaughter generation – often 4–5 years. However, once initiated, progress is maintained year-on-year.

The mainstay of central testing philosophy is the reduction of environmental effects and the placing of all candidates in the same environment to allow equal opportunity to express genetic merit. Outstanding questions remain of genotype–environment interactions and the suitability of one test regime to all candidate types. There also remain serious questions relating to herd of origin effects, where success on tests is rather too closely related for comfort to pre-test environment and treatment, although this latter can be countered by starting at an earlier age and lighter weight, and by the use of BLUP models. It is disturbing to note that

![Breeding pyramid](image)
the correlation between conventional test and a modern test with BLUP and earlier start to reduce pre-test effects may be as low as 0.5, rather suggesting that the conventional test was not specially effective. The ready availability of BLUP, which corrects for differences in time and place and allows non-contemporaneous comparisons of individuals, has now rendered both contemporary comparison and central testing largely defunct. All that is perceived as requisite are genetic linkages across herds in different places and times, and this may be achieved readily by ‘sire referencing schemes’ and by the distribution of artificial insemination from a central boar nucleus across a number of breeding sow nucleus herds. BLUP together with AI fully supports the large (but dispersed) nucleus approach for breeding improvements now adopted by the larger breeding companies.

The loss of the pivotal role of central national testing in contemporary pig breed improvement should not be taken to imply any dilution of general national breeding effort, rigour, intensity or accuracy. Rather the reverse, only the activities of the test station are now mostly handled in-company, on-farm. Most breeding companies are pursuing, with even greater effect, the same performance testing protocols so painstakingly set up by the erstwhile national schemes.

The test regime

Selection objectives will interact with the test regime, and the test regime deeply influences the character actually selected for. Clear indicators came from the original UK national scheme whose index purported to advance growth rate, feed conversion efficiency and carcass quality, but which advanced only backfat reduction, growth rate remaining unaltered over all the years of the use of the index and there being no efficiency effect occurring independently of that created by backfat reduction.

An index weighted towards growth would allow fatness to increase if feed was offered *ad libitum*, but would not allow fatness to increase if feed was offered at a restricted level. In populations that are no longer overfat, it is reasonable to select positively for appetite, which requires both measurement of individual feed intake and index weighting towards growth. Indices in which low fat depth and good feed conversion efficiency have high economic weightings will bring about appetite reduction when used in populations of fat pigs. Because positive selection for lean tissue growth rate, together with positive selection for muscle size and ham shape, is likely to predispose the population to a fall in meat quality, then meat quality characters are worth weighting heavily in an index used for populations of lean pigs with already excellent growth and muscle size characteristics.

Test regimes offer many and varied possibilities, from which may be taken, amongst others, any combination of the following:

- **Start**: age; weight; weight within a given range.
- **End**: time from start; weight; consumption of a given amount of feed.
- **Feed intake**: severely or moderately restricted; to appetite; *ad libitum*. 
Diet: high density; low density; average density.
Select for: leanness; lean tissue growth rate; lean tissue feed conversion.
Select against: fatness; poor feet and legs; low meat quality.

The earliest possible start weight, within a given range of age, is beneficial only so long as the increased susceptibility of the young piglet to disease and environmental abuse does not adversely influence the test by increasing variation. Start weights of 30–35 kg are conventional, but in excellent facilities 20–25 kg may now be possible. For measurement of growth traits, the test end should be as far distant from the start as possible within the bounds of costs and the need to minimise generation interval and the disposal of culls. The longer the test period, the more accurate can be the measurement of growth characters. The test should not, of course, continue after growth impulsion has diminished, because the sensitivity of the test will be reduced, and the separation of candidates into rank order will be less effective (Figure 6.18).

End of test is most conveniently fixed as a given number of days from the start. This helps management and planning, and facilitates the use of a fixed-feed, fixed-time ration scale where all pigs get the same feed allowance which is incremented weekly regardless of pig weight. Most tests are continued for 10 or 12 weeks, targeting for end weights in the region of 90–120 kg (the better candidates being heavier).

Termination of test by weight appears convenient from the point of standardisation of carcass attributes, but in fact it is unsatisfactory for the interpretation of growth rate and feed intake data due to various candidates finishing at different times and having eaten different amounts of food. Adjustments to measurements of backfat thickness to allow for the effects of pigs finishing at different weights can, fortunately, be readily and accurately made from knowledge of the relationship

Fig. 6.18  Length of test appropriate for two pig types (a) and (b).  x and y indicate the respective appropriate test lengths.  To test population (b) over the same length of time as (a) would discriminate against (b), while to test (a) over the same length of time as (b) would fail to optimise.  In both cases the period of testing includes a small part of the acceleratory phase of growth as well as the linear phase.  The figure shows how difficult it would be to devise a single test regime suitable for two different pig populations.  Tests should be designed to be population-specific and used only to rank candidates from within a single population.
between weight and fatness for the population concerned, and this may be obtained by the simple expedient of determining the regression of backfat depth upon live weight. One such estimate, for example, would predict P2 to rise by 0.15 mm for each kilogram increase in live weight for pigs in a particular population finishing test at around 100 kg. This coefficient would be expected to be higher for fat populations of pigs and lower for leaner populations. Such regressions, whilst convenient, can become a source of error as they are often specific to particular genotypes and environments, and are not accurate in any general way.

The amount of feed consumed by candidates on test has interesting repercussions for the interpretation of the test (Figure 6.19). Feed intake during early growth (L) is inadequate to distinguish between the two candidates (a) and (b). Over the period (M) during which feed intake is adequate to maximise lean tissue growth rate for candidate (b), the test progressively better differentiates between the two types. Over the period identified as L, pigs with larger appetites will have faster lean tissue growth rates; thus these pigs will be favoured even though subsequently the maximum lean tissue growth rate may not be greater for such candidates. If this is the case the test loses accuracy as the two characters tested (early appetite and maximum lean tissue growth rate) are confounded.

Figure 6.20 shows how if both candidates eat the same amount of food, providing that amount is in excess of n, then candidate (b) will lay down more fat, and fat depth comparisons positively assist in differentiating the two different lean tissue growth rate genotypes. If, however, candidate (b) eats less than candidate (a), then it will not necessarily be fatter. Optimum feed intake to separate the two candidates is at the beginning of the intake phase identified at n, with both candidates eating the same amount of food. Pigs with large appetites allowed to eat more food on test than contemporary candidates may combine fat accumulation with improved lean tissue growth rate (Figure 6.20). It is because of this sort of response that feed intake should be either fixed and equal for all candidates or known for each individual. Ad libitum feeding systems for candidates housed in groups are particularly difficult to
interpret, and it has been estimated that measuring daily feed intake can add 25% or more to the accuracy of selection of nucleus stock for improved growth rate.

Contemporary test regimes may often use one or other of the following feed allowance systems:

1. All candidates are provided individually with the same levels of feed on a time-based feed scale over a fixed time period. For example, 1.5 kg daily for the first week, incremented weekly by 0.15 kg over a 10-week period. If the scale chosen is readily within the appetite of all candidates, then feed intake will be guaranteed to be identical for all pigs, but some candidates with particularly high lean tissue growth rates may not be able to fully demonstrate their true genetic worth.

2. All candidates are provided individually with levels of feed to allow appetite expression for pigs with good appetites. This scale is constructed similarly to (1) above, but with greater weekly increments. Pigs with lower appetites refusing feed will be assumed to have eaten that feed. Such a scheme will favour animals with high lean tissue growth rate potential and high appetite.

3. Candidates are fed individually according to a weight-based or metabolic weight-based scale such as $0.12LW^{0.75}$. A tightly restricted feeding level would be ensured at $0.10LW^{0.75}$, while $0.14LW^{0.75}$ would ensure a scale close to or above ad libitum. Feeding a group of candidates on a weight-based scale related to the average of the group would, of course, be nonsensical. Weight-
based scales have the consequence of according to faster growing, heavier pigs the greater feed allowance for which they have demonstrated a need. This avoids the time-based feed scale problem in which the smaller (poorer candidate) pigs are offered the same level of feeding (and therefore effectively more feed) than the larger (better candidate) pigs, thus favouring the poor and penalising the good. The evidence, however, does not confirm the practical reality of this effect. Feeding to a time-based scale pressurises the good pig to grow lean from its limited ration, whilst the poor pig is encouraged to grow fat – thus helping to differentiate between them. It is also the case that time-based scales need not be restrictive on the better pigs if that scale is generously allocated as for case (2), in which the needs of the better pigs with the larger appetites should be the basis for the decision about the size of the weekly increment.

Further, in practice, the weight-based scale may do no more than spend 9 weeks of test reinforcing the first week’s performance, which often is the arbitrary result of a range of non-genetic effects. Good performance in week 1 ensures a slightly heavier weight at the end of the first week, and this will then be immediately rewarded by a greater feed allowance than given to competitive candidates. This greater feed allowance now encourages superior gains to be made. The weight-based feeding scale is therefore open to the serendipity of the early phase of the test, rather than utilising the whole span of the test for pig differentiation. Additional problems of the weight-based scale are:

(a) the need to weight all candidates at least weekly;
(b) the problem (impossibility) of interpretation of the feed intake data in order to make proper between-candidate assessment of performance;
(c) the need to individually calculate and individually allocate the feed allowance to each pig, with the result that there may be as many different daily feed allowances in the test house as there are pigs!

The ultimate in apparently sensible, but in reality disastrous, test regimes is the one that is operated on a weight-based feeding scale to a fixed end weight.

(4) Candidates are housed in groups and fed *ad libitum*. This reflects most closely the likely production environment, but suffers from the disadvantage that individual feed intake is not known. It is, however, a simple method to manage and, where the main selection pressure is on reducing the fatness of pigs, can be effective, providing that some degree of appetite reduction is an acceptable consequence. Although not as sophisticated as method (2) above, this choice of rationing may be more accurate if the management structure cannot cope with individual candidate feed provisioning.

(5) Candidates are housed in groups and each pig fed *ad libitum* through the medium of an electronically controlled feeding device which identified each individual candidate, allowing continual access for voluntary feed consumption. The computer controlled system logs the daily individual pig-feed intake. It is evident that this system contains within it all the advantages and none of
the disadvantages of the alternatives described above, and therefore has much to commend it. There are, nevertheless, provisos:

(a) the equipment is dependable;
(b) the possibility of adverse selection for behavioural aggression is avoided.

This last point is made on evidence that aggressive individuals may deny access to the feeder by those pigs that are more placid. This results in feed being available *ad libitum* only to the more aggressive animals, which would be counterproductive for group performance.

At present the most favoured regime for an index with positive pressure upon improvement of lean tissue growth rate would appear to be either scheme (2) [the development of scheme (1) which helps to improve appetite] or scheme (5), both being operated from a fixed weight at start and conducted over a fixed time of 10–12 weeks.

So far the discussion of feed regime has rested on the assumptions that the index targets for selection will be either a reduction of backfat through appetite reduction (see Figure 6.20, B toward A) or an increase in lean tissue growth rate (Figure 6.19, (b) toward (a)). The case of fat reduction at lower feed levels, however, has not yet been dealt with. It will be noticed in Figure 6.21 that the ratio of fat to lean has been represented as not changing at feed intakes between O and Q for either pig (a) or pig (b). If this level of fatness is satisfactory for meat quality, then clearly no action is necessary. However, in some traditional pig types (and certainly in most pig types before the modern era of selection against fat) even the amount of fat grown by pigs in circumstances of limited feed supply is more than that required by the customer/consumer. Reduction in fat at lower feed levels requires a change in the metabolism of the animal such that feed is diverted from the production of fat to the production of lean so that there is an effective increase in the regression slope of daily lean gains on feed intake and an effective decrease in the regression slope of daily fat gains on feed intake, with a consequential improvement of the fat:lean

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![Fig. 6.21](image) **Fig. 6.21** At feed intake levels that support lean tissue growth rates which are less than the potential (feed intakes of less than Q), the fatness of pigs (a) and (b) can only be reduced by achieving a change in animal metabolism and the favourable partitioning of feed away from fat toward lean, as shown by the arrows.
ratio in favour of leanness. This description is typical of the different behaviour of castrated and entire males, and also of ordinary pigs and those to which porcine somatotropin has been administered. It appears from past experience that selection against fat on a restricted feeding regime may well bring about these changes in the population, and that such did indeed occur in some of the early central test selection programmes. For most improved contemporary pig populations, however, the problem of fatness at limited feed intakes should no longer exist.

Choice of diet requires a view on genotype–environment interaction effects, as have been discussed earlier. Where there is a particular need to identify genotypes that are especially competent to deal with forages there may be merit in considering a low density diet. However, in general, traits such as lean growth rate, feed efficiency, fatness and meat quality are likely to be best expressed on diets of high quality. The use of the average diet of the industry where the industry itself tends to be conservative with regard to diet quality may well only ensure slow genetic progress and perpetuate an unsatisfactory situation for the industry concerned.

**Future objectives for within-population selection**

Before 1980, primary selection objectives in northern Europe were for fat reduction. Test regimes were chosen to achieve this and, by and large, were successful. Over the last decade, emphasis has changed to enhancement of lean tissue growth rate with associated increases in appetite, and continued improvement in feed conversion efficiency (the latter now consequent upon a reduction in maintenance requirement due to more rapid growth to slaughter, rather than as previously upon a reduction in the rate of fat deposition). There are developing contemporary interests in selecting in the female more strongly for reproductive capacity and longevity, and selecting in the male for muscle size and shape independent of the halothane gene, and also for meat quality. These characters have already been added to lean tissue growth rate, and are now the important issues for considering in the index. However, the industry is not yet particularly well advanced in the identification of appropriate testing regimes to facilitate the maximum differences between candidates for characters such as litter size and meat quality, and the determination of appropriate test regimes for individuals superior in these characters would benefit from attention. Health, in the form of both specific disease resistance and general robustness to environmental abuse, is likely to be an important preoccupation for the future. If fat reduction was the initial target for within-population selection, and if lean growth rate is the current target, then future selection pressures are most likely to be in the additional arenas of meat quality, reproductive rate and health.

Animals have evolved resistance to most diseases: of all the possible disease organisms, relatively few produce clinical symptoms and the majority of these will only do so when the host is compromised. The notion of selecting for disease resistance is therefore realistic. Resistance for specific organisms can indeed be selected for – as has been the case for *Escherichia coli* K88. Progress in human medicine is
leading to marker assisted selection for specific disease resistance, and this will give transferable benefit for selection against pig diseases with a clear genetic base.

An alternative approach would attempt to deal with the more conventional disease challenges to the pig’s respiratory, digestive and reproductive systems by selecting not against specific organisms (these being many and various), but rather for a higher general level of immunity – a more active and effective immune system. A strong immune response has been suggested as characteristic of the Duroc breed, and this has led to the production of dam-lines containing 12.5–25% of Duroc genes, and having a (purportedly) higher level of immune competence and disease resistance.

In an environment where there is a likelihood of a significant level of disease challenge, such as the world’s contemporary intensive pig industry, the notion of selecting for genetically improved disease resistance is attractive. It is well appreciated that certain genotypes are susceptible to certain diseases, and some particular syndromes may have a direct genetic cause consequent upon an abnormality on the chromosome (e.g. the fatal susceptibility to halothane gas, atresia ani and some hernias). It is also understood that susceptibility to a specific disease may be inherited – thus certain strains of pig are more susceptible than others to certain types of \textit{E. coli}. There is likely to be a range of genetically related susceptibilities to certain disease organisms, but by and large this phenomenon has been poorly researched.

Breeding to avoid disease susceptibility is no more nor less important than its obverse: positive genetic selection for disease resistance. There are a number of levels at which resistance to a disease may be shown: target tissues or cells may not respond adversely to a challenge from a disease organism or a toxin; or the immune system may be particularly competent or enhanced in some pig strains. It would seem self-evident that there will be a number of disease resistances with a genetic base which can be selected for in a population if they were to be identified.

Of special interest presently is the possibility that some strains of modern pigs may be more or less immunocompetent in a general (rather than specific) way. Anecdotal evidence would suggest that certain modern highly improved strains of pig have in some way carried through their improvement programme for specific growth and reproductive traits a progressive reduction in immunocompetence, and therefore a greater likelihood of suffering from disease when challenged. This has led to the presumption that some strains of pig may have become ‘soft’, and in order to thrive require higher standards of management and rigorous defence against challenge from high levels of disease organisms. In contrast, there are other strains/breeds of pig available today that are understood to be ‘robust’. Robustness or ‘rusticicity’ is exhibited by an ability to thrive in more challenging environments where management is less good and where there are a variety of disease challenges presented to the pig at high level. Whereas the ‘soft’ pig will go down with respiratory, alimentary or reproductive disease, the ‘robust’ pig will not. It may be presumed that these latter pig strains have in some degree a stronger general immune system. If this were the case, then selection for genetic strains with a higher level of immunocompetence would be a worthwhile breeding goal. Thus far there has been
little progress beyond the belief (backed by field experience) that there are strains of pigs which appear to show a higher level of general disease resistance than (particularly) some strains of improved ‘White’ pigs. Until such time as this phenomenon is confirmed, understood, its causes identified and a means of satisfactory measurement defined, there may be difficulty in pursuing a logical search for additive genetic variance and for progressive positive selection for the trait of disease resistance.

Breeding schemes

Logistics, not science, is the underpinning force of a successful breeding policy. Without a system for handling the details of livestock identification, classification and movement, the science is of little avail.

Combining together the three breed improvement strategies, (1) importation of new breeds, (2) selection within nucleus populations, and (3) utilisation of hybrid vigour, and then organising the subsequent supply of improved pigs through the system down to meat production level is a logistical exercise of scale and complexity which requires excellent management planning.

Use of a central testing facility by breeders (Figure 6.22)

Of the total population of pigs, a very small proportion is in the hands of breeders, but the influence of the breeder upon the efficiency of both an individual commercial grower and the national herd in general is far reaching. A national structure for pig improvement identifies superior individuals, helps to concentrate improved characters into nucleus herds and then allows improved genes to filter down from the pure-breeding nucleus herds through the multipliers and into commercial slaughter pigs. Alongside, central testing facilities – usually a Government or quasi-Government agency – help to identify the presence of genetic merit in pure-bred stocks and can compare the results of breeders’ efforts. The need for and effectiveness of a national test facility depend greatly on the individual country’s pig industry structure and the level of central control possible. There also needs to be a generally understood and agreed need to service the pig breeding companies and smaller nucleus breeders aspiring to become larger.

The independent pedigree (nucleus) breeder of limited herd size (Figure 6.23)

To achieve generation-by-generation progress in a population of foundation (nucleus) stock, the breeder will usually concentrate on a single pure breed and usually only on one type within that breed, taking the best individuals as parents for the next generation. Selection might be for one character, perhaps lean growth
Fig. 6.22 National structure for progressive pig improvement by identification, selection and dissemination of pigs of above average merit. Such structures may now be of historical interest only.

Fig. 6.23 Example breeding scheme for a small pedigree (nucleus) breeder ('boar sales' may be through the medium of live males or through semen for AI).
rate, or for a complex of characters by use of an index, together with positive selection for reproductive performance.

The pedigree breeder is always on the look-out for really outstanding individuals – males with very rapid growth, or females with extreme prolificacy – and once they have been found these individuals will tend to be held in the herd for as long as possible. If the rate of improvement slows, or a neglected character slips back, it may be opportune to import new genes into the herd in the form of stock from another breeder. The availability of semen from males of merit standing at artificial insemination centres makes this a relatively simple move.

The smaller breeder finds it difficult/impossible to make progress in reproductive performance for reasons outlined earlier. Many breeders therefore resort to a policy of ensuring merely that all candidates for selection are from reasonably large litters, which is unlikely to improve reproductive performance but may prevent its decline.

Growth characteristics are more easily tackled, and can be measured directly in both males and females. As the proportion of female candidates necessarily selected is large (about 20 times higher than the males), accurate testing is not particularly cost beneficial. Candidates for selection as breeding mothers may be taken from group grow-out pens at 80 kg or so, their growth rate being determined from their age and their backfat depth estimated with the use of an ultrasonic meter. Liberal feeding of candidate pens would ensure that no animal is prevented from demonstrating its potential because of an inadequate feed supply. However, where carcass quality is a significant factor in the value of slaughtered animals, a large number of fattening pens of pigs put onto an over-liberal feeding regime may be costly, as those females not selected as herd replacements may be down-graded at slaughter for being over-fat.

There is more reward for increasing the accuracy of tests for male candidates. A greater differential between selected animals and the herd average is possible as the numbers required are few, and the influence of the male on the herd is greater and longer lasting. Candidate males can be penned separately or in small groups of two or three brothers, so that some estimate of intake and feed efficiency can be made. In addition to growth rate, feed efficiency and ultrasonic backfat measurement, it is helpful if information about carcass quality is brought to bear from the less fortunate slaughtered relatives.

Central testing can offer help to pedigree breeders by providing facilities at which candidate males and/or their relatives can be grown and assessed. To test for carcass quality, slaughtered relatives can be dissected into lean, fat and bone, and the muscle quality assessed. At central testing stations the breeders’ stock can be scored in comparison to contemporary stock on the same test. On the basis of the score achieved, breeders can decide whether the animals should be returned to their herds or sold off. There can be a reciprocal arrangement whereby the central testing agency publishes the performance characteristics of animals tested. The information is of benefit to other breeders, and enables pigs of merit to remain in herds of merit. Some contemporary small breeders may find benefit in the central testing of siblings, but in combination with the on-farm testing of candidate sires.
Speciality lines may also be rewarding, such as types with especially high meat quality, or shape or ability to deal with extensive production systems. As always for the small business, a unique selling quality is essential if the large breeding companies are to be successfully competed against.

**The general approach of the breeding company (Figure 6.24)**

The companies have the advantage of size. With 1000 sows or more in each major nucleus, the benefits of picking a few animals from a large diverse population can be exploited, and there can be a wide difference between the best selected great-grandparent males and the average of the pig population upon which they are to be used. The breeding company is looking for a rapid turnover of animals of outstanding merit. Progress is made by frequent small steps forward, and the turnover time in such a scheme is crucial. Stock sires are not kept for as long as possible, but for as short as possible, so the next generation contributes its small effort to positive progress as soon as it is able.

Whereas the pedigree breeder stakes his or her reputation upon the sale of a relatively small number of males of outstanding merit, the breeding company is in the animal supply business. Breeding companies sell both males and females, often in the form of a stock package. The purchaser is offered brand-named parent females as herd replacements, together with parent males specifically bred as sires for use with the branded females. Breeding companies will also offer – at higher prices – grandparent stock to those wishing to breed their own replacements. Typical breeding company commercial products are shown in Figure 6.25.

The company therefore offers two services: (1) trouble-free provision of male (live, or by semen through AI) and female herd replacements, and (2) improved pig stock. However, it is only by the latter that the company will stay in business. It is fundamental to commercial success in the open market that the goods offered are demonstrably competitive in terms of quality and price, and a step ahead in terms of improved growth rate, carcass quality and reproductive characteristics. Breeding companies, because of their larger size and stronger financial base, will be able to test in their pure-bred nucleus herds to a much greater degree of rigour than smaller pedigree breeders. In addition, they will cash in on hybrid vigour by presenting a cross-bred female (and often also a cross-bred male) as the branded product.

Besides considerations of improved genetic merit, companies concerned with the sale and movement of stock are rightly preoccupied with the health status of the animals. Disease prevention and control will be a significant part of company policy.

The structure of the breeding company reflects its needs. Nucleus (great-grandparent) pure-breeding herds are maintained in strict isolation. Within these herds vigorous testing for growth, carcass and meat quality and reproductive performance is undertaken on both male and female lines. Selected out of these nucleus herds are the grandparent stock, a few of the best of which are used to refurbish the nucleus, whilst most others are sent to the multiplier herds which generate parent stock for sale. Because of health control, animals once shipped to multipliers cannot
Fig. 6.24  Example of a breeding scheme for a breeding company. E₁, E₂, and E₃ represent three different exotic breeds. E₄ represents the possibility of gene importations from types such as super-prolific females or specialty males. S represents a synthetic ‘sire line’ made from three exotics and the main breed type. The sire line should have outstanding growth and carcass quality characteristics. LW and L represent Large White and Landrace types, respectively, making up the ‘dam line’. These female lines should have outstanding reproductive (as well as growth) characteristics. These breeds are to serve only as examples, and in practice the nucleus pure-breeding herds will themselves be of synthetic composition and particular to the breeding company. (Breeding company ‘boar sales’ may be through the medium of live males or through semen for AI.)
come back into the nucleus. To improve reproductive performance in the nucleus herds, proven females may be contract mated to the best males and the offspring earmarked for selection back into the nucleus rather than going on to the multiplier phase.

The type of grandparent maintained in the nucleus herds has developed from three requirements. First, stock must already be of high genetic merit, but open to further improvement. It should not be assumed that nucleus grandparent stock is necessarily ‘pure-bred’; it may well have synthetic lines from a variety of origins. However, the term ‘pure-bred’ may be understood to cover breeding colonies where both the male and female are of similar genetic type, and they are bred together to yield offspring of similar type to the parents (although – if selected – hopefully also improved with regard to that type). Second, types chosen for nucleus herd must exhibit hybrid vigour when crossed. Third, the breeding company may wish to maintain a nucleus herd of a variety of breeds of pigs which might impart, currently or in the future, special characteristics into the final product.

A breeding company could keep, for example, two large nucleus herds, one of Large White type and the other of Landrace type. The nucleus breeding herds may number 250–1000 sows or more. The smaller breeding colonies of pigs, such as the Hampshire, Pietrain, Duroc, Belgian Landrace, Lacombe and Saddleback may be maintained to produce the male side of the sire line, or in hope of their being found useful, at some future date, as providers of characteristics such as hardiness, shape, lean mass and so on. Alternatively, or in addition, a line may have been developed that contains an amalgam of various breeds and this is then treated as if it were a new breed. The result is the creation of a new synthetic line, particularly appropriate as a top-crossing sire for the slaughter generation level. Now many of the breeding company nucleus stocks in the dam lines are also synthetic, containing, perhaps, mixtures of Large White, Landrace and Duroc genes.

It is often the case with breeding companies that their pure-breeding nucleus stocks are, de facto, synthetics, having been subjected to various gene importations. Thus, whilst a breeding company nucleus may be referred to as ‘Large White type’, these will not be the same as the Large White that might be found in a pedigree herd book, nor indeed the same as another ‘Large White type’ to be found in another breeding company. It is part of breeding company policy that its nucleus stocks are demonstrably different from those of the competition, despite the fact that they may be classified as ‘Large White-type’ or ‘Landrace type’ or ‘Meat-line type’. With breeding company nucleus stocks, it is best to consider each nucleus herd as a new and unique breed.
Figure 6.24 gives an example of how the organisation of a breeding company might be put together.

The products sold from breeding companies may be tested against each other in ‘national’ central testing facilities. The central testing agency would purchase from multipliers random samples of young females and would mate them with boars supplied from the company nucleus. The females could be tested for reproductive performance and their offspring for growth rate, feed efficiency and carcass quality. The naïveté of commercial product evaluation and the possibility of misuse of results therefrom has, however, been alluded to elsewhere.

Breeding companies create a progressively improving product (breeding female replacements, boars, semen for AI) that will sell in competition with others. Each breeding company has different selection goals, systems of management and trading policies, but all ultimately wish to maximise sales of product to commercial pig producers (mostly F1 parent females and top-crossing sires). To do this, the companies are organised usually into three production levels. At the top are nucleus herds of great-grandparent (GGP) pure-breeding populations of pigs, which are intensively tested and selected. From the nucleus, the next generation is involved in multiplying up and forming GP stock, which in turn moves to the multipliers. Multiplier herds organise the crossing of the grandparents and create the parent stock available for sale. These parents produce the slaughter generation.

Health status at the top of this pyramid is paramount and all herds are closed, any entry being only through hysterectomy, embryo transfer or artificial insemination. To transfer improved genes from the nucleus where they are first identified to the parent generation where they are used may take up to 5 years. This genetic lag time can be reduced significantly by cutting out the pure-bred multiplication phase at GGP/GP level, and creating instead a much larger pool of nucleus animals, but in which intensive selection nevertheless takes place at the expected nucleus level. From this GGP nucleus, improved stock can be moved directly to multiplication level. Maintaining such large nucleus herds and testing so many candidates at the maximum level of rigour and intensity is expensive, but the rate of genetic progress is much improved due to greater population size, more accurate measurement, a higher selection rate and a lower generation interval. The customer also benefits by the genetic lag time being cut to only 2 or 3 years. The widest possible distribution of genes of excellence by use of AI through the nucleus herds is an essential element of ‘fast-track’ schemes.

Breeding companies will be sure to utilise to the full all four methods for maximising improvement of performance by genetic means:

1. selection within populations;
2. incorporation of new genes by importation;
3. creation of hybrid vigour through cross-breeding;
4. the setting up of separate sire lines and dam lines, each allowing concentration on specific selection objectives respectively for the sires and dams of the final slaughter generation.
Selection objectives are likely to include:

(a) lean-tissue growth rate;
(b) economy of production and lean-tissue feed conversion;
(c) litter size;
(d) quantity, quality and distribution of carcass lean;
(e) control of the halothane gene;
(f) improvement of meat quality.

**Breeding lines (A–Z)**

Each breeding line is a population of a particular pig type. These populations are maintained in the form of pure-breeding nucleus herds of breeding females and males. The genes may, however, be composite mixtures from two or three separate breed types. A low level of Duroc genes may be introgressed into dam-line nucleus stocks, and the same method may be employed to utilise Meishan genes. In the sire-line nucleus stock, genes may be introduced into the basic Large White genome from breeds with particular qualities for leanness, for example the halothane-free Belgian Landrace type. Within each nucleus breeding line, a particular programme of selection is undertaken. The selection programme will not be the same for each of the lines, the lines having different end-uses. Males and females are passed from the nucleus to multiplier herds from where cross-bred parent females and terminal sires are made available for sale to customers (see Figure 6.25).

(A) **Dam-line males for cross-bred parent gilt production:**
   Landrace type: nucleus herd size 1000–2500 sows.
   Selection emphasis on growth and litter size (a, b, c).

(B) **Dam-line females for cross-bred parent gilt production:**
   Large White type: nucleus herd size 1000–2500 sows.
   Selection emphasis on litter size and growth (c, a, b).

(C) **Sire-line males for general purpose terminal sire production:**
   Large White type: nucleus herd size 500–1000 sows.
   Selection emphasis on growth and carcass quality (a, b, d, f).

(D) **Sire-line females for general purpose terminal sire production:**
   Large White type: nucleus herd size 500–1000 sows.
   Selection emphasis on growth and carcass quality (a, b, d).

(E) **Sire-line males for cross-bred terminal meat-line sire production:**
   Synthetic type originating from a mix of halothane positive breeds with high lean percentage and excellent muscle distribution: nucleus herd size 250–750 sows.
   Selection emphasis on growth and carcass quality (a, b, d, e, f). The halothane gene can now be wholly removed from all pig stocks.

(F) **Sire-line females for cross-bred terminal meat-line sire production:**
   Large White type: nucleus herd size 250–750 sows.
   Selection emphasis on growth and carcass quality (a, b, d, f).
Speciality line for cross-bred dam and sire production:
Duroc type: nucleus herd size 200–600 sows.
Selection emphasis on growth, carcass quality and litter size (a, b, c, d, f), and also for special qualities such as hardiness, suitability for extensive systems and muscle quality characteristics. (The Duroc can now be bred to be homozygous white in colour.)

Small breeding populations of different pig types: nucleus herd sizes 50–250 sows.
As the future need for these types is not known there is specific care for no selection objective to be pursued, but for maximum variation in the gene pool to be maintained.

Method

The method employed is that of especially high health status of all herds from nucleus, through multiplier, down to customer lever. There is a three-tier pyramid with large nucleus herds at the apex to maximise rate of genetic improvement and minimise the genetic lag between improved genes appearing in the nucleus and being passed on to the customer. Figure 6.26 shows the pyramid for lines A and B, producing the F1 hybrid parent female.

The various nucleus herds are supplied with genes through the medium of artificial insemination (Figure 6.27). Only the few best selected males from each of the populations (A to G) are available at the AI centre. The selection intensity for males is around 1% or less. BLUP methods are used to compare candidates from different nucleus herds within each line. Each of the lines A to F requires about 15 males at any one time at the AI centre. The boars are used for no more than 10 weeks, and only serve 40 sows each, in order to maximise the rate of genetic advance and minimise generation interval. Sixty males per year will handle, through AI, 1000 nucleus sows. Dissemination of semen of high genetic merit throughout the nucleus herds through AI is indeed seminal to breed improvement schemes.

Female selection takes place within each of the nucleus herds on the basis of an index combining litter size and lean growth, and using maximum information from as many relatives as possible. The proportion of females selected is around 40%.

Fig. 6.26  Breeding company three-tier pyramid for the production of hybrid parent females (courtesy: Cotswold Pig Development Company Limited).
Pigs are moved from the nucleus units to multiplier farms who hold grandparent stocks supplied from the nucleus. Rates of replacement in the herds should be about 100% annually for males and 50% annually for females. The grandparents are crossed to produce parent females and top-crossing sires available for sale. The latter may also be derived directly from nucleus level. Around 60% of cross-bred females born at multiplier level will be selected as appropriate for sale and use as parents of the slaughter generation. The remaining 40% will have been culled for inadequate quality of feet, legs, conformation, insufficient nipples or other such blemishes.

The commercial breeder/grower (Figure 6.28)

Some commercial growers, although concerned to improve the genetic merit of their herds, may not wish to buy ready-made cross-bred parent generation replacements from breeding companies. Improved grandparent males can be purchased from pedigree breeders, or breed company nucleus herds or in the form of semen from AI centres.

Pure-bred parent males, used by the grower to generate pigs for slaughter, can also be purchased from outside – often as close relatives of males of proven excellence – or they may be home bred. In any event, to generate to cross-bred parent gilts, the breeder must maintain some pure-bred nucleus sows of at least one of the two required breeds.

Testing may often be limited to female selection for growth rate and ultrasonically measured backfat depth, together with rejection of animals on the basis of poor reproductive performance. Females found to be particularly excellent would be singled out for contract mating to replenish the nucleus. In the top half of Figure 6.28 the actions are those of a pedigree breeder, while in the bottom half of the figure the actions are those of a multiplier. Some producers might opt to forego the joys of pure breeding. For them, breeding companies offer grandparent stock of two breeds for multiplication on the farm. There would be little point in making a selection of the cross-bred stock so produced, and the animals are sorted only on the basis of adequate legs, feet and nipples.
The breeding scheme may be further simplified by use of AI, which can entirely replace the need for males at the grandparent nucleus and multiplier levels. Flexibility is also possible between the females in the grandparent nucleus and in the multiplier group, animals being interchangeable between these two levels. The nucleus female is essentially any pure-bred animal selected for contract mating.
The commercial grower (Figure 6.29)

The objective of the commercial grower is not to become involved in the breeding of improved parent pigs, but rather to procure them. The breeding companies service the grower directly by offering cross-bred females and selected males to go with them (Figure 6.29), or indirectly by provision of grandparent stocks for farm multiplication (Figure 6.30). Growers wishing not to depend on the breeding companies as a source of supply of breeding females may maintain a cross-bred herd by simple selection on a visual basis, and hope for some improvement in genetic merit by the purchase of males from reputable herds (Figure 6.31). To sustain the benefits of heterosis, the breed of male may be alternated every so often. Although purebred boars are the more likely option, some producers may go for a cross-bred boar.

The most commonly occurring breeding plan for commercial growers is to purchase directly from the breeding company hybrid F1 parent females, together with the top-crossing sire line that goes with them (Figure 6.29). Such policy must maintain commonality of health status between company and customer, and it is therefore important that stocks from different companies are not mixed on a single customer unit and, indeed, that stocks are purchased from the same multiplier unit. The commercial herd will usually have, per 100 breeding sows, approximately eight...
maiden gilts on hand at any one time. In terms of monthly purchases from the breeding company, the commercial grower will need, per 100 breeding sows in his or her herd, approximately four hybrid gilts and 0.3 sires.

**New biotechnology techniques**

Genetic engineering and its associated technologies have a reputation for breed improvement well in advance of the evidence! One may be forgiven for believing that genes could even now be shifted at will from one organism to another, transferring particular genetic attributes into populations where they never before existed. This is so only to a limited extent, and not yet so for production traits associated with reproduction and growth in pigs. However, DNA recombinant technology has allowed the manufacture of hormones and drugs from simple organisms, as witness r-PST. It is likely that at some time in the future genes will be transferable with facility and genetic change achieved, although the difficulties in multiplying up a single successful gene transfer to an effective commercial breeding population are not to be underestimated.

Meanwhile, there are many other biotechnologies that have already added significantly to the rate at which genetic progress can be made. It has been considered
by some that the likely increasing availability of hormones and drugs, through recombinant DNA technology, will obviate the need for genetic selection, characters such as lean tissue growth rate and reproductive efficiency being open to enhancement by hormone therapy. Such activity would, however, need to deal with factors such as the following:

1. Public concern about repeat (at each and every generation) hormone dosing of livestock for human consumption.
2. The cost of individual treatment of each generation, as compared to genetic improvement by selection which creates a lasting effect and (being inherent) does not require any further development effort once achieved.
3. Inadequate knowledge to predict the consequences of hormone or immunisation therapy, in particular with regard to associated effects. Most production responses are compound; thus the animal requires a complex of appropriate responses to a metabolic change. An example would be the ability of an individual to cope with an elevated lean tissue growth rate imposed upon a body system developed for a lesser rate of gain, or the ability of a reproductive tract to cope with an elevated ovulation rate.
4. Exogenous therapies are likely to add on to the existing genetic base for the expression of any given character; therefore the higher the base created by positive conventional genetic selection, the better will be the overall effect, but the less obvious the need.

**Gene transfer**

The insertion of genes from other pig populations or species will greatly help in the importation of particular characters, as only the wanted gene, or gene complex, would be transferred (rather than the whole gene complement). Thus, genes for muscle size might be transferable independently of the genes for stress susceptibility, and the genes for enhanced ovulation rate and embryo survival which are characteristic of the Meishan might be transferred independently of the counterproductive genes for slow growth and fatness also present in that breed.

Transfer of genes with particular disease resistance capabilities which are simply inherited is a particularly attractive notion, and one that is receiving active attention presently, with some degree of success. It appears that a gene offering resistance to swine influenza has been effectively transferred. Obvious other candidates are genes that may enhance resistance to the common respiratory and gastrointestinal diseases.

Transgenic pigs are still best created by microinjection of DNA into the pronucleus of the ovum where the transgene is usually carried in tandem with the resident gene at a single chromosomal site. Transgenic pigs have already been created and shown to contain genes from other species, but there remain many problems before these are fixed and express positive benefit generation after generation. Microinjection of DNA gives about 0.5% transgenic offspring, and these usually
with low viability. Integration of genes into chromosomes still remains random, whereas an effective transfer system would require close targeting. Firing genes into an existing genome complement also raises a problem for the gene previously resident; logic would suggest that the previous resident should be evicted before the incomer is inserted; however, the means of identifying genes and gene constructs remains difficult.

Targeting assumes detailed knowledge of the gene map. It is always helpful to know which genes express the traits required, and where they are on the chromosome, so that they can be pulled out for DNA integration by transgenesis. Gene mapping will come to provide this information, and also that for marker genes which allow identification of the gene(s) chosen for transfer. A classic (but yet unachieved) target for the genetic engineers is to take the genes for high reproductive rate found in the Meishan breed, and by transgenesis transfer them (and only them) into a conventional White breed. This would create a new genome with the advantage of large litter size, but with none of the disadvantages of the Meishan breed such as fatness, slow growth and precocious sexuality. Thus far, one at least of the genes responsible for large litter size has been mapped and flagged with a marker, the so-called oestrogen receptor (ER) gene.

The most likely first contenders for effective gene transfer are characters that are simply inherited, characters that result from major genes with large single effects or characters that achieve their expression through complexes of genes that are grouped closely together. The operational genes must be known and identifiable. They must be discreet. They must not interact with other genes in other places before they can be fully expressed. This latter can be a severe shortcoming as many genes only operate through cascade effects down-line of the initial metabolic impulsion. The genes must be free of negative associated effects such as reproductive or health failure.

Associated negative effects are a problem which has frustrated such progress as has been made thus far. Transgenic pigs containing implanted genes for growth hormone have tended to suffer from unfortunate associated disorders – often terminally. However, it remains likely that the most fruitful way of using genetic engineering to improve growth, lactational and reproductive traits is through transgenic manipulation of the physiological processes by targeting genes involved in the production of hormones, the sensitivity of organs to hormone action or the control (limitation) of expression of hormones, in all cases resulting in the same effect: elevated levels of response. In the case of successfully transferred growth hormone genes, the transgenic pigs had dramatic increases in lean tissue growth and reductions in fatness, but they also suffered from sterility, lethargy, arthritis, general ill health and early death.

Perhaps most important of all, and most difficult to ascertain, is that the level of improvement effected by gene transfer must be greater than could be achieved by conventional selection and must reach the commercial level of usage at a faster rate. Recent calculations would suggest that for most of our production traits this might be a fond hope, and one that certainly should not be depended upon.
Gene transfer and the creation of transgenic pigs is the most exciting of the novel biotechnologies, but as far as the production traits are concerned it is not yet with us. Transgenics require knowledge of the system before the system can be modified. If it is complex and not understood, then transgenics may have less to offer. Replacement of the genes pertaining to a part of a complex system can be more disruptive than beneficial. Further, the multiplying-up and testing phase may incur a lag time that is equal to or greater than conventional breeding for the same rate of improvement. Conventional breeding with modern technologies can shift most traits by 2–3% per year. This would be hard to beat by gene insertion, followed by multiplication and testing. Gene insertion would need to give a clear lift of 10–20% before it would be likely to be the preferred route to animal improvement.

**Exogenous hormone manipulation**

The endogenous hormone system controlling growth and reproduction can be manipulated either by direct administration of exogenous hormone (as for example by r-PST administration) or, more viably, by administration of substances that act against endogenous hormone blockers and feedback mechanisms, so enhancing endogenous hormone production. Such treatments may be relevant to breed improvement strategies because:

1. they may replace conventional selection in areas where the latter is particularly difficult, slow, expensive or inconvenient; or
2. they may interact with some aspect of conventional selection and allow more effective expression of the selected character in commercial situations. Thus selection for increased ovulation rate may be assisted in its expression in the form of increased litter size if the system is augmented by hormone therapy to increase embryo survival. Another conventional selection–hormone interaction might be that between selection for lean tissue growth rate and cholecystokinin which is a gastrointestinal hormone acting as a satiety controller and available in the form of an exogenously administrable material.

**Embryo transfer and cloning**

Embryo transfer is especially interesting in dairy cattle and sheep as a means of both promulgating improved genes and allowing a more effective progeny test of candidates. The first interest in embryo transfer in pigs was for the transfer of genes into nucleus herds of high health status by use of fertilised embryos, so avoiding importation of disease that would come with the whole live animal. Embryo transfer is not likely to receive much attention with pigs, due, amongst other things, to the difficulty in harvesting the eggs (see also Chapter 4). There may be some use amongst top nucleus breeding herds for purposes of gene transfer, however. Cloning allows the production of eggs without embryo harvesting, but at present success rate remains low.
The fertilised embryo can be divided by biotechnological manipulation of nuclei, and in this way clones are created. The presently favoured cloning idea is to transfer nuclei from the parent embryonic cell into an enucleated ovum that has had its own nucleus removed. The transferred nucleus then takes over. The parent embryo can continue to create nuclei available for transfer and, if hopes are achieved, the clone size is infinite and relates only to the availability of recipient cells for enucleation. A clone of many identical individuals offers opportunities for promulgating unique transgenic individuals, but production herds comprising clones have no particular attraction to a commercial production unit. There is no special merit in having all pigs genetically identical, although much merit, at present, in having them similar. The relevance of cloning is therefore primarily as a useful adjunct to transgenesis, as it ensures retention of the useful transgene. Nonetheless, enthusiasts for cloning biotechnology point to the following:

1. Superior genotypes could be better identified through more efficient estimation of $\sigma^2_E (\sigma^2_A$ being approximately equal to zero), and a greater number of relatives would be made available to produce information on a particular candidate.

2. Cloning means that the end product could be created at source, without needing to go through multiplier levels. Thus the best genes available from dam and sire could be combined in an embryo which is then subdivided to make many identical, highly superior, individuals which could move directly down to the user end of the breeder pyramid. In fact, genetic lag is effectively made negative by this technique; the end user would get a better product than the average of the great, great grandparent nucleus!

3. Sire lines that combine excellent carecass characteristics with poor reproductive capacity are expensive to breed because the dams are less efficient. With a combination of cloning and embryo transfer, sire lines can be produced from dams of high uterine capacity. This will increase selection rate within the line, reduce cost and increase the rate of proliferation of the line.

That an egg can turn on the nucleus of another egg is less remarkable than the proposition that the nucleus of a cell that is not from another egg but from the body – a differentiated somatic cell – may be similarly turned on and reprogrammed back to its undifferentiated and fully potential state, and develop into another full individual. In this case the whole genome is carried from one (parent) individual to the other (offspring) – a clone. At the Roslin Institute, Edinburgh, sheep (not pig) nuclei have been taken and successfully transferred from embryos, fetuses and most recently even from the cells of a fully adult mammary gland (Annual Report 1996–97, Roslin Institute, Midlothian). Some research workers see cloning of valuable transgenics as beneficial to the utilisation of targeted transgenes following on from gene mapping. The benefit to the pharmaceutical industry may be more immediate than the benefit to commercial meat production.
Marker assisted selection: the contribution of genomics

As has been shown, the selection of a genotype and its use at commercial level is predicated upon the effective identification of that genotype in the first place. Until recently the definition of the genetic make-up of a pig has been a best approximation derived from the measurement of phenotypes. Now, however, the genotype can, in the case of some traits, be described more directly; not only from the phenotype of the candidate pig and its relatives, but also from simple analysis of the pig’s DNA, thus accessing the fundamental source of the animal’s inherent make-up – its genome.

To identify an animal’s qualities from knowledge of its genome, the parts that control important traits of interest must be identified. Usually this is achieved through ‘markers’, often characteristic sequences of DNA. The finding of a quantitative trait locus (QTL) is confirmed by a close relationship between the marker selected for and the trait sought. One way of doing this is to cross two very different breeds of pigs (such as the Chinese and the Large White) to create a diverse population of the characteristic in question. Then the presence of a character can be associated with the presence of a marker, and vice versa. Within a QTL there will be the particular DNA configuration(s) that bring about the desired (or undesired) characteristics.

The pig genome is not much more than half sequenced at present. Furthermore, even when the job is completed it will be far from clear which bit is responsible for what. As the ‘bits’ will usually bring about changes in more than the character of direct interest, absence of an unwanted QTL may also bring absence of useful (but yet unidentified) characters. The more general the marker, the more likely this will be the case.

Nonetheless, there are more and more useful QTLs being identified. The markers allow them to be identified by DNA analysis and selected for (or against). If the markers are good, and the trait is associated with few of them, selecting for a pig with the wanted variation in DNA (polymorphism) can be more accurate and direct than conventional examination of the phenotype. Some traits seem indeed to be associated with only one or few QTLs, but many others are much more complex. In the latter case it is more difficult to associate the characteristics of the offspring of diverse breeds with the appearance (or non-appearance) of markers in the genome. So it is more difficult to test the population of pigs for the presence or absence of a marker, and know that selection will result in the actual expression of the desired trait.

Despite these caveats, genomics are already making significant impacts upon the improvement of pigs by genetic selection. The ability to test early in life, and with enhanced accuracy, for the presence of beneficial genes substantially increases the likelihood of correct individual animal selection. The possibility of identifying the presence and/or strength of a character by possession of a marker has great attraction.
The genetic basis to porcine stress syndrome (PSS) and pale, soft exudative muscle (PSE) led to a search by molecular biologists for the particular part of the DNA coding that was responsible; thereby increasing the possibility of the separation of the positive aspects of slaughter pigs possessing the halothane gene (muscle depth, carcass yield) from the negative (predisposition to sudden death, reduced meat quality). The halothane gene can be removed either by generation upon generation of selection against it (testing for positive reaction through the halothane gas test) or by establishing the presence of the (unwanted) gene through DNA fingerprinting. The halothane test itself (administration of the halothane gas and observation of presence or absence of consequent stress) is not only tiresome, but also imperfect in its rigour, and can only find homozygote (nn) forms, failing in its detection of the heterozygote carrier (Nn).

More than a decade ago a biochemical blood test for the particular DNA elements responsible for PSS/PSE was found. This allowed easier and more rigorous testing for the gene associated with PSS/PSE, and the likelihood of its elimination. By being able to identify the Nn carrier as well as the nn homozygote, the test speeded complete elimination of the n gene from female lines. In 1991 the DNA test was developed at the University of Toronto for the presence of the halothane gene. DNA finger-printing through the HAL-1843 nm (for non-mutant, i.e. NN) testing programme identifies the presence of the n gene in the heterozygote as well as the homozygote. This biotechnological advance allows the removal of the halothane gene, not only from the female line (where its presence could only be considered as wholly negative in any event), but also from the sire lines from which meaty terminal sires are derived.

The susceptibility of some pig types to PSS and adverse reaction to halothane gas is shared with man, in whom there is a rarely occurring gene (the ryanodine receptor) causing malignant hyperthermia under anaesthesia. There is a single point mutation at position 1843 in the gene. What appears to have happened is that a CGC group has mutated to TGC, and that is what causes the problems of PSS and PSE associated with halothane-positive pigs. Following blood testing and a negative finding at the HAL-1843 position, the pig may be described as HAL-1843 nm. Using the DNA test to remove n from nn and Nn lines incurs the loss of ‘nn-type’ characters (lean mass, large muscular hams and loins, killing-out percentage etc.) to the extent of about 30%. Taking out the problem of stress susceptibility leaves the requirement to win back by conventional positive selection techniques only some 30–40% of lost positive characteristics.

Given the disbenefits of the halothane gene, and that its elimination leaves more than half of the beneficial characters in place, there is little argument for doing anything other than using the HAL-1843 test and eliminating this mutation; not to say anything about the welfare benefits that ensue for the pigs themselves. The HAL-1843 nm test now allows marker assisted selection for the creation of pig populations in which the halothane gene is completely absent. Through the medium of this test the long-sought-after goal can be realised of creating pig strains with the positive benefits that had previously been associated with
the halothane gene, but with none of the negative effects of the gene itself (PSS and PSE).

The oestrogen receptor gene (ER) is a major gene for litter size, and has a marker gene which can be found in the Meishan and some Large White strains. The gene gives +1 piglet in the gilt litter, +0.5 piglets in the sow litter and an increase in nipple number (that is, it does not account for the whole of the difference in litter size between the two types, which is +3 or 4). The marker is close to the ER gene, i.e. it is in the region of the chromosome that is associated with differences in litter size. There will doubtless be a range of markers (and indeed a number of genes). Presently, pigs possessing the marker have been suggested also to grow slower by some 100g and are fatter by some 2mm backfat depth.

In the case of the Meishan, the beneficial quality of litter size is sought to be incorporated into European White breeds, but with the necessary exclusion of all the other qualities of the Meishan which are largely negative (fatness, slow growth rate, etc.). The marker for the ER gene will allow such differentiation and effectively target individuals in the cross-bred carrying the gene of interest and fix it, while all the negative characters can be stripped out.

It has been suggested that some part of (positive) pork flavour may be due to a specific gene (the RN) identified in the Hampshire breed. The gene also seems to bring with it, unfortunately, a higher drip loss. However, identification gives the breeder the choice.

Thus it is that if a gene (or group of genes located close to each other in a segment of the chromosome) with important effects upon productivity is associated on the chromosome with identifiable markers, then analysis for the presence of the marker gives a level of presumption for the presence of the gene of interest (as both cohabit the same chromosome segment). Whole segments of chromosomes can be traced from parent to offspring. Markers on the chromosome have advantages over observations of phenotype, especially as:

- they can allow the heterozygote to be distinguished from the homozygote, where dominance would otherwise obscure such distinctions in the phenotype. This is of special value, for example, for removing the gene for PSS from a population, or for identifying heterozygous white (not wanted) from homozygous white (wanted) when breeding coat colour out of the Duroc (white is dominant);
- DNA identification of markers allows identification of the presence of a gene in an animal not directly showing the trait in its phenotype, as, for example, litter size in a boar or ultimate carcass quality in the neonate or newly weaned piglet;
- when they are closely associated with the gene(s) in question, markers can give a firmer view of gene possession than observation of the phenotype alone, which is so open to non-genetic variation. Rather than the presumptive possession of a gene on the basis of circumstantial evidence, there is an actuality; to such an extent that a dependable marker would obviate the need for phenotypic measurement prior to selection;
given thorough analysis of the presence of markers in a genome, it would be possible to associate markers with observed phenotypic characters without precise knowledge of the physical location and effects of different genes. Thus offspring marker combinations would act as effective tracers for wanted (or unwanted) characters having been effectively transferred from parent to offspring.

The pace of gene mapping is bringing into reality the possibility of large numbers of markers throughout the genome which can act as identifiable reference points for important genes and groups of genes (segments of chromosomes) influencing production. Thus far, promising markers for genes (or groups) have been identified inter alia for: litter size (fertility and fecundity); growth rate; appetite; fatness; meat quality (PSE); intramuscular fat; taint associated with entire males, and skatole; specific disease resistance (K88, PSS); general disease resistance (immune function); placid behaviours; and coat colour (white). In some cases the influence of the marked gene or chromosomal segment is absolute (as for PSS), but in other cases the influence can be partial and may be quite small (as for lean growth, fatness and reproduction). In the latter eventuality, marker selection may even be slower than conventional phenotypic selection for the trait of interest. The list grows rapidly, and the identification of markers to assist selection is the very stuff of a modern breeding company. Substantial commercial advantage results from the sole possession of knowledge of a marker for a valued trait.

It is relevant to consider the difference between simple genes with major effects (such as those for halothane susceptibility and coat colour) and QTLs which are often only responsible for a part of the genetic variation in the character of interest, such as most of the important production traits: reproductive performance, growth, carcass quality and efficiency. When bringing genes from one breed into another (introgression), and when one or few genes only are wanted, the question should be asked whether this technique, with the genetic lag which it imposes before the gene is spread through the population, is quicker and cheaper than conventional phenotypic selection in the main lines. Rates of gain in litter size by phenotypic selection using mixed animal model BLUP techniques (see below) may be greater than by introgression of Meishan genes for litter size. It is estimated that to be worthwhile, the trait of interest in the donor population needs to be 10–20% superior to the performance of the recipient population.

**Best linear unbiased prediction (BLUP)**

BLUP has been referred to earlier, but it can legitimately claim to be the most important of all the new biotechnological innovations of the last 5 years, not least because it is in widespread working practice. The main feature of BLUP is that it disentangles the management from the genetic effects, both of which contribute to the animal’s merit as observed and measured, but only the genetic contribution
being of interest. Together with BLUP, an animal model is used which accommodates all the information from all available relatives in the database, the genetic merit of all related animals being estimated simultaneously. With BLUP and animal models together, maximum use is made of all available information over a wide pedigree base.

Selection of pigs by individual performance or with an index including information from progeny or siblings allows comparison of candidates and the derivation of breeding value, usually only amongst those in a contemporary group at the same time and place, and preferably reared prior to test in similar circumstances. Increased accuracy is achieved in an individual’s assessment if a much wider and catholic variety of relatives from other generations, times, places and pig herds contribute to the judgement. This demands not only sophisticated computerised record-keeping, but also appropriate statistical techniques which combine information of different types and correct for the various confounding factors. BLUP programmes allow accurate evaluation of genetic effects and improve greatly the accuracy of test and the construction of indices, especially for traits of low heritability such as those associated with reproduction. BLUP operates through statistical models giving estimates of the consequences of a mixture of both fixed (management) and random (genetic) effects, and thereby allows more accurate prediction of the breeding value of individuals, especially where heritability is low and environmental effects are large. Because BLUP allows comparison between animals in different herds at different times on different sites, it can include in the estimate for breeding value information from all the relatives, regardless of their location. As BLUP has the ability to link separate herds, central testing for lowly heritable traits (such as reproduction) is obviated. This is helped if there is sufficient commonality of parentage provided across different herds within the population under examination, which is often best achieved by a central artificial insemination station and dissemination of semen to various nucleus breeding units at which selection of superior individuals for the trait concerned may be carried out. BLUP procedures, together with artificial insemination, therefore also allow a large single nucleus population to be distributed over numerous herds and geographical sites.

**Sex determination**

The separation of male (Y) from female (X) sperm still remains extraordinarily difficult (Chapter 4). The fertilised embryo can, of course, be sexed as it has possession of its complete gene complement immediately upon fertilisation. Embryo transfer and cloning techniques can therefore accommodate determination of sex. For the breeder there might be benefit in ensuring all the piglets in a litter generating terminal sires were to be male, and all the piglets in a litter generating F1 hybrids were to be female. Sexing by sperm separation may therefore be of some interest to those involved in breed improvement programmes because it allows differential selection pressures where they are needed (males in the male line and
females in the female line). However, even if sexing were to become rapid and cheap, the benefit to commercial producers is not immediately apparent as the entire male or castrate would not invariably be considered a liability as a meat-producing animal. An unlikely – but nevertheless suggested – possibility for sexing would be the production of transgenic single-sex clones.
Chapter 7
The Maintenance of Health

Introduction

The clinical appearance of disease is influenced by the pigs’ environment. The convention that pathogen plus pig equals clinical disease is nearly always incorrect. There is therefore much that can be done to maintain pig health in the inevitable presence of pathogenic organisms.

Herd health maintenance is a function of:

- development of herd immunity;
- biosecurity;
- pig flow;
- medicine management;
- stock health monitoring;
- pig environment;
- management of disease.

Pig health is a team responsibility involving the whole production chain; but key players will always be the stockworkers at the production units. If the quality of the husbandry lapses then the presence of pathogens will indeed result in disease. At all levels, good management is paramount in disease control. For example, mycoplasma (enzootic) pneumonia need not be a problem where standards of care are high and other organisms likely to induce secondary infections, such as Actinobacillus and Pasteurella, are maintained at low levels.

Development of herd immunity

Disease organisms are present at low levels in most pig units most of the time; these do not always present a problem because immunity builds up naturally. Disease outbreaks (as opposed to the presence of disease organisms), and consequential loss of productivity, can be controlled (1) by maintaining a low level of the organism in the environment and encouraging the build-up of natural immunity, and (2) by reducing the susceptibility of the stock to the disease by maintaining high standards of nutrition, housing and care; or, occasionally, the breeding of resistant stock. Often it is the initial outbreak of disease in a herd naïve to the organism that is responsi-
ble for the greatest loss. Sometimes, however, the level of immunity in individual animals breaks down when the challenge abates, and becomes inadequate to prevent continuing or resurgent problems, especially in young growing stock. Thus a breeding herd may show full resistance to a disease that continually plagues the grow-out unit; or a unit may suffer cyclical recurrences of infection as the strength of the immunity level fades so that, when initiating factors appear in the system, the disease flares up again. Excellent management can result in the maintenance of a strong immune response in the herd, and absence of clinical disease. However, for some diseases it is more cost-effective to maintain the herd free of the disease and to prevent its entry. It has been possible for decades to repopulate herds and maintain them with the absence of diseases such as transmissible gastroenteritis, Aujeszky’s disease, swine dysentery, atrophic rhinitis, lice, mange, streptococcal meningitis, actinobacillus (haemophilus) pleuro-pneumonia, leptospirosis, brucellosis and salmonellosis, and of course the major epizootics, such as foot-and-mouth disease, classical swine fever and African swine fever.

Some diseases can be completely eradicated from a region by a slaughter policy, as has been the case for swine fever and foot-and-mouth disease, and in some cases for Aujeszky’s and swine vesicular disease. Equally, some disease organisms, such as those producing swine dysentery and mange, can be eradicated from a pig unit by management and medication procedures. For pig units of high health status, free of the major diseases, it is important that these diseases are permanently excluded, for the clean herd will have no immunity. If the herd does become infected the consequences may be particularly severe. Examples would be outbreaks of mycoplasma pneumonia and actinobacillus (haemophilus) pleuro-pneumonia in herds where these organisms were previously absent.

**Biosecurity**

Biosecurity is the responsibility of the farm health team of stockworkers, managers and veterinarians. It is impossible to prevent the transmission of many disease organisms; for example, various serotypes of *Escherichia coli* or earth-borne pathogens such as *Erysipelothrix rhusiopathiae* (Figure 7.1). Some diseases, such as parvovirus, may spread long distances through the air. Other pathogens are more locally spread; the respiratory pathogen *Mycoplasma hyopneumoniae* will affect farms within some 3 km. Only farms located in an area of low pig density may expect to remain in an *M. hyopneumoniae*-free status for any significant period of time. Some diseases, such as external parasitic infection by *Sarcopties scabiei* var. *suis*, require physical pig contact, and with modern avermectin therapies eradication of mange on pig farms is achievable. A pathogen that is absent from a locality due to its eradication, such as Aujeszky’s disease, does not (of course) require either treatment or prevention. It therefore follows that the absence of pathogens allows for errors in environmental management without prejudicing production performance.

The major threats to the security of the perimeter of a pig unit and the relative magnitude of the different threats depend upon particular circumstances. These are
therefore best identified by individual farm health teams. This is a matter for hazard analysis, identification of critical control points and risk reduction.

The major pathogen spread threats to a pig unit are usually:

- other pigs, especially replacement gilts and boars;
- dead pigs being disposed of;
- transportation systems;
- neighbouring pig units;
- pigs owned by the pig unit staff;
- staff visiting pig markets, shows and slaughterhouses;
- vets and other advisors;
- visitors and service suppliers with previous pig contact;
- presence of a major road;
- clothing from another unit;
- birds, rodents, cats, dogs and flies;
- feed, water, bedding and straw;
- purchased second-hand and new equipment;
- catering waste containing pork products (ham, salami, sausage, pizza).

**Pigs and their products**

The principal carriers of infective agents into the pig unit are pigs and their products. If animals are to be introduced, usually as stock replacements (or semen for...
AI), their health status needs to be better than, or similar to, that of the receiving unit. Breeding company supply herds should demonstrate the absence of specific diseases (the presence of organisms associated with disease and the presence of the disease itself are, of course, two different things, the latter being the more easily monitored). The receiving farm should always try to buy its replacement females from the same single despatch farm. Pigs from different breeding companies are best not mixed together on the same production unit.

In any event the introduction of pigs must include rigorous regimes first for isolation (quarantine) and then for acclimatisation, these two being quite different in their purpose and method of operation. Six to eight weeks is required to provide adequate isolation and acclimatisation. This significant lapse of time needs to be factored into pig replacement management protocols.

Isolation separates the incoming animal’s pathogens from the farm’s stock. The introduction procedure must be adequate to ensure that a specified pathogen (such as porcine respiratory and reproductive syndrome (PRRS), Brachyspira hyodysenteriae, Pasteurella multocida, lice, mange, M. hyopneumoniae or Actinobacillus pleuropneumoniae), if found present in the incoming pigs, is capable of being removed from the isolation site without being a risk to the pigs on the main unit. The isolation site therefore needs to be located distant from the main site, and looked after by someone who is not passing regularly between the main site and the isolation site. Danish experience, where quarantine is the norm for all incoming stock, suggests that whilst failure to quarantine will almost invariably result in transfer of disease, proper quarantine arrangements will reduce any likelihood there is of disease transmission ten-fold.

Acclimatisation exposes the incoming stock to the pathogens normally present on the farm. The incoming new stock need time to develop immunity and to recover, lest they upset the microorganism ecology of the main unit and precipitate a disease outbreak (which is a classical consequence of poor acclimatisation to PRRS virus).

Incoming pigs can be immunised against those disease agents that are present on the receiving unit. Immunisation can be achieved by vaccination (there are vaccines widely available for erysipelas, parvovirus, pseudorabies, foot-and-mouth disease, A. pleuropneumoniae, M. hyopneumoniae, atrophic rhinitis, E. coli and many others) or by natural immunity (e.g. E. coli, Mycoplasma pneumonia, transmissible gastroenteritis and parvovirus).

**Transportation systems**

Unclean feed and animal trucks, even when empty of pigs, are liable to bring in feacal material from other pig units. Swine dysentery (Brachyspira hyodysenteriae) is easily transmitted between units by contaminated feaces. In cold climates, material can collect in the wheel trim and it has been demonstrated that PPRS can be transmitted many kilometres around the countryside in a medium of snow and ice. Animal transport is often poorly cleaned and disinfected, despite this being a regulatory requirement in many countries following visits to pig units, markets and
slaughterhouses. It is justifiable to refuse entry to vehicles arriving at the farm in an unacceptable state of cleanliness. In any event, effective perimeter biosecurity should allow the delivery of feed and pigs and the uplift of pigs for sale and slaughter without recourse to vehicles entering the unit (Figure 7.2). In the summer time, a vehicle can even act as a transport system for insects, flies and mosquitoes which serve as effective vectors of diseases such as African swine fever and PRRS.

**Locality**

Proof of the principle of the different aerial spread capabilities of various disease organisms is difficult to establish. Potential distances are given in Table 7.1. Biosecurity will be optimised by placement of pig units and their associated isolation units
in neighbourhoods free of other pigs and major roads. These considerations are particularly germane to the siting of units wishing to maintain especially high health status, such as AI studs and nucleus breeding farms.

**Perimeter of the farm**

Often, but wrongly, pig units have inadequate perimeter security. However, a perimeter fence and closed entry gates are potent means of preventing entry of pigs, people, other animals and dogs, and vehicles. In some areas, wild and feral pig populations are endemically infected with classical swine fever and brucellosis. Fencing should ideally be 2 m high and dug deep into the ground (pigs burrow).

**Entry and exit points**

There are a number of entrances and exits onto the farm (Figure 7.2) and these all need to be examined in detail to ensure that they comply with the biosecurity arrangements as laid down by the farm health team.

_Vehicle parking_. Vehicles should not be allowed to drive around or between the farm buildings, so there needs to be a suitable parking area outside the fence.

_Door_. The farm should have a secure human entrance (a normal pedestrian door) which is locked. A working horn and signs informing visitors of the security rules can be placed adjacent. Through the door may be placed the ‘dirty-side’ office and undressing facilities.

_Shower entrance_. People may progress to the pig unit itself through a shower unit or other suitable provision for cleaning people. ‘Clean-side’ (pig-side) pig unit clothing and boots can be placed ready on the other side of the shower. Asking people to shower into the unit not only ensures biosecurity, but also deters casual visitors from intruding, and also allows the staff to shower out and go home clean. If a

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Table 7.1. Aerial spread potential of various disease organisms.

<table>
<thead>
<tr>
<th>Disease agent</th>
<th>Possible spread</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Actinobacillus pleuropneumoniae, Pasteurella multocida,</em> <em>Haemophilus parasuis,</em> <em>Mycoplasma hyosynoviae,</em> <em>Streptococcus suis,</em> porcine reproductive and respiratory syndrome virus</td>
<td>Short distances of up to 1 km</td>
</tr>
<tr>
<td><em>Mycoplasma hyopneumoniae,</em> swine influenza virus, porcine respiratory coronavirus, porcine multisystemic wasting syndrome</td>
<td>Medium distances of 1–10 km</td>
</tr>
<tr>
<td>Parvovirus, Aujeszky’s disease, foot-and-mouth disease</td>
<td>Long distances of more than 10 km</td>
</tr>
</tbody>
</table>
shower facility is not available, at least a substantial measure of the biosecurity risks posed by people bringing pathogens onto the unit through contaminated clothing can be avoided if essential visitors wear only the farm’s own clothing and boots, discarding all of their own clothing and footwear on the ‘dirty side’. Even with these precautions, most pig units practising an active disease avoidance policy would stipulate a 3-day rule, where all visitors to the unit must have had no contact with pigs for at least 3 clear days before the visit.

Feed entrances. Feed is delivered regularly to the farm unit (and feed delivery vehicles visit other pig units) so protocols for feed delivery should be written and enforced. It is best that feed bins on site are accessible by delivery vehicles parked outside the perimeter fence.

Pig entrances. Replacement pigs, brought from the isolation unit in the farm’s own transportation, should be unloaded at the perimeter and moved by clean-side transport into the acclimatisation quarters.

Loading area exit. The animal loading ramp should be clean and well maintained. Animal trucks must remain outside the farm, the ramp being a bridge between the clean and dirty sides. The ramp may be designed so that farm staff do not enter the animal truck, nor may the driver under any circumstances enter the farm. No pig entering the truck should ever re-enter the unit.

Dead animal disposal. Pigs falling dead or being destroyed on-farm should be disposed of at the farm perimeter (preferably by incineration) according to local regulations. In some localities carcasses can be composted. Stored carcasses awaiting removal must be secure from vermin.

Each house or barn. The external security of the buildings is important in order to control not just the pigs, but also birds, rodents and other vermin. Each building should have a 1 m walk-way completely around it. This should be free of plant weeds, abandoned equipment or any other materials supporting a refuge. The integrity of the outer walls should be intact to ensure that any easy access into the walls of the building is avoided. Drainage pipes are major access routes for vermin. Carefully managed and continuously attended rodent bait boxes can be placed around the perimeter of the building. The eradication of flies reduces disease spread; PRRS virus is only one of the pig pathogens that can be transmitted by mosquitoes and biting flies.

Boot hygiene

Foot baths alone are not an adequate method of maintaining internal biosecurity. Boot hygiene can only be achieved by manual cleaning – ideally using a pressure washer. Foot baths are good, however, at disinfecting clean boots and cleaned farm equipment such as brushes and shovels.
Pig flow – managing an all-in/all-out system

All-in/all-out

Disease is transferred primarily through contact between pigs held in the same air space. ‘Air space’ may be a room, a house or a farm site. Continuous production systems are difficult to avoid on small units and this also ensures continuous disease transfer. Under excellent management and housing, this need not be a recipe for disaster; indeed it can be a recipe for maintaining a high level of natural immunity and disease resistance in the unit. However, under the stresses of intensive production systems, particularly with units that are not closed, there is a predisposition to clinical disease manifestations. All-in/all-out production breaks the disease cycle by preventing the sharing of air space of pigs carrying clinical disease with pigs susceptible to infection by that disease. Much can be done with all-in/all-out systems using rooms, more can be done using whole houses, and most using the whole unit or site. The more distant the location from other pigs, the more advantageous the method. It is a point of principle that between batches of pigs the location (be it room, house or site) is completely cleared, disinfected and rested to ensure the cycle of infection is broken and premises do not themselves serve as a reservoir for infective material. Freedom from disease challenge unquestionably gives freedom from disease, but it also raises the spectre of the absence of immunity and susceptibility to disease organisms should the barrier against infection fail.

Prevention of disease transfer in these two ways – from adult to juvenile populations and from one group of pigs to the next – represents important opportunities for disease control; but only when management can ensure strict adherence to the rules of hygiene.

Pig flow

The concept of pig flow has developed in response to previous inadequate regard to the importance of pig biology in the control of pig disease. Producers, driven by the need for an economic return within the constraints of buildings and local legislation, have been abetted by veterinarians turning to antimicrobials to maintain health in the presence of an otherwise disease-inducing pathogen load. Without biological counter-measures, and helped by inadequate cleaning, environments become progressively infected with an increasing number and variety of pathogens. Eventually the disease challenge overwhelms the natural defence mechanisms of the pigs, an increasing proportion of which come to present with clinical disease.

The easiest way to control pathogen load is to move clean pigs into clean buildings. However, it can be approached by adopting a strict all-in/all-out protocol for the pig unit, combined with the sourcing of incoming stock from a single and compatible farm of origin. All-in/all-out together with cleaning, drying and resting controls the passing of disease from one group to the next. Buildings must
be dry (and given down-time) before re-use. Walls and floors not dried properly harbour pathogens and will also cause pig chilling. Seminal to all-in/all-out is pig flow.

‘All-in’ necessitates the programmed provision into the accommodation of pigs of the same age and health status. This can only be achieved by a stable size of pig population on the farm as a whole, and within the farm’s subsections; neither more nor less than agreed targets (the maximum allowable live weight variation recommended is no more than 5% below target and no more than 10% above target). This creates stable farms.

Pig flow prescribes the number of animals that the farm can accommodate and then models a production method to fill these buildings. Pig flow failure on many farms begins right at the beginning of the production process, with the pool of replacement breeding females. Too few gilts of the correct weight and immune status results in a reduction in output. Too many gilts results in a glut of animals in oestrus, the irresistible temptation to mate, which gives way to overproduction and overstocking of the facilities.

The farm plan

Only two pig farm records can be trusted absolutely:

- the price per kilogram of pig meat paid by the slaughterhouse (customer); and
- the size of the farm, i.e. the number of farrowing crates, the capacity of the pregnant sow accommodation, the square metres of finishing floor, the number of feeders and drinkers, etc.

Farms are not best assessed on composite output figures such as pigs per sow per year because such figures are often untrustworthy and can be meaningless in terms of efficiency. The farms that produce the most pigs per sow per year are not necessarily either the most profitable, or the most cost effective or the most welfare satisfactory. Twenty pigs sold per sow per year does not give an action point if for every twenty, one is condemned. On the other hand, the annual weight of pig meat paid for is an unarguably secure endpoint by which to set targets. Likewise the size of the farm is an actuality that can be verified by direct measurement.

A pig flow model considers the output target for a unit, and is composed of four major areas:

1. number of gilts in the gilt pool;
2. number of sows bred in a batch;
3. number of sows farrowing in a batch;
4. kilogrammes (dead weight) of finished pig meat sold.

Each of the four activities (drawing from the gilt pool, breeding, farrowing and growing to weight at sale) needs to be in balance with the others to allow for the flow to occur. For example, a farm farrowing 10 sows a week (approximately a 250 sow unit) would have an idealised pig flow model as follows:
The seven specific records appropriate for the above plan are:

- Gilt pool 95 kg to service: 12–15
- Females in a batch to serve: 12
- Sows in a batch to farrow: 10
- Kilograms of piglets in a batch to wean: 800
- Kilograms (dead weight) of finished pigs in a batch to sell: 6840
- Kilograms of pig meat paid for annually: 355680
- Number of pigs sold annually: 4940

There are some targets that have to be met: the farm weans every week; the 90 percentile farrowing rate is 82% (the farrowing rate is over 82% 90% of the time); 10 piglets are weaned per farrowing crate, with an average weight of 8 kg at 24 days of age; a 5% post-weaning mortality. Therefore 95 pigs at 72 kg dead weight are paid for each week. The gilts are given 10 weeks’ introduction to allow for adequate time for growth to mating and for compliance with biosecurity arrangements. Finally, to take finishing pigs to 72 kg dead weight (95 kg live weight), a period of 26 weeks is presumed.

**Setting up a pig flow model**

The following statistics are required to start: number of farrowing crates; number of farrowing rooms; number of crates in each room. An example using 24 day weaning and a 5 week turnaround for a farrowing room would be:

- Number of farrowing crates: 125
- Number of farrowing rooms: 9
- Number of crates in each room: 5 rooms of 15, 5 rooms of 10, 1 room of 25

Layout of the farrowing rooms:

```
15 15 15 15 15 10 10 10 10 10 25
```

The pig flow model will work with an output of 25 sows farrowing per week. To achieve all-in/all-out and no variability in output per week the rooms are organised into the groupings shown below, which accommodates the necessary five room pattern for a 5 week turnaround:

```
15 + 10 15 + 10 15 + 10 15 + 10 25
```
The pig flow model would be (taking similar target parameters as before):

<table>
<thead>
<tr>
<th>Gilts</th>
<th>Sows bred</th>
<th>Sows farrowed</th>
<th>Finished to 72kg dead weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>31</td>
<td>25</td>
<td>19040 kg</td>
</tr>
<tr>
<td>10 weeks</td>
<td>17 weeks</td>
<td>22 weeks</td>
<td></td>
</tr>
</tbody>
</table>

With specific records of:

- Gilt pool: 95 kg to service 35–45
- Females in a batch to serve: 31
- Sows in a batch to farrow: 25
- Kilograms of piglets in a batch to wean: 2000 (10 piglets × 8 kg × 25 crates)
- Kilograms (dead weight) of finished pigs in a batch to sell: 17136 (95% of 250 kg dead weight)
- Kilograms of pig meat paid for annually: 891072
- Number of pigs sold annually: 12376

In many cases concerning existing pig units, the numbers of available crates and rooms cannot be made to meld with target turnaround times. Solutions include the altering of these (say to 28 day weaning), the construction of extra facilities to provide the requisite number or the reduction of the stocking density targets for the unit. The important point of principle is that chaotic pig flow makes for the batching of pigs of unequal health status, the prevention of all-in/all-out stocking regimes and overstocking elsewhere in the pig unit. All of these predispose to pathogen challenge resulting in the (otherwise avoidable) outbreak of disease.

**Managing the pig flow, gilt pool, breeding numbers and the finishing floor**

Whilst the farrowing house is generally the start of the pig flow calculation process, ultimate output is determined by the floor space available for the growing/finishing pigs. Abuse of this self-evident truth results in overcrowding, loss of health and progressive failure to reach growth rate targets. Frequently, overcrowding in the grow-out sector of the unit is triggered by an increase in sow productivity. Quality assurance compliance will increasingly require producers to stock within regulatory pig densities. Table 7.2 gives examples for the UK and the European Union. Only with a pig flow model can compliances be ensured.

For example, if the total finishing herd space for pigs from 30 kg to slaughter at 72 kg dead weight (95 kg live weight) is 741 m², then to comply with Table 7.2 at least 0.65 m² should be provided for each pig when the average weight is between 85 and 110 kg. In consequence, there is only room for 1140 finishing pigs on the farm at any one time. To finalise the computation, if 12 weeks are allowed for the pigs to grow from 30 kg live weight to 72 kg dead weight, 95 pigs per week can be marketed. With a 5% loss, 100 pigs a week can be weaned; therefore 10–11 sows a week will be required to farrow. Marketing at heavier weights (if above 110 kg, the maximum
number of pigs will be 741) will have the inevitable result of either reducing the size of the sow herd, or increasing the available space or contriving to increase pig growth rate.

The current description of utilising pig flow to manage health has concentrated on flooring space. However, any aspect of the building/pen design could act as a limiting factor to health and therefore disease expression. Given adequate floor space, pigs also require appropriate feeder space, air ventilation and drinker provision. Pig flow is controlled by the first limiting resource. It is necessary for this to be identified by the farm health team, and either the flow to pivot around the availability of that resource or the resource to be supplemented so that it is no longer first limiting. Loss of health caused by shortage of a resource of one sort or another has over recent years been suppressed by use of antibiotics, a prophylaxis that is no longer sustainable.

**Medicine management**

Effective disease control depends upon both early medical treatment of emerging disease and the use of preventative medical measures such as vaccinations. The presumption of efficaciousness is ill-founded if the medicines are no longer potent due to failures in their storage and use. For example, inadvertent freezing of vaccines for swine influenza virus or *M. hyopneumoniae* will likely be followed by outbreak of respiratory disease, while the inappropriate use and overuse of needles and syringes have been demonstrated in the transmission of many pig pathogens, including PRRS and classical swine fever virus.

Most quality assurance schemes now require compliance with written protocols for disposal of unused medicines and used bottles, and the disposal of used needles and syringes in a designated sharps container. Broken needles left in pig tissue are a rarity, but are a hazard that needs to be dealt with through strict protocols for the disposal of the affected pig.
**Cold medicine storage**

Many medicines, including vaccines, need to be kept between 2 and 8°C in a refrigerator. Freezing most vaccines will render them useless, negating the preventative medicine programme. Refrigerators that have a freeze–thaw cycle are to be avoided. Refrigerator dials are not an adequate means of monitoring temperature; this can only be done with frequent checks of a maximum and minimum thermometer placed in the body of the fridge in the same place as the medicines are held. The fridge should be kept clean and out of date medicines removed.

The medicine refrigerator is not the place for human food and drink. Health and safety issues preclude the storing of human food in chemical stores, and, importantly, significant swine diseases can be spread through human food, notably foot-and-mouth disease and classical swine fever.

**Warm medicine storage**

Many other medicines used on farms, such as the antimicrobials, need to be stored (clean and dust free) at steady temperatures generally not exceeding 25°C. This temperature is readily exceeded both seasonally and by day/night fluctuations in many parts of the world. Neither the ‘farm office’ nor the back of the farm car make for an adequate warm medicines store, neither giving the required temperature control and security.

**In-feed medication**

Medication via the feed supply is a normal route of administration. While there are advantages to supplying medicines to large numbers of pigs via the feed, the sick pigs have to eat the feed; and in several diseases, such as *A. pleuropneumonia*, pigs do not eat. In-feed medication is ideal for prophylactic use, but once pigs are sick, in-feed medication can be ineffective. Medicating the correct group of pigs requires precise management of the feed bin; in relation to not only their identification and flow routes, but also the evenness of mixing of medication throughout the feed material. Observation of withdrawal periods before slaughter (to avoid residues in the meat) demands attention to detail and the ability to thoroughly clean the system, including the feed troughs in the pens.

**Medication through the water supply**

A properly functioning water supply is an ideal route for the mass medication of pigs. Thorough mixing is, of course, essential. Many medications and vaccines require that the chlorine is removed from the water supply prior to their administration. In the USA, the water supply is becoming an accepted method of supplying vaccines, as well as medicines and prophylactics, to large numbers of pigs without the stress of restraint and injection.
Monitoring of stock health

The presence of chronic disease and impending acute outbreaks can be detected by continuous monitoring of pig performance, pig appearance, coughing levels, the presence of diarrhoea levels, house environment, feed use, feeding and drinking behaviour, body condition and the like. Units guaranteed free of certain stated diseases (minimal disease) are obliged to monitor for those conditions, and pigs from such units are inspected at the slaughterhouse for evidence of diseases such as atrophic rhinitis and pneumonias. It is necessary for expected farrowing rates, numbers born, still-births, growth rate, vaginal discharges and all other such characteristics to be noted and used for comparing records week-by-week. Interference levels can be set appropriate to each unit. If expected mortality post-weaning is 1%, then when a 3% level is reached the management and veterinarian are required to interfere, find a cause and ameliorate it. Problems for which normal and interference levels are set should relate to the particular diseases of importance on a particular unit and at a particular time. Disease monitoring schemes should be special to the problems of the unit, the requirements of the stockworker and manager, and the prevailing circumstance. Above all, such records should be kept up to date and be seen as useful by the person who is collecting them. Usually the paper record will require identification of date and place, the animal afflicted, the symptoms, the suspected cause, associated observations such as appetite, environment, stock movement and so on, treatment (including the name of the drug and identification of its source) and any subsequent actions that may be thought likely to be required.

The ability to clinically examine, recognise and treat disease in pigs is the responsibility of the entire farm health team (managers, stockworkers and veterinarians). Adequate training in the recognition of disease by stockpeople is a responsibility of the farm’s attending veterinarian. New diseases appear continuously, such as PRRS and post-weaning multisystemic syndrome (PWMS) (Figure 7.3), and established diseases (such as Glässer’s disease) evolve along with changes in pig industry techniques and technologies. Continuing professional development is prerequisite throughout the practising careers of both pig stockpeople and pig veterinarians.

The pig itself carries the ability to succumb to or to fight off disease agents. This is part of the development of immunity, and interacts with the extent of the challenge and the quality of the environment. There is a strong genetic component to a pig’s ability to stay healthy in the presence of disease organisms, and as the pig’s genetic make-up becomes more understood, commercially available resistance factors will include more than just resistance to certain strains of *E. coli*. A major problem in pig health management is of course compromised or sick pigs, which are major sources of disease pathogens, and often the cause of upset in the ecological balance of organisms on the farm. Hospital accommodation and proactive treatment regimes are central to systems control.
Observation of the undisturbed animals

Watching undisturbed animals and in particular their sleeping and lying patterns can provide vital clues to the presence of diseases, drafts and other stressors such as overstocking. Room windows are helpful to observation, but quiet entry at times of day when pigs are usually not disturbed is equally as effective. Group observations should target:

- animals that stand or lie separate from the others;
- feed that is not eaten;
- variation in the size and condition score of the animals;
- hairy pigs (particularly weaners and piglets);
- the consistency of the faeces;
- coughing or sneezing;
- signs of diarrhoea;
- signs of lameness;
- signs of respiratory distress.

In order to achieve an accurate diagnosis of a group problem it may be necessary to sacrifice a pig and/or to carry out a post mortem examination of any recently dead pigs. Post mortem examinations provide a generally accurate diagnosis, but may not always be representative of the group.

Pens of pigs are made up of individuals. Identification of problems in groups arises from observation of the individuals. With the individual animals, examine for the following:

*Fig. 7.3* Post-weaning multisystemic syndrome in a group of weaner pigs. Courtesy of the Swine and Wine Vet Group.
• behavioural changes:
  (a) locomotion;
  (b) lying place and posture;
  (c) eating behaviours;
  (d) drinking frequency and amount;
• skin changes;
• presence of lumps;
• vices in the animals;
• prolapses;
• changes in the animal’s breathing;
• discharges – ocular, nasal, aural, anal, vaginal, prepuce;
• reduction or refusal to eat;
• vomiting;
• presence of parasites;
• faeces consistency;
• urine colour;
• changes in the reproductive cycle;
• lymph nodes visibly swollen.

In order to achieve a diagnosis, samples may be required to be taken. These would include a blood sample, bacterial or viral swabs (from the nose for atrophic rhinitis, for example), tissue samples (from a lump, for example, to demonstrate an abscess) or scrapes from the ear for mange.

Pig health programmes and quality assurance

Health/disease monitoring provides knowledge of the status of an individual herd or groups of herds or, indeed, of a geographical region. The purposes of such knowledge are many, including:

• product quality assurance, perhaps the most important purpose: pig meat product sold with assurances as to the health of the animals from which it came, the levels of use of medicaments and growth promoters, standards of housing and welfare, etc.;
• possibilities for disease eradication;
• provision of an ability to match farms of similar disease status so that stock can be moved from one farm to another with minimal health challenge to either population. For example, movement of young breeding females carrying pneumonia from multiplication farms to commercial farms otherwise previously free of pneumonia can be avoided. Equally, the positive choice of such gilts for moving to commercial farms known to be already infected can be arranged. Such practices will avoid disease breakdowns in herds where a disease has been eradicated, and allow amelioration of the disease challenge to animals free of a specific disease when they are moved to a farm with that disease.
A pig health programme should enhance the value of the pig meat product and increase the efficiency of its production. For this to occur, the programme must: (1) assess the problem (monitor), (2) apply known technologies (control), (3) investigate the possibilities for new technologies (research and development), (4) evaluate results, and (5) transfer new knowledge to where it is needed. Quality assurance and welfare issues are necessarily an integral part of any pig health programme; they are part of the route to obtaining value-added returns to pay for the costs of a pig health programme.

A comprehensive pig health programme should comprise both a producer-driven monitoring and control scheme, and independent inspection and certification.

To address the issues, there is a requirement for continuing communication between those who monitor and investigate, on the one hand, and those who practise at the production and retail ends, on the other hand. Disease monitoring at farm and meat processor level, together with tissue collection and examination, is an essential prerequisite to a co-ordinated pig health plan, and to the enactment of specific disease eradication programmes. Effective monitoring, disease control and ultimate eradication of specific diseases requires co-ordination between pig producers, breeding companies, veterinary practitioners, meat inspectors, meat retailers, investigators and inspectors.

Pig health scheme monitoring usually involves the classification of farms as free from certain named diseases or named groups of diseases. Some diseases to be registered as eradicated are easy to select, such as swine fever; others are relatively easy, such as swine dysentery; others are more difficult, such as Mycoplasma pneumonia; and yet others verge on the impossible, such as E. coli diarrhoeas and parvovirus.

Perceived pig health benefits may be described in terms of the resolution of specific disease problems, such as: pneumonias and respiratory diseases; meningitis; internal parasites; nephritis/cystitis; leptospirosis; external parasites; locomotor problems; disease of the alimentary tract and diarrhoeas; reproductive disease; meat processor condemnations; and deaths. Alternatively, pig health benefits may be described in more general terms, such as: improved welfare; inception of quality assurance schemes (including pig health assurance schemes) in order to enhance product value; pollution control in an environmentally aware political climate; alternative systems to close-confinement regimes; reduction of the impact of outdoor pigkeeping on pig health; improvement of the interface between disease, management and technology; and the application of acceptable measures and vaccinations to reduce the consequences of diseases that cannot be eradicated and of those that can.

**Control of pig environment**

The expression of clinical production diseases is often precipitated by the environmental stressors to which the pigs are subjected. These may be listed as: physical interactions between man and pig, the water supply, the feeding system, the floor area, the air quality and the air temperature.
The stockworker

A good stockworker provides the pig with:

- a stress-free environment;
- the possibility to express normal behaviour patterns;
- freedom from fear, disease and pain.

Good buildings and proper feeding are fundamental to the creation of an environment of good stockmanship, but also important is the interaction between person and pig. Unhealthy pigs do not make for a contented working environment for people; and, conversely, discontented people predispose pig units to disease problems.

Overt manifestations of poor pig care are nervous pigs and negative interactions such as kicking and slapping. Talking to and touching pigs may seem idiosyncratic but are essential components of good stockmanship. Unfortunately, part of the stockperson’s responsibilities is with pig processing; teeth clipping, tail docking, animal identification (ear notching) and castration. All of these processes are mutilations, but may be necessary to ensure that the pig’s long-term welfare is not compromised. If processing has to occur, it should only be with equipment that is well maintained. Castration blades provide a direct route for disease spread, and poorly maintained teeth clippers can begin infections that end up in piglet joint ill (strep-tococcal infection) and lameness. However, teeth clipping is not always necessary, and satisfactory environments and stocking regimes can minimise pig cannibalism and obviate the need for tail docking. Ear notching and other individual animal identification may only be required for genetic identification and trial work and may not be necessary on all farms. In many countries, marketing opportunities result in the possibility of avoiding any need to castrate.

The water supply

A continuous supply of fresh, uncontaminated drinking water is essential to pig health. ‘Supply’ includes adequacy of flow and appropriateness of drinker design and height. Header tanks should be clean, of adequate size for the room served and covered to reduce algae growth and to reduce aerial contamination of the water. The header tank can be valuable for possible water medication routines. Drinkers should be examined daily (twice daily for lactating sows) for:

- any leaking drinker – a major cause of wasted water;
- cleanliness – a dirty looking drinker is generally not working properly;
- location – can the pig gain access to the drinker properly?
- height and angle – is it appropriate for the pigs using the drinker?
- flow of water – this may need to be measured using a 250ml cup and a stopwatch;
- temperature of the water – measured by an infra-red gun on the collected water above;
• the colour and possible taste of the water – water high in iron is reddish and if high in sulphate can be foul tasting.

Table 7.3 gives suggestions for drinker heights and flow rates.

**The feeding system**

Growth rates are determined by the ability of pigs to eat. The type of feed, presentation of feed and hygiene of feed are factors that the farm health team needs to assess to ensure that health and production are maintained. Feeding system construction impacts upon:

• dust emissions, which occur primarily at feeding;
• bin hygiene and vermin and bird control;
• wastage from bins, barrows, containers and in-pen troughs;
• spoilage by in-room storage (leading to off flavours – particularly in creep feeds);
• proliferation of fungal mycotoxins, which can impair reproduction, reduce appetite and cause enteric disease.

Recommended feeder lengths are shown in Table 7.4. Simplistically, meal-fed pigs in groups should have sufficient feed space that they are all able to eat at the same time. This also, and importantly, applies to nursery pigs during the first week post-weaning.

On many farms there is too much feed available in *ad libitum* feeders. This increases waste and allows the pigs to mouth and play with the feed, turning it into a meal. This accumulates in the corner of the feeder where it can become a breeding ground for flies. On the other hand, too little feed available will reduce growth rates and increase the risk of gastric ulceration.

**Feed pathogenic contaminants**

Occasionally pig feedstuffs may be contaminated with industrial chemicals, pesticide residues and the like, which can have deleterious toxic effects. Some feeds can contain foreign bodies, such as plastics in feed-grade fats, and metal and glass in

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**Table 7.3. Suggested flow rates and height for drinkers.**

<table>
<thead>
<tr>
<th>Animal type</th>
<th>Water flow (l/m)</th>
<th>Height to drinker (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suckling pig</td>
<td>0.3</td>
<td>10–13</td>
</tr>
<tr>
<td>Weaner</td>
<td>0.7</td>
<td>13–30</td>
</tr>
<tr>
<td>30kg grower</td>
<td>1.0</td>
<td>30–46</td>
</tr>
<tr>
<td>70kg finisher</td>
<td>1.5</td>
<td>46–61</td>
</tr>
<tr>
<td>Adult</td>
<td>1.5–2.0</td>
<td>61–76</td>
</tr>
<tr>
<td>Lactating sow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bite drinker</td>
<td>1.5–2.0</td>
<td>76–91</td>
</tr>
<tr>
<td>Nose drinker</td>
<td>2.5</td>
<td>76–91</td>
</tr>
</tbody>
</table>
human food waste and food by-product. Medicines may be inadvertently included in an inappropriate diet or, more likely, there may be cross-contamination of one feed with another that contains a medicinal preparation suitable for one species but unsuitable for pigs. This most commonly occurs in feed plants preparing compounds for a variety of different purposes sequentially, but with limited ability to completely separate feed batches.

The most serious feed contaminants, however, are pathogenic viruses and bacteria which may be present in animal products, such as meat and bone meal, blood meals and fats, made from slaughterhouse and meat-packing plant wastes. These by-products of human meat preparation are valuable sources of animal feed, especially high-grade proteins and lipids; and animal feed represents a highly satisfactory outlet for an otherwise troublesome – and potentially polluting – by-product. Of the total animal product entering slaughterhouses and meat-processing and packing plants, some 60% leaves as appropriate for human use; the remaining 40% goes to the rendering plant, and 80% of rendered material returns to animal feedstuffs, having been effectively recycled. The possibility of transfer of infectious agents, for example bovine spongiform encephalopathy (BSE) and *Salmonella*, through the food chain by use of inadequately prepared animal by-product in animal feed has received much recent attention in Europe, and has resulted in more stringent control of the product processes for meat and bone meals and fat rendering. Bacteria that are often thought to require particular vigilance are *E. coli*, *Salmonella* and *Treponema hyodysenteriae*, all of which may cause diarrhoeas in pigs. In a recent survey of pig feedstuffs for the presence of salmonellae, more positive samples were found amongst vegetable protein concentrates than meat and bone meals, and in no case was *Salmonella enteritidis* found in meat and bone meal. Feedstuffs are only very rarely suspected of containing *Clostridium botulinum* or *Bacillus anthracis*.

### Table 7.4. Recommended feeder lengths for different weights of pig.

<table>
<thead>
<tr>
<th>Weight of pig (kg live weight)</th>
<th>Length of trough or hopper (mm per pig feeding)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Restrict fed</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>130</td>
</tr>
<tr>
<td>15</td>
<td>150</td>
</tr>
<tr>
<td>35</td>
<td>200</td>
</tr>
<tr>
<td>60</td>
<td>240</td>
</tr>
<tr>
<td>90</td>
<td>280</td>
</tr>
<tr>
<td>120</td>
<td>300</td>
</tr>
<tr>
<td>Sow</td>
<td>400</td>
</tr>
</tbody>
</table>
Feed mycotoxins

In many parts of the world mould-contaminated feedstuffs and resultant mycotoxin levels in the diet constitute a considerable health hazard. Feed of all kinds may become infected due to faulty production, harvesting or storage of ingredients before compounding and/or faulty storage of the mixed diet on the production unit. Mycotoxins in feed cause reduced appetite, poor growth, poor efficiency of feed use, anoestrus, reduced ovulation rate, vulval swelling, reduced fertilisation rate, embryo death and resorption, fetal death and mummification, still-births and low birth weights. These problems are wholly avoidable if only well-stored, wholesome ingredients are purchased, and storage bins on the production unit are kept in good order and regularly cleaned. Commonly occurring toxins are aflatoxins and ochratoxins, such as from *Aspergillus* species, and zearalenone (F2), T2 toxins and vomitoxins (trichothecenes), such as from *Fusarium* species. At least 17 species of toxigenic fungi may be readily isolated from various contaminated feedstuffs, and at least 40 mycotoxins identified as having important negative consequences upon animal performance. New mycotoxic compounds continue to be isolated in this rapidly expanding area of knowledge. The seriousness of the chronic effects of mould toxins upon growth rate, feed intake and fertility of pigs is only yet partly realised.

The floor area

Stocking densities for all stages of pigs are becoming a regulatory constraint on pig production throughout the world (see Table 7.2). Pig health and individual growth rate improve with increased space allowance per pig, but total pig meat output per farm per year may sometimes (but by no means always) be reduced. An acceptable balance between space and production is sought.

Even for perfectly healthy pigs, as space allowance per pig decreases so also does growth rate and efficiency of feed use. Additionally, at higher stocking densities (Figure 7.4) the likelihood of heightened aggression, cannibalism and disease outbreak rapidly rises, and when this happens the negative relationship between space and growth becomes even worse. For pigs likely to be challenged by disease, space allowance needs to be increased if economic growth is to be maintained. Benefits of increasing space allowance, and the penalties of decreasing space, are thus greater if disease organisms are present. Space allowances above/below 0.7 m² per 100 kg of pig live weight in the pen will increase/decrease individual pig growth rate by about 2.5% for every 0.1 m² change in space allowed. If there is significant disease presence on the unit then (1) there is benefit from increasing space allowance above 0.7 m² per 100 kg of pig, and (2) the value of the benefit (or disbenefit) of changing the space allowance increases.

By reducing growth rate, disease itself causes stocking densities to rise, creating a downward spiral of increased disease level and reduced performance. Pathogenic organisms become more concentrated in the environment, while the pigs are placed...
closer to each other and closer to their excreta, so aiding disease spread by droplets from the lungs or mouth, or via particles of faecal material. Increasing stocking density exacerbates pig disease, while decreasing stocking density is an important part of most preventative and curative regimes.

As farms age, flooring and other contact surfaces (walls, doorways and passages) become eroded, particularly around feeders and water supplies. Poor maintenance routines ultimately result in compromised pig health through physical injury and the entry of organisms causing abscesses and lameness, and through the harbouring of pathogens to allow transfer from one batch of pigs to the next. Damaged floors lead to failure of all-in/all-out routines, and the impossibility of adequate cleaning routines. Organised pig flow will set aside sufficient time to allow stockpeople to adequately care for the floor. Specifications for slatted floors are given in Table 7.5. Floors (slats and solid) may afford insufficient grip to the pigs, with their feet sliding from under them. This can result in splayleg, dog-sitting and terminal leg injury. Lameness in the rear limbs, dropped pasterns, weakened tendons and ligaments and foot abrasions are commonly caused by excessively close confinement and by slippery floors, and also by over-abrasive floors; the sows having difficulty in rising and lying down without incurring injury.

Up to one third of sows are culled from the breeding herd because of lameness, joint problems, strained tendons or infections of the toe, foot or leg. Some of these follow from abrasions, knocks and sprains from poor housing, slatted concrete floors and inadequate husbandry during the growing period. An alarmingly high percentage of intensive pigs show some form of malaise (although often mild) of leg, joint, bone, skin or hoof. Abrasions can become infected, while physical injuries debilitate

Fig. 7.4 Growing/finishing pigs which have been given inadequate space allowance.
the animals. Bursitis, swellings on legs caused by pressure on poor hard floors, may be resolved by deep bedding. Growth and feed efficiency can be affected and the stress caused could render the pigs prone to other infections. In the breeding herd sows can be restricted in their movement when housed in tethers, stalls and crates for most of their lives, and they may find themselves placed onto improperly prepared or inadequately maintained flooring. Such situations, together with unhygienic conditions, provide a ready cause of internal skeletal and muscle damage, lameness, sprains, erosions and cracks of the foot (hoof, toe and heel), necrosis and various limb infections.

Mineral and vitamin deficiencies are usually only the cause of leg disorders when there are frank and gross inadequacies of required nutrients. However, over- and under-nutrition in respect of the total quantity of food (animals being too fat or too thin) may readily predispose to lameness. Fat sows are heavy and clumsy and the legs must bear an extra burden, while thin sows are prone to abrasions, sores, abscesses and skin infections. Pigs forced to lie on cold floors suffer more frequently from arthritis and joint problems. Slippery, dirty floors in pregnant sow and lactating sow houses cause the sows to lose their grip and fall.

Ideally there should be no steps in the floor area. However, in bedded systems steps are commonly used to constrain the bedded area. In this event they should be no greater than 50 mm high for weaners and growers and no more than 100 mm high for finishing pigs and sows.

Slopes likewise should be minimised. This should include loading areas and ramps onto trucks. Ideally, slopes should be 20° or less. Hydraulic lifts for transportation trucks are advantageous.

Bedding can ameliorate floor problems, and with solid floors creates a good pig environment. Many types of materials can be used as bedding. Bedding serves to protect the pig from the floor surface (mats may be useful post-weaning), to provide warmth by insulation and manipulable material which enhances welfare. However, bedding may also be a health hazard. Bedding contaminated with moulds can result in abortions and reproductive problems. Various types of sawdust and shavings may be associated with *Klebsiella pneumoniae* mastitis. Rodent urine and contamination may be associated with leptospirosis.

<table>
<thead>
<tr>
<th>Table 7.5. Slat recommendations (compliant with EU regulations).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void width (mm)</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Sow and litter</td>
</tr>
<tr>
<td>Pre-nursery</td>
</tr>
<tr>
<td>Nursery</td>
</tr>
<tr>
<td>Growing/finishing</td>
</tr>
<tr>
<td>Gestating sows</td>
</tr>
<tr>
<td>Pens</td>
</tr>
<tr>
<td>Stalls</td>
</tr>
<tr>
<td>Boars</td>
</tr>
</tbody>
</table>
Pigs are destructive; they will clear woodlands. They will do the same with their powerful snouts and neck muscles to building floors, walls and any other structure in reach. The result can be sharp and dangerous edges which will be damaging to the pig and allow pathogens to enter the broken integument. This may set up a cycle of damage, as when pigs become itchy with mange.

Growing and finishing pigs are often bored in unenriched environments. To prevent vices and allow for play and normal behavioural expressions, distractions are necessary, and these can be in the form of toys or other manipulable materials.

**Air**

Failing ventilation systems allow respiratory pathogens to flourish. Seasonal variations put pressure on ventilation systems and require them to actively manage temperature, humidity, gas pollutants (NH$_3$, CO$_2$, CO, H$_2$S), dust and endotoxins. Poor building ventilation leads to chilling, overheating, foul air, disease spread, diarrhoea, poor pig respiratory health and increased vices. The pig’s lying and sleeping patterns will help diagnose inadequacy in air control systems.

Ventilation inlets and outlets, fans and cowlings need active maintenance and regular cleaning. Airways may become obstructed with bird nests, plants, growing trees, half-eaten Mars bars, dirt-dried faeces and the like.

Fans drive air in or out of a building. For draught avoidance, the actual position of the extracting fan is not as critical as the position of the inlet. Pigs will generally sleep in the most draught-free area of the pen. Fans should be clean, run quietly and have sufficient size and control variation to handle the volume of air and the number of air movements required of a fully stocked house in summer and the same house just receiving a new batch of pigs in mid winter.

A major failing in many ventilation systems is the open doorway. Air will take the least resistance to enter the room and if the door is open then this will result in massive air movement through the gap.

The human nose, eyes and ears are effective at identifying:

- endotoxins – producing breathing difficulty (originating from bacterial cell walls, causing bronchial spasm);
- dust levels – resulting in vision impairment and breathing difficulty;
- ammonia concentration – characteristic smell and runny eyes;
- carbon dioxide/carbon monoxide – resulting in a headache (and danger of death);
- noise disturbance;
- lighting pattern;
- pig lying patterns and pig behaviour;
- vices such as tail, flank and ear biting, which are aberrant behaviours indicative of environmental inadequacy of one sort or another.
Dust

Dust emanates from dried faecal material, dander from the pig’s skin and (mostly) feed particles. Covering the feeder can make a significant difference in the air dust concentration. Dust comes in three basic types:

- Non-respirable dust which has particular sizes larger than 3 µm. A healthy respiratory tract will remove all of these particles with the help of the turbinates of the pig’s snout.
- Respirable dust (3–1.6 µm) can be difficult to see, other than as the haze in sunlight shafts. Long range vision clarity is also affected.
- Dust smaller than 1.6 µm is actually too small for much to remain in the respiratory tract. The particles can be blown out without settling.

High levels of dust clearly cause physical respiratory distress; at lower levels the deleterious effects are more difficult to quantify, but it is evident that not only are pathogenic bacteria and viruses respirable in size, but also they may use respirable dust as a carrier.

Dust concentrations should be kept below 10 mg/m³.

Gas

Ammonia is a pollutant produced by the bacterial breakdown of urine products. Ammonia can be monitored by gas measuring equipment, but the concentration of ammonia can be approximated by the senses, as shown in Table 7.6. The table illustrates the range of ammonia concentrations detectable. Ten parts per million is the usually accepted upper limit for pigs.

Hydrogen sulphide is also produced from the slurry. It is extremely toxic and is an unusual cause of sudden death in sows, particularly if housed above a mixed slurry pit. It smells of rotten eggs at low concentrations, but lack of smell is no guarantee of the absence of toxic levels. The acceptable limit is 0.1–5 ppm.

Carbon dioxide is a good indicator of poor ventilation. Toxic effects are not seen until the concentration is higher than 5000 ppm (2000 ppm is acceptable). If the stockworker gets a headache within 10 minutes of entering a pig house, it may be polluted with high concentrations of carbon dioxide. Such buildings may also present with problems such as Streptococcus suis II meningitis in weaned pigs.

<table>
<thead>
<tr>
<th>Table 7.6</th>
<th>Effect of ammonia on the human.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration of NH₃ (ppm)</td>
<td>Typical human effects</td>
</tr>
<tr>
<td>Below 5</td>
<td>No effect</td>
</tr>
<tr>
<td>5–10</td>
<td>Detected by smell</td>
</tr>
<tr>
<td>10–15</td>
<td>Causes mild eye irritation</td>
</tr>
<tr>
<td>Above 15</td>
<td>Causes eye irritation and tear flow</td>
</tr>
</tbody>
</table>
Carbon monoxide is also a significant pollutant and the product of poorly ventilated heater sources. Concentrations in excess of 5 ppm should warrant investigation.

**Noise**

Noise levels above 85 dB need to be avoided, as above this damage to the ears can occur. Noise levels are important as they can interfere with reproduction and farrowing comfort. A fan with a failing bearing can stress finishing pigs.

**Lighting patterns**

Light intensity needs to be at least 40 lux for a stockperson to examine animals. From a production point of view, gilt reproductive cycling is affected by poor lighting patterns, in terms of both intensity and duration. A minimum of 500 lux (which is as bright as a kitchen), with a pattern of 16 hours on and 8 hours off is required all year round to minimise seasonality effects. Failing light is commonly due to poor bulb replacement or a gradual build-up of dust and fly faeces on light bulbs and glasses.

It is a general recommendation that pigs should not be kept in total darkness. However, total darkness can be used as part of the treatment programme for the control of vices, such as tail biting or ear biting.

**Humidity**

In general pigs are relatively insensitive to humidity. However, the relative humidity of the room should be kept between 55 and 70%. The purpose of ventilation control in the winter is to remove moisture. The purpose of ventilation control in the summer is to remove waste gases.

**General control of respiratory disease**

Much can be done to ameliorate the effects of endemic respiratory disease in growing/finishing pigs. In addition to high standards of husbandry and cleanliness, the pigs should have: greater than 3 m$^3$ of air space per pig; less than 5 mg dust/m$^3$ of air; less than 25 ppm ammonia in air; a total floor area of greater than 0.75 m$^2$ per 100 kg of pig live weight; an absence of draughts (maximum wind speed across pen of less than 0.4 m/s); good ventilation and clean air; the correct air temperature (normally 18–22°C depending on live weight); maximum temperature fluctuations of ±2°C; pen sizes of <15 pigs/pen; and room sizes of <100 pigs/room.

**Temperature**

Conventional recommendations for air temperatures (together with acceptable variation) for pigs are given in Table 7.7. Effective temperature is best judged from
maximum and minimum temperature readings taken in the pigs’ locations, on the floor and at the air inlet points and at the outlets.

The warmth of a building depends upon the number of (heat-producing) pigs in it, but the ability of an individual pig to keep warm depends on the amount of feed it is eating. Newly weaned young pigs eat little feed and therefore are likely to get cold more easily. At around 6 kg live weight a baby pig requires an ambient temperature almost as high as 30°C. This should be combined with sufficient ventilation to keep the air fresh and clean, but with no cold draughts. As the pigs begin to eat and grow, this temperature can be reduced, until by 12 kg live weight 25°C is usually adequate. For healthy, fast-growing pigs temperatures as low as 22°C can be satisfactory at 20 kg. As room temperatures rise from being too cold toward the optimum, the incidences of pneumonias and pen soiling reduce. As the temperature rises above the optimum, the incidences of diarrhoea, tail-biting and meningitis increase.

Air movements remove toxic gasses and aid cooling. It is commonly understood that fluctuations in temperature may be as much involved in triggering respiratory and enteric disease as the absolute temperature. Draught is often defined as a cold air movement of 0.2 m/s or more. Draughts can create clinical problems, such as tail biting in finishers and diarrhoea in piglets.

### Diagnosis of pig comfort

Pig behaviour and posture reveal pig comfort level. Pigs normally sleep in a semi-spread-out pile. Chilled pigs lie on the floor with their legs tucked under their body to reduce floor contact (see Figure 7.5). They lie huddled with other pigs, often close to a wall and well away from damp/cold areas. The pigs may shiver and become hairy. Hot pigs lie spread out away from other pigs, with maximum contact with the floor and legs stretched out from the body (Figure 7.6). They are likely to be dirty and prone to lying in the wet and cool.

### Table 7.7. Suggested temperature zone for pigs.

<table>
<thead>
<tr>
<th>Type of pig</th>
<th>Weight range (kg)</th>
<th>At air inlet point (°C)</th>
<th>At air outlet point (°C)</th>
<th>Acceptable variation (± °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suckling piglet</td>
<td>1–7</td>
<td>30</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>First stage flat deck</td>
<td>7–15</td>
<td>30</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>Second stage nursery</td>
<td>15–25</td>
<td>24</td>
<td>21</td>
<td>1.5</td>
</tr>
<tr>
<td>Growing</td>
<td>25–50</td>
<td>21</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>Finishing</td>
<td>50–110</td>
<td>20</td>
<td>16</td>
<td>2.5</td>
</tr>
<tr>
<td>Lactating sows</td>
<td></td>
<td>18</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>Individual adults</td>
<td></td>
<td>19</td>
<td>19</td>
<td>2.5</td>
</tr>
<tr>
<td>Group housed</td>
<td></td>
<td>18</td>
<td>16</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Managing disease

Disease may be managed such that, although present, the effect is minimal.

As will by now be evident, herd health failures may often be the direct result of management failures, and by the same token pig herds can be managed into a state of health even when challenged by disease. This cannot be the case for pathogens causing cataclysmic infections in unprotected herds, but a definition of a well managed pig herd is one where unavoidable disease does not impact upon production. Many such syndromes have been discussed above; here a number of specific issues will be further developed.

Many (most) of the important day-to-day problems of reduced health on the pig unit are not due to single organism infections (PRRS, influenzas, PWMS, pneumonias, diarrhoeas and so on), but to combinations of organisms. These are endemically present on pig units and not, of themselves, necessarily pathogenic. However, in combination and in the presence of inadequate health management measures and biosecurity, these organisms act in a complex to cause disease. This means that both prevention and cure require an holistic and all-embracing approach.

Porcine stress syndrome (PSS)

Often, but not always, PSS is associated with the halothane gene and with rapidly growing meaty pigs subjected to stress. Pigs will show an acute temperature rise, muscular rigidity, sudden death and a blueing of the extremities. Muscles will be pale, soft and exudative (PSE). PSE and the associated PSS are evidenced through hypothermia and acidity and rigidity in the muscle, with subsequent loss of tissue wall integrity and movement of water out of the muscle. Symptoms are brought on by stress and enacted through the abnormal regulation of calcium release by the
muscle sarcoplasmic reticulum, and resultant increased rate of metabolism. Symptoms will occur after mixing, fighting, transport, hot weather, absence of water cooling facilities, bad slaughterhouse lairage, ill treatment or any other acutely stressful situation. Less acute stressful situations will bring about changes in hormone levels, reduce the immune response, lower productivity and induce behavioural aberrations.

**Stomach ulcers**

Stomach ulcers are present in most herds and associated with stressful housing conditions, poor environment, poor management, over-crowding, excessive confinement and the use of diets that are high in energy or low in fibre, or finely ground, or pelleted or all of these.

**Constipation**

Constipation is most commonly found in pregnant or newly farrowed sows, where it is usually associated with inadequate water supply, high ambient temperature, inadequate dietary fibre – especially from cereal grains (particularly wheat, which appears most beneficial) – excess of dietary fibre from grass meal and lucerne sources, or an elevated body temperature.

**Sucking piglet mortality**

Normal losses of live-born piglets between birth and weaning amount to 12% (one per litter) but can range from 5–25%. Common causes of variation (in addition to management routines around farrowing) are the presence or absence of agalactia or *E. coli* organisms. Agalactia may in some cases be exacerbated by high level late pregnancy feeding, but this is not the cause. Failure to obtain colostrum, together with its milk antibodies, predisposes the piglet to early infection and death, especially from diarrhoeas.

In circumstances where diarrhoea is the cause of less than 1% of the mortality of live-born piglets, the major cause of neonatal death is crushing by the sow. Most of the pigs that die before slaughter or culling do so by being squashed to death in the first few days of life. Litters of low birth weight (less than 1.25kg average piglet live weight) will have higher levels of mortality associated with starvation and disease. Birth weight has a strong and positive influence upon piglet vigour and survival. However, it appears that large and small piglets are equally prone to being crushed. While the sow is retained in a farrowing crate, crushing levels are, in general, significantly reduced. However, there are wide differences between crate designs, and other factors such as sow restlessness have a considerable bearing on the number of piglets trampled to death in early life. Piglets that have not been injected or orally dosed with iron and have no access to other sources of dietary iron will suffer (because of the low iron content of sow milk) from piglet anaemia.
Iron preparations are readily available, and dosing routine and the avoidance of anaemia on intensive units straightforward.

**Cannibalism and aggression**

Outbreaks of cannibalism amongst growing pigs can be disturbing and costly. Occasionally one rogue pig is to blame and the solution is to isolate it. More often pigs attacking each others’ tails, flanks and ears do so because of management malpractice. The severity of the outbreak and the number of animals in the unit affected can be variable, and the trigger for this aberrant activity is sometimes inexplicable. Cannibalism can occasionally be seen amongst pigs even with a high level of welfare kept in good environments at proper density and well fed, but more usually the reverse is the case. It is most frequent amongst pigs that: are on slatted, concrete or metal floors, are in barren environments, are over-crowded, are suffering from other diseases, are too hot or too cold, have too frequent or too infrequent a change of air (faulty ventilation), are experiencing too high or too low relative humidity of the atmosphere, are in environments where the concentration of gases (ammonia, carbon dioxide, hydrogen sulphide) is excessive, or that have a lighting intensity in windowless houses that is too bright, and so on. Nutritional deficiencies in terms of feed composition (energy, protein, minerals, vitamins) and especially feed level are also implicated. Increasing feed fibre and trough space can be helpful, as can docking of the tail. When faced with an outbreak there is often no other satisfactory action than to manipulate the environment on a trial and error basis to try to identify the predisposing factors.

Pigs will fight to assert dominance and determine their place in the social hierarchy. Fighting will therefore occur whenever pigs are mixed into new social groups such as at weaning, moving on to grower or finishing pens, or during transport and lairage. Aggression will cause loss of appetite, loss of growth and inefficiency of feed use; sometimes such losses can be considerable. If fighting occurs near to the time of slaughter, meat quality can be severely reduced.

Fighting amongst sows in communal groups will cause anoestrus, embryo losses, reduced litter size and poor milk yield. Pregnant sows loose-housed are especially prone to aggression and to acts of cannibalism such as vulva biting. Whilst release from sow stalls and tethers may provide greater freedom of movement, sow welfare may be compromised in many loose-housing systems.

**Infertility in the sow**

Infertility can occur at each stage of the reproductive process in the form of anoestrus, poor ovulation rate, reduced conception, poor fertility, reduced embryo or fetal survival or dystocia. Excessive empty days, lowered farrowing rates, reduced litter size and early-life culling through infertility account for huge losses in the world’s pig breeding herds, especially in young sows early in breeding life. There is no aspect of diet nutrient content, level of feeding (especially), genetics, housing,
environmental temperature, management or disease that does not impinge upon the fertility of the breeding sow (Table 7.8).

The causes of reduced litter size may include an inadequate ovulation rate, poor fertilisation or losses of embryos or fetuses. Reduced ovulation may result from nutritional problems, disease, inadequate management or pig genotype. It may be associated with an extended weaning to oestrus interval. Poor fertilisation is often associated with regular returns to oestrus, and may be caused by infertility of the male or faulty management at the time of mating. Embryo and fetal death is often associated with irregular returns to oestrus, and is usually related to disease invasions of one type or another.

The most frequent cause of oestrus failure within 7 days after weaning is poor sow body condition due to inadequate feeding and excessive weight and fat losses in lactation. All lactating sows should be fed to appetite and high feed intakes encouraged. High lactation feed intake will follow from the frequent provision of a high energy diet given wet in a cool environment.

Regular repeats, low levels of abortions, sows not in pig, fetal deaths in late pregnancy, still-births and low litter size are usually not caused through infective agents unless there is evidence of vulval discharge or mummified pigs. Regular repeats, low litter size and sows not in pig point to the need for better mating management and higher feeding levels in lactation and immediately after weaning. Time of mating is crucial to both conception and litter size. Three-times mating at 12-hourly intervals usually gives at least 1 pig per litter more than once-only mating. The period over which the sow is mated should always extend to more than 24 hours. Late insemination means ageing eggs at fertilisation and these are prone to death as embryos. Litter size is also related to previous lactation length; increasing the age at weaning from 3 to 4 weeks can increase litter size by 1 piglet or more per litter on some units (lactation length 18, 23, 28 days; litter size 9, 10, 11 pigs born alive). After weaning, sows that have lost body condition in lactation are not helped by having their feed reduced when they are already in nutritional stress. Weaned

Table 7.8. Tolerance levels for sow fertility.

<table>
<thead>
<tr>
<th>Event</th>
<th>Tolerance Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeat oestrus 21 days after mating (%)</td>
<td>8</td>
</tr>
<tr>
<td>Repeat oestrus at more than 21 days after mating (%)</td>
<td>2</td>
</tr>
<tr>
<td>Abortions (%)</td>
<td>1</td>
</tr>
<tr>
<td>Not in pig (%)</td>
<td>1</td>
</tr>
<tr>
<td>Culled while pregnant (%)</td>
<td>2</td>
</tr>
<tr>
<td>Numbers live-born per litter (primiparous sows)</td>
<td>10</td>
</tr>
<tr>
<td>Numbers live-born per litter (multiparous sows)</td>
<td>11</td>
</tr>
<tr>
<td>Numbers born dead per litter</td>
<td>0.5</td>
</tr>
<tr>
<td>Number of mummified piglets per litter</td>
<td>0.2</td>
</tr>
<tr>
<td>Live-born pigs not surviving to weaning per litter</td>
<td>1</td>
</tr>
<tr>
<td>Gilts ready for mating (per 100 breeding sows)</td>
<td>6</td>
</tr>
<tr>
<td>Weaning to mating interval (average) (days)</td>
<td>7</td>
</tr>
<tr>
<td>Weaning to conception interval (average) (days)</td>
<td>12</td>
</tr>
<tr>
<td>Litters per sow per year</td>
<td>2.3</td>
</tr>
</tbody>
</table>

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sows should be fed to appetite twice daily until mated. When sow body condition is a cause for concern, they can also continue to be fed up to 3–3.5 kg daily after mating. Poor body condition will have a more deleterious effect upon ovulation rate and embryo survival than elevated feed levels. Losses of embryos at implantation can also be caused by cold conditions and inadequate (less than 16 hours) day length at this time. Regular returns to oestrus usually mean a failed conception; irregular returns result from embryo losses such that less than four remain and the pregnancy self-terminates through lack of hormonal support from the products of conception.

Infertile agents may cause uterine infections and vulval discharges, and result in embryo losses, giving irregular returns to oestrus (often between 23 and 40 days), fetal death and part-resorption in mid-pregnancy, resulting in more than one mumified fetus, reduced litter size, increased numbers of pigs still-born, abortions and sows found not-in-pig. The most frequent agents to cause these symptoms are mycotoxins, infections of the reproductive tract, parovirus, Aujeszky’s disease (pseudorabies) and Leptospira. Uterine infections and infertility often associate with cystitis; the latter causing bloody urine and sow death in some afflicted units. Parovirus is widespread throughout all pig populations in the world. Infection may take place at any time, resulting in permanent immunity. However, if infection occurs in a herd for the first time during the first third of pregnancy, then there will be an outbreak of the disease with resultant fetal death. The end result is the presence of mumified pigs. Breeding animals at risk should be vaccinated as gilts.

On some units natural immunity to opportunists invaders of breeding sows is built up by challenging new entrant gilts when they come into quarantine. This can be done by exposing them to weaner excreta or to finishing pigs on their way out of the unit. One routine is the presentation to acclimatising gilts of piglet faeces (and sometimes also placentae) from the farrowing rooms and weaner pens for a period of 2 weeks. Some veterinarians allow piglet faeces but abhor placentae, as the latter may contain too high and diverse a level of pathogenic material. Weaner faeces are also more infective than the faeces of older pigs. This practice is terminated 3 weeks before conception. Faeces (only) may then be offered again for a week in mid and late pregnancy. Young growing pigs are the most infective class of animals on the whole of the pig unit. Exposure to young growing pigs and to their excretions can thus represent a high-level and multi-organisinal challenge to naïve new entrants to the pig unit.

Vaginal discharges due to a range of ascending infective organisms (such as Pasteurella, E. coli and Corynebacterium) entering through the vagina and disrupting the reproductive tract will give painful urination, cystitis, regular and irregular returns to oestrus, reduced litter size, fetal death, abortion and, most confusing of all, may stop the non-pregnant animal from cycling altogether (only determined at term or by pregnancy testing). Fetal resorptions and mumified fetuses are not usually associated with ascending infections, but rather with parovirus. The normal levels of vaginal discharge are about 1% of sows; when the level rises to 1.5% or more, action is required. Treatment demands cleanliness in the pregnant sow house,
antibacterial washing and douching, antibiotic injection of all affected sows and routinely after farrowing and at weaning, and a delay of one cycle before remating. The boar may be carrying the organism himself, so he also will require treatment by injection and by systematic delivery of intramammary antibiotic into the prepuce. A more positive, if rigorous, treatment programme is to cull all discharging animals without any attempt at remating, and to increase the rate of entry of gilts into the herd to compensate.

**Low numbers of viable sperm**

This is usually associated with high temperature, malnutrition, ill health and boar over-use, or can be characteristic of a particular individual. Boars that are tentative in mating can also show reduced conception rates and litter size. This may be an individual characteristic or due to inadequate mating pens, especially slippery floor surfaces and insufficient space. Boars should not be reared in isolation and should start mating once a week when $7\frac{1}{2}$–9 months of age. At about 12 months they can manage up to 4 or 5 copulations/ejaculations a week. The average age of all the boars on the unit should not be greater than 2 years.

Boars giving less than 1000 offspring born alive per 100 matings should be considered suspect. To mitigate the effects of low sperm numbers and poor viability, multiple mating of individual sows and the culling of the inadequate male once detected can be considered. All matings should be supervised carefully.

Boars used for artificial insemination are usually collected from once or twice weekly; each collection of some 50–100 ml sperm-rich fraction of ejaculate containing about $50 \times 10^9$ sperm at $0.5–1 \times 10^9$ sperm/ml being used to cover 20–30 females, depending on sperm concentration quality and motility. An effective sperm dose is about $2–3 \times 10^9$ mobile sperm in about 100 ml of diluent fluid; with three doses per oestrus, each set 12 or so hours apart. Double insemination routines should be spaced 24 hours apart.

**Internal and external parasites**

Pigs may be infected by a range of helminths invading the stomach, the large and small intestines, the lungs and the liver. Specific in-diet and injectable curatives are readily available. The consequence is reduced growth and efficiency, diarrhoea and general debility. Sometimes worm infections will cause abortion in sows that are otherwise in good condition. The major external parasites are (1) lice (*Haematopinus suis*), whose presence will also reduce growth and cause anaemia as well as irritation, and (2) mites. Both may be dealt with by use of external anti-louse and anti-mite preparations. Mites are a serious menace causing sarcoptic mange; a dermatitis leaving a grey, encrusted skin which is irritating, and when rubbed and scratched leaves dark red patches. Infestations are evident after slaughter where the pig’s skin shows a rash. Mites can live for 2 weeks in the absence of pigs. Pig growth rate and efficiency can be severely affected.
Modern anthelmintics are available which are active against all internal parasites of pigs, with a possible exception of lungworm. This latter parasite, however, would be unusual in intensively reared pigs since access to the earthworm (an intermediate host) is essential to complete the life cycle. Injectable or in-feed preparations of the Ivermectin group of anthelmintics deal comprehensively with all internal and external parasites. Perhaps the best known internal parasite is the round worm, *Ascaris suum*, which infests the small intestine, causing reduced growth rate and diminished carcass quality. The parasite is evidenced by white lesions on the liver (milk spot).

It is impossible to maintain an absolutely parasite-free population due to the contamination and mechanical transmission of worm eggs by birds and other means; parasite problems are more prevalent in semi-intensive and extensive systems than in intensive systems. It is possible, however, by good management procedures, to break the life cycle and hence maintain minimal populations and obviate the requirement for worming. This is particularly so in indoor pig units where dung is removed every 3 days or sows have no access to dung. There is no longer any reason for internal worms, external lice or mites or mange to be a problem in pig herds.

**Colibacillosis (infection with Escherichia coli)**

*Escherichia coli* is a ubiquitous organism with many serotypes causing, *inter alia*, septicaemia in neonatal piglets, diarrhoea in sucking piglets, diarrhoea in newly weaned piglets and oedema in young growing pigs. There are many pathogenic strains. Septicaemic strains invade susceptible tissue and cause lesions. The enteric strains attack the brush border of the intestine, causing reduced absorption, diarrhoea and toxicity. Young sucking pigs affected show severe loss of condition, acute septicaemia, diarrhoea and possibly death. Antibodies in both colostral (especially) and normal milk provide protection to sucking piglets from sows that have built up immunity to specific *E. coli* strains. This protection is lost at weaning consequent upon the withdrawal of sows' milk. Piglets weaned at 3 weeks of age are particularly susceptible; a susceptibility that is exacerbated as the intestine is simultaneously required to cope with the change from a liquid to a solid diet (especially if the latter has a high concentration of vegetable proteins and carbohydrates). Delayed weaning to 4–5 weeks often reduces the seriousness of the condition. Vaccines are available against a range of serotypes, while incoming breeding stock can also be subject to a natural challenge before they are mated for the first time. Gilts can be vaccinated twice before first parturition. This will allow them to build up their own immunity and pass the appropriate protection on to the litter. Failure to encourage the build-up of natural immunity may lead to consistent outbreaks of diarrhoea in the sucking piglets of primiparous gilts brought into the breeding unit from remote locations not harbouring the same serotypes. Within a stable population of pigs, acquiring natural immunity in the normal way, there may still be outbreaks of diarrhoea, especially in the young piglets, consequent upon rapid multiplication of *E. coli*. *E. coli* will multiply when there is over-stocking, environ-
mental problems or the presence of other disease organisms. Its control is primarily by antibacterials, and by good management and a high level of cleanliness and disinfection within the lactating sow house. Diarrhoea is seen mostly in young sucking piglets and in newly weaned piglets. In both cases animals lose appetite, weight and may die from dehydration. Animals suffering, together with others in the same pen, should be orally dosed or injected with antibiotic immediately, offered glucose and electrolytes in their water and given protective levels of antibiotic additives in their feed. Recent experience indicates that 3 kg zinc oxide per tonne of feed assists in the control of diarrhoea in weaned piglets. In Sweden zinc is used (together with improved nutrition and management) as an effective substitute for routine in-feed antibiotic dosing. Control is aided by maintaining the proper environment and ambient temperature, by hygiene and by reducing the density of stocking. For pigs challenged with *E. coli* organisms, there is a strong inverse relationship between the percentage of pigs showing diarrhoea and the temperature of the weaner accommodation. In the course of the infection, *E. coli* produces massive amounts of toxin under conditions of rapid multiplication, and there is also loss of gut motility and destruction of the villi lining the intestinal wall. The diarrhoea can range from mild to extreme. All young animals in stress are likely to suffer; the extent of the debilitation caused by the disease will be directly proportional to the degree of immunity that has been built up in the animal by the time it was infected, and the level of prevailing management.

Faulty nutrition predisposes sucking and weaned pigs to *E. coli* attack. This is particularly the case with young newly weaned animals offered diets containing high levels of uncooked starch and vegetable protein sources. Pigs weaned at less than 30 days of age do not have the digestive capacity to deal effectively with raw vegetable carbohydrates and proteins. Furthermore, there may be additional problems in the gut lining of adverse antigenic reaction to the presence in the gut of particular vegetable protein moieties. Some vegetable protein sources appear to be more severe in this respect than others. Where problems are initiated by dietary factors in weaned pigs between 20 and 35 days of age, *E. coli* organisms invade opportunistically, and severe diarrhoea, rapid loss of condition and death may result. Young pigs having suffered from *E. coli* diarrhoea during their early life will never fully recover from the experience and will always grow slower and less efficiently thereafter. The economic consequences of damage by this organism are therefore considerable.

It is helpful if piglets have been accustomed to consuming substantial quantities of solid feed before they are weaned, and further are not removed from milk as the main nutrient supply until the digestive tract is fully competent to deal with non-milk substrates. Weaning at a greater age and heavier live weight is therefore helpful in the control of post-weaning diarrhoea. As the disease may sometimes be associated with a high stomach pH, probiotic treatments to enhance gastric acidity may be helpful.

*E. coli* may be found in breeding sows as an opportunist invader of the reproductive tract, and injections of antibiotics at farrowing and weaning and appropriate
treatment of the boar are required. Outbreaks in the lactating sow house are reduced by effective environmental control, the presence of foot dips at the entrance to each room and a high level of cleanliness for floors, equipment and personnel.

**Other causes of diarrhoea**

Young piglets may also suffer coccidiosis-induced diarrhoea associated with poor hygiene and dung contamination of pen floors. Specific oocidal disinfectants are required. Similarly, *Clostridium* infections will also cause piglet diarrhoea in sucking litters where mother and young are challenged but do not have adequate immune protection. *Campylobacter* infection shows similar symptoms to *E. coli* and is prevalent in young piglets. Treatment is likewise with antibacterials.

**Porcine intestinal adenomatosis (PIA), ileitis and colitis**

These diseases appear often to be interrelated and share the common symptoms of loose, dark, sloppy faeces and dirty pigs, with mild to severe losses in growth rates and feed efficiency. The symptoms are less acute than those of swine dysentery.

PIA causes necrotic enteritis, ileitis and proliferative haemorrhagic enteropathy (intestinal haemorrhagic syndrome). Both morbidity and mortality rates are variable. Often the intestine wall is thickened and there is bleeding into the intestine, with loss of weight and growth. Pigs look thin and do not thrive and the faeces are often characteristically loose and dark. When there is a large amount of blood loss the pig itself becomes white in appearance. Mortality can be high where there is haemorrhage into the lower part of the intestine. The disease has been associated with *Campylobacter*, *E. coli*, *Clostridia* and *Rotavirus*, and with other organisms – but perhaps especially with *E. coli*, where gut thickening is not symptomatic. Investigations at Edinburgh of proliferative ileitis have suggested that an important causal bacterial organism is the newly identified *Lawsonia intracellularis*, which colonises the upper digestive tract, causing diarrhoea and having the propensity to spread rapidly through both growing and finishing pigs. Control can be arduous, but the position can be substantially improved by in-feed medication in the form of antibacterials, specifically tylosin, tetracyclines and tiamulin. The organism, in addition to causing ileitis, can induce colonic irritation and thus bring about symptoms of colitis. Ileitis is not necessarily indicative of poor husbandry and can strike in otherwise high-health herds with fast-growing and efficient animals, often of improved lean genotypes.

Colitis also causes sloppy, dark faeces and dirty pigs, and it is also associated with chronic losses in growth rate and feed efficiency. Its cause is now known to be the result of interactions between infective agents and diet ingredients. Amongst the infective agents appear to be *L. intracellularis* and *Serpulina* species (including *Serpulina pilosicoli*) related to those causing swine dysentery (*Serpulina hyodysenteriae*) but producing milder symptoms. Control of these spirochaetes can be attempted with powerful antibiotics at high dose rates. It is generally accepted that
the *Serpulina* spirochaete, commonly isolated from the colon in cases of colitis, interacts with husbandry, dietary ingredients and feed processing to bring about a complex syndrome involving a series of largely mysterious interactions. Colitis may be associated with over-stocking, substantial variation in temperature, and where high levels of water consumption (wet feeding) is associated with highly digestible feed materials. These latter predispose to rapid flow rates of digesta to the colon, where a higher than normal level of undigested residues can create an ideal environment for the growth of unwelcome organisms.

It has been noted that a change in feed type (especially from fine ground and pelleted feeds to more coarsely ground meals) and/or a reduction in feed level can give temporary relief – presumably through a disruption of the microbial population of the colon – but the problem will tend to return. The most important feed problems appear to be anti-nutritive factors found in specific non-starch polysaccharides (NSPs). Originally it was suspected that oil-seed rape, peas and beans contained such factors (for they are associated with other anti-nutritional agents); more recently implicated have been sunflower meal, lupin meal and even high levels of soya bean meal. Wheat has similarly been found both innocent (high wheat diets causing no problems), but more frequently guilty (the converse). It is possible that wheat variety may be important in explaining this divergence of view. Doubts have also been raised about the involvement of other cereals with known unusual non-starch polysaccharide components (such as triticale and rye) and of low-quality dietary fats. No suggestion has been made that barley is associated with the syndrome; indeed, the inclusion of barley in diets containing suspect ingredients may offer some protection. It has been assumed that the causal component in wheat may be pentosan arabino-xylans, in which case there may be logic in adding in-feed enzymes (pentosanases) – if they are shown to be effective – which could deal with these particular NSP plant structures.

The resolution of colitis/ileitis problems therefore usually requires attention to dietary ingredients (often interpreted as a return to simple mixtures of conventional feedstuffs), together with improvements in husbandry and feeding practices, and, if all else fails, the usage of relatively powerful antibacterials.

**Mycoplasma (enzootic) pneumonia**

This is caused by a ubiquitous organism, *Mycoplasma hyopneumoniae*, bringing respiratory distress, with characteristic plum-greyish lesions on the anterior lobes of the lungs and a sharp, dry (barking) cough when disturbed, with, in the acute form, deep (thumping) breathing and chest heaving. Most pigs in intensive units are affected, but the symptoms and consequences are absent or slight if the management is good. *Mycoplasma pneumonia* has been evident in about half of the intensively kept pig herds in the northern hemisphere and even more widely present in North American herds. Chronic infections will bring about reductions in daily gain and feed conversion efficiency of up to 10%, but performance reductions greater than this can be evident in acute infections striking previously uninfected herds (as
when there is a breakdown on high-health status units, or in poorly managed herds and bad environments). Outbreaks in herds previously unaffected can be severe, causing debility, considerable loss in growth and mortality. Treatment with specific antibiotics can be helpful. Vaccination is now a realistic option, and the new generation of vaccines appear to be significantly reducing clinical signs of the disease in many circumstances. If mycoplasma does not exist in the herd, it is essential to maintain this state by purchasing incoming stock from proven pneumonia-free stock. Attention requires to be given to maintaining the defensive barriers of the pig unit to the proximity of other infected pigs (infection as, for example, brought in on visiting stock lorries), bearing in mind that the organism can be wind-borne over distances of up to 5 km. The organism is usually passed from the sow, which shows no clinical symptoms, to the piglet in the first few weeks of life and becomes active at around 8–12 weeks of age. Transfer across cohorts of growing pigs is rapid and morbidity high. The disease resolves and lung lesions are repaired as pigs mature. Symptoms are therefore absent in previously infected (but nevertheless infective) adult pigs. In herds carrying mycoplasma at high levels, doses of antibiotic at this time will help control. This pattern of transfer has led to attempts at control by eradication through medicated early weaning (MEW), where the organism is suppressed in both sow and piglet by high levels of medication and early weaning (less than 14 days), with segregation of sows and piglets (segregated early weaning, SEW) to geographically separate sites (three-site production).

It is vital that young growing pigs are kept warm and well-fed, in small groups (less than 12) and at low stocking density if this delicate phase is to be passed through successfully. It has been suggested that there is predisposition to disease when a pig unit receives pigs supplied from multiple sources, when there are more than 100 pigs in a single air space, when less than 0.5 m$^2$ of lying space and less than 0.8 m$^2$ of total space is allowed per 100 kg of pig live weight, where ammonia levels are above 20 ppm, where dust levels are above 5 mg/m$^3$, where the rate of air movement is $<0.2$ m$^3$ per hour per kilogram of pig live weight, where there is $<3$ m$^3$ of air space per pig, where there are more than 12 pigs per pen, where all-in/all-out policies are not used, where there is inadequate cleaning and disinfection between batches, or where there are draughts or temperature fluctuations.

On units carrying low chronic levels of pneumonia the consequences may not be severe. On well-managed units with excellent environmental conditions there can sometimes be no detectable consequences. Problems usually arise when mycoplasma pneumonia is associated with secondary bacterial infection, often triggered by stress in the pigs, inadequate environmental control, the presence in the air of dust, mixing pigs, overcrowding and failure to achieve batch throughput and effective disinfection of growing pens between batches. Sometimes acute outbreaks in chronically infected herds may be triggered by the purchase of infected pigs and/or by the mixing of sources of pigs. Where a problem is likely in the herd, pigs should be treated with in-feed antibiotics in order that the organism can be controlled to subclinical levels.
In badly infected herds for which it seems that the disease level cannot be controlled by effective management, units can be depopulated and repopulated with mycoplasma pneumonia-free (SPF) stock. In this case, unless the unit is far distant from other pigs and from roads down which pigs may travel on lorries, a breakdown can usually be expected within 5–10 years. When a herd becomes infected, the consequences may be severe unless it is controlled. In herds where there are chronic levels of the organism, severe disease outbreaks with coughing, loss of condition and sometimes death are often associated with the introduction of other pneumonia organisms, usually *Pasteurella, Bordetella* or *Actinobacillus (haemophilus) pleuropneumoniae* bacteria. It is perhaps in predisposing the pigs to secondary respiratory attack that mycoplasma pneumonia is most threatening to productivity.

**Exudative epidermitis (greasy pig disease)**

This is found in young suckling and newly weaned pigs and is caused by a *Staphylococcus* infection of the skin through abrasions. The skin becomes a dirty brown colour, exudative scales and scabs form and the animal may die from toxaemia and liver damage. It responds in about half the infected cases to early use of antibiotic treatment together with medication of the skin surface with an antibacterial agent. It is often to be found where young pigs have the surface of their skin abraded due to fighting or roughened floor surfaces. It tends to affect individuals, and should not be seen frequently. In herds at risk, the teeth of newborn piglets should be carefully clipped down to the level of the gum, leaving a smooth surface. Disinfection of the farrowing accommodation is required frequently and this is helped by a batch-farrowing system.

**Mastitis**

Mastitis is caused by *E. coli, Staphylococcus* or *Streptococcus* (or other) infection of the mammae, resulting in loss of milk, elevated temperature and reduced piglet growth in early life. It responds well to antibiotic and improved farrowing house hygiene. Mastitis can also be associated with metritis (vaginal discharge) and agalactia (MMA) in the early phase of lactation, with resultant starvation of the sucking litter. Oxytocin can be helpful.

**Salmonellosis**

*Salmonella* is a ubiquitous and common organism in nature. It is unsurprising therefore that in the absence of positive control measures some 20% of pig herds in a geographical area may show positive when tested for the presence of *Salmonella* organisms. This is not to say that these farms are a *de facto* risk to the wholesomeness of pig products derived from them. However, it is to say that there is a potential for risk if the density of organisms in pig products reaches levels that might
threaten enteric disorder in a human consumer. Although *Salmonella* infections in humans sourced from pigs is rare, levels of enteric disease are rising, and there is a natural desire to reduce the level of presence in national pig herds. There is therefore increasing interest in *Salmonella* reduction or eradication schemes.

Slaughterhouse sampling takes place through the testing of meat juice for antibodies. Positives are taken as indicative of an individual pig meeting with *Salmonella* at some point in its life through to the point of sampling. Following tracing back to the farm of origin, faecal samples will allow an assessment of the level of contamination on the unit. Because of the low correlation between the presence of *Salmonella* organisms on a farm and a threat to the health of humans eating pig products, positive tests are not cause for alarm, but for considered action.

In the case of low level, there is encouragement to eradicate; in the case of high level, to reduce. National schemes may divide their positive farms into three or so categories, according to the level of contamination and the frequency with which that level is reported from the slaughterhouse sampling. Farms consistently testing at the highest level will be required to take action and demonstrate reduction; action in this regard relating to treatment of all animals, improvement in hygiene and premises cleanliness, and attention to all the aspects of biosecurity discussed above. As an ultimate sanction, persistent appearance of farms at the highest level can result in withdrawal of the pigs from the quality assurance register, thus preventing the pigs entering the assured pig marketing chain. Categorisation of farms to levels would normally not be on an absolute basis, but a proportional one. Thus a given percentage of farmers in the whole population would be designated as ‘unacceptable’, and action taken against those farms that were persistently in that percentile. By this means, problem farms are focused upon, and the presence of *Salmonella* in the national herd progressively forced down.

**Porcine reproductive and respiratory syndrome (PRRS)**

The Lelystad virus infection PRRS (blue ear disease) struck a small number of European pig units in 1991, and may previously have existed as MRS (Mystery Reproductive Syndrome) elsewhere in the world. Subsequent spread has been rapid and the disease is now endemic in most parts of the world. Seventy percent of European pig herds appear to have been infected. The form of the virus probably differs between global geographical regions. Infections tend to be cyclical and can range in severity from mild to catastrophic – largely depending upon the level of immunity, the standard of herd management and the presence of other diseases. Thus perceptions of the severity of PRRS vary greatly across farms and geographical areas. In some cases the disease is seen as of trivial importance; in others it may have a ruinous effect upon the local pig industry and cause continuing failure to achieve adequate performance levels for such crucial criteria as conception rate, growth rate and feed conversion efficiency. The effects of initial infections are the most marked, having struck at herds with no immunity. The organism is transferred both horizontally, by carriers, and vertically to the fetus during gestation. Upon
infection, herds do not necessarily show clinical signs, despite becoming sero-positive. It is suggested that the virus is readily carried on syringe needles used for various injections around the time of weaning. Following self-resolution of the disease, herds can become progressively sero-negative, and there is a danger that herds lowering their immunity again become susceptible. Thus PRRS can often show a cyclical infection in herds due to the loss of immunity in new generations, and breakdown occurring from the infective reservoir which causes a resurgence of clinical symptoms, which in turn pass away following the creation of high herd immunity. Such patterns of infection are not uncommon in viral diseases, which may become endemic in herds and in geographical areas. The cycle may be broken either by eradication or, perhaps more realistically, by maintaining a balance of challenge and immunity. Herds that have never had PRRS are not immune. Herds that have had PRRS may or may not produce stock that is immune and suitable for moving on to other herds with active PRRS. If PRRS has been active but has disappeared from the herd, then new generations will not be immune. To ensure immune animals, they should be derived from PRRS herds where the organism is still active, allowing immunity to develop.

If it is required to create immunity in non-immune breeding herd replacements moving into herds suspected of having PRRS, animals should be moved at 100kg into isolation quarters and kept there for 7 days. At the end of 7 days they should be subjected to infective material (such as faeces from weaned pigs) or to infective animals. The period of exposure should last for about 3 weeks. After exposure, animals should be moved to the breeding herd quarters where they should remain for a further 2 weeks before mating (giving the required 6 weeks between 100kg and mating).

Symptoms of PRRS are inappetance, lactation failure, chronic and acute respiratory distress, abortion, still-birth, failure to conceive, diarrhoea, poor growth, general malaise and death. Piglet losses of 50% may be experienced during the active phase of the disease (around 8 weeks), which will reduce overall annual production by 5–10%. These wide-ranging symptoms are now known to be a result of the disease attacking the immune system of the pig. Thus units with high underlying disease levels will be harder hit, and those underlying diseases will be the ones that become evident after the first phase of the disease has struck. It is not unusual for pigs on some units to be infected mildly and unknowingly, and to carry antibodies to the disease. Vaccines are now available, but their efficacy is not yet established.

Post-weaning multi-systemic wasting syndrome (PMWS)

PMWS has been spreading through national pig populations to an alarming degree, and is considered as the major cause of lost production in many parts of the world. It mostly affects the kidneys, lungs, liver and lymph nodes of pigs of between 5 and 10kg live weight, causing weight loss, lack of appetite, breathing difficulty, diarrhoea, pale, jaundiced, blotched skin, and practically all other symptoms common to other disease syndromes. This is unsurprising as one of the major targets appears to be
the immune system, thus allowing any other pathogens present to run amok. Particularly aggressive in this regard is the PRRS virus.

PMWS is invariably associated with a dramatic rise in levels of porcine circovirus type 2 (PVC-2). However, this is a ubiquitous organism that may also be found (at lower levels) on unaffected farms (although PVC has occasionally been associated with reproductive problems in sows and disability in piglets born to affected sows). It is possible that a complex of ‘other associated factors’ has conspired to change the behaviour of PCV-2 in such a way as to become pathogenic. On some farms PMWS-like symptoms, especially dermatitis and nephropathy (PDNS), are found in older pigs. It is unclear whether this is a (much less common) PMWS variant or a different syndrome, possibly Pasteurella associated.

PMWS affects around 5–20% of all piglets born in an afflicted herd, and of those affected most will die. Unaffected piglets will act as carriers, thus encouraging the syndrome to be persistent and cyclical.

Damage limitation is achieved by improving the standards of husbandry, insisting on strict imposition of biosecurity measures, and the minimisation of the presence of other pathogens on the unit. There is some fashion in the creating of lists in this regard, but they add up to ‘all of the above’. High on these lists, however, should be: removal of all stressors, maintenance of stable pig groups from birth up to 10 weeks of age (or longer if possible), reduction in stocking density, employment of all-in/all-out pig flow management, later weaning, control of PRRS and the avoidance of injecting pigs at weaning.

Multi-site production and segregated early weaning as disease control systems

Multi-site systems

Disease is transferred down the generations – sows to sucklers, weaners to sucklers, growers to weaners. Breaking the age chain prevents disease transfer. A site for breeding sows, another site for weaners and a third for growers and finishers not only assists prevention of down-the-line transfer but also allows specialisation of workforce and management skills on each site. Whilst sow-to-suckler and finisher-to-grower are important mechanisms of vertical disease transfer, it is the newly infected animals that excrete most infective material and cause horizontal clinical disease spread. The ‘newly infected’ animals are those that have not yet received any disease challenge, and are therefore susceptible to invasion by the organism. In particular, weaners are potent sources of excreted disease organisms as they will be meeting the disease challenge for the first time, their immune systems will be poorly developed, they are stressed, one of their sources of antibodies (mother’s milk) has been recently lost and their own acquired immunity levels will be falling. Weaners are therefore a major cause of clinical disease spread in pig populations, with consequent advantage of their separation to a special site.
In multi-site production systems, the sites must be sufficiently distant to prevent aerosol infections and transfer of disease by birds and pests. Distance brings with it a need for transportation. Weaner transport requires sophisticated environmental control to ensure adequate ventilation and temperature. Furthermore, all herding, loading and transportation procedures act as stressors. Largeness of scale is an essential component of multi-site production systems. Each site (breeding, weaning and grow-out) must be sufficiently large to support an effective self-contained workforce and infrastructure. This can mean the supply of weaners to the specialised weaner site coming from more than one breeding herd source. As has been amply demonstrated, a primary cause of health breakdown is the sourcing of animals from a number of different suppliers.

There are many variants and interpretations of multi-site systems. At one extreme may be found many weaner houses on one large nursery site, from which pigs go to a further, large, grow-out site with many finishing houses. Such sites benefit in allowing team-up organisational structures at each site, but predispose to lateral disease transfer. At the other extreme multi-site can mean many single-building (or few-building) nursery sites, from which pigs go to one of many single-building (or few-building) grow-out sites. This allows maximum containment of disease outbreak. This latter interpretation of multi-site (rather than that of two or three large sites for each production phase) may be the more important in terms of disease control and management, and experience may be suggesting that the element of segregation in segregated early weaning (SEW) is more important to breaking the cycle of re-infection than the early weaning element. Whilst the usual interpretation of ‘multi-site’ is three-site, two-site (placing the weaner operation either with the breeding herd or with the grower/finisher herd) systems are now to be found.

It is presently suggested that multi-site has not, in practice, delivered the disease control and production efficiency gains that were originally expected. The principles of disease management may perhaps be as readily applied on a single site as on multiple sites.

**Early weaning and medicated early weaning (MEW)**

Many important diseases – but especially the respiratory diseases – are transferred from the sow to the sucking young in the first 2 weeks after birth, amongst others: Aujeszky virus, *Actinobacillus*, *Mycoplasma*, *Pasteurella*, *Haemophilus*, PRRS, *Salmonella* and transmissible gastroenteritis (TGE). Weaning at less than 14 days of age will therefore reduce vertical disease transfer. There can be infection, however, even in the first week of life, which can only be avoided by removal of the pigs from the uterus before birth under aseptic conditions and the artificial rearing of the piglets. This most expensive technique has been used by breeding companies in the past to set up nucleus herds of specific pathogen-free (SPF) pigs. More realistically, disease organisms can be suppressed from infecting the neonates by massive medication and vaccination of both mother (before and after farrowing) and young (after birth, and before and after weaning) during the times of possible
disease transfer; combined with weaning as early as possible and movement to a clean site. The principles of medicated early weaning (MEW) were developed by Alexander at the Cambridge Veterinary School in the early 1970s.

Early weaning has been practised as a production technique since the 1950s (when 7- to 10-day weaning was introduced) and there has been adequate time and research investment since then to confirm that weaning at 21 days is difficult enough, with those difficulties compounding with each day of weaning earlier than 3 weeks of age. Trends in Europe over recent years have been toward later weaning, and whilst in the 1980s the ‘industrial standard’ was 21-day weaning, this has now been steadily and progressively extended toward 28-day weaning. Although short-term maximum output of piglets per sow per year does seem to be associated with 21-day weaning, this is often seen as (1) unsustainable over the longer term, where prophylactic use of antibiotics to control disease will be disallowed by regulation, (2) of high risk, and (3) unwarranted in terms of management, equipment and drug expense. Optimum output of piglets per sow per year is achievable with 28-day weaning. Weaning at less than 18 days brings serious problems for the rebreeding of the sow and for the successful care of the weaned piglets, which, at that time, rarely have either the digestive system or the immune capacity to thrive independently of their mothers in challenging environments. Whereas the original SEW systems advocated 10-day weaning, the difficulties experienced soon caused this to be amended to 14 days, and there is now a trend for the 14-day rule to slip further toward 21 days, for which conventional production techniques are better tried and tested. However, with each day of lengthening lactation, the possibility of sow-to-suckler disease organism transfer becomes more likely, and the possibility of disease eradication becomes less certain. Because of the difficulties associated with weaning at much less than 21 days, there has been movement in practice to 24- to 28-day (8 kg) weaning and the adoption of a strategy of disease containment, limitation, mitigation and control (rather than elimination). Disease management is helped by multi-site production, and breaking the cycle of re-infection may be a more useful and realistic strategy in the longer term than trying to prevent sow-to-piglet transfer by 10- to 14-day weaning. Disease control can sometimes be more about encouraging natural immunity and preventing an overload of disease challenge than about total avoidance of contact between animal and disease organism. The route taken – mitigation or eradication – depends greatly upon (1) the disease in question and (2) the management objectives of the production unit in question.

Present drivers for production systems to be operable independently of regular antibiotic drug usage would point to an increase in weaning age.

Avoiding disease

As suggested above, many of the consequences of a disease presence can be managed to a level of small or no significance; but there are many diseases that cannot be so managed, and even for those that can, there is some management cost.
Where disease can possibly be avoided, it is best to do so, even though this itself is not without difficulty, and avoidance is not without risk. The absence of a pathogen means susceptibility if subsequent exposure is a possibility. Nonetheless, there are diseases where the extent of their devastation is such as to merit control by avoidance rather than by management.

Avoidance strategies take two forms:

1. passive immunity by use of vaccines;
2. prevention of contact between pig and pathogen.

Some of the diseases not readily open to their effects being managed down to reasonable proportions are identified in this section.

**Swine dysentery**

Found in growing pigs on many units, swine dysentery is caused by a *Treponema* spirochaete (*Brachyspira hyodysenteriae*) which infects the large intestine, resulting in mucus and blood in a thin, light-brown coloured diarrhoea. Breeding stock can be affected at the time of the initial outbreak. Morbidity in growing pigs can rise to 100%, with mortality up to 8%. The disease is transmitted by the ingestion of faeces from infected pigs. The organism has a long life in faecal material (2–9 weeks) and is often spread by this route. The disease can also be carried between units by dogs, rodents and birds as well as man. Antibiotics (tiamulin, oxytetracycline, tylan at high level) are valuable in combating the disease, with subsequent in-feed preventive medication. Overcrowding and a poor environment exacerbate the severity of dysentery. Possibilities for live oral vaccines are being explored. Those animals that do not die and are not effectively treated become thin and the economic loss is very severe. On breeder/feeder units, the disease can be eradicated by the long-term medication of sows and boars, farrowing into thoroughly clean and disinfected quarters, and then moving the (now clean) weaners into fully disinfected and rested growing/finishing accommodation. Full depopulation of the unit, disinfection, resting and restocking with clean stock is a realistic option. This disease merits high security and repays its avoidance by ensuring pigs have no possibility of access to infection, which is through infected pigs, carrier pigs or a contaminated environment.

**Transmissible gastroenteritis (TGE)**

This contagious viral disease causes greenish diarrhoea and a high level of mortality especially in young sucking pigs. When infection enters the unit for the first time, most piglets under 3 weeks of age die. The disease may become endemic, with continuing outbreaks of diarrhoea resulting in ongoing growth reductions in fattening pigs. The organism is transmitted through infected pigs, faecal material, vehicles that have been carrying infected pigs, dirty boots and sometimes birds. Vaccines are available, but effective control and treatment remain difficult. The avoidance of TGE is
one of the reasons for carrying out detailed procedures for the prevention of entry of pigs, people and vehicles from unknown sources into the unit. Purchased animals entering the unit should come from sources known to be free of the disease. Testing for the presence of TGE is currently compromised by cross-reactions that take place with a common respiratory coronavirus (which appears to cause little harm to the pig). Infected herds develop immunity which is solid over the lifetime of the individual pig. Continued immunity in susceptible herds can be maintained by feedback infection procedures by older pigs when the infection is transient and less threatening.

**Epidemic diarrhoea**

Rather similar to TGE and, like TGE, caused by a coronavirus, epidemic diarrhoea can enter the herd via contaminated feedstuffs (such as meat and bone meal), rodents or infected pigs. It is usually characterised by green–brown diarrhoea, vomiting and dehydration but low mortality, especially in sucking and young weaned pigs. Appetite is reduced and growth and feed efficiency mildly affected. As with TGE, an immunity to the virus develops within the herd, but in growing herds there is the potential for an ongoing chronic problem.

**Paratyphoid**

The organisms *Salmonella choleraesuis* and *S. typhimurium* and others cause paratyphoid, which results in high mortality from septicaemia and enteritis mostly in growing pigs and abortion in sows. It may or may not be associated with diarrhoea, breathing difficulty, blocked lungs and skin blotching. It is usually confirmed by rectal swab. A vaccine is available and *Salmonella* may be treated with antibiotic. Due to the high level of mortality, the best strategy is to ensure the organism does not enter the unit in the first place.

**Atrophic rhinitis**

This is usually contracted early in life while sucking. The incidence can be reduced if the farrowing quarters are kept clean and free from ammonia and dust. The condition is particularly exacerbated by dusty conditions and excessive density of stocking. Infected pigs show nasal discharge, sneezing and respiratory distress, reduced appetite, loss of feed conversion efficiency and reduced growth rate. In the most acute cases the snout will become distorted and the turbinate bones within the snout will atrophy. Outbreaks are particularly associated with bad housing and poor environmental control. There used to be some doubt as to which organism is responsible, with both *Pasteurella* and *Bordetella* organisms usually being present. However, work at Compton Laboratory in England has now pointed to a necrotising toxin from *Pasteurella* as the main causal agent. As a bacterial disease, it is controlled through the use of antibiotics. Vaccination of sows is an option commonly
used in the USA. The severity of atrophic rhinitis is usually proportional to the standard of husbandry and the quality of the environment (as also indicated for *Mycoplasma pneumonia*). Pigs should only be purchased from an atrophic rhinitis-free source.

**Actinobacillus (Haemophilus) pleuropneumonia**

When *Actinobacillus (Haemophilus) pleuropneumoniae* enters a previously uninfected herd it is often first identified as soft coughing in the growing pigs. The disease can sometimes follow an outbreak of mycoplasma pneumonia. Vaccines are available although the organism has many serotypes which sometimes cause vaccination to be variable in its effect. Susceptible pigs should be medicated with antibiotic in the feed, and if necessary in the water, on entry to the grow-out unit. The disease may appear suddenly and there can be high morbidity and acute distress with a sharp cough. Death can occur in young and growing pigs, and when exposed to large numbers of organisms they suffer from pleurisy, high temperature and sudden death, going blue at their extremities and having dark blue lung lesions spread throughout the upper lobes of the lungs, together with the pleurisy. Because breathing is painful, pigs do not breathe deeply or thump; rather the breathing is seen to come from the stomach (as opposed to the chest). For infected animals or animals thought likely to become infected (consequent upon an outbreak in the grow-out unit) the first line of control is an injection of antibiotic, followed by antibiotic in the drinking water and finally in-feed antibiotic medication. After the initial outbreak has swept through the unit, during which time it may cause a significant number of deaths and losses in growth rate and performance, long-term medication will be needed and then general control levels in order to ‘live with’ the disease organism and allow animals to build up adequate immunity. In this regard it is important to reduce the concentration of the organism to as low a level as possible by appropriate cleaning and disinfection of the houses, and by operating an all-in/all-out batch system, cleaning the houses between batches. The animals should avoid being stressed and should be adequately fed and cared for. Stocking levels require to be reduced and a high level of environmental control exercised.

The chronic form of the disease is commonly associated with the other organisms of respiratory disease. Outbreaks in chronically (sub-acute) affected herds are usually associated with some sudden stressor, such as increased stocking densities or changes in environment. The organism is spread by contact in droplet form, so it is usually brought in with infected pigs. Sows and other older pigs not showing clinical symptoms following resolution of earlier infections may pass the disease on to sucking or growing pigs. The organism has a short life outside a living pig. Units free of the disease can maintain their position by ensuring no introduction of pigs carrying the organism. Those units failing to keep a chronic level of infection under adequate control may consider the possibility of clearing the unit and repopulating with stock free of the disease. There is some danger, however, in that an *Actinobacillus*-free population as such would be highly susceptible to infection. A
beneficial option is vaccination or other exposure to non-pathogenic strains, with the consequence of subsequent immunity and the absence of disease.

**Glässer’s disease**

The bacterium *Haemophilus parasuis* (often found with associated streptococcal infections) may produce similar symptoms to *Actinobacillus (Haemophilus) pleuropneumoniae*, but mostly infects the joints (arthritis), inflames intestines and pleura and causes meningitis. It is present in many herds, often following PRRS and other respiratory infections or other stressors such as weaning, but strains vary in their capacity to produce disease. The organism is common and a satisfactory level of natural immunity is not unusual. The complaint is open to treatment by vaccination and with antimicrobials.

**Swine influenza**

Swine flu is caused by viruses and is seriously affecting productivity in many pig herds at the present time. Airborne transmission ensures high infection rates in pig-dense areas, but the greatest risk of infection results from fattening herds bringing in pigs from a variety of sources. Most infections are self-limiting through natural immunity developing in the herd, but only provided there is not a continuous influx of susceptible animals. Densely populated pig farms in areas of concentrations of pigs do tend to be open to continuous influx. After the initial infection the viruses may clear from the herd or remain endemic in it. Re-infection of herds that have lost their natural immunity from lack of challenge, following resolution of a previous outbreak, can bring about cyclical infections. For herds that have developed immunity, the sows will be protected and piglets covered by maternal protection through until about 7 or 8 weeks old, after which they may be susceptible until they develop their own immunity.

Influenza viruses cause pneumonia and inflammation of the lungs, leading to breathing difficulties, coughing and fever. There is also sneezing, together with nasal and eye discharge. Temperatures may go up to high levels and result in pigs losing substantial amounts of weight and condition. The disease will spread quickly through susceptible (non-immune) groups of pigs, especially the fattening animals. Recovery usually takes place in about a week, and few pigs die. The outbreak will likely be followed by secondary infections such as those caused by *Actinobacillus, Bordetella* and *Pasteurella*, Glässer’s disease and PRRS. Influenza alone causes substantial growth reduction, but the most serious consequences arise from a combination of the virus infection and the secondary infections, or together with PRRS virus.

**Parvovirus**

Immunity to this virus is obtained either naturally or through vaccination. Infection is a once-for-all event resulting in life-time immunity. Boars and gilts should be vac-
cinated on entry into the herd or, if a vaccine is not available, by exposing gilts to weaner faeces before mating, or by penning new herd entrants in isolation quarantine pens directly adjacent to pens holding sows due to be culled from the herd, and allowing limited contact between the two groups. When the virus strikes pigs that are not immune it has little effect unless those animals are about to become pregnant or have recently been made pregnant. In this case the virus will cause embryonic death, fetal death, piglets weak and small at birth, and dead piglets at birth. It is a prime agent associated with infertility and reproductive losses in sows. In early pregnancy all fetuses may die and the pregnancy may be lost; the sow returning to oestrus or found not in pig. In later pregnancy the fetus becomes mummified or still-born or stunted. The disease is progressive and therefore varying sizes of mummified fetuses may be seen at parturition. The symptoms of parvovirus (and other enteroviruses) are those of ‘SMEDI’ syndrome, still-births, small piglets at birth, aborted or mummified piglets, embryo losses, dead born piglets and infertility in the sow.

Most herds world-wide carry parvovirus. Within a herd, infection may range from a quarter of the animals to all of them, which allows periodic flare-ups of the disease in apparently infected herds due to natural immunity not necessarily being universally acquired.

Whilst parvovirus disease is ubiquitous and its effects traumatic, its influence can be readily curtailed by the use of a simple vaccination programme. Young (susceptible) pigs entering an infected farm may also be protected by deliberate infection through faeces of fattening pigs or contact with outgoing stock, provided that this exposure is completed 3 weeks prior to mating.

**Aujeszky’s disease (pseudorabies)**

This is caused by a herpes virus. When first introduced into the herd, there is high mortality and loss of growth in breeding sows, with abortions and mummified piglets and meningitis in sucking piglets. The disease usually becomes chronic, leaving animals sneezing and coughing, with reduced appetite and pneumonia complications. Pneumonias bring respiratory distress, loss of growth and invasion by secondary respiratory disease organisms. If there is a relatively low incidence in a particular country or area, a slaughter policy (continuous removal of infected animals) may be considered worthwhile. It is essential, however, that the borders of the slaughtered-out area are effectively maintained. Vaccinated animals do not suffer from the symptoms of the disease, but they may contract a field infection, excrete the live virus and therefore become carriers. Thus if a vaccination policy is to be adopted, then, like the slaughter policy, it is best if total across all pigs. Breeding companies should maintain freedom from this major disease, and where animals are traded to countries where it is prevalent, vaccination is advised. Vaccination recommendations currently vary between vaccines, countries and veterinary opinion. Aujeszky’s is transmitted mainly by pigs but may also be carried 2km in the air. The most usual source of infection is by reactivation of the latent virus. After an
epidemic animals in the unit will progressively lose their own natural immunity. However, within the herd there will be latent virus carriers. If these carriers excrete the virus, all the non-immune animals go down. Slaughtering diseased pigs does not solve the problem of latent carriers, who would not be destroyed by such a policy.

After infection the virus hides in cells and the animal is quite healthy with no viral excretion. Following stress or another disease, the animal excretes the virus but itself shows no symptoms. The newly infected herd collapses. In piglets the nervous disease causes loss of appetite, epilepsy or paralysis. Mortality rate can be as high as 90% for pigs of less than 10 days of age, 70% for pigs between 10 and 20 days of age and 10% for pigs between 20 and 50 days of age. After 60 days of age there is no longer such a serious mortality problem. In growing pigs there is pneumonia, weight loss and a 10% mortality at maximum. The loss of productivity, however, is catastrophic. In sows the disease causes abortion, sterility and fetal death, but no mortality. After an epidemic the situation will clear itself, but during the 2 months after the initial infection up to 75% of all sucking piglets may be lost and 15% of all pregnant sows could abort.

Vaccines must be used in sows, in order to give protection to the young piglets via the colostrum, and it is also necessary to vaccinate growing pigs.

It is possible to start an eradication scheme through vaccination and such schemes are now being pursued in Europe. Blanket covering of sows and growing pigs is required in the eradication region, and genetically engineered vaccines (‘marked’) allow vaccinated animals to be distinguished from carriers. All animals are then blood-sampled in order to identify latent carriers of field infection, which are then slaughtered. If this scheme is adopted over large populations, it should eradicate the disease in the due course of time. It is necessary to combine the slaughter policy with the vaccination policy. Vaccination alone is unlikely to eradicate the disease due to the problem of latent carriers.

Endemic disease is a major problem in spite of vaccination, because ultimate control is through the elimination of the latent carrier. Chronic Aujeszky’s exists by way of the herd having within it sows that have gained natural immunity and which become latent carriers. New sows can come into the herd not protected, or even young pigs bred within the herd may not develop adequate protection if there has not been an outbreak for some time. Should the latent carrier excrete, animals not naturally protected will suffer. If a commercial herd becomes infected and is in an area where the disease is endemic, depopulation should only be considered in special circumstances, such as a need to trade with producers in areas where the disease is not endemic.

**Leptospirosis**

There are various *Leptospirae*, including *pomona* and *bratislava*. Leptospirosis infection of the reproductive organs may pass as short-term symptoms of elevated
body temperature and feed intake depression. More seriously and chronically affected pigs will show digestive disturbance, reproductive failure, abortions and small and weak piglets at birth. A vaccine is available, but its effect can be unpredictable. Antibiotics are helpful but tend not to fully eliminate infections. Antibiotic treatment may, however, prevent infection of at-risk stock in herds in which individuals are infected. The disease may sometimes be seen as associated with poor rodent control and low levels of hygiene.

**Streptococcal meningitis**

This is a bacterial disease, causing joint infections, pneumonia, brain dysfunction, nervous convulsions and death. If treated early with penicillin, 80% of affected pigs will recover. Individual animals may be seen *in extremis*, whilst others show reduced growth rate. During treatment stocking density requires to be considerably reduced and ventilation increased. It is important that the proper temperature in the house is maintained and variations in temperatures are avoided. This distressing disease can be prevented from entering the unit by purchasing stock from a herd with no history of disease over a minimum 5-year period. Its presence, once in a unit, is greatly to the disadvantage of production efficiency, especially during the first 28 days after weaning; during this time in-feed medication is helpful. Streptococcal infections can also cause septicaemia, meningitis, joint-ill, arthritis, joint swellings and sore feet in young piglets.

**Erysipelas**

This is caused by a ubiquitous organism but may be readily controlled by vaccination. All breeding animals should be vaccinated twice. If this routine is not undertaken then adult animals are at high risk. Symptoms include sudden death, usually (but not always) septicaemia with raised, purplish, diamond-shaped marks on the skin, chronic joint and heart conditions, and inappetence, constipation and loss of productivity.

**Mulberry heart disease**

This causes sudden death, with evidence of heart damage. It is probably of multiple causation involving stressors and genetic predisposition, but sometimes linked with the unavailability of vitamin E and/or selenium, and thus sometimes associated with organic acid-treated cereals and/or high fat diets.

**Arthritis**

Mycoplasmal synovitis (arthritis) is the consequence of invasion of the joints by *Mycoplasma hyosynoviae*, causing stiffness in growing pigs. It may be treated with
Practicalities of health maintenance, disease prevention and disease avoidance

The incidence of diseases will change with time and with alterations in production management. In the mid-1970s, abortion, osteochondrosis, cystitis, endometritis, infertility, leptospirosis, influenza, PRRS and PWMS were not significant diseases, but parvovirus, mange and internal parasites were. In the mid-1990s all the former diseases had become significant problems, not least infertility and osteochondrosis; but parvovirus and internal parasites had become insignificant. Arguably, the most significant diseases of the present day may be PWMS, PRRS, swine influenza and the secondary respiratory infections that follow.

The most common syndromes concerning the day-to-day management of commercial pig units relate to colibacillosis diarrhoea, pneumonias, cannibalism, lameness and infertility in the breeding herd. Their ubiquity inevitably means that the task of husbandry is to accept their presence and control severity.

The following diseases are commonly found, but their incidence may be controlled and their effects minimised by good management: agalactia; anaemia; mastitis; coccidiosis; cystitis; leg weakness; erysipelas; Glässer’s disease; exudative epidermitis; porcine intestinal adenomatosis; porcine stress syndrome; internal parasites; mycoplasma pneumonia; PRRS; PWMS; influenza; mycoplasma arthritis; oedema disease; parvovirus; Rotavirus; stomach ulcers; joint infections; vulval discharges; prolapses; disorders caused by mycotoxins.

It is possible to establish and maintain freedom from the following diseases: streptococcal meningitis; swine dysentery; paratyphoid; atrophic rhinitis; external parasites; cannibalism; Actinobacillus pleuropneumonia; Pasteurella; Aujeszky’s disease; transmissible gastroenteritis; salmonelllas; African swine fever; classical swine fever; foot-and-mouth disease; mycoplasma pneumonia; swine vesicular disease; Leptospira; swine pox; Trichinella parasites.

Vaccines are being rapidly developed for an ever-widening variety of diseases. At present they can be used, amongst others, for parvovirus, leptospirosis, Aujeszky’s disease, erysipelas, atrophic rhinitis, influenza (some types), PRRS, E. coli diarrhoea, TGE, pneumonias and pleuropneumonias. Antibiotics (of which there are more than 40 in-feed and more than 100 injectable products listed) are effective against infections of bacterial origin including: Streptococcus, Staphylococcus, Treponema, Leptospira, E. coli, Campylobacter, Corynebacterium, Pasteurella, Mycoplasma, Actinobacillus, Haemophilus and Salmonella.

Classical and African swine fever, foot-and-mouth disease and the clinically similar swine vesicular disease, brucellosis and probably Aujeszky’s disease (pseudorabies) are beneficially the subject of slaughter policies. These cataclysmic
diseases do not therefore enter into any part of health maintenance, nor indeed pig management.

**The cost of disease**

The price paid by a pig industry for unhealthy pigs is the sum of:

- the costs of veterinary visits, veterinary medicines, vaccines, etc. A recent survey in North America has estimated that some 40% of growing pigs and some 30% of sows are vaccinated regularly, and some 60% of growing pigs and 30% of sows receive antibiotic treatment;
- the cost of in-feed medicines. In Europe in recent years more than half the feed offered to weaner pigs contains in-feed disease preventatives or curatives. Regulations preventing the use of antibiotics for prophylaxis and growth promotion will certainly reduce this, but in consequence losses in production may become substantially greater. The average on-cost is conservatively an additional 5% of the feed cost. Sustained use of in-feed antibiotics through to the point of slaughter can accumulate on-costs equivalent to the value of 1–2 kg of pig carcass meat;
- cost of lost efficiency pre-farm gate due to reduction in sow productivity, diminished growth rate and reduced efficiency of feed use;
- loss of product quality and market sympathy (wholesomeness of meat product) post-farm gate;
- loss of saleable product through meat processing condemnation.

In intensive European pig units it would appear from various surveys that *Mycoplasma* (enzootic) pneumonia is endemic in more than half of all herds, and in over one third of these pleuropneumonia also seems evident. PRRS is present in at least 50% of herds, but symptoms are evident in less than half of these. PWMS is geographically patchy, but where present it can be endemic in a high proportion of herds. *E. coli* diarrhoea is endemic in about one third of breeding farms, with at least half of all herds suffering irregular outbreaks. The most universal of all disorders is that of lameness. Other regular complaints are: reproductive disease; Glässer’s (*Haemophilus parasuis*) disease; colitis; swine dysentery; mycotoxin-contaminated feed; atrophic rhinitis; and mange.

The direct ongoing costs of intervention veterinary treatment alone can be higher than 2% of the worth of the pig at slaughter. In addition to the direct costs of treatment, the present levels of disease in the industry are perceived to cause the wastage of some one sixth of production from the breeding herd (equivalent to four piglets weaned per sow per year), and of causing further loss of performance (mortality and feed efficiency) in weaner and growing pigs equal to at least 3% of the worth of the pig at slaughter. Abattoir condemnations account for a further loss of around 0.4% of the value of slaughtered pigs. Disease penalties are expressed in Table 7.9 in terms of kilograms of feed equivalence that are being lost. These statistics relate not to abnormal but to normal herds with accepted (but not acceptable) levels of
day-to-day endemic disease. These losses are avoidable, and cost savings of similar magnitude are evident on farms that achieve high levels of disease prevention, principally through the inception of high-quality management routines. The international pig health consultant Mr Mike Muirhead famously estimated that even merely chronic outbreaks of transmissible gastroenteritis, *Mycoplasma pneumonia*, *Actinobacillus* (*Haemophilus*) pleuropneumonia, atrophic rhinitis and mange may each individually add respectively to the time from birth to 90 kg about 5, 20, 15, 15 and 10 days.

It is difficult, of course, to assess the exact costs of disease outbreak; and equally difficult to calculate the cost–benefit of disease eradication. First there is variation in the severity of disease attack, next in the level of defence available in the pig, and last there are a plethora of critical environmental factors which influence the consequences of a disease presence on a unit; from trivial to extreme. It is self-evident that it is best to create an environment that minimises the effects of unfriendly organisms, to avoid the incursion of overt disease into the unit and to build animal immunity defences. The investment for such actions can be high, but worthwhile. Repopulation of a disease-ridden unit is drastic financially, but may readily reduce days to 100 kg from 200 to 150, reduce feed conversion ratio from 3.0 to 2.7 and increase pigs sold per sow per year from 17 to 23. These statistics add up to something like a 20% improvement. This will, of course, be prone to some progressive diminution; the extent of that being a function of the quality of the management.

<table>
<thead>
<tr>
<th>Penalties</th>
<th>Penalty as equivalent kg of feed lost per pig slaughtered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Veterinary and medicine costs</td>
<td>10.0</td>
</tr>
<tr>
<td>Disease-related feeder pig mortality</td>
<td>3.0</td>
</tr>
<tr>
<td>Disease-related piglet mortality</td>
<td>1.5</td>
</tr>
<tr>
<td>Abattoir condemnations</td>
<td>2.0</td>
</tr>
<tr>
<td>Chronic disease-related fertility losses</td>
<td>2.0</td>
</tr>
<tr>
<td>Chronic pneumonias, diarrhoeas and lameness</td>
<td>4.9</td>
</tr>
<tr>
<td>In-feed medication</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total as equivalent kg of lost feed per pig slaughtered</strong></td>
<td><strong>23.9</strong></td>
</tr>
</tbody>
</table>
Chapter 8

Energy Value of Feedstuffs for Pigs

Introduction

Energy is yielded from oxidation of the carbohydrate, protein and lipid components of feed. Respective gross energy (GE) values are 17.5 MJ GE/kg for carbohydrate (starch and cellulose), 39.3 MJ GE/kg for fat and oil and 23.6 MJ GE for protein. Following digestion, the energy in these nutrients can be used by the body in three ways. First, in the context of their existing chemical structures; amino acids from feed to amino acids of pig muscle growth, lipids from feed to lipids of pig fat growth, and simple sugars from feed to liver glycogen or to milk lactose. Second, nutrients may be converted from one type of structure in the feed to another type of structure in the pig; thus the end-products of the digestion of feed carbohydrate can take part in the anabolism and retention of pig protein or pig fat. The third and major use of energy-yielding nutrients is, however, for just that: the yielding of energy that is needed to fuel the metabolic activities of the life and work of the pig, and which ultimately leaves the body as heat.

The primary carbohydrate energy source is starch, yielding up its energy after enzymic digestion in the small intestine, and absorption in the form of simple sugars. More complex non-starch polysaccharide (NSP) also has some part to play, especially if the feedstuff is high in fibre, but in this case much of the digestion is by way of bacteria in the caecum and large intestine, and the end-products are volatile fatty acids (VFA) and lactate which are less efficiently used. Protein yields energy after absorption as amino acids and then through the (rather inefficient) process of gluconeogenesis. Dietary fats may be absorbed in their constituent parts of glycerol and free fatty acids.

Feed energy is used by pigs (1) for the basic maintenance of normal body processes such as muscle movement, digestion, respiration, blood circulation, the renewal of worn-out body tissues and the recycling of existing body tissues; (2) for driving the manufacturing activities of milk synthesis, reproductive effort and protein and lipid growth; (3) for maintaining body temperature in the face of a cold ambient environment; and (4) for retention in the body products of secreted milk, the fetal load and lean and fatty tissue growth. All the energy but that which is retained (5) leaves the body as heat. The more heat created in the work functions of maintenance and manufacture, the less likely will be the need for energy to keep warm; energy for cold thermogenesis is therefore only needed for that specific
purpose when ‘by-product’ heat from other purposes is not available to do the job.

Not all the energy in a feed is available to be metabolised for purposes of maintenance and production. Some energy-yielding ingredients are not digested and pass out in the faeces, while other energy may leave the body as gases or in the urine. The total energy-yielding potential of the feedstuff may be determined by its complete oxidation and measuring the heat directly generated in a calorimeter (usually an adiabatic bomb calorimeter). This is the gross energy in feed (GE<sub>t</sub>). After subtraction of the undigested energy associated with the faeces (GE<sub>f</sub>), the digestible energy (DE) can be determined:

\[
DE = GE_t - GE_f 
\]  

Metabolisable energy (ME) is estimated as the DE less the energy found in the urine (GE<sub>u</sub>), and also less the energy that may be found, mostly as CH<sub>4</sub>, as gaseous escapes – mainly from the large intestine via the anus:

\[
ME = DE - (GE_u + GE_{gas}) 
\]  

The metabolisable energy is now available to be metabolised and would usually be handled by the animal in the order (1) maintenance, (2) cold thermogenesis (if needed), and (3) driving the manufacture of products and deposition within products. When feed intake is particularly low a reverse order can apply; previously deposited body products – especially fatty tissue but also protein tissue – can be catabolised to yield energy essential for maintenance of the basic life processes.

A schematic representation for energy use in the body is shown in Figure 8.1. Table 8.1 shows some example values that might pertain for each of the various aspects of energy use.

Often little attention is given to the energy costs of physical activity in pigs, it being assumed to be accounted for within maintenance. This is not reasonable, as pigs in the process of having their heat outputs determined at maintenance will be less active than those living in groups in open pens. An arbitrary addition to the maintenance allowance of a further 5–10% is justified. Some modern production systems now encourage greater physical activity in both sows and growing pigs, and it is likely that substantive energy costs equivalent to some 10–20% of maintenance should then be added on to assumptions of energy expenditures and heat losses at ‘maintenance’.

The ultimate energy value of a feedstuff will depend upon both the proportional contents of the various energy-yielding nutrients and the end-product destinies. The latter are dependent (as may be apparent from Table 8.1) not only upon the feedstuff itself but also upon the balance of metabolic activities pertaining in the pig at the time of the feedstuff’s utilisation. The proportion of the digested energy that leaves the body as heat is clearly greater in the case of the sow in early pregnancy than in young pigs that are rapidly growing and therefore retaining substantial amounts of energy in tissues.

Whilst it will be argued that the most universally useful pig-independent descriptor of a feedstuff is likely to be the digestible energy (DE), the use by a pig of its
Fig. 8.1  A schematic representation of energy use in the body of the pig.

Table 8.1.  Example values for various aspects of the energy economy of a 60 kg growing pig gaining about 850 g live body weight daily. All values are given in terms of MJ per day.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE&lt;sub&gt;i&lt;/sub&gt;</td>
<td>34</td>
</tr>
<tr>
<td>GE&lt;sub&gt;f&lt;/sub&gt;</td>
<td>8</td>
</tr>
<tr>
<td>DE</td>
<td>26</td>
</tr>
<tr>
<td>GE&lt;sub&gt;u&lt;/sub&gt;</td>
<td>0.8</td>
</tr>
<tr>
<td>GE&lt;sub&gt;gas&lt;/sub&gt;</td>
<td>0.2</td>
</tr>
<tr>
<td>ME</td>
<td>25</td>
</tr>
<tr>
<td>E&lt;sub&gt;bm&lt;/sub&gt;</td>
<td>8.5</td>
</tr>
<tr>
<td>E&lt;sub&gt;u&lt;/sub&gt;</td>
<td>1.5</td>
</tr>
<tr>
<td>E&lt;sub&gt;m&lt;/sub&gt;</td>
<td>10</td>
</tr>
<tr>
<td>E&lt;sub&gt;t&lt;/sub&gt;</td>
<td>0.4</td>
</tr>
<tr>
<td>E&lt;sub&gt;w&lt;/sub&gt;</td>
<td>6.7</td>
</tr>
<tr>
<td>E&lt;sub&gt;r&lt;/sub&gt;</td>
<td>7.9</td>
</tr>
</tbody>
</table>

<sup>1</sup>  E<sub>r</sub> and E<sub>w</sub> have been calculated as 160 g protein retention at 3.8 MJ and 105 g lipid retention at 4.1 MJ, with the associated work energies being 5 and 1.7 MJ, respectively.
energy resources can only be understood through analysis of the whole system. That is by an understanding of the derivation and use of net energy (NE).

**Measurement of the energy economy of pigs**

Heat ($E_h$) output can be measured directly but is best measured indirectly as the difference between the metabolisable energy and the energy stored in products ($E_r$):

$$E_h = ME_i - E_r \quad (8.3)$$

$ME$ in turn is measured as the difference between the energy intake and the energy losses in faeces and urine (the energy losses in gas are usually taken to be trivial):

$$ME_i = GE_i - (GE_f + GE_u + GE_{gas}) \quad (8.4)$$

The energy retention ($E_r$) can be measured by comparative slaughter; the total body content of energy and protein at the end of a period over which the metabolisable energy intake has been measured is compared to the protein and lipid content at the beginning of that period. The difference between these two masses is the retention of protein and lipid pertaining to the period for which the metabolisable energy intake had been measured. Knowledge that protein contains 23.6 MJ/kg and lipid contains 39.3 MJ/kg allows simple calculation of the energy retained. Of course, a relatively long period of time must elapse if this difference measurement is to be accurate, and this means painstaking measurement of the ME intake in addition to the non-trivial exercise of analysing the pigs’ bodies at the beginning and end of the experiment.

In order to overcome the difficulties of the comparative slaughter technique, heat output may also be estimated from a knowledge of the oxygen consumed and the carbon dioxide, methane and urinary nitrogen emitted. It is, of course, in the oxidation of feed nutrients that heat energy is created; with the consumption of oxygen and the release of carbon dioxide in the process of respiration. Measurement of heat production in this indirect way requires quantitative measurement of oxygen use and carbon dioxide release. Accurate measurement of gaseous exchange is sufficiently complex for the comparative slaughter method to recommend itself to many research workers. It does appear reasonable to assume that energy ingested ($GE_i$), but not subsequently found in faeces ($GE_f$), urine ($GE_u$) or animal products ($E_r$), must have left the body as heat ($E_{h1}$), as Figure 8.1 confirms.

Measurements of heat production do not, of course, distinguish between energy that has been used for maintenance ($E_m$), for cold thermogenesis ($E_{h1}$) or for work ($E_w$). Experimentation at a thermoneutral temperature may assume cold thermogenesis to be zero, while for animals that are creating no products, heat losses may be assumed to measure maintenance. Zero product formation may be considered to occur when no food is ingested; in this case maintenance energy is derived from the catabolism of body tissues (mostly lipid). A more rational interest might be in the amount of energy being used for maintenance ($E_m$) when the body is neither
anabolising nor catabolising body tissues; that is, when it is in stable energy balance.
This will occur at some given (unknown at the time of measurement) nutrient intake, and may be approached by the use of graded levels of nutrient intake in the experimental protocol. The efficiency of use of energy for maintenance is higher than the efficiency of use of energy for growth. Thus the point of zero energy retention and of the true measurement for maintenance will coincide with a change in the slope for the regression of energy retention on metabolisable energy intake (Figure 8.2).

While for a mature and non-productive animal the notion of maintenance is credible, the idea that maintenance can be a process that looks after the basal metabolic activities independently of all the other energetic processes going on inside the body of a productive pig may be seriously challenged. The whole concept of maintenance at the point of energy balance is difficult to accept as a rational way of estimating non-productive energy expenditure in a rapidly growing pig on full feeding, or of a lactating sow. For purposes of quantifying the energy economy of productive pigs, there is a view that maintenance should be considered not so much as an indicator of a basal metabolic requirement, but more simply as a residual cost accruing to the system as an unavoidable fixed loading. The comparative slaughter technique is particularly adept at measuring maintenance with this latter idea in mind. Groups of animals are each given graded levels of nutrient intake. Some animals on the experiment are therefore slow-growing and others progressively more rapidly growing. The analysis of the carcasses will yield graded levels of protein retention (Pr) and lipid (Lr) retention from which the energy deposition in products can be calculated (using the values 23.6 and 39.3 MJ/kg as the energy contents of protein and lipid respectively). Expression of available energy as metabolisable energy from knowledge of faecal and urinary losses now allows the construction of a regression relationship, the constant for which must be maintenance. The regression technique is used here to divide up the metabolisable energy intake into its constituent parts:

\[ \text{MAE}_i = E_m + (E_r)/k \]  

\( (8.5) \)
The system may be expressed graphically, as in Figure 8.3.

The slope of the line gives the efficiency of the use of energy for retention of protein + lipid; that is, for growth. The same set of data may be used in a multiple regression analysis, and this may differentiate between the efficiency with which energy is used for protein deposition and the efficiency with which energy is used for fat deposition – it being implicit that the graded levels of energy intake will also have resulted in different levels and proportions of protein and lipid retention:

\[ \text{ME}_i = E_m + \frac{(Pr)}{k_{Pr}} + \frac{(Lr)}{k_{Lr}} \]  

(8.6)

Energy costs of maintenance are invariably related to the live body mass. This is logical because ‘maintenance’ costs include the work of movement, pulmonary and cardiac activity, and all the vital processes of tissue turnover and refurbishment. The relationship, however, is such that per unit of mass a lighter animal will have a higher requirement than a heavier animal, possibly (it used to be thought) because of the changing relationship between body surface area and body weight; thus the frequent use of an exponent of less than 1 (often in the range 0.6–0.8). For example:

\[ E_m (\text{MJ/day}) = 0.440 \text{LW}^{0.75} \]  

(8.7)

where LW is the live weight.

The amount of heat lost from the body is also influenced by the digestive processes themselves; that is, the work of obtaining the metabolisable energy from the dietary gross energy. The heat of digestion \((E_{h'})\) results from the energy costs of mastication, the propulsion of the food through the tract, and heat losses from enzymic digestion and from microbial fermentation; \(E_{h'}\) usually amounts to about 5% of the total GE and, of course, is highly dependent upon foodstuff type. The more complex and demanding the digestion for the particular nutrient concerned, the more energy that will be lost in consequence of making it available. For example, simple sugars and lipids are less energy demanding in their digestion than proteins and much less demanding than complex structural carbohydrates. The influence of feed type upon heat loss does not, however, stop there. Work heat tends to be described by single values either for protein accretion or for fat accretion. Thus,
31 MJ of work is required for each kilogram of protein deposited \( (k_{Pr} = 0.44) \) and 14 MJ for each kilogram of lipid deposited \( (k_{Lr} = 0.75) \).

However, this simplified view cannot be realistic. First the efficiency of deposition of energy as fat using an appropriate dietary fat as a substrate is much greater than if the substrate for body lipid accretion is dietary carbohydrate, or dietary protein (the efficiencies being about 0.9, 0.7 and 0.5 respectively). The actual work associated with pig fat growth when this is achieved from the direct incorporation of a suitable dietary fat is more probably around 5 (not 14) MJ/kg. The second reason why fixed efficiency values cannot be realistic is that the efficiency of use of energy for protein retention is also variable, ranging from some 0.35 up to 0.65; depending mostly upon the heat losses resulting from expenditures in protein tissue turnover, which in turn depend upon both pig size and the rate of protein accretion.

The body of a growing pig is happy to receive simple sugars and lipids as sources of metabolisable energy, and can deal with these without large consequential heat energy losses; efficiencies of use for the purposes of metabolic work being about 0.85 for sugars and 0.75 for lipids. However, absorbed proteins and volatile fatty acids (the latter from fibre digestion) incur greater costs in their metabolism (efficiencies here being around 0.65 and 0.50). To yield energy from protein deamination requires a considerable input of work energy itself (about 5 MJ/kg protein deaminated), and there are further losses of energy in the urine consequent upon deamination and the formation of urea (about 7 MJ/kg protein deaminated). So, of the gross 24 MJ/kg in the absorbed protein, only some 12 MJ is realistically available for use as energy. The heat losses occurring from the yield of the given amount of available energy are therefore much greater from a feed whose energy is mainly in the form of fibrous feeds and protein, than with a feed whose energy is mainly in the form of simple starches, sugars and (especially) lipids. The carbohydrate fraction of wheat, for example, is about 85% starch and 13% non-starch polysaccharide; respective values for wheatfeed are 32% and 59%. Lupin meal has negligible starch, while more than 80% of the carbohydrate is as non-starch polysaccharide. Differences in the effective energy values of these three feeds would only be evident consequent upon a study of the complete energy economy of pigs being given them.

### The possibilities for generalised conversion between DE, ME and NE

It can be assumed that as the urinary losses of energy in the form of nitrogenous compounds (urea) comprise normally about 3% of the digestible energy, and gaseous losses about 1%, ME will then be around 0.96 of DE. High rates of tissue turnover (following enhanced protein intakes and retention rates), as is often now usual, would lead to the expectation of urinary losses being around 4% (rather than 3%) of the DE; and higher again if the protein is not well balanced, or is fed in excess. High fibre diets, being degraded by microbial action in the hind gut, will also enhance gaseous losses. It is unusual, however, for the ME of pig diets to be much
lower than 0.94 of the DE, and as gaseous losses are rarely measured, the standard value of 0.96 is commonly used.

DE is transferred to net energy (NE) with an efficiency that is variable, but for compounded diets is often around 0.71 (NE/DE = 0.71). The absolute efficiency of transfer of DE to the absolute amounts of NE available for maintenance and production therefore cannot be handled with a conveniently agreed multiplier. Strictly speaking, NE is that energy which is retained in body products (Eₚ) together with the energy needed for basal metabolism (Eₐ). As in Figure 8.1 it is the difference between ME and the energy lost as heat, excluding the heat associated with basal metabolism. So it is ME less the heat increment; the heat increment being the increase in heat production that occurs when a pig in the basal metabolic state is fed and uses energy for the work associated with tissue retention (or milk synthesis or conception products). Net energy is a function of (1) the end-products of digestion being metabolised, (2) the relative proportions of energy going to protein retention, lipid retention or maintenance, and (3) the physiological state of the animal. NE, as strictly defined, can never therefore be used to describe the value of a feed before it is fed; only afterwards.

It is because the efficiency of transfer of ME to NE is dependent upon the metabolic activity of the animal that often NE is constrained to be measured as ‘NE for fattening’, and estimated in mature animals whose deposition is in the form of the single entity, lipid. The efficiencies of use of ME for fattening are in the region of 0.75 for starch, 0.90 for oil and 0.65 for protein. That part of diet crude protein not used for accretion in lean tissue, but rather for the creation of work energy, incurs a high work cost of deamination itself, with the result that the NE yield is only about half of the ME apparently available. On the other hand, the direct transfer of lipid from diet to tissue can result in the NE yield being close to 100% of the metabolisable energy. NE yield from carbohydrate ME is highly variable; the efficiency of transfer ranging from 0.5 to 0.75, depending principally upon the proportions of fibrous to starchy carbohydrates. This is because of the dramatic difference in the efficiency of utilisation between volatile fatty acids and glucose for the creation of work energy.

**Energy classification of pig feedstuffs**

Expression of energy value in food by measurement of DE takes the most simple line that the estimate does not concern itself with efficiency of absorbed energy utilisation, but only with the difference between GE ingested (GEᵢ) and GE excreted from the body in the faeces (GEᵢ). Thus the DE measurement cannot give a totally accurate picture of energy value as perceived by the animal. Especially, DE fails to account for the feed-dependent energy losses in urine and gases that occur. DE further fails to register the differences in the heats of digestion of various feedstuffs. Last, DE takes no account of the important distinctions between the effi-
ciencies of utilisation of digested sugars, amino acids and volatile fatty acids as energy generators.

The DE measurement does give, however, a straightforward view of the level of the apparently digested energy in a feed, and does so in a way that is independent of animal effects. It is therefore realistic to use DE as a descriptor of the energy value of a feed in a range of different circumstances and at different times. For example, the DE of a diet, in contrast to the ME, is not confused by the quantity and quality of dietary protein supply in relation to the ability of the pig to accrete products in the form of lean tissue or milk protein.

It may also be readily accepted from the foregoing sections that NE is influenced to such a great extent by the activities of the animal itself that a single NE value cannot be accurately or properly ascribed to a feedstuff.

The determination of energy value of feeds by DE measurement (rather than GE, ME or NE) has been found particularly useful because it is quite readily undertaken with the use of simple experimental techniques (in contrast to live animal calorimetry), and it has also tended to yield adequately consistent relationships with achieved animal performance. This latter has much to do with pig diets usually comprising a conservative and restricted range of ingredients compounded into diets given to pigs differing little in their rates and compositions of growth; so the coefficients relating DE to ME and ME to NE are relatively stable. However, these relationships are different for diets of similar DE when: (1) DE yields up for metabolism the energy in the form of different substrates energy in fats, energy in proteins, energy in starches, energy in non-starch polysaccharide (NSP); (2) the feed is digested by pigs with different degrees of development of their digestive systems (adults can digest more of the fibrous NSP than young pigs, yielding energy substrate in the form of volatile fatty acids arising from microbial digestion in the hind gut); and (3) pigs pursue a different balance of production activities (maintenance, lean growth, fatty tissue growth, milk synthesis). So the coefficients relating ME to NE are not stable over ranges of feed ingredients and ranges of pigs. Of particular importance are the digestibility and use of complex carbohydrate components which differs between young piglets and adult pigs, and when fibrous NSP replaces dietary starch. This results in quite different NE values being ascribed to high fibre diets when fed to young or adult pigs.

The major practical limitation of DE is indeed to do with its inability to reflect the proper values of high grade dietary lipid (whose value it underestimates for direct lipid accretion), low grade dietary fibre (whose value it overestimates) and protein (whose value it overestimates due to failure to account for the costs of deamination and energy release). The lipid effect is important in diets of high energy concentration, while the fibre effect requires some accommodation if the dietary crude fibre level rises above 6%, as may well be the case when pigs are fed by-product or forage-based diets.

Apparent digestibility merely relates to disappearance, saying nothing of the nature of the end-product disappearing or its usefulness. Thus similar DE values
would be erroneously given to simple sugar energy disappearing from the ileum as glucose as would be given to energy derived from complex carbohydrate energy leaving the caecum as volatile fatty acids, or even the anus as gaseous methane escapes. The change in the site of digestion of dietary components from the small intestine to the large intestine will weaken the relationship between dietary DE and animal response. Table 8.2 shows that compared to using DE as the descriptor for the energy value of feedstuffs, the use of NE elevates the value of starchy and oily feeds, diminishes the value of protein and fibre containing feeds, and credits a higher value to fibrous feeds when fed to pregnant sows.

Despite these caveats, digestibility remains the major factor affecting the value of a feed ingredient to a pig, and DE remains a simple means of classifying individual feedstuff ingredients and mixed feeds in order to allow predictable pig performance, monetary evaluation of diets and diet ingredients, proper incorporation of ingredients into mixed diets at the correct levels to give a balanced feed, and the ultimate rationing of compounded feeds to pigs in the form of the final total dietary allowance.

While DE is the chosen level for feed description, it is self-evident that when it comes to determining the ultimate utilisation of energy by the animal, and predicting the animal’s performance, it is the NE that gives the only final and definitive statement of energy balance. NE is dependent upon the nature and activities of both the animal and its environment, as well as upon the intrinsic energy-yielding characteristics of the food. The calculation of NE yield from DE supply cannot be satisfactorily achieved through a series of fixed or semi-fixed conversion factors. The only effective route for the determination of NE is by dynamic estimation of nutrient utilisation through the medium of a simulation model for prediction of nutrient flow and production response within the body. However, the first requirement for any model is a (reasonably) universal description of the first and major determinant of the energy value of a feedstuff, which is its digestibility. This is provided by the measurement of DE.

<table>
<thead>
<tr>
<th>Feedstuff</th>
<th>NE/DE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley fed to young pigs</td>
<td>0.74</td>
</tr>
<tr>
<td>Barley fed to pregnant sows</td>
<td>0.76</td>
</tr>
<tr>
<td>Wheat bran fed to young pigs</td>
<td>0.66</td>
</tr>
<tr>
<td>Wheat bran fed to pregnant sows</td>
<td>0.72</td>
</tr>
<tr>
<td>Rapeseed meal fed to young pigs</td>
<td>0.55</td>
</tr>
<tr>
<td>Rapeseed meal fed to pregnant sows</td>
<td>0.58</td>
</tr>
<tr>
<td>Fishmeal fed to growing pigs</td>
<td>0.59</td>
</tr>
<tr>
<td>Fishmeal fed to pregnant sows</td>
<td>0.59</td>
</tr>
<tr>
<td>Vegetable oil fed to young pigs</td>
<td>0.86</td>
</tr>
<tr>
<td>Vegetable oil fed to pregnant sows</td>
<td>0.86</td>
</tr>
</tbody>
</table>
Determination of digestible energy by use of live animal studies

The determination of DE is achieved by feeding a measured amount of the given feed material to a pig crated in such a way that the faeces can be separated from the urine, quantitatively collected and then preserved to avoid energy losses after excretion (Figure 8.4).

Sample collection may be undertaken with the help of a marker; the concentration of marker giving a means of determining the proportion of the whole represented by the sample. Markers themselves have problems, indigestibility alone being an insufficient quality to ensure exactly proportional excretion. In any event, the need is not great as crating is no particular problem, and total faecal collections for 1 week or so present no particular hardship for either pig or scientist. It is essential, of course, that animals are adequately habituated to the material being given (habitation can take from 3 days to more than 3 weeks) and for the collection to last long enough to avoid the problems of end-effects. At Edinburgh, a continuous period of 10 days is usually employed for total faecal collection under acid. (In the case of specific work on fibre or lipid digestibility, which would be disrupted by the acid medium, the material is collected fresh daily and frozen.)

An average level of feeding is usually chosen. Too low a level will cause an underestimate of digestibility due to the endogenous faecal losses, but this effect is small if the feeding level is at or above maintenance. Usually 1.5–2.0 times the maintenance level is chosen, as this may be expected to be readily eaten.

High levels of feeding (three times maintenance and above) – an important consideration in ruminant balance trials where rate of passage may significantly affect digestibility – do not appear greatly to affect digestibility of energy determination in growing pigs. However, whilst this latter may have been exhaustively studied and well proven with young pigs given concentrate diets, the matter is inadequately researched for adult pigs, for pigs given diets high in roughage or for pigs given diets of low DM or based on liquid by-products. In the event of a diet high in fibre, when...
there is significant reliance upon energy yielded from volatile fatty acids consequent upon microbial fermentation in the caecum and large intestine, the ruminant value of a reduction of 0.02 in the digestibility coefficient for each multiple of intake above maintenance may be used in the absence of better information. Cooking, in contrast, will enhance the digestibility of raw starchy carbohydrates by up to 0.05 units.

As particle size has some effect upon digestibility, most probably through the simple mechanism of surface area exposed to enzyme attack, it is essential that an adequate, but not excessive level of comminution of the feedstuff is achieved (Figure 8.5).

For a 40–50 kg crated pig, 1500 g of feed given daily in two separate meals might be appropriate. GE determinations are carried out on both ingested (i) and faecal (f) material. Where GE\textsubscript{i} is the megajoules of GE ingested daily, and GE\textsubscript{f} is the daily faecal excretion, then \((GE_i - GE_f)/GE_i\) gives the digestibility coefficient which, when used with the GE concentration of the ingested material, will give the megajoules of DE per kilogram (fresh or dry) of the diet in question (see Table 8.3).

Increased accuracy may be gained from replicating the treatment four or more times and/or by feeding three or more levels. This latter would also allow an additional check against a level of feeding effect (Figure 8.6).

When determining the digestibility of the energy of a diet ingredient, additional complications arise in inverse proportion to the normally expected level of inclusion of the ingredient in a balanced diet. The DE of a cereal of reasonable protein level could be determined by feeding the material alone, or with a small supplement of minerals and vitamins. However, it is inconceivable that physiological normality

Table 8.3. Example energy balance for determination of digestible energy (DE).

<table>
<thead>
<tr>
<th>Intake (kg/day)</th>
<th>= 1.500 kg fresh feed at 0.870 dry matter (DM) = 1.305 kg DM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross energy of feed</td>
<td>= 17.65 MJ/kg DM; GE\textsubscript{i} = 23.03 MJ</td>
</tr>
<tr>
<td>Faeces (plus dilute preservative)</td>
<td>= 1.179 kg slurry at 0.212 DM = 0.250 kg DM</td>
</tr>
<tr>
<td>Gross energy of faeces</td>
<td>= 15.56 MJ/kg DM; GE\textsubscript{f} = 3.889 MJ</td>
</tr>
<tr>
<td>((GE_i - GE_f)/GE_i)</td>
<td>= 0.831</td>
</tr>
<tr>
<td>DE value of feed</td>
<td>= 0.831 \times 17.65 = 14.67 MJ DE per kg DM</td>
</tr>
<tr>
<td>or</td>
<td>= 12.76 MJ DE per kg of fresh feed</td>
</tr>
</tbody>
</table>
would pertain if fish meal or rice bran was given alone – let alone soya oil or tallow. Usually, then, the DE of individual feed ingredients is determined within the environment of a diet including other ingredients. The procedure in this event is to manufacture for the test ingredient a balancer meal. The DE of the balancer meal is determined as a first step, and the DE of the balancer plus test ingredient as a second step. The difference between the two estimates gives the contribution of the test ingredient. Suppose the GE of the test (T) ingredient per kilogram of dry matter (DM) is 22.0 MJ/kg DM and the GE of the basal balancer (B) is 18.0 MJ/kg DM. First, 2 kg DM of B is given, providing 36 MJ GE per day. Of this, 7.2 MJ GE daily is recovered in the faeces. Next, 0.5 kg DM of T is given, in addition to the 2 kg of B. This amounts to 47 MJ of total diet GE (36 from B + 11 from T). Of this, 8.3 MJ GE is recovered in the faeces. As 7.2 MJ was recovered from B, then the energy recovered from T was (8.3 – 7.2) = 1.1 MJ. It can now be concluded that, as 11 MJ of T was given, the digestibility of T is \((GE_i - GE_f)/GE_i; (11 - 1.1)/11 = 0.90\). The DE of T is therefore \((0.90 \times 22.0) = 19.8\) MJ/kg DM.

When the test ingredient is added into, rather than on top of, the basal meal, then the calculation must, of course, be weighted by the relative contributions of the basal balancer and the test ingredient to the final diet; bearing in mind that it is not the proportional contribution to the DM that is of concern, but the proportional contribution to the gross energy:

\[
x(DE_T) + y(DE_B) = DE_D
\]

Suppose the GE of the test (T) ingredient is determined as 24.0 MJ/kg DM and the GE of the basal balancer (B) as 18.0 MJ/kg DM, and the two materials are mixed together in the DM proportions of 0.33 and 0.67: the GE of the mixed diet (D) is 7.92 + 12.06 = 19.98. Of this, 0.396 is from the test ingredient and 0.604 from the basal balancer. In the first step, 36 MJ GE of B is given daily and 7.2 MJ GE recovered in the faeces: \((GE_i - GE_f)/GE_i = 0.80\); the digestibility coefficient (DE_B). In the second step, 40 MJ GE of the mixed diet is given daily and 6 MJ GE recovered in the faeces: \((GE_i - GE_f)/GE_i = 0.85\); the digestibility coefficient (DE_D). Where \(x = 0.396\) and \(y = 0.604\), \(DE_B = 0.80\) and \(DE_D = 0.85\) and \(DE_T\) is unknown, then the equation above solves to:

![Fig. 8.6 Estimation of digestibility using three levels of intake. A negative effect of intake upon digestibility would be shown by curvilinearity (b). The slope gives the digestibility coefficient \((Y/X = 0.80)\). The constant term should be equal or close to zero.](image-url)
Det DIGESTIBILITY DE APPLICATIONS

The digestibility of the test ingredient is therefore 0.93 and the DE value (0.93 \times 24.00) = 22.2 MJ DE per kilogram of DM.

This method – the difference method – is clearly more prone to error the lower the proportion of GE contributed by the test ingredient. Further, a small error in the determination of the digestibility of the balancer, or the mixed diet, can have a large effect upon the result for the test ingredient. Say, for example, that the coefficient for DE_D had been underestimated by merely two percentage points. DE_T would be 0.88 and the DE value of the test ingredient underestimated by fully 5%. Additivity between the basal balancer and the test ingredient is explicit.

It is difficult to interpret a response when the inclusion of the test ingredient has been achieved simultaneously with and at the expense of a withdrawal of the equivalent amount of basal balancer. One is studying two events and not one. This becomes especially important if the type of energy in the balancer (say, starch) is suspected of being physiologically different from the type of energy in the test ingredient (say, protein), or if a chemical component of the energy fraction is being studied, such as would be the case for an examination of the digestibility of neutral-detergent fibre (NDF).

These problems can be greatly diminished by the procedure used for many years at Edinburgh. To a single level of basal diet are added incremental levels of test ingredient. In one experiment, to 1 kg of basal balancer (B) given daily was added 0, 0.2, 0.4 and 0.6 kg of test ingredient (T_1), and again 0, 0.2, 0.4 and 0.6 kg of a second test ingredient (T_2). Three animals were used at each level. The type of plots obtained were as shown in Figure 8.7. The slope of the line indicates the DE value of the added test ingredient (T), and the constant indicates the DE value of the basal diet (B). Similar values for B in the cases of both experimental procedures for

$$0.396(\text{DE}_T) = 0.85 - 0.604(0.80) \quad (8.9)$$
$$\text{DE}_T = 0.926 \quad (8.10)$$
T₁ and T₂ give reassurance as to the correctness of that value in different dietary combinations, whilst the lack of curvilinearity demonstrates additivity. The use of the regression slope rather than the single difference estimate gives much greater accuracy of determination of the DE value of T.

**Estimation of digestible energy from chemical composition**

It is feasible for most common ingredients to be run through live animal digestibility trials to provide updated DE values, and feed evaluation units may be routinely used for such purposes. It is not feasible, however, to undertake live animal trials on individual batches for individual foodstuff importations, which may differ one from another in important ways. Common cereals and protein-rich residues from the oil extraction business often display a range of their fibre, lipid and protein contents, with consequent effect upon DE.

Equally in need of solution is the problem of compounded feeds, the nutrient specifications and ingredient compositions of which frequently change, so altering the final DE value.

It is also the case that live animal feed evaluation units are invariably to be found only at research institutes, university departments and some research facilities of larger feed compounders. Very many other organisations without live animal metabolism facilities nevertheless wish to monitor the energy content of pig feeds and pig feed ingredients. Not least among these are pig producers, agricultural businesses, feed compounding mills and commodity buyers and importers.

For continuous monitoring of the nutritional content of individual feed ingredients and of complete compounded pig feeds, a scheme based upon simple laboratory chemical analysis would be beneficial. Towards this end, attempts have been made over many years to provide prediction equations for DE from chemical analysis.

Live animal determinations of DE, together with analysis for chemical components, allow multiple regression analysis to relate DE to chemical composition. Regression is a particularly effective means of stating in as closely exact a mathematical way as possible relationships found in any particular set of data. Regression itself does not, however, imply effective prediction. If regression is to be used for forward prediction, rather than historic description, then accuracy is greatly helped if the variables in the equation are themselves the causal forces of the variation in the parameter to be predicted. Further, the coefficients and constants should have biological logic and relevance. Should these requirements not be met, a regression equation is in danger of giving erroneous predictions, regardless of the numerical accuracy with which it describes the data set from which it was constructed. Errors become the more likely when the prediction is required to relate over a wider range than the original data, or to differing combinations of ingredients.

Regression of the data set in Figure 8.8 may, for example, give a line of best fit (a) with a constant term of around 20 and a slope of 0.010, indicating that each addi-
tional gram of oil increases DE by 0.010 MJ. Such a line indicates that: (1) oil has a DE value of about 30, and (2) diets with no oil will have a DE of about 20. These propositions require to be checked against the common sense that (i) the DE of a diet without oil should approximate to the expected DE of the remaining components (fibre, starch and protein), and (ii) that oil is highly digestible to the pig and will have a DE value not dissimilar from the GE. Such ideas as these latter would accord much more closely with a line (b) of slope 0.022 and constant term 17.5.

The major causal forces of variation in DE concentration in the DM of feedstuffs may be put forward as: a negative contribution from the presence of fibre (Figure 8.9); a positive contribution from the presence of oil; no contribution from the presence of carbohydrate (starch contributing primarily to the average DE of the diet, rather than to deviations from that average); and a small positive effect of protein. Active variables in useful regression equations should bear some relationship to the above suppositions.

Expectations for the form of an effective regression might be something as follows:

(1) A constant term close to zero if either gross energy or carbohydrate is included in the equation.
(2) A constant term close to the average DE of the diet if carbohydrate or gross energy are not included in the equation.
(3) Fat and fibre should have large effects within the equation, with protein (and ash) contributing less.
(4) Coefficients should bear some relationship to the logic set out in Table 8.4.

It may be postulated, therefore, that prediction equations for DE should approximate to the examples presented in Table 8.5. Indeed, were they not to do so, the biological logic of the prediction equation could be questioned. Examination of the
research literature yields a range of published equations relating DE to chemical composition. Some examples are given in Table 8.6. The first equation has a negative multiplier for crude fibre that is higher than might be expected. This suggests either that crude fibre does not measure all the indigestible fibrous components negatively active in the diet, or that the presence of crude fibre disrupts the digestibility of other diet components. The constant term in this equation is also a little low, implying that a diet with no ether extract and no crude fibre (i.e. made up of carbohydrate and protein) has a DE value of only 16.0 MJ/kg DM. The second equation would please phlogistonists as it appears that, upon digestion, more GE is yielded than was ingested. This is then corrected by a negative constant term. The third equation was, as it happens, a remarkably accurate description of the data set in question, but has unexpectedly high multipliers on crude protein, ether extract and ‘starch’ (estimated as nitrogen-free extractives – NFE). Fibre is absent from the equation, but is included by implication via NFE. These anomalies are resolved in statistical terms by a weighty negative constant.

Table 8.4.  Expected contributions of chemical components to the concentration of diet DE.

<table>
<thead>
<tr>
<th>Chemical component</th>
<th>Approximate GE (MJ/kg)</th>
<th>Assumed digestibility</th>
<th>Contribution made by 1 g (MJ DE per kg DM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starch</td>
<td>17.5</td>
<td>0.8–1.0</td>
<td>0.016</td>
</tr>
<tr>
<td>Oil</td>
<td>39</td>
<td>0.8–1.0</td>
<td>0.035</td>
</tr>
<tr>
<td>Protein</td>
<td>24</td>
<td>0.7–0.9</td>
<td>0.019</td>
</tr>
<tr>
<td>Fibre</td>
<td>17.5</td>
<td>0–0.1</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 8.5.  Postulated forms for equations to predict DE from chemical components.

(1) $\text{DE (MJ/kg DM)} = 0.016 \text{ starch (g/kg)} + 0.035 \text{ oil (g/kg)} + 0.019 \text{ protein (g/kg)} + 0.001 \text{ fibre (g/kg)}$

(2) $\text{DE (MJ/kg DM)} = 17.01 + 0.018 \text{ oil}^2 (g/kg) + 0.002 \text{ protein (g/kg)} - 0.016 \text{ fibre}^3 (g/kg) - 0.001 \text{ starch (g/kg)}$

1 70% starch, 20% protein, 5% oil, 5% fibre. This term may also be expressed by using GE (MJ/kg) multiplied by the expected overall digestibility coefficient for GE, e.g. 0.84 GE.

2 Removal of 1 g of average DE and substitution of 1 g of oil DE: $-0.017 + 0.035 = 0.018$.

3 Removal of 1 g of average DE and substitution of 1 g of fibre DE: $-0.017 + 0.001 = -0.016$.

Table 8.6.  Three example prediction equations drawn from the literature (all elements per kg DM)

(1) $\text{DE (MJ/kg DM)} = 16.0 - 0.045 \text{ CF (g)} + 0.025 \text{ EE (g)}$

(2) $\text{DE (MJ/kg DM)} = -4.4 + 1.10 \text{ GE (MJ)} - 0.024 \text{ CF (g)}$

(3) $\text{DE (MJ/kg DM)} = -21.2 + 0.048 \text{ CP (g)} + 0.047 \text{ EE (g)} + 0.038 \text{ NFE (g)}$

CF = crude fibre; EE = ether extractives; CP = crude protein; NFE = nitrogen-free extractives.
The roles of fibre and fat

To quantify by experiment the exact roles of fibre and fat in influencing the digestibility of feedstuffs, a series of investigations were completed at Edinburgh throughout the 1980s.

Acting on the proposition that fibre was the most important component reducing diet digestibility, the relationship between analysed chemical fibre content and digestibility in the live animal was examined using three different fibre types. These were those found in oat feed, rice bran and beet pulp. Oat feed contains about 250 g crude fibre/kg DM, rice bran about 160 g, and sugar beet pulp about 190 g. The basal balancer used was wheat/soya, and to 1 kg/day of this were added graded levels of the test materials. By the regression method of plotting DE intake (GEi – GEf) against level of addition of test material (X, kg), the following equations were derived:

\[ \text{GE}_i - \text{GE}_f(\text{oat feed}) = 13.53 + 8.56X \]  
(8.11)

\[ \text{GE}_i - \text{GE}_f(\text{rice bran}) = 13.76 + 10.25X \]  
(8.12)

\[ \text{GE}_i - \text{GE}_f(\text{beet pulp}) = 13.86 + 11.16X \]  
(8.13)

The regressions suggest that the DE of the basal balancer (given by the constant) is relatively unaffected by the source of added fibre, but that the DE value for the three materials (MJ DE/kg, as given) were 8.56, 10.25 and 11.16 respectively.

Crude fibre (CF) is a term used to describe an analytical procedure and it has little meaning in terms of structural plant elements. Plant ‘fibre’ is more realistically the NSP and plant lignin. NSP includes a variety of materials including hemicellulose, cellulose, pectins, arabinans and xylans. The Van Soest procedures attempt to differentiate between various fibre fractions in a sequential analysis. Lignin is the most complex fibre material, followed by cellulose and hemicellulose. Lignin is a totally indigestible polyphenolic polymer. It becomes associated with the structural carbohydrates cellulose and hemicellulose. Cellulose is a glucan, like starch, but with beta links, and therefore digestible only by micro-organisms. Hemicellulose, unlignified, would be supposed to be more digestible, being of pectins and gums derived from xylans and mannans. Both cellulose and hemicellulose may be lignified to varying degree. There is agreement that lignified polysaccharide is indigestible to the small intestinal digestive enzymes of the pig, and also indigestible to all other enzymes; even those of bacterial origin found in the large intestine and caecum. It may be supposed that cellulose is indigestible in the small intestine, but potentially digested posterior to the ileum. Argument rages as to the potential for, and site of, the digestibility of hemicellulose. However, the weight of current opinion is that hemicellulose may in fact be rather less digestible than cellulose, being more resistant than cellulose to degradation in the large intestine and caecum. In the analytical series, neutral detergent extraction separates out the cell content of lipids, sugars, starches and protein; leaving the neutral detergent fibre (NDF) comprising...
the cell wall hemicelluloses, celluloses, lignins and ash. Acid detergent extraction of this residue separates the hemicellulose from the acid detergent fibre (ADF) comprising the cellulose, lignin and ash. The final separation of cellulose from the acid detergent lignin residue (ADL) is achieved by acid hydrolysis.

Fibrous components of four example fibrous feeds are shown in Table 8.7. Straw is rich in cellulose, oat feed and rice bran have similar structural carbohydrate compositions, while sugar beet pulp has relatively more cellulose and relatively less lignin. The digestibility of the feed material will be consequent upon the absolute amount of total fibrous components, and the balance of hemicellulose, cellulose and lignin within the fibre. Thus the relatively higher total fibre content of sugar beet pulp as compared to rice bran appears to have been more than offset by sugar beet pulp having a much lower proportion of lignin within the fibre. The digestibility of oat feed as compared with rice bran reflects the greater absolute quantities of structural carbohydrate components in oat feed as compared to rice bran.

When the various ways of analysing for fibrous components were examined with a view to determining their efficacy in predicting DE, it was evident from both the logical and the statistical points of view that NDF was much more effective than the others, whilst CF was especially poor. This might be considered as a predictable outcome, as CF is an empirical analysis not based on any particular fibre source (see Table 8.7), whereas NDF includes all three fibre fractions considered to be more or less indigestible in the pig.

The statistically determined best-fit prediction equation based on the combined data for all three fibrous sources was:

$$\text{DE (MJ/kg DM)} = 17.4 - 0.016 \text{ NDF}$$

which accords remarkably well with the propositions laid out in Table 8.5.

Acting next on the proposition that oil was the most important component enhancing diet digestible energy value, the relationship between analysed oil content and digestibility was examined using three different sources of human-
edible grade oil – tallow, palm oil and soya oil – added at progressively increasing levels (X, kg) to a basal balancer of 1 kg of a barley/soya diet:

\[
\begin{align*}
\text{GE}_i - \text{GE}_i(\text{tallow}) &= 12.90 + 38.82X \\
\text{GE}_i - \text{GE}_i(\text{palm oil}) &= 12.60 + 37.54X \\
\text{GE}_i - \text{GE}_i(\text{soya oil}) &= 12.92 + 40.83X
\end{align*}
\] (8.15, 8.16, 8.17)

In the case of the added oils, the test materials were pure, whereas with the fibrous feeds the test materials were high in fibre, but not solely comprising fibre. As the GE of oil is 39.6 MJ/kg, the regressions indicate high digestibilities. The expectation that the more highly hydrogenated tallow was not as digestible as the unsaturated palm and soya oils was not realised.

The best-fit regression over all oils produced a positive coefficient of +0.025 for ether extractives (EE) (g/kg), which is higher than the 0.018 proposed in Table 8.5, but not too far distant from the 0.023 that logic would have proposed for a high-grade oil, which might be completely digestible.

These results gave the Edinburgh workers sufficient confidence to set up a full-scale experiment involving the use of 36 compounded diets covering most, if not all, of the ingredients to be found in pig feeds (33 in total), and giving a composition range of 23–123 g CF/kg, 149–258 g crude protein/kg and 21–116 g EE (oil)/kg. These diets were each given to four growing pigs housed in metabolism crates and the complete data set used for multiple regression analysis to derive equations for the prediction of DE from the chemical analysis of compounded diets.

A very large number of equation forms were derived. Of the 62, of particular interest are the following:

1. Using crude fibre, ash and oil:

\[
\text{DE(MJ/kg DM)} = 18.3 - 0.037 \text{ CF} - 0.019 \text{ ash} + 0.011 \text{ oil}
\] (8.18)

This is not particularly accurate (residual standard deviation = 0.65), neither are the coefficients particularly logical. The high multiplier for CF may indicate either that CF estimates only a part of the indigestible diet constituents or that the presence of CF disrupts digestion of other non-fibrous diet components. If either of these possibilities pertain, the naïve use of an elevated multiplier is unlikely to be sufficient means of ensuring the accuracy of a prediction equation. In any event, it was perfectly clear from the whole exercise that, of all the analyses for fibre, for the purpose of DE prediction NDF was considerably superior to any other measure, and CF was particularly inferior.

2. Including gross energy:

\[
\text{DE(MJ/kg DM)} = 3.77 - 0.019 \text{ NDF} + 0.758 \text{ GE}
\] (8.19)

This equation is rather accurate, with a residual standard deviation of only 0.38. The coefficient for GE reflects the digestibility coefficient itself, although it is less than the mean digestibility, due to the presence of a positive constant term of 3.77 MJ.
The coefficient for NDF is within expectation. Unfortunately, many analytical laboratories are insufficiently equipped to be sure of an accurate measurement of GE.

(3) Using NDF and oil together with a constant term:

\[
DE(MJ/kg \, DM) = 17.0 - 0.018 \, NDF + 0.016 \, \text{oil} \quad (8.20)
\]

This equation is quite accurate, having a residual standard deviation of 0.44, and has the benefit of restricting itself to the two major causal forces of digestibility: the negative force of fibre and the positive force of oil. It conforms with the propositions put forward in Table 8.5. Further, the coefficient for NDF accords with the expectations derived from the first Edinburgh fibre experiment. The coefficient for oil is lower than that in the first Edinburgh oil experiment, where the three human-grade oils were used. In that previous case the coefficient was 0.025, as compared with 0.016 here. The value of 0.016 is, however, more in line with expectations for feed-grade added oils and oils naturally occurring in feed ingredients; these latter being the effective contributors to oil in the commercial-type compounded diets used in the 33-diet matrix experiment. The coefficient of 0.016 for oil indicates an achieved DE of dietary fats of around 33 MJ/kg. For simplicity and logic, this equation has much to commend it.

(4) Using NDF, oil, ash, protein and a constant term:

\[
DE(MJ/kg) = 17.5 - 0.015 \, NDF + 0.016 \, \text{oil} + 0.008 \, \text{CP} - 0.033 \, \text{ash} \quad (8.21)
\]

This equation is the most accurate of all, having a residual standard deviation of only 0.32. The inclusion of ash and CP helps to make the equation more robust over a wide range of circumstances.

The potential of a net energy system for use in the evaluation of feeds

While DE or ME is the most ready description of energy in feeds, it is evident that the realised out-turn of energy from a feed can only be determined as NE; the energy actually and ultimately put to productive use by the animal. There is therefore justifiable interest in the determination of NE, and the possible use of an NE system for evaluating diets and describing the energy requirements of pigs. Anything that will add to the accuracy of energy description will also add to the efficiency of feed compounding.

The net utilisation of energy in feedstuffs necessarily depends upon factors other than the characteristics of the feed, as has been adumbrated earlier. The principal issue, therefore, when comparing DE and NE systems is that the former is independent of the animal in question, whilst the latter is animal-dependent and requires a detailed understanding of what a given animal at a given time is actually doing with the energy that is provided to it.
The Edinburgh group suggested early on in the ‘DE vs NE debate’ that DE can be usefully divided into its protein (23.7 DCP) and protein-free (Epf) components, and then the Epf can be further subdivided:

\[
\text{Epf} \approx (1.1 \text{ DE}_l) + (0.5 \text{ DE}_f) + (1.0 \text{ DE}_c) - (23.7 \text{ DCP}) \tag{8.22}
\]

where \(\text{DE}_l\) is the digested energy from dietary lipid, \(\text{DE}_f\) is the digested energy from dietary fibre and \(\text{DE}_c\) is the digested energy from everything else. The equation suggests that uncorrected DE values undervalue dietary lipid which can be used so efficiently for fat formation, and overvalue dietary fibre which – because it yields VFA – is less effectively used. It was suggested that the general equation could be extended to differentiate between ME from different fibre fractions (cellulose, hemicellulose, lignin), from different fat sources and from differently digested starch sources (which vary in the extent to which they pass to the hind gut to yield VFA).

As a general rule the digestibility of proteins, fats, starches and sugars is usually quite high (0.7–0.9), the major cause of variation in digestibility being dietary fibre. NSP used in plants for structural purposes are resistant to digestion, and this is conventionally indicated by the determination of NDF, hence the relationship:

\[
\text{DE} = 17.4 - 0.016 \text{ NDF} \tag{8.23}
\]

where NDF estimates cellulose, hemicellulose and lignin. NDF can be used as a measure of NSP, but NSP strictly does not include lignin, but does include pectins. Maize contains some 70% starch, 2% sugars and 10% NSP. Barley contains some 60% starch, 25% sugars and 20% NSP. Starches and sugars are made available by direct digestion and absorption from the small intestine, whereas NSP requires microbial fermentation in the hind gut.

The digestibility of NDF is usually low (0.1–0.2), but NDF, although a convenient chemical method for estimating NSP plus lignin, does not inform as to the components of the NSP, and different sources of NSP can have digestibilities as diverse as 0.0–0.8. NSP digestibility is a function of the degradability of the material itself, the propensity of the material to increase endogenous losses by surface abrasion of the gut wall and the ability of NSP to disrupt the enzymic digestion of other (otherwise digestible) feeds in the fore gut. The digestibility of NSP in sugar beet pulp can be as high as 0.9, but the digestibility of NSP in wheat straw as low as 0.4. Thus there may be significant differences between the NE of feedstuffs with the same presumptive DE. The digestibility of NSP in wheat straw, when given to growing pigs, is only about 0.2; that is half of that found with sows.

This means that the extent to which the NE yield of feedstuffs differs according to the age of the pig is directly related to the NSP content of the feed. In compounded diets it appears that on average an adult sow can digest some 20% of the dietary energy contained in fibrous fractions that is not digestible by the growing pig. This may be calculated as some 2.8 MJ/kg indigestible (when measured with a growing pig) material. It is of course the microbial content of the sow’s large intestines and caecum that facilitates fermentation of complex structural fibres to yield VFAs. Although VFAs as energy sources are not as efficiently utilised by the
body as glucose (about half), NSP can yield enough energy to satisfy pig maintenance requirements if there are relatively low levels of complexing with lignin. Sugar beet pulp NSP can contribute to a greater extent than wheat straw NSP.

It will be recalled that the net (utilisable) energy (NE) yielded up from a feed is:

\[
NE = E_{bm} + E_r
\]  

(8.24)

It will also be recalled that in compounded pig diets NE is usually some 0.7 of DE. Importantly, this ratio differs between feed ingredients, being greater than 0.7 for oily feeds, slightly above 0.7 for cereal grains and less than 0.6 for highly fibrous or highly proteinaceous feeds (see also Table 8.2).


\[
NE(MJ/kg DM) = 0.0113 DCP + 0.0350 DEE + 0.0144 ST + 0.0000 DCF + 0.0121 DRES
\]

(8.25)

where DCP is the digestible crude protein, DEE is the digestible ether extract, ST is starch, DCF is digestible crude fibre and DRES is all of the remaining digestive organic matter. This equation helps to indicate the relative contributions of the different fractions of the feedstuff to NE (the coefficients for EE and ST are a higher proportion of their GE value than is the case for the coefficients for CP and CF) and shows that DE tends to underestimate the value of feeds rich in oil and starch and to overestimate the value of feeds rich in protein and fibre. However, the equation is limited in its ability to predict NE because it does not allow for pig-related factors; especially the ratio of maintenance to fat deposition and the ratio of fat deposition to protein deposition, each of which has differing efficiencies for the use of metabolisable energy.

In presenting nutrient requirement standards for pigs [Whittemore, C.T., Hazzledine, M.J. and Close, W.H. (2003) *Nutrient Requirement Standards for Pigs*. British Society of Animal Science, Penicuik, Midlothian, Scotland], the British Society of Animal Science quotes, for use in determining equivalent nutrient values for feedstuffs, the equations used by the French groups in the publication *INRA Editions A F Z Tables de Composition et de Valeur Nutritive de Matières Premières Destinées aux Animaux d'Élevage*, as follows:

\[
NE = 0.0121 DCP + 0.0350 DEE + 0.0143 starch + 0.0119 sugars + 0.0086 DRES
\]

(8.26)

and

\[
NE = 0.703 DE + 0.0066 EE + 0.0020 starch - 0.0041 CP - 0.0041 CF
\]

(8.27)

for which NE was expressed in MJ/kg DM and the nutrient composition in g/kg DM.

Energy in lipid is 39.3 MJ/kg and the energy expended in its deposition is about 14 MJ/kg, so the total energy of lipid deposition is about 53.3 MJ/kg; or k_{1L}, the effi-
ciency of conversion of energy into deposited lipid, is about 0.75. The energy in protein is 23.6 MJ/kg and the energy expended in its deposition is about 31.0 MJ/kg, so the total energy cost of protein deposition is about 54.6 MJ/kg; or \(k_{Pr}\), the efficiency of conversion of energy into deposited protein, is approximately equal to 0.44. The NE yield of a given feed will therefore be higher if fat is being formed than if protein is being retained. The balance of protein to fat in the gain of the pig thus substantially affects the value of the feed. Further variability in efficiency of the use of ME arises from the extent to which protein is deaminated. The ME in feed protein can have different fates. Some of the energy will never be yielded up as it will remain in the amino acid moieties deposited in protein growth. Other energy found in protein, which is not used for protein growth, is broken down and voided in the urine, yielding energy. However, the energy produced is only half of what might be expected from the original DE value of the protein because, first, energy is lost in the urine (7.2 MJ/kg), second, energy is used for deamination (2.4 MJ/kg) and, third, energy is used for restructuring (2.5 MJ/kg). The greater the amount of protein deaminated therefore, the greater the variance between ME and NE.

The assumption that a given feed can have a single all-embracing value of feed energy, as if all sources of dietary energy were used with equal efficiency when being metabolised by the pig, is thus heavily faulted.

Energy is of course consumed as physical nutritional entities – carbohydrates, lipids and proteins – and all of these are used with differing efficiencies for maintenance, or for the deposition of protein, or for the deposition of lipid. Starch ME is highly efficiently used for maintenance, but protein ME is not. The coefficients of utilisation of ME for the deposition of body fat are about 0.5, 0.9 and 0.7 for ME derived from protein, fat and starch respectively. A proportion (some 40%) of protein will be used for incorporation into body protein itself with an efficiency of up to 0.9, but the other proportion (about 60%) will be used with a lower (about 0.5) efficiency to yield energy for metabolic work, or for body fatty tissue deposition through deamination (this of course depending upon diet quality and pig protein deposition rate). The efficiency of utilisation of energy for maintenance and for metabolic work is probably about 0.8 for ME from glucose and fat, and about 0.6 for ME from protein, and about 0.5 or less for ME from fibre when provided via VFA. The efficiency of use of energy to provide for the work required in the deposition of protein growth is probably about 0.8 for energy provided by protein (after the costs of deamination have been accounted for) and 0.9 for energy provided from glucose. VFA (from NSP) generates only 0.6–0.7 of the ATP that is possible to be yielded from glucose. The DE of sugar beet pulp is used only 0.7 as efficiently as the DE from maize. The NE:DE ratio is therefore variable between feedstuffs depending on the proportion of the DE arising from fibrous materials and on the site of digestion. In contrast to the position for fibre, ME from some dietary lipids may be transferred with great efficiency, and almost without modification, to deposition in pig body fat. \(k_{Pr}\), \(k_{Lr}\) and \(k\) values for lactation are therefore variable and not fixed values; the efficiency of use of ME for production depending upon the particular substrate being used for any given end-product.
NE is thus a variable (not fixed) quality of the feed and requires knowledge of:

- the status of the pig’s digestive system with regard to its ability to digest NSP;
- the ultimate uses of feed energy, and the ratios of energy demands for maintenance, protein deposition and fat deposition;
- the compositional quality of the diet especially in relation to the likely rate of protein deamination;
- the structure of the energy-containing components of the feed (starch vs structural non-starch polysaccharide; one type of NSP vs another) in as much as that structure influences both the end-products of digestion and the efficiency of transfer of the various end-products through to utilisation.

It may be concluded that there is no future for NE as a constant descriptor of the energy value of a feedstuff, and simultaneously that the only ultimately useful descriptor for the energy value of feedstuffs is NE! DE and ME effectively describe the forward budget, are independent of the animal and may be used as a single constant value expressing the energy content of a feed. However, DE and ME cannot describe the ultimate usefulness of the energy in a feed; that can only be done with knowledge of the retrospective out-turn of the energy account for the feed, which is necessarily variable. This is handled through using NE. Because NE is influenced by a plethora of factors, many of which are variable and animal-dependent, the only route to the determination of NE is through a knowledge of the metabolic activity of the animal in question. The solution of this conundrum lies in simulation modelling, which is the subject of subsequent chapters and present active research programmes (Chapter 19).

Guide values for the energy content of pig feedstuffs

Reports of in vivo digestibility experiments and in vitro chemical analyses of pig feedstuffs from many countries have been collated into a set of guide values and feed composition tables, now given in Appendix 1. Feed composition tables are invaluable for the proper formulation of diets and for the calculation of monetary worth of individual feedstuffs. There is no substitute, however, for regular reappraisal of both chemical composition and in vivo digestibility of conventional feedstuffs. Nor is there any substitution for live animal digestibility studies and performance response trials for new feedstuffs, feedstuffs of questionable quality or feedstuffs of novel origin.

In the Appendix, energy values are given in terms of digestible energy as the determined – rather than the derived – estimate. Energy values given in terms of NE are derived from prediction equations. Compounders may wish to work with ME, which is dependent to some extent on non-feed factors, such as level of protein provision, but may be estimated as 0.96 DE. Both DE and ME are budgeted values, whilst the out-turn value can only be expressed as NE. Tables for NE values for feedstuffs are something of a contradiction in terms due to their substantial vari-
ability resultant from non-feed (animal-related) factors such as have been described above. However, although determination of the true NE must be a dynamic activity, and as such cannot be expressed in static tables, the values given do allow the formulation of diets to satisfy nutrient requirements given in terms of NE.

Although tables cannot account for the animal factors influencing NE, they are an advance on DE as they value oil and starch higher and protein and fibre lower, and can accommodate the influence of pig age upon NSP utilisation.
Chapter 9

Nutritional Value of Proteins and Amino Acids in Feedstuffs for Pigs

Introduction

In addition to carbon, hydrogen and oxygen, the major functional element in protein, and the amino acids which link together to make up protein, is nitrogen (N).

The protein content of the whole live pig will vary between 15 and 18%, depending on fatness. On average, 21% of the fat-free carcass is protein; the protein content of lean meat varying between 20 and 25%, increasing with age. Between 45 and 60% of the whole body protein mass is present in dissectible muscle or lean meat. The remainder of the body protein mass is present in visceral organs, skin and hair, bone, blood and other organs.

Estimation of milk protein production by sows requires estimation of daily milk production and measurement of milk protein content, which is about 6%.

In addition, pigs require the amino acids contained in protein for the synthesis of a range of non-protein compounds (hormones, neurotransmitters, immunoglobulins, other bioactive peptides) and replacement of proteins that are lost with skin and hair or into the digestive tract.

Because the construction of absorbed diet amino acids into pig protein is an energy-consuming process in itself, some 30–50% of the energy used by growing pigs may well be involved in the anabolism of lean tissue. The substantial involvement of protein synthesis in the overall energy economy of the pig gives some measure of its importance in proper nutrient provisioning.

Feedstuff protein is the essential source of amino acids. Amino acids are required: (1) to build protein in the body of the pig, mostly in muscle; and (2) to replace proteins lost in the course of protein tissue turnover (maintenance) and voided in the form of cells, amino acids, other nitrogenous compounds and unabsorbed enzyme secretions from the intestine (termed metabolic faecal losses or endogenous faecal losses), and also in the form of urea from the kidney (termed urinary losses). Of the approximately 20 amino acids that are present in feedstuffs for pigs, nine amino acids can be considered dietary essential. These amino acids (lysine, methionine, threonine, tryptophan, histidine, isoleucine, leucine, phenylalanine and valine) need to be supplied in the pig’s diet as they cannot be synthesised by pigs and are required
for one or more body functions. Two amino acids can be considered dietary semi-essential as they can be synthesised only from essential amino acids: cysteine from methionine and tyrosine from phenylalanine. The latter implies that pigs have dietary requirements for methionine plus cysteine and phenylalanine plus tyrosine, as well as methionine and phenylalanine. In cereal grain-based pig diets, lysine is generally the first limiting amino acid. However, as a wider variety of amino acid sources are included in pig diets other amino acids may become limiting as well, in particular threonine, methionine plus cysteine, tryptophan and isoleucine. Moreover, in some situations, in particular in newborn piglets, the pig’s capacity for endogenous synthesis of some amino acids (glutamine, arginine) is limited, in which case a proportion of these amino acids needs to be supplied in the diet as well.

On the other hand, pigs can use dietary amino acids as a source of energy, carbon and hydrogen, after it has been deaminated, to support various body functions or to synthesise body lipid. Because the process of making pig protein from feed protein is usually only about 30–60% efficient, the energy yield from the deamination of amino acids not deposited in the pig’s body or milk can be quite significant. Amino acids not destined for pig protein may also, upon their deamination, yield useful precursors for other body activities, for example the formation of fatty tissues. Mainly, however, feed proteins are seen as providing the amino acid elements for the deposition of pig protein in growth or milk and for the maintenance of proteinaceous pig tissues.

Feed proteins are not constructed in the same way as pig proteins. The necessary restructuring from the one to the other involves costs. In the digestion, breaking-down, absorption and building-up processes: (1) energy for biochemical work is used up; (2) amino acids unwanted for deposition and retention are turned to other uses; (3) they are finally excreted in faeces, urine and sweat; or (4) oxidised to be lost as heat. This apparent inefficiency is, in reality, a highly valuable and effective way of turning vegetable proteins (such as from cereals), which are not of high value to humans, and animal proteins (such as fish by-products), which humans may not wish to eat, into lean pig meat which is highly nutritious and readily eaten.

Most of the protein in the pig’s diet is derived from cereal grains (wheat, barely, corn, sorghum) or grain by-products (wheat shorts, wheat middlings). The concentration of crude protein (CP) in cereal grains is usually low at around 8–12%. This means that the diet requires to be supplemented with higher protein seeds (such as soya bean, oilseed rapeseed, peas or beans) with 20–30% protein, or with plant products in which the protein has been concentrated to 30–60% due to the extraction of other components such as oils (such as extracted soya bean and extracted rape-seed meals).

Synthetic amino acids may also be used to make good specific deficiencies; especially lysine, methionine, threonine and tryptophan. Vegetable proteins are less easily handled by the pig (especially the young pig) because, in addition to affecting immune function and immune response, plant proteins can be more difficult to digest, the concentration of essential amino acids is relatively low, and much restructuring and reorganisation of the amino acids is needed in order to make pig protein
out of vegetable protein. For this reason, protein of animal origin, such as from milk, meat-and-bone meal or fish meal, may have an important part to play in the compounding of high-quality pig diets. Not only are animal proteins easily digestible, but also their amino acid balance is, self-evidently, already much closer to that required for the construction of pig protein in lean meat muscle tissues.

As has been described, the unavoidable inefficiencies of the conversion of diet protein to pig protein in the form of growth, products of conception or sows’ milk is acceptable to the extent of creating useful products from less useful ones. However, within any given system efficiency must be optimised by reconciling the biological cost and benefits with the economic ones. This requires information on the net yield to the pig of usable amino acids obtainable from feedstuff proteins. The yield of amino acids from a feedstuff is a combination of amino acid content, amino acid digestibility and amino acid utilisability.

The final amounts of amino acids deposited and retained by the pig are also dependent upon the balance of amino acids available at the time. This quality is therefore usually a function not of any individual feedstuff, but of the combination of feedstuffs in the diet as a whole.

Across and within types of feedstuffs amino acid contents vary with total protein content and the types of functional or structural proteins that are present in these feedstuffs. For example, in cereal grains, glutelins, proteins associated with the seed coat, contain about 4.4% lysine, while prolaminates, proteins associated with starch bodies, contain about 0.5% lysine. Given the variable relative contribution of individual proteins to total protein, amino acid profiles and contents vary considerably among types of feedstuffs and even among different samples of the same feedstuffs. Variation in growing conditions, plant variety or processing conditions can contribute to this variation as well. The nutritional value of a feedstuff lies in its amino acid composition, not its protein (or N) composition. Feedstuffs should therefore be evaluated according to their amino acid contents. However, amino acid analyses are costly and there is still considerable within and between laboratory variability in amino acid analyses, in particular for methionine, cysteine and tryptophan. As an alternative to analyses, empirical relationships between protein and amino acid contents within individual feedstuffs are used routinely to predict the amino acid contents. More recently, rapid and non-invasive methods, such as near infrared reflectance spectroscopy, have been used to predict amino acid content in feed ingredients. These methods of predictions have inherent inaccuracies, while the prediction or calibration parameters need continuous updating with changes in feedstuff characteristics.

Table 9.1 presents the mean amino acid contents of the main feedstuffs for pigs. These values illustrate the large variability in protein and amino acid contents across feedstuffs. The table also illustrates that the amino acid composition of crude protein varies considerably across feedstuffs. Based on lysine to protein ratios, soya bean meal protein is close to twice as valuable as corn protein. Variability in amino acid content should be considered as well. For example, in soya bean meal lysine content readily ranges between 2.5 and 3.5%.
The relatively low efficiency of conversion of ingested protein into body or milk protein (30–60%) implies that most of the protein consumed by pigs is excreted with faeces and urine, which can have a negative impact on the environment in areas of intensive pig production. Because of environmental concerns and the relatively high cost of feed protein, attempts should be made to enhance or optimise protein utilisation efficiency in pigs. There is interest from countries with a dense population of intensive pig units in the minimisation of the amounts of nitrogen excreted both in faeces and in urine. Nitrogenous output from the pig in the form of slurry is considerable, and this may contribute to environmental contamination. The higher the digestibility of the diet protein, and the better the amino acid balance, the less will be the level of faecal nitrogen and the lower will be the level of urea excretion. This improvement in biological efficiency, although probably only attainable by increasing the cost of the diet, may well have more than proportional benefits in terms of pollution control.

### Digestibility of protein

Meat and vegetable protein contains about 16% nitrogen. Total protein, or crude protein, is therefore used widely as a measure of total amino acid content of feedstuffs. Crude protein content in feedstuffs is generally calculated as N content × 6.25, assuming that protein contains 16% N. However, the N content of different proteins is known to vary between about 15.5% for milk protein and about 18.5% for cereal protein. Moreover, in feedstuffs that contain substantial amounts of non-protein-nitrogen, such as urea, the use of a constant N multiplier of 6.25 can result in a substantial overestimation of total amino acid content.

The linkages between the amino acids which form into proteins are broken down in the hydrolysing processes of digestion. After some hydrolysis in the stomach to
peptides, the major enzyme attack is by proteases and peptidases reducing the proteins to short chains of 2 or 3 amino acids, which are either absorbed as such or further hydrolysed by the intestinal wall to free amino acids. There is some utilisation of amino acids by the gut wall itself, but most amino acids pass through into the body proper and are taken by the bloodstream to the liver and body cells. In the large intestine there is microbial degradation of the residues from digestion and of the endogenous secretions. This releases ammonia and amines which, while disappearing from the gut and being apparently digested, are of no nutritional worth.

Digestion is invariably incomplete, the extent of digestion (digestibility) depending upon the circumstances of both animal and feedstuff; but primarily the latter. Protein that has been ingested, but that has not been subsequently excreted in the faeces, has, by definition, disappeared from the tract and is assumed to have been digested. Thus if 20 g of protein (as N × 6.25) appear in the faeces for every 100 g protein (N × 6.25) ingested, then digestibility is 0.80. This value usually ranges between 0.75 and 0.9, with an average for high-quality pig feeds of 0.8–0.85 (Table 9.2). Protein structures themselves, even when large complex molecules are involved, are usually open to enzymic digestion. Reductions in digestibility are often associated with treatment of the natural protein (such as by heat), or the presence of interfering factors in the diet, or the actions of non-starch polysaccharides which can reduce the digestibility of dietary amino acids, probably through coating and protecting effects. Digestibility, as measured by the difference between ingestion and faecal excretion, is termed apparent digestibility because it measures that part of what is eaten that disappears from the intestine, appears within the body-proper of the animal and is available for metabolism. The apparent digestibility is less than the true digestibility of feedstuff protein. This is because some feed protein has indeed been digested, but then returned back into the tract in the form of digestive juices and cells lost from the intestinal wall lining as the food passes down the tract. In a growing pig of 50–80 kg there can be around 23 g of nitrogen or 140 g of endogenous (metabolic) protein secreted into the tract daily in this way (Table 9.3).

### Table 9.2. Digestibility coefficients of protein for some feedstuffs.

<table>
<thead>
<tr>
<th>Feedstuff</th>
<th>Apparent faecal digestibility</th>
<th>Apparent ileal digestibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish meal</td>
<td>0.90–0.95</td>
<td>0.80–0.90</td>
</tr>
<tr>
<td>Meat-and-bone meals</td>
<td>0.50–0.70</td>
<td>0.40–0.70</td>
</tr>
<tr>
<td>Maize meal</td>
<td>0.80–0.85</td>
<td>0.70–0.80</td>
</tr>
<tr>
<td>Wheat meal</td>
<td>0.80–0.85</td>
<td>0.70–0.80</td>
</tr>
<tr>
<td>Barley meal</td>
<td>0.75–0.80</td>
<td>0.70–0.80</td>
</tr>
<tr>
<td>Wheat offals</td>
<td>0.50–0.75</td>
<td>0.30–0.60</td>
</tr>
<tr>
<td>Extracted soya bean meal</td>
<td>0.85–0.90</td>
<td>0.75–0.85</td>
</tr>
<tr>
<td>Extracted cotton, coconut and rapeseed meals</td>
<td>0.50–0.70</td>
<td>0.40–0.60</td>
</tr>
</tbody>
</table>

1 These values are the difference between ingested and faecally excreted proteins (N × 6.25) divided by the amount ingested (i−f)/i. Artificial amino acids may be assumed to be completely digestible.

2 These values are the difference between ingested proteins and those found passing the terminal ileum divided by the amount ingested (as N × 6.25). Artificial amino acids are completely digestible.
Endogenous N can be a significant proportion of the digesta, especially at lower feed intake levels. True digestibility can be 5–20% higher than apparent digestibility; the extreme often being consequent upon a high level of fibre in a diet fed at low level. Most, but not all, of the endogenous protein secreted into the tract is reabsorbed, the residue being passed out in the faeces as the metabolic faecal protein component, joining the indigestible dietary protein in the faecal residues. This is shown schematically in Figure 9.1.

The presence of the endogenous component in faecal protein means that apparent digestibility is somewhat intake-dependent and measurements of digestibility must be made at realistic intake levels. If endogenous faecal protein (fe) amounts to 20 g and 150 g of protein is ingested with a true digestibility of 0.87, then 40 g of faecal protein will be lost; comprising 20 g of metabolic faecal protein and 20 g of indigestible diet protein, giving an apparent digestibility of 0.73. If, however, 300 g of protein is ingested and metabolic faecal protein remains at 20 g, then 60 g of faecal protein will be lost, comprising 20 g of metabolic faecal protein and 40 g of indigestible feed protein. Apparent digestibility for the feed protein is now 0.80.

The measurement of endogenous loss is difficult as it is so dependent upon the animal and dynamic state of the gut, so is usually taken as the level of appearance in the faeces when the level of ingested protein is low or absent. As animals grow bigger and eat more, the absolute levels of metabolic losses tend to increase, which causes apparent digestibility to slightly decrease. More importantly, as the amount of food eaten increases, both the rate of enzyme secretion and the loss of cells from the gut lining are elevated. Fibrous and abrasive feedstuffs are associated with greater levels of metabolic faecal losses, and thus the inclusion of straws, cereal husks or sand and like materials into pig diets will induce a decrease in the apparent digestibility of the protein and the net yield of feed protein to the pig. Feeds of low protein content and high in fibre may, through their influence upon metabolic

<table>
<thead>
<tr>
<th>Protein secreted daily¹ (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pancreas</td>
</tr>
<tr>
<td>Bile</td>
</tr>
<tr>
<td>Saliva and stomach</td>
</tr>
<tr>
<td>Cells</td>
</tr>
<tr>
<td>Intestinal secretions</td>
</tr>
<tr>
<td><strong>Total²</strong></td>
</tr>
</tbody>
</table>

¹ The threonine and tryptophan content, relative to other amino acids, is higher in the digestive secretions than in the digesta. As a result, more of these amino acids will pass the terminal ileum and their ileal digestibilities may be expected to be relatively lower than the other amino acids.

² About 80% of the total secretions are reabsorbed and available for reutilisation; some 20% pass unabsorbed beyond the terminal ileum and will be degraded by microbes in the hind gut or lost in faeces as metabolic faecal protein.
faecal losses, contribute little, or negative, amounts of protein to the nutritional economy of the animal.

Usually metabolic faecal protein amounts to 6–12 g for each kilogram of compound feedstuff if this has around a 5% level of fibre. For a pig consuming 150 g of protein in each kilogram of feed, the metabolic faecal losses will amount to around 30% of total faecal protein.

The animal can only benefit from the digestive processes to the extent of the apparently digested protein moieties; only that which has disappeared between ingestion and faecal excretion being available for productive uses (Figure 9.1). For practical purposes, therefore, interest until recently has been confined to the determination and expression of the apparent digestibility of feedstuff nitrogen, protein and amino acids. The term ‘digestible’ may therefore be taken as synonymous with ‘apparently digestible’. It is important, however, when placing values on feedstuffs as to their content of digestible protein – or digestible amino acid – that the determination has been undertaken at reasonable levels of intake, and in conjunction with balancer meals of reasonable fibre level. Indigestibility is, as has been seen, part feed function and part animal function; and the measure of apparent digestibility fails to apportion these. Were this to be done, the accuracy of feed formulation would be enhanced. This has led to the development of the ‘standardised digestibility’ system, which is considered later on in the chapter.
Measurement of digestibility and retention of crude protein (N × 6.25)

Digestibility is determined by balance using the same methodology as described in the previous chapter for energy. Crude protein (CP) ingested is determined as the product of the amount of feed eaten and the concentration of N × 6.25. Apparent digestibility is calculated as the difference between crude protein consumed (CP<sub>i</sub>) and crude protein (N × 6.25) excreted in the faeces (CP<sub>f</sub>):

\[
\text{Apparent digestibility} = \frac{(\text{CP}_i - \text{CP}_f)}{\text{CP}_i} \quad (9.1)
\]

It is important that no ammonia leaves the excreta between the time of being voided and the time of analysis; this can be prevented by collection under dilute sulphuric acid.

While the protein value of a feedstuff is considerably influenced by the overall (faecal) digestibility of the CP, there is also great interest in the part of the gastrointestinal tract where the CP moieties were digested and disappeared. Digestion and disappearance from the small intestine yields usable end-products, while disappearance from the caecum or large intestine yields useless products. It is evident that the greater the proportion of a feedstuff’s protein content that is digested in the small intestine, the greater is the value of that feedstuff. To differentiate between small intestinal and large intestinal digestion, a cannula can be inserted at the end of the ileum (Figure 9.2). Withdrawal of the digesta from the terminal ileum allows a direct measure of the level of digestion that has occurred in the small intestine – the ileal digestibility. This is considered to be a truer reflection of realised protein value than the faecal digestibility.

Although there may be gaseous losses of N and also losses of N in skin and hair, CP retention (CP<sub>r</sub>) can be adequately measured by determining the faecal (CP<sub>f</sub>) and urinary N × 6.25 losses (CP<sub>u</sub>):

\[
\text{CP}_r = \text{CP}_i - (\text{CP}_f + \text{CP}_u) \quad (9.2)
\]

Urine can be readily collected, under acid, in the course of a standard digestibility procedure, as described in the previous chapter (see Figure 8.4).

CP retention can also be determined by comparative slaughter techniques, the difference between the CP mass in the pig at the end of the trial period and at the beginning of the trial period being – evidently – a direct measure of the crude protein (N × 6.25) retention. The efficiency of the retention is determined with knowledge of the intake of CP over the period:

\[
\text{Daily food intake} \times \text{number of days (day}_1 \text{ to day}_n) \\
\times \text{CP concentration of feed} = \text{CP}_i \quad (9.3)
\]

\[
\text{Whole body mass} \times \text{CP content of body at day}_n - \text{whole body mass} \\
\times \text{CP content of body at day}_1 = \text{CP}_i \quad (9.4)
\]

\[
\text{CP}_r/\text{CP}_i = \text{Efficiency of CP retention} \quad (9.5)
\]
Obviously, the direct measurement of whole body protein content in the pig’s body is unequivocal, but laborious, requiring careful homogenisation and sampling of the pig’s carcass. New emerging technologies, such as image analyses, may make this method less arduous and less invasive. A clear advantage of the N balance method is that estimates of whole body protein deposition can be obtained over shorter time periods (7–10 days) than the serial slaughter method (at least 4 weeks in the case of grower-finisher pigs). However, the N balance method is more prone to error, generally providing higher estimates of whole body protein retention than the serial slaughter assay; likely because of incomplete collection of wasted feed or N in excreta.

The efficiency of CP retention may not, however, be a particularly fruitful measurement for comparing the relative value of the protein content of feedstuffs because it is pig dependent as well as feed dependent. The amount of CP retained in relation to the amount ingested is: (1) a function of the digestibility and the quality of the protein in terms of the amino acids absorbed; (2) a function of the amount given in relation to the amount needed; (3) a function of the amino acid balance in the diet compared to amino acid balance in the retained product; and (4) a function of the other diet constituents. Thus a good protein may show a poor efficiency of retention if supply greatly exceeds requirement, because the unwanted excess has overflowed out via the urine. Equally a protein may have a low efficiency through a shortage of one amino acid which prevents effective construction of pig protein, but which may be simply and cheaply redressed by balancing with another protein high in the missing amino acid, or even with an artificial amino acid source.

The digestibility of protein in feedstuffs is not well predicted from in vitro laboratory analyses involving digestion with pepsin and enzyme mixtures, as these methods are general for nitrogen (N), and do not address the organic nature of the protein moiety itself, although heat damage to protein, which reduces digestibility, can be assessed through analysis of the extent to which the amino acid lysine is bound up and rendered unavailable. In vitro laboratory analysis is, however, effective at measuring protein quality as perceived from the balance of total amino acids.
Because protein quality is as much related to its amino acid content as to its digestibility, chemical analysis for amino acids, especially the nine essential amino acids, allows an effective evaluation of the protein worth of a feedstuff. Knowledge of the amino acid make-up enables ready calculation of the cost that will be incurred in balancing the feed to create an appropriate amino acid mix for the needs of the pig. For example, fish meal and soya bean proteins have more lysine than cereal proteins; thus the former may effectively complement the latter when placed together in a diet mix.

At present therefore, the best estimate of protein value in a feedstuff would appear to arise from information on the amino acid composition and on disappearance proximal to the terminal ileum.

Factors influencing digestibility of protein

Although differences exist in the apparent digestibility of crude protein (N × 6.25) of pig feed ingredients, the concept of digestible crude protein (DCP) has not been readily taken up by feed formulators. Variation in digestibility has – wrongly – been considered as not as important for protein as for energy. The digestibility of most protein of animal origin (milk, fish and meat) is about 0.90, and most of the proteins of vegetable origin (cereals, legumes, roots and young leaves) about 0.80. However, there are many important exceptions to these generalities which are deeply significant to cost-effective feed formulation. Despite the reluctance of some nutritionists to accept the importance of DCP as a feedstuff descriptor, protein digestibility is a most useful indicator of feed value and is profoundly affected by both extrinsic and intrinsic factors.

The basic amino acids that make up protein are highly digestible. Nevertheless, in the small intestine there is more protein passing down the gut than was eaten. This is because the gut contents are inundated with proteinaceous secretions (mostly enzyme-containing fluids), and also the cells lining the intestine have a high turnover rate and are lost in quantity into the gut lumen. Fortunately, reabsorption of these secretions is just as highly efficient as the primary absorption of the amino acid products of enzyme degradation of diet proteins.

Heat damage

Digestibility falls dramatically if the protein is heat damaged; such damage may occur when animal or vegetable proteins are overcooked as part of the production process. The consequences of such damage are difficult to predict due to their variable nature, and therefore almost impossible to incorporate into a quantitative nutritional evaluation of feedstuffs. Suffice it to say that heavily damaged materials – once identified – should be treated circumspectly as sources of amino acids for pigs. If used, on the grounds of economic expediency, the effects upon growth and reproduction are difficult to elucidate other than by empirical trial.
Heat damage changes the protein structure, which reduces its digestibility. The greater the degree of heating, the higher the loss in digestibility. To some extent, all cooked proteins are less digestible than raw ones (about 5% less). However, in cases of overcooking, when actual damage occurs, the matter becomes serious and digestibility may be reduced to 50% or less, as, for example, in overheated soya bean meal, fish meal and meat-and-blood meal. Specific amino acids may be bound on heating. The classic case is the binding of lysine to sugar compounds; this reduces the digestibility and utilisability of lysine. ‘Available lysine’ is particularly important because: (1) it is a general indicator of heat damage; and (2) cereals being lysine deficient, lysine is the most valuable amino acid in most supplementary protein sources. If the lysine is unavailable, then all the other amino acids in the protein, even though utilisable, cannot be utilised.

**Protein structure**

The amino acid sequence and tertiary structure of proteins may be such that they are resistant to degradation by digestive enzymes. This applies in particular to proteins in skin and feathers and appears related to the cross-linkages of the sulphur groups in cysteine. Many proteins, as determined by analysis for N, may appear to be useful nutrient sources, but are not.

**Abrasion**

Certain foodstuffs may increase the rate of cell wall loss from the gut lining and/or prevent efficient reabsorption of this protein of body origin. This will increase the protein in faeces and decrease perceived digestibility. Straw has been implicated in such activity, and also other highly fibrous and abrasive feeds. The evidence is, however, not straightforward.

**Feeding level and rate of passage**

In the digestive tract enzymes need time to interact with the feed. Digestibility can thus be reduced by feed and animal factors that increase the rate of passage of digesta through the intestine. For example, by increasing the feeding level and by housing animals in groups as opposed to individually in pens, feed passage rate is increased and protein digestibility is slightly reduced. Feeding liquid diets with water to dry feed ratios higher than about 4:1 can reduce protein digestibility as well.

**Anti-nutritional factors**

Most feedstuffs that are of plant origin contain factors that interfere with the utilisation of dietary nutrients. These factors, causing depressions in growth, feed efficiency and/or animal health, can be defined as anti-nutritional factors. In plants and seeds, these anti-nutritional factors act primarily as biopesticides, protecting the
plants and seeds against moulds, bacteria and birds. Specific anti-nutritional factors that interfere with protein digestion and utilisation include various types of lectins, protease inhibitors, tannins and to some extent phytates. In most cases, feedstuffs contain different types of anti-nutritional factors, including those that interfere with carbohydrate utilisation (amylase inhibitors, polyphenols), mineral utilisation (phytates and glucosinolates) or immune function (antigenic proteins) or that have toxic effects on specific tissues (cyanogenic glycosides, alkaloids, vicine/convicine, oxalic acid, gossypol) (Table 9.4). Because of its potential negative effects on protein utilisation, dietary fibre may be considered an anti-nutritional factor as well.

Winter-sown rapeseeds can be goitrogenic, containing generous levels of glucosinolates, as well as harbouring erucic acid; while in some spring-sown varieties these poisons are at much lower levels. Rapeseed meals may in addition contain sinapine and saponins, and also non-starch polysaccharide anti-nutritional factors. The feeding of full-fat rapeseed meal has been found satisfactory for growing pigs, provided the material is treated. Suitability of full-fat rapeseed for sows has yet to be fully tested.

Cyanogenic glycosides, such as linamarin, may be found in inadequately prepared cassava meals, and occasionally in sorghum.

Tannins are polyphenolic compounds with various molecular weights, variable chemical complexity and capable of precipitating proteins from aqueous solutions. They are difficult to destroy. Although tannins are chemically not well defined, they are usually divided into two subgroups: hydrolysable and condensed tannins. Condensed tannins form complexes with proteins and carbohydrates in the feeds and with digestive enzymes, resulting in depressed nutrient digestibility. Other effects of tannins include reduced feed intake, increased damage to the gut wall, reduced absorption of some minerals and toxicity of absorbed hydrolysable tannins. Tannins are the main anti-nutritional factor in sorghum, but tannins are present in a variety of other feedstuffs including rapeseed, sunflower seed, groundnuts, beans and peas (Table 9.4).
Alkaloids can be found in lupin (but not sweet lupin), potatoes and ergot sclerotia.

Lectins, or haemagglutelines, are proteins that are generally present in the form of glycoproteins. They vary considerably in molecular weight and chemical structure and are characterised by their ability to bind to specific sugars. Glycoproteins in the gut wall contain sugars to which lectins have affinity. Binding of lectins to epithelial cells contributes to growth depressions as a result of the damage to the gut wall, increased mucin production, impaired digestive function and even immunological reactions. A prerequisite for the anti-nutritional properties of lectins is resistance to proteolysis. A variety of lectins exist, both within and between different types of seed, which have differing effects on the animal. In general, the lectins in *Phaseolus* beans are highly toxic, while lectins in peas and faba beans appear to be the least toxic. Even after cooking by toasting there remains reduction in performance when lectins are ingested.

Although phytates (found in legumes and many other plants) are usually associated with the tying-up of phosphorus and the chelating of calcium, magnesium, zinc and iron (and thereby render all these less available), they also have the capacity of reducing the effectiveness of protease (and amylase) enzymes.

Many cruciferous plants, not just oilseed rape, can be goitrogenic. The plant glucosinolates are hydrolysed by enzymes to yield the goitrogens which depress growth.

Goitrogens, tannins, saponins, gossypols (of cotton seed meal) and alkaloids are heat stable, but the lectins, protease inhibitors and other poisonous amino acids are destroyed by heat. Heat treatment remains the most effective way of counteracting heat-labile anti-nutritive factors. Such processing requires careful control in order to achieve adequate cooking to detoxify while also avoiding overcooking and heat damage; this balance is crucial to the effective production of soya bean meal following the extraction of soya oil. Heat-stable poisons can only be extracted by complex exchange technology and/or washing (as for oilseed rape meals) or, more commonly to date, by breeding improved strains of plants not carrying the offensive material. The most notable recent case of breeding toxins out of plants has been that of the spring-sown ‘Canadian’ rapes, in which levels of anti-nutritional factors are reduced.

Some commonly used feedstuffs, unless treated, contain high levels of protease inhibitor activity. The main protease inhibitors in legume seeds and cereals are the trypsin and chymotrypsin inhibitors. These are peptides that form stable, inactive complexes with some of the pancreatic enzymes. As a result the activities of trypsin and chymotrypsin are reduced. Inactivation of these enzymes in the gut induces the pancreas to produce more digestive enzymes. Protease inhibitor contents are highest in raw soya beans, intermediate in common beans and lowest in peas and some cereal grains (Table 9.4). It should be noted that there are important differences in trypsin inhibitor content between different varieties of the same seed. For example, soya bean and pea varieties have been developed that are low in specific trypsin inhibitors. Uncooked soya and potato can have protein digestibilities lower than 30%. These protease inhibitors act not just specifically in relation to the feeds that
contain them, but generally within the whole of the gut environment. Thus all the protein in a diet containing raw soya will have reduced digestibility.

It is because protease inhibitors are themselves made of protein that their activity is destroyable by heat treatment. Partial cooking causes partial destruction, and it is this gradation of treatment effect that makes quality control so important for soya beans (and for potato) intended for pig diets. One way of counteracting a low level of inhibitor activity is to give luxury amounts of the protein, and it has been accepted for many years that diets containing field beans should be compounded to a more generous protein content. Recent varieties of low trypsin inhibitor soya beans have been developed. However, when fed raw, protein digestibility is still significantly depressed and full heat treatment remains necessary. Heat treatment does not address the issue of the antigenic properties of some vegetable proteins, especially soya, when fed to young pigs.

Plant materials contain fibre, mostly in the form of non-starch polysaccharides (NSP), but some more than others, as described in the previous chapter. NSP is less digestible than starch, and can have a disruptive effect upon the digestibility of feed proteins. There is much present interest in the role of NSP as a negative influence upon the net utilisation of dietary nutrients.

Fibre can influence protein digestion and amino acid utilisation in various ways. First, fibre from cell walls can physically enclose protein in feedstuffs and hinder the access of digestive enzymes to this protein. Second, endogenous protein secretions into the gut (enzymes, mucus, sloughing of mucosal cells) and endogenous ileal and faecal protein losses can be induced by feeding fibre to pigs. Third, fibre – and viscous fibre in particular – will interfere with digesta movement and the mixing of digestive enzymes and nutrients in the intestinal lumen, hindering both protein digestion and absorption. Fourth, soluble fibre can stimulate microbial fermentation and increase the amount of microbial protein at the terminal ileum or in faeces and increase the use of dietary and endogenous amino acids for microbial fermentation. Finally, feeding fibre may alter intestinal morphology and the capacity of the gut to absorb nutrients. The net result is that fibre reduces amino acid utilisation largely due to (1) reduced digestibility of amino acids in the ileum, (2) increased loss of amino acids secreted into the hind gut of pigs and (3) increased use of amino acids as substrate for microbial fermentation. There is some evidence that microbial protein that is produced in the upper gut can contribute to the amino acid supply of pigs. This potential benefit is unlikely to outweigh the negative effects of dietary fibre on utilisation of dietary amino acids for protein in pigs.

In general, it has to be stated that anti-nutritional factors in plants adversely affecting protein absorption remain mysterious and poorly understood.

**Feed processing**

A wide variety of feed processing methods are available to enhance the feeding value of feedstuffs. The main aspects of feed processing are particle size reduction, heating and (pre-)digestion. Particle size reduction – through grinding, rolling or
cracking – increases the surface area and disrupts cell wall and fibre structures, resulting in improved access of digestive enzymes to nutrients contained in the feedstuffs. Particle size reduction will thus benefit energy as well as protein digestion.

Mild heat treatment will denature protein and is an effective means to inactivate protein containing anti-nutritional factors, such as protease inhibitors, lectins and immune proteins that are present in raw soya beans and other feedstuffs. A variety of heat treatment methods exist that have varying effect on anti-nutritional factor content, and differences in ileal digestibility of amino acids across heat treatments are largely due to reductions in endogenous ileal lysine loss and not to improvements in ileal lysine digestibility per se. When heat-processing feedstuffs care should be taken that the feedstuff is not overheated, which can reduce digestibility and availability of amino acids, of lysine in particular.

The addition of enzymes to the feed, or simply soaking of feedstuffs prior to feeding, will allow some breakdown of proteins, anti-nutritional factors (phytate) and fibre to occur and thus enhance protein digestibility and amino acid utilisation. The effectiveness varies with the type and source of exogenous enzymes. For example, it is well documented that the inclusion of exogenous phytases in phytate-containing pig diets enhances digestibility of phosphorus and somewhat improves protein digestibility, while the effectiveness of proteolytic and fibre degrading to improve nutrient digestibility in pig diets has not been demonstrated consistently. It should be noted that extensive soaking of feedstuffs likely leads to uncontrolled fermentation, which can result in loss of protein, particularly of free amino acids.

Site of digestion

Usually the digestibility of protein determined as \((\text{CP}_i - \text{CP}_f)/\text{CP}_i\) is some 10% (5–20%) higher than the digestibility determined at the point of exit of digesta from the terminal ileum. Much of the reason for this is the disappearance of ammonia and amines from the large intestine. Thus while ‘digestion’ may mostly occur in the small intestine proximal to the terminal ileum, ‘disappearance’ may occur anywhere in the tract, including the large intestine. Nitrogenous materials disappearing from the tract count towards crude protein absorbed but not towards protein moieties realistically available to the pig, as the nitrogenous products of fermentation in the large intestine tend to go directly to urinary excretion. Where the measured DCP value may therefore often be in the region of \(0.85 \times \text{CP}\), the effective DCP value may well be nearer \(0.70 \times \text{CP}\). Because of this, interest in the ileal digestibility of the protein in feedstuffs is now rather greater than interest in faecal digestibility. The faecal excretion of amino acids is, in fact, pig-dependent to quite some degree, being in part of endogenous cells and secretions, and this element of total faecal loss is therefore relatively less affected by food types within the conventional range. Diet protein is, of course, no better or worse than its constituent amino acids; it is the amino acids that the animal is seeking to be provided from feed proteins. Therefore protein content is often best expressed in terms of the amino acid constituents, and
a measure of the effective utilisability of the protein expressed in terms of the digestible, that is the ileal digestible, amino acids.

Proteins ingested by pigs are subject to (1) enzymatic digestion in the stomach and small intestine and (2) microbial fermentation, which occurs largely in the hind gut. Enzymatic digestion involves the breakdown of protein to small peptides and free amino acids which can be absorbed by intestinal cells, while absorbed peptides are hydrolysed to free amino acids within intestinal cells. Intestinal cells will utilise some amino acids, but most absorbed amino acids are released into the blood circulation. It has been clearly established that ileal digestibility, digestibility prior to the end of the small intestine, provides a better estimate of amino acid bioavailability in feedstuffs for pigs than faecal digestibility. Amino acids that are fermented in the hind gut yield ammonia and amines that, when absorbed, have close to no nutritional value.

The effectiveness of the small intestine in digesting some of the amino acids appears rather superior to its effectiveness in digesting others. Thus the balance of amino acids, one to the other, in the food will not be perfectly reflected in the balance of amino acids found at the terminal ileum. The differential absorption of amino acids from the small intestine is variable amongst feedstuffs and therefore an important character for consideration in feed evaluation.

There is some bacterial degradation of amino acids in the small intestine, but it is slight. It is only when passing from the ileum to the caecum and large intestine that the protein residues are subjected to a significant level of microbial attack, while enzymic yield of amino acids is now low. Hind gut microflora, present at 10^{10} bacteria per gram of digesta, may well deal with a further 15–20% of proteinaceous material in the digesta distal to the terminal ileum, but to no benefit to the pig, as the nitrogen is mainly in the form of unusable non-amino moieties and is passed out directly via the urine.

Values for digestibility of crude protein at the terminal ileum – ileal digestibilities – are usually about 8% lower than faecal digestibilities [for over 43 feedstuffs, ileal digestibility of crude protein = 0.92 (± 0.08) faecal digestibility of crude protein]. If this relation were to be constant, no greater precision would be achieved by using ileal rather than faecal digestibility values. However, it is not constant, and importantly varies between amino acids and between feed ingredients. One reason for this is that for some feeds (such as meat-and-bone, meat offals and some more difficult to digest plant protein sources) a larger proportion tends to escape digestion in the small intestine and passes into the large intestine, where protein is more likely to be degraded by the microbial gut flora to non-amino nitrogen than be absorbed as amino acids. In the important case of soya bean meal, whereas the ileal digestibility of amino acids is normally some 8 percentage units less than faecal digestibility, for under- or over-heated beans the difference increases to almost 20 percentage units.

While the difference between faecal and ileal digestibility of protein is evidently feed-dependent, it is also the case that this difference is variable amongst amino acids. Thus, while the difference between faecal and ileal protein digestibility of cereals is about 10 percentage units, the difference between faecal and ileal lysine...
Digestibility of cereals is about 5 percentage units. Threonine and tryptophan are particularly liable to disappear by deamination or decarboxylation from the large intestine, whilst for methionine net bacterial synthesis may even occur. The rate and type of degradation occurring in the large intestine is highly dependent upon the ingesta environment, especially the level and type of carbohydrate present and the presence or absence of toxins.

These differences in the behaviour of amino acids in the small and large intestines are exemplified by a general tendency for the ileal digestibilities for threonine and tryptophan to be relatively lower than the general digestibility of protein, whilst the ileal digestibility of methionine is generally higher.

The ileal digestibility of protein and four of the most interesting amino acids in some feedstuffs is given in Table 9.5, whilst Table 9.6 shows the ratio of ileal digestible amino acid to ileal digestible crude protein averaged over 43 feedstuffs. Although the ileal digestibility for lysine is shown in Table 9.5 as being quite similar to the ileal digestibility for crude protein as a whole, this relationship is feed depen-

Table 9.5. Ileal digestibility of some amino acids in some feedstuffs (values mostly from few measurements only).

<table>
<thead>
<tr>
<th></th>
<th>Protein</th>
<th>Lysine</th>
<th>Methionine</th>
<th>Threonine</th>
<th>Tryptophan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley</td>
<td>0.70–0.80</td>
<td>0.70–0.80</td>
<td>0.75–0.85</td>
<td>0.65–0.75</td>
<td>0.70–0.80</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.70–0.80</td>
<td>0.70–0.80</td>
<td>0.75–0.85</td>
<td>0.65–0.75</td>
<td>0.70–0.80</td>
</tr>
<tr>
<td>Maize</td>
<td>0.70–0.80</td>
<td>0.70–0.80</td>
<td>0.75–0.85</td>
<td>0.65–0.75</td>
<td>0.70–0.80</td>
</tr>
<tr>
<td>Wheat offals</td>
<td>0.30–0.60</td>
<td>0.30–0.70</td>
<td>0.30–0.50</td>
<td>0.40–0.50</td>
<td>0.50–0.60</td>
</tr>
<tr>
<td>Maize gluten feed</td>
<td>0.40–0.60</td>
<td>0.50–0.60</td>
<td>0.57–0.70</td>
<td>0.40–0.55</td>
<td>0.30–0.40</td>
</tr>
<tr>
<td>Extracted soya bean meal</td>
<td>0.75–0.85</td>
<td>0.80–0.90</td>
<td>0.80–0.90</td>
<td>0.75–0.80</td>
<td>0.75–0.80</td>
</tr>
<tr>
<td>Rapeseed meal²</td>
<td>0.40–0.60</td>
<td>0.50–0.70</td>
<td>0.60–0.80</td>
<td>0.50–0.70</td>
<td>0.50–0.70</td>
</tr>
<tr>
<td>Meat-and-bone meal</td>
<td>0.40–0.70</td>
<td>0.50–0.70</td>
<td>0.60–0.80</td>
<td>0.50–0.65</td>
<td>0.40–0.60</td>
</tr>
<tr>
<td>Fish meal</td>
<td>0.80–0.90</td>
<td>0.85–0.95</td>
<td>0.85–0.95</td>
<td>0.75–0.85</td>
<td>0.70–0.75</td>
</tr>
</tbody>
</table>

¹ In general, ileal digestibility of crude protein is about 8% lower than faecal digestibility of crude protein. Interesting exceptions are rapeseed meal (12% lower), corn gluten feed and corn gluten meal (16% lower), wheat middlings (17% lower) and meat-and-bone meal (14% lower).

² Often typical of cotton seed meal, coconut meal and lupin meal, some other by-products and some secondary ingredients.

Table 9.6. Ratio of ileal digestible amino acid: ileal digestible crude protein (average of 43 feedstuffs).

| Isoleucine | 1.06 |
| Lysine     | 1.02 |
| Methionine¹ | 1.20 |
| Threonine  | 0.95 |
| Tryptophan | 0.95 |

¹ Methionine is almost twice as variable for this character as the other amino acids. In the case of maize, the ratios for lysine, threonine and tryptophan are 0.88, 0.94 and 0.92. For feather meal the ratio for lysine is 0.72.
dent. Thus, while the ileal digestibility of lysine in fish meal is somewhat higher than
the ileal digestibility of crude protein, the ileal digestibility of lysine in feather meal
is considerably lower than the ileal digestibility of feather meal crude protein.

The use of ileal digestible essential amino acids appears to be an appropriate way
of assessing the potential of feed ingredients to satisfy the amino acid specifications
for a pig diet. This supposition has been borne out by feeding trials in which growth
rate was much more closely correlated to the ileal digestibility than to the faecal
digestibility.

**Ileal digestibility of amino acids**

Since ileal digestion of ingested proteins is both incomplete and variable, ileal
digestibility is a means to assess routinely amino acid availability in feeds for
pigs. However, ileal amino acid digestibility is influenced by animal factors as well
as feed factors. In particular, in newly and early weaned piglets digestive capacity is
not fully developed. Ileal amino acid digestibility will increase with live body weight
and up to approximately 25 kg live body weight. As mentioned earlier, ileal amino
acid digestibility may underestimate bio-availability, especially in heat-treated
ingredients.

Establishing ileal amino acid digestibility requires sampling of digesta at the
distal ileum. The necessary surgical intervention (usually a cannula at the distal
ileum) not only is complex and expensive, but also can alter digestive function in
pigs and influence observed digestibility. Experimental methodology thus con-
tributes to differences in observed ileal amino acid digestibility across studies.

The apparent ileal digestibility of protein and individual amino acids (AA) is
derived from dietary intake (AA$_{\text{diet}}$) and ileal flow (AA$_{\text{ileal}}$):

\[
\text{Apparent ileal AA digestibility} = \frac{(\text{AA}_{\text{diet}} - \text{AA}_{\text{ileal}})}{\text{AA}_{\text{diet}}} \quad (9.6)
\]

These values are referred to as apparent since no differentiation is made within ileal
amino acid flow between endogenous ileal amino acid losses and non-digested
dietary amino acids.

Endogenous amino acid losses should be considered explicitly as they represent
a cost to the animal and may interfere with additivity of apparent ileal digestibility
values in mixes of feeds. The latter is a result of the non-linear effect of diet
amino acid level on apparent ileal amino acid digestibility (Figure 9.3). This non-
linear effect can be attributed largely to the basal endogenous ileal amino acid losses
that occur even when pigs are fed protein-free diets (Figure 9.4). These basal losses
contribute relatively more to total ileal amino acid flow at low diet amino acid levels,
and, importantly, have a relatively large negative impact on apparent ileal amino
acid digestibility at low diet amino acid levels.

The endogenous ileal amino acid losses reflect the proportion of endogenous
amino acids that are secreted into the digestive tract – as components of digestive
enzymes, mucus, sloughed-off epithelia cells and other secretions – and that are not
re-absorbed (Figure 9.5). The amount of endogenous protein that is secreted into the digestive tract may approach in quantity the amount of protein that is digested and, just like ingested protein, may be digested in the intestinal lumen and re-absorbed (Table 9.7). Therefore, ileal and faecal endogenous amino acid losses only represent a fraction of the endogenous proteins that are secreted into the digestive tract and considerable recycling of endogenous protein occurs in the gut. The latter is associated with a metabolic inefficiency, which represents energy and amino acid costs to the pig.

To define the true digestibility of the dietary amino acids only, unbiased by the inflow of endogenous amino acids, the two streams of undigested amino acids, dietary and endogenous, passing the end of the ileum must be separated. Given that the total ileal flow of undigested material comprises that from the diet ($AA_{ileal-from-diet}$) and that from the body secretions ($AA_{ileal-from-endogenous}$), then the ileal flow of non-digested dietary amino acids is calculated from total ileal flow and endogenous ileal losses ($AA_{ileal-from-endogenous}$):
Fig. 9.5 Absorption and secretion of crude protein (CP) in the digestive tract of pigs. In this scenario, the apparent faecal CP digestibility is 0.89 (that is, \( \frac{280 - 21}{280} \)); the apparent ileal CP digestibility is 0.80 (that is, \( \frac{280 - 56}{280} \)); the true ileal CP digestibility is 0.93 (that is, \( \frac{280 - 31}{280} \)). The efficiency of recycling endogenous CP secretions at the ileal level is 0.86 (that is, \( \frac{215}{250} \)). It should be noted that the apparent ileal digestible CP intake (280 - 56 = 224 g/day) is a better predictor of net absorption (474 - 250 = 224 g/day) than true ileal digestible CP intake (280 - 21 = 259 g/day). Endogenous CP secretion into the hind gut represents amino acid losses to the animal as CP absorbed from the hind gut does not contribute to the pig’s amino acid supply.

Table 9.7. Endogenous crude protein (N × 6.25) secretions into the digestive tract of a 40 kg pig consuming 1.7 kg of feed.

<table>
<thead>
<tr>
<th>Source</th>
<th>Amount</th>
<th>Percentage of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saliva and stomach</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>Pancreas</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>Bile</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>Small intestine</td>
<td>200</td>
<td>72</td>
</tr>
<tr>
<td>Large intestine</td>
<td>25</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>277</td>
<td>100</td>
</tr>
</tbody>
</table>
Now, by relating the ileal flow of non-digested dietary amino acids (\(AA_{\text{ileal-from-diet}}\)) to amino acids intake, the true ileal amino acid digestibility is derived:

\[
\text{True ileal AA digestibility} = \frac{AA_{\text{diet}} - AA_{\text{ileal-from-endogenous}}}{AA_{\text{diet}}} \quad (9.8)
\]

True digestibility is always higher than apparent digestibility. The proper characterisation of endogenous ileal amino acid losses represents a substantial scientific challenge. Traditionally these losses were quantified by feeding pigs protein-free diets or diets that contained 100% digestible protein. Alternatively, pigs were fed different diets with graded protein levels and by mathematical extrapolation the flow of (endogenous) amino acids at the distal ileum of pigs fed protein-free diets was estimated (Figure 9.4). Based on recent observations from studies in which isotope tracers or labelled proteins were used, it is now known that these conventional methods can lead to a substantial underestimation of actual endogenous ileal amino acid losses. When using the conventional methods, only basal endogenous gut amino acid losses are quantified (see Table 9.8), while additional endogenous gut amino acid losses that are induced by feeding protein-containing feedstuffs are not quantified and confounded with non-digested dietary amino acids. Total ileal endogenous amino acid losses can thus be broken down into two components: (1) basal ileal endogenous losses, which are largely a reflection of the animal and are generally expressed per dry matter feed intake, and (2) specific ileal endogenous losses, which are a reflection of diet characteristics such as protein type or type and level of fibre and anti-nutritional factors (Figure 9.4). Because of the difficulty of routinely measuring total ileal endogenous amino acid losses, actual estimates of true ileal amino acid digestibility of feedstuffs are not widely available. Until more data become available on true digestibility it is more appropriate to consider basal endogenous ileal amino acid losses only, in which case digestibility values should be referred to as standardised digestibility:

\[
\text{Standardised ileal AA digestibility} = \frac{[AA_{\text{diet}} - (AA_{\text{ileal}} - AA_{\text{ileal-from basal endogenous}})]}{AA_{\text{diet}}} \quad (9.9)
\]

Table 9.8. Estimated basal endogenous ileal losses for key essential amino acids.

<table>
<thead>
<tr>
<th>Basal ileal endogenous losses (g/kg dry matter intake)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lysine</td>
</tr>
<tr>
<td>Methionine</td>
</tr>
<tr>
<td>Cysteine</td>
</tr>
<tr>
<td>Threonine</td>
</tr>
<tr>
<td>Tryptophan</td>
</tr>
<tr>
<td>Isoleucine</td>
</tr>
<tr>
<td>Crude protein (N x 6.25)</td>
</tr>
</tbody>
</table>

where

$$AA_{\text{ileal}} - AA_{\text{ileal-from basal endogenous}} = AA_{\text{ileal-from diet}} + AA_{\text{ileal-from specific endogenous}} \quad (9.10)$$

Alternatively, standardised ileal amino acid digestibility may be calculated from apparent ileal amino acid digestibility and diet amino acid level:

$$\text{Standardised ileal AA digestibility} = \text{Apparent ileal AA digestibility}$$

$$+ \left( \frac{AA_{\text{ileal-from basal endogenous}}}{AA_{\text{diet}}} \right) \quad (9.11)$$

The substantive advantage of using standardised digestibility over apparent ileal digestibility values for the formulation of pig diets is that the standardised digestibility values are independent of diet protein level (Figures 9.3 and 9.4) and more likely to be additive in mixtures of feedstuffs.

Unfortunately, there is considerable variation between estimates of minimum endogenous ileal amino acid losses, and different estimates are used in various publications in which standardised ileal amino acid digestibility values are summarised. Some care should thus be taken when combining standardised ileal digestibility values from different studies. Moreover, when moving from apparent to standardised ileal amino acid digestibility for the formulation of pig diets, the basal endogenous amino acid losses should be reflected in dietary amino acid requirements or allowances. Increasing the apparent ileal digestible amino acid requirements or allowances with the basal endogenous ileal amino acid losses will accommodate this.

**Utilisation of absorbed amino acids – bio-availability**

It might be assumed that, once absorbed, amino acids are available for use by the pig for purposes of maintenance, growth or lactation. Level of ultimate use is, of course, modified by the level of requirement (excess over requirement not being used), and by the appropriate balance, one to the other, of amino acids absorbed in relation to the balance of amino acids needed for anabolic processes (amino acids supplied, but not in balance with others, not being used).

However, even after these predictable losses of absorbed amino acids are accounted for, ileal digestibility values still overestimate net nutritional worth. The rate of utilisation of balanced ileal digestible amino acids not provided surplus to requirement (the bio-availability) is seen to be less than completely efficient. It may be surmised that no biological process can possibly be 100% efficient. So a loss due to mechanical efficiency should be justifiably allocated. However, such efficiency loss (say 6%) can go no way to fully describing the difference between the potential utilisation of absorbed ileal digested and balanced amino acids (theoretically 100%) and the actuality. It appears that an appropriate value for the potential efficiency of transfer of absorbed balanced amino acids to tissue protein (v) may usually range from 0.60–0.80 for conventional high-quality feedstuffs. Such a value appears to be supported by achieved retentions of ileally digested amino acids from fish meal and soya bean. As has been shown by the work of Ted Batterham at Wollongbar in
New South Wales, some of this efficiency loss in the last step before tissue retention may still be influenced (in some unknown way) by the original feed source if these are of questionable quality, or perhaps by the nature of the circulating amino acid moiety. This latter may be associated with relative rates of absorption, the chemical construct in which the amino acid is absorbed, the presence of toxins, the binding of absorbed amino acids at gut level or beyond, or some other undiagnosed biochemical phenomenon (which may or may not be a function of feedstuff type and processing method).

Edinburgh workers showed that a minimum level of energy is required to maximise \( v \); its value rising from 0.5 to 0.8 with decreasing protein to energy ratio. It appeared that \( v \) was not maximised (at 0.8) until there was less than 14 g ileal digested protein per MJ ME (or more than 70 MJ ME/kg ileal digested protein). Suffice it to say that protein concentrations of greater than 14 g ileal digested protein per MJ ME would be unusual in a pig diet, so the influence of the energy:protein ratio upon \( v \) would not usually be of practical importance.

The present position is the view that it is amino acid cycling that accounts for the greater part of \( v \), the loss of efficiency between the absorption of a given quantity of balanced amino acids (when not supplied in excess of need) and tissue retention. Even though the material inefficiency of transfer of amino acids from blood to retained tissues might be small, if this inefficiency is repeatedly experienced due to repetitive breakdown and build-up of tissue amino acids (protein cycling), then a substantial inefficiency will be accumulated. Indeed recent mathematical modelling exercises at Edinburgh show that protein cycling can readily account for most, if not all of the ‘lost’ efficiency. The highest realistic values for \( v \) fall between 0.75 and 0.85.

The concept of \( v \) and its possible variability amongst feedstuffs, raises the importance of considering the ultimate utilisability of amino acids as the true measure of nutritional worth; availability adding to the co-efficient of ileal digestibility a further co-efficient for utilisation. Due to the importance of \( v \), together with the difficulty of its capture, in practice, the overall available amino acids may often be best measured by biological assay such as growth response studies. One such method is the slope ratio assay which uses graded levels of the test ingredient against graded levels of standard feed, or artificial amino acid (Figure 9.6). The relative responses (as N retention, growth, carcass gain, efficiency or whatever) are measured. Where the comparison is against an artificial amino acid, the ileal digestibility co-efficient and the \( v \) value for the artificial amino acid can be taken as units. The ratio of the slopes of the performances will give a co-efficient of the relative utilisation of the tested feed amino acid. Slope-ratio assays have various drawbacks. First, they are rather expensive, time-consuming and laborious assays. Second, inherent variability in animal performance and the method of statistical analysis can have substantial impacts on the interpretation of the generated data. Finally, observed responses may be confounded by nutrient balances in the experimental diets and may thus not provide a ‘true’ estimate of amino acid availability.

Unfortunately, and until recently, no quick, inexpensive and repeatable assay has been available to determine amino acid bio-availability in feedstuffs. For this reason,
(ileal) amino acid digestibility values are used widely in pig diet formulation. It is, however, important to recognise some of the limitations of using digestibility values in feed formulation and the inaccuracies of obtaining digestibility values. In particular in heat-treated feedstuffs, amino acids may form complexes with carbohydrates or other diet components that may be digested and absorbed in a form that renders amino acids present in these complexes unavailable for metabolism by the animal. The Wollongbar workers showed that heat treatment may have only little effect on ileal digestibility, but a very great effect on efficiency of subsequent use – the bioavailability. (This issue appears particularly relevant to lysine because of the highly reactive ε-NH₂ group present in lysine, but probably applies to other amino acids as well, such as threonine and methionine.) Chemistry-based assays have recently become available to allow for direct measurement of lysine bio-availability, based on (ileal) digestibility of chemically available or reactive lysine in heat-treated feedstuffs. These assays indicate that ileal digestibility may overestimate availability by as much as 16% in skim milk powder, and 20% in cottonseed meal and wheat shorts. These assays should be used more widely and the effect of heat processing on the availability of amino acids other than lysine should be explored further.

It is sufficiently evident that feed description requires some approach toward a definition of available amino acids, as given by the product of ileal digestibility (standardised or otherwise) together with v. The modelling approach appears to have addressed the basis for v, and the means toward putting together factorial estimates.

**Fig. 9.6** Slope-ratio assay to establish the bio-availability of a specific amino acid in a particular feedstuff. Feedstuff A represents a standard while feedstuff B represents a test feedstuff. The relative bio-availability of the amino acid in feedstuff B is represented by slope (b) divided by slope (a). It should be noted that bio-availability can be assessed accurately only when the response to graded levels of amino acid intake is linear.
However, the measurement of $v$ and/or the determination of overall availability by growth trial assay require continuing attention. Where feed ingredients such as high-quality animal products, cereals and high-quality vegetable proteins from oil extraction processes are readily available, these issues may seem matters of scientific rather than practical interest. However, where less conventional feedstuffs must be used, or a wider range of feedstuffs due to inconsistent product quality, or variable product availability, or when new feedstuffs require to be evaluated, the matter of the efficiency of utilisation of absorbed amino acids ($v$) is paramount.

**Guide values for protein and amino acid content of pig feedstuffs**

Guide values to the levels of crude protein, digestible protein, faecal and ileal digestible amino acids, and standardised ileal digestible amino acids, together with notes referring to likely final availabilities, are to be found in Appendix 1. These values may be used to assess the monetary value of feedstuffs and to formulate them correctly into diets. Book values for nutritional content are never as precise as those determined directly for the sample feedstuffs concerned. However, it is often neither cost-effective nor necessary always to determine nutritive values directly. Given a carefully constructed set of guide values, and a mechanism for monitoring performance response, formulation of diets on the strength of information such as in Appendix 1 can be quite adequate for most purposes. This comment particularly pertains where well-known and conventional ingredients are used.
Chapter 10

Value of Fats and Oils in Pig Diets

Introduction

The available energy in utilisable fats and oils is about 2.25 times that from utilisable carbohydrates (although there is a considerable range in values), they supply essential fatty acids, can have an influence on carcass quality and are useful in reducing dust and promoting palatability of compound diets.

The major fatty acids in feed fats are palmitic (C16:0), stearic (C18:0), oleic (C18:1) and alpha-linoleic (C18:2); but lauric (C12:0), myristic (C14:0), palmitoleic (C16:1), alpha-linolenic (C18:3), arachidonic (C20:4), eicosapentaenoic (C20:5), erucic (C22:1) and docosahexaenoic (C22:6) may also be found. The standard nomenclature for fatty acids used above is based on the number of carbon atoms in the chain followed by the number of double bonds. Thus alpha-linoleic acid (C18:2) has 18 carbon atoms and 2 double bonds.

Those fatty acids with no double bonds (for example C18:0) are termed saturated and have high melting points. One double bond (e.g. C18:1) gives a monounsaturated fatty acid, and when there are two or more double bonds (e.g. C18:2) the fatty acid is polyunsaturated (PUFA). The ratio of unsaturated to saturated fatty acids in fats and oils has important consequences for their dietary value and for the value, both textural and nutritional, of the pig meat that results.

The major sources of vegetable oil are as follows:

- Soya beans (20% oil) which contain about 10% C16:0 and 5% C18:0 (20% saturated); 30% C18:1 and 50% C18:2 (80% unsaturated).
- Palm (50% oil) from the mesocarp contains about 45% C16:0 and 5% C18:0 (50% saturated); 40% C18:1 and C10% 18:2 (50% unsaturated). Palm kernel oil is rich in C12:0 and C14:0.
- Sunflower seed (40% oil) rich in C18:2.
- Rape seed (35% oil) rich in C22:1 (erucic) or C18:1 (so-called zero varieties where erucic acid is almost absent). Erucic acid is toxic.
- Groundnut (45% oil) rich in C18:2.
- Coconut (65% oil) rich in C12:0.
- Cotton seed (20% oil) rich in C18:2 and C18:1. Cotton seed oil may contain cyclopropenoid fatty acids which may be toxic.

The major sources of animal fats are as follows:
• Cattle tallow which contains about 25% C16:0 and 20% C18:0 (50% saturated); 40% C18:1 and 5% C18:2 (50% unsaturated).
• Sheep fat rich in C18:1, C16:0 and C18:0.
• Pig lard rich in C18:1, C16:0 and C18:2.
• Fish oils rich in C18:1 and C16:0 but consisting predominantly of long chain polynsaturated fatty acids including C20:5 and C22:6. This makes them prone to rancidity and off-flavours, but the long chain fatty acids are essential and presumed to be beneficial to both pig and human health.

Industrial oils are available, but are of variable composition. A major waste source is recovered vegetable oil (RVO) available from the food processing industry as this may have up to 45% C16:0 and as little as 1% C18:2 RVO may be of poor quality. Another industrial oil is partially hydrogenated fish oil; this process is designed to improve the stability of fish oils which contain a high proportion of long chain PUFA (which oxidise readily). However, although more stable, this product is more saturated and hence of lower DE value (as explained below).

Table 10.1 shows the fatty acid compositions of some common feed fat sources.

In addition to chain length and degree of saturation, a further chemical characterisation of relevance to nutritional value of fats is the content of free fatty acids.
Acid oils, such as soya acid oil and palm acid oil, have high levels of free fatty acids (about 80%) and are available from industrial fat hydrolysis processes (e.g. refining of human grade oils). Often a blend containing soya acid oil or palm acid oil together with, for example, tallow and soya oil may readily contain 40–50% of free fatty acids. Acid oils now comprise a significant proportion of non-tallow feed grade fats available as feedstuffs. High levels of free fatty acids from varying sources can also adversely affect the palatability of diets.

High fat dietary ingredients for pigs are usually described (and often traded) as named commodities; examples are ‘yellow grease’, ‘grade 3 tallow’ and ‘choice white grease’ – there are many more. These names are of little use for nutritional valuation of these commodities. Fats and oils included in diets for pigs are often blends of a number of individual commodities. The chemical composition of dietary fats and oils described above has a pronounced influence on their dietary energy value.

Importantly, increasing unsaturation leads ultimately to higher digestible energy (DE) values, and elevated levels of free fatty acids lead to reduced DE content. Chain length is of significance, but, with the relatively limited differences among those fats and oils fed to pigs, is probably of minor importance.

Saturated fatty acids have a reduced potential for micelle formation (an essential phase in the absorption of the products of fat digestion), and are therefore absorbed less well than unsaturated fatty acids. The relationship between the degree of unsaturation (expressed as the ratio of unsaturated to saturated fatty acids, or U/S) is curvilinear, as demonstrated in Figure 10.1. The greatest increase is from 1 (approximate U/S of tallow) to 3 (achieved with a blend of around 30% tallow and 70% vegetable oil); thereafter the response approaches the horizontal. There is little difference between the energy value of mono- versus poly-unsaturated fatty acids;

![Fig. 10.1](image_url)  
**Fig. 10.1** Influence of the ratio of unsaturated (U) to saturated (S) fatty acids on the digestibility/digestible energy value of fats on oils.
it is for this reason that attempts to relate degree of unsaturation through iodine value to dietary energy value have not been successful (the iodine value of C18:2 is much higher than that of C18:1 but DE would be similar).

The second chemical characteristic influencing the dietary energy value of fats and oils is the content of free fatty acids (FFA). Despite the popular belief that the problems of reduced nutritional value only occur at relatively high levels of FFA, there is in fact a linear reduction with increasing FFA (see Figure 10.2).

The combined response to degree of saturation and FFA content has resulted in the generation of prediction equations to calculate DE value; these equations, derived from comprehensive studies at the University of Nottingham, UK, are presented in Table 10.2. These equations allow estimation of the DE of a fat or an oil, or a blend from the FFA level and the fatty acid profile. Two weights of pig are described as there is a modest improvement with age in fat digestibility. Young pigs, although using the dietary fat from milk efficiently (obviously), do not digest feed fats well, but unsaturated long chain fatty acids are more readily digested than saturated and/or medium chain fatty acids. It is not entirely clear why vegetable fats

![Fig. 10.2](image_url) Influence of free fatty acid content on the digestibility/digestible energy value of fats and oils.

<p>| Table 10.2. | Prediction equations relating the digestible energy (DE, as MJ/kg) to ratio of unsaturated to saturated fatty acids (U/S) and free fatty acid content (FFA, g/kg fat) of fats and oils. The function was found to account for 80% of the variance in younger pigs and 77% in older pigs. |</p>
<table>
<thead>
<tr>
<th>常量</th>
<th>每10-20公斤体重的猪</th>
<th>每35-85公斤体重的猪</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>36.90</td>
<td>37.89</td>
</tr>
<tr>
<td>B</td>
<td>-0.005</td>
<td>-0.005</td>
</tr>
<tr>
<td>C</td>
<td>-7.330</td>
<td>-8.200</td>
</tr>
<tr>
<td>D</td>
<td>-0.906</td>
<td>-0.515</td>
</tr>
</tbody>
</table>
are less well digested than sow milk fats, but this is evidently the case for newly weaned pigs that are not as effective at digesting fatty acids as older pigs. The relative inability of piglets to digest feed fat is probably because these fats are not emulsified whereas milk fat is.

It has been thought that the effects of degree of saturation cannot be considered in isolation of the phenomenon of synergism. Synergism occurs when the DE of a relatively saturated fat is assumed to be improved if blended with a more unsaturated oil. The physiological basis for this has been established when considering individual fatty acids. Thus unsaturated fatty acids help to increase the solubility (and absorbability) of non-polar saturated lipids, such as stearic acid, into the micellar phase; therefore the presence of linoleic acid will enhance the absorption of the more saturated fatty acids.

However, extending this principle to a consideration of fats and oils is not straightforward. Thus the established improvement in the DE with increasing unsaturation (higher U/S) is reliant on the greater utilisation of not only the increasingly important ‘U’ fraction but also the ‘S’ fraction (which, whilst declining in concentration, is still present). Therefore, ‘synergism’ between individual classes of fatty acid has already been included in the non-linear responses of DE to U/S. What ‘synergism’ is not is a numerical improvement in the DE of a blend of two sources over and above that which would be predicted from their individual DE values. Thus a 50:50 mixture of two sources with respective DE values of, for example, 36 and 30 MJ/kg would be 33 MJ/kg, not higher.

**Value of fats in pig diets**

It does not appear that levels of inclusion of fats up to 10% will significantly decrease the efficiency of digestion (or utilisation) in pigs, although opinion on this is hotly contested and some authorities suggest that DE value is likely to fall off at levels of above 7% inclusion of fat in the diet. Thus the effective DE value of fats may fall with level of inclusion, giving a quadratic rather than a linear change in DE value of diets with increasing levels of added fat. In all likelihood these differences are attributable to the considerable variation that exists between fats and oils from different backgrounds. Thus in comparison to the DE of the highly digestible unsaturated fats (where the response of DE is probably linear over a relatively wide range of inclusion), fats based on the less digestible and more saturated tallows and the less well used free fatty acids are the most likely to show the phenomenon of the DE value being reduced as level of dietary fat inclusion increases.

Progressive increments of usable fats to pig diets up to levels of 8%, and possibly more, may be assumed to give *pro rata* increments in energy concentration of the diet. Increasing the energy concentration of young piglet and growing pig diets appears to be associated with linear corresponding improvements in the growth rate of animals restricted by limited appetite. The economics of this growth depends upon the cost of the fat added, but not only will the faster growth improve efficiency
in modern strains of pigs, but also the reduction in days to slaughter increases
throughput, defrays fixed costs and allows lower stocking rates (with consequent
further improvements in growth rate). There is a proposition that pigs will ‘eat to
meet energy requirements’; that is they will voluntarily eat less of a diet rich in
energy. Whilst this is the case to some extent, the ‘compensatory’ effect is not perfect
(Chapter 13), so energy intake rises on energy-rich diets. The addition of fats to diets
of animals already given a restricted allowance is, of course, not logical (unless cost
per unit of available energy is less for fat than for carbohydrate) and, so long as
carbohydrate energy is cheaper than fat energy per MJ of net energy yielded, more
of a feed of a lower energy concentration is a better production tactic than the
same amount of a more concentrated diet.

Although feed fats are often competitive with cereal energy sources on the basis
of cost per unit of utilisable energy, there are other advantages that accrue from the
inclusion of fat into the diet.

In pigs, dietary fats can slow the rate of passage and improve the digestibility of
other feed components – especially carbohydrates – thus enhancing the assumed
DE of the carbohydrate fraction of the diet and attributing to the fat a remarkable
energy value. Because the presence of diet fat can improve the efficiency of use of
the assumed total diet DE, it is technically possible for the DE values for fats in pig
diets to be equal to or above the gross energy value.

At equal feed intake, a diet containing added fat will provide more energy; this
is particularly important where physical capacity limits appetite, as in young pigs
and lactating sows. In addition, diet fats can increase appetite (feed consumption)
in pigs through: (1) increasing palatability and (2) decreasing the need to dissipate
body heat (being efficiently absorbed and then efficiently converted from diet con-
stituent into adipose tissue, energy provided in the form of fat has the consequence
of a low heat burden in comparison to carbohydrate energy). This phenomenon is
particularly important in animals that can have appetite depressed due to a high
level of heat production, such as lactating sows and pigs kept in hot climates, where
the level of voluntary feed intake is seen to be unacceptably low on account of a
high environmental temperature.

The major limitation to the use of high levels of fat in pelleted diets is pellet
quality; thus fat-coated pellets (i.e. additional fat sprayed onto the surface of the
pellet) are of particular value both nutritionally and because of reduced dust in feed
mills. Not only does this reduce wastage and improve the environmental atmos-
phere, but also it will reduce respiratory disease and thereby improve growth rate
and feed conversion.

By virtue of the presence of one or more double bonds, fats are by nature unsta-
ble commodities, the more so the greater degree of unsaturation. Accordingly, the
risks of oxidation (oxidative rancidity is a chain reaction, so once started proceeds
ever faster) should be minimised with the addition of anti-oxidants as early as
possible in the processing of fats as oxidation is irreversible – once a fat is oxidised
it cannot be brought back to its original unoxidised state. Anti-oxidants will also
protect diets in which fats are contained (oxidising fats will reduce palatability,
damage the gut wall and reduce the potency of vitamins and amino acids). An example is butylated hydroxytoluene (BHT) which is used in fat-supplemented animal diets.

It is frequently, but erroneously, considered that vitamin E is an effective dietary anti-oxidant. Its major role is in fact as an in vivo anti-oxidant. If the fat source is high in polyunsaturates vitamin E may often be recommended for inclusion at the rate of 0.6 mg/g linoleic (18:2) acid to protect the animal from the consequences of oxidation of this fatty acid when it is present in cells.

In addition to saturation and high levels of free fatty acids, a common cause of lowered energy value (arising from reduced digestibility) is the presence in a fat blend of structures that would appear in the fat fraction following analysis but which are not available to the pig. Typical of these are oxidised and polymerised fats which are often associated with fats that have been heat-treated during processing and which can constitute well over 10% of the blend. A further fraction also normally regarded as of no nutritional value is the unsaponifiable (U; not to be confused with unsaturated) content. Whilst fat soluble vitamins are unsaponifiable, this fraction if found in a fat blend is usually regarded as a problem (it would, for example, include polythene). Added to this is moisture (M), which is a diluent and also acts as a pro-oxidant, and impurities (I; usually particulate matter), giving MIU as an overall fraction which in contracts of sale is conventionally kept to a maximum of 2%. It is difficult to quantify oxidised and polymerised fats (some of which may indeed appear in the MIU fraction) but ‘non-elutable matter’ (NEM) is often employed.

In addition to providing dietary energy, fats and, particularly, oils will contain essential fatty acids which, by definition, must be present in the diet. Fatty acid families are characterised by the position of the last double bond before the terminal methyl group. Thus alpha-linoleic acid (C18:2) has 6 carbon atoms after the last double bond and is referred to as an n-6 (or omega-6) fatty acid; alpha-linolenic acid (C18:3) has 3 carbon atoms after the last double bond and is referred to as an n-3 (or omega-3) fatty acid. The key point is that, although animals can insert double bonds (desaturate) at some positions into fatty acids (e.g. synthesising C18:1 oleic acid, an n-9 (or omega-9) fatty acid, from C18:0 stearic acid) they cannot insert them between the last double bond and terminal methyl group and, accordingly, cannot synthesise n-6 or n-3 fatty acid families. The latter are precursors of a number of key mediators of cell function (e.g. prostaglandins) which explains their essentiality. There is much debate on the actual requirements of these two families and indeed on the ideal ratio of n-6 to n-3. There is even some doubt that pigs can utilise efficiently the two initial family members (alpha-linoleic acid and alpha-linolenic acid) which raises the interesting possibility that higher order precursors (found widely and almost exclusively in fish oils) may need to be in the diet.

Fat additions to lactating sow diets can increase milk production. The use of high energy concentration diets for lactating sows whose total energy intake is limited by appetite is of some considerable value in helping to reduce the rate of body fat losses. As sow fatness (and, hence, condition score) makes an important contribu-
tion to reproductive efficiency, fat losses or low absolute levels of body fat are perceived as a problem in lactating sows, and enhancing diet energy concentration by the addition of fat is likely to be an effective nutritional tactic. Neonate pigs of less than 1 kg at birth are likely to have a greater mortality rate. Feeding of 200 g of fat per day in the last 2 weeks of pregnancy can improve post-natal survivability of pigs, new-born to sows that are thin.

Fat reduces the digestibility of fibre at low fibre levels. Dietary calcium and magnesium levels above 1% may significantly reduce the DE value (from 35 down to 30 MJ/kg) due to the formation of soaps, of which those from saturated fatty acids are the least digestible.

As dietary fat also increases palatability and intake, addition of fat to the diet can result in excess energy intake. This will cause an enhanced predisposition by the animal to lay down extra carcass fat. The absolute rate of adipose tissue growth will, however, only increase if there is excess total energy supply over the needs for maintenance, protein growth and minimum fat growth. Thus there will be a tendency for high nutrient concentration, enhanced with added fats, to produce increased levels of carcass fat only if (1) the amount of energy relative to protein in the diet is imbalanced in favour of excess energy, or (2) the total energy intake (balanced or otherwise) is excessive due to an increase in energy ingestion because the animal’s appetite has increased as a result of reduced heat challenge or increased diet palatability (or any of the other related causes of diets with added fat giving enhanced intake).

Incorporation of diet fats into animal carcass fat

The adipose tissue of pigs reflects the diet fatty acid composition as fatty acids are absorbed largely unchanged and frequently deposited directly into carcass fat. Accordingly, the use of unsaturated vegetable oils in pig diets will result in enhanced levels of linoleic acid (the major polyunsaturated fatty acid in oils, with the exception of rapeseed oil which is composed mainly of oleic acid) in pig fat. In addition, it is because long chain unsaturated fatty acids can be incorporated directly, or with little change, into animal adipose tissue that they have such high net energy values.

Body fat synthesis from dietary fat is about 90% efficient, whereas body fat synthesis from carbohydrate is only about 70% efficient. As a result, the ratio of net energy to digestible energy (NE:DE) is about 0.85 for fats and oils and 0.75 for carbohydrates (this is one of the reasons why net energy systems give a better estimation of the value of dietary fats than digestible energy systems).

A high dietary level of linoleic acid will produce high linoleic adipose tissue in pigs; levels can increase from a normal 10–15% linoleic acid in adipose tissue up to 30–40% linoleic acid with a consequent dramatic softening of the carcass fat. This does not happen in ruminants, as linoleic acid is hydrogenated in the rumen. There is a time lag between a dietary change in the fatty acid profile and the consequent
effect on adipose tissue. Data from the University of Nottingham suggest that the majority of this change will take place in around 5 weeks (which equates to around 30kg live weight gain), as presented in Figure 10.3.

Linoleic acid is, as has been described above, essential for pigs and a minimum of up to 1.5% of the diet is recommended for young pigs, falling to 0.75% for older animals. It is therefore prudent to reduce dietary levels of linoleic acid to account for this reduction in essential fatty acid requirement over the finishing period at a time when, in any event, the animal is better able to digest more saturated fats.

The addition of fats into diets will not, on that account alone, make pigs fat. Pigs have the propensity to become fat if appetite is enhanced to the extent that energy is consumed in excess, and diet fats will usually enhance appetite. Similarly, excess energy may be consumed if the energy density of diets is increased, and diet fat additions will increase energy density. Pigs will grow fat if there is insufficient protein in the diet, and if incorrectly valued, fat additions may upset the intended energy:protein ratio. Diet fat will only result in pigs becoming unwontedly fat if the nutritional value of their diet is wrongly estimated.

### Compounding diets that include fats and oils

- Pure oils can be of reasonably certain origin, acid oils are more variable, while tallow is extremely variable in quality – from high-grade tallow, which are excellent, to fully hydrogenated low-grade materials, which can be effectively useless in pig diets. Recovered vegetable oil and various other sources of oil may be of low value. The energy value of a fat blend can therefore range from almost zero to even above 40 MJ effective DE/kg, depending entirely upon the sources chosen and the integrity of the blender. It is not unreasonable to suggest that,
at an assumed given value of 32 MJ DE/kg, available commercial materials may show effective values ranging between 24 MJ DE/kg for some commercial blends and 40 MJ ED/kg for high-grade pure oils. Some commercial blends may have effective ME values little greater than 25 MJ DE/kg; particularly if used at high levels of inclusion.

- Ideally, the use of fats and their dietary energy value should be based on their chemical composition as their DE and NE values can be predicted comparatively accurately from such an analysis; trade names for diet ingredient commodities are usually ineffective descriptors of nutritional value.

- Some fat materials are precluded from use in diets because of concerns over their origin. For example, in the UK tallow is disallowed following the imposition of regulations relating to BSE, and recovered vegetable oils within the European Union.

- High quality fats and oils may be of considerable benefit to a diet above the given ME value. Thus assumed multipliers for chemically analysed oil, often around 30–35 MJ DE/kg, may underestimate as well as overestimate the effective value of fat. Such added benefits include improved digestibility of other diet components, improved pellet quality and increased feed intake. Even with a favourable tallow price in comparison to vegetable oils, it is always worthwhile blending some 20% vegetable oil into the tallow (and perhaps some 25% of palm oil) in order to improve overall digestibility.

- Young pigs digest fat rather poorly, but soon improve. Pigs always do better on vegetable oils than on tallow, but, apart from very high quality starter diets, high quality tallow can be used in the blend at levels increasing with age. In countries that do not allow the use of tallow, palm oil is an effective substitute (although marginally more saturated than tallow and hence of lower DE).

- Pigs can benefit, in the right conditions, from up to 8–10% fat in the diet. This can be added into the mixer, in the die, used to coat the pellets after leaving the cuber, added through the medium of full-fat soya or any combination of these.

- Given some improvements in the general level of fat quality entering the trade and discrimination against the use of low-grade materials, there is every reason to suppose that, if the price is competitive with other energy sources, the amounts of fat used in animal diets will increase. Recently many benefits of dietary fat, in addition to the energy value, have been identified. Care must be taken, however, to balance the extra energy from fat with adequate high quality protein, or the resultant imbalance will cause excess energy supply and fat carcasses.

- Specifications for the various fat blends required by feed manufacturers are best obtained from the feed manufacturers themselves. Broadly, the manufacturer may use a general purpose blend for all species, or choose to use a special blend for pigs. Three blends allows for the possibility of two types for the pigs (a higher tallow – where permitted – for the older animals). Sometimes, a general purpose mix of about 75% tallow and 25% soya oil can be used together with full-fat soya for pigs to redress the shortage of unsaturated fatty acids.
Tallow has a ratio of saturated:unsaturated fatty acids of about 1:1. Highly unsaturated vegetable oils such as that from rapeseed have an unsaturated:saturated fatty acid ratio of about 12:1. The digestibility of fats, and thus their DE value, increases dramatically with the level of unsaturation from an unsaturated:saturated ratio of 1:1 to a ratio of 2.5:3.0. Thereafter response is minimal.

There is a linear reduction in DE with increasing levels of free fatty acids. Work at the University of Nottingham has confirmed that soya bean acid oil and tallow acid oil have DE values some 5 MJ/kg fat lower than unhydrolysed soya bean oil or tallow.

Sources of fats and oils for pigs are usually blends of tallow, the vegetable oils from soya bean, maize, sunflower, rape and palm, together with acid oils (free fatty acids) and by-product and recovered oils. The best quality blend is likely to be a soya bean oil and high quality tallow mix. A specification appropriate for young growing pigs may set a maximum of 30% free fatty acids, a maximum of 30% for saturated fatty acids, a minimum of 20% linoleic (C18:2) and 4% linolenic (C18:3), with about 40% oleic (C18:1) acids, (the balance containing, amongst others, around 5–10% of stearic and 15–20% palmitic), and a ‘tallow:soya’ ratio of 50:50. The ratio of unsaturated to saturated fatty acids in soya oil is around 7:1, while the ratio of that in tallow is around 1:1. The ratio of unsaturated to saturated fatty acids in a 50:50 mixture will be around 2:1. For older growing pigs the free fatty acid maximum may be raised to 40%, the maximum for saturated fatty acids to 40% and the ‘tallow:soya’ ratio to about 60:40. Often, these standards for pigs will move toward more tallow in the blend if the price differential between tallow and soya oil widens, or a danger of soft carcass fat is perceived, and a general purpose mix for pigs of 70:30 would not be unusual.

Employing the prediction equations presented in Table 10.2 will remove much of the qualitative analyses that accompany recommendations on ratios of various blend components, as the DE value of any blend can now be predicted.
Chapter 11

Energy and Protein Requirements for Maintenance, Growth and Reproduction

Introduction

Nutrient requirements are met by nutrients in feedstuffs. Requirement must therefore be expressed in terms wholly compatible, and open to 1:1 linkage, with descriptors for feedstuffs.

Many thousands of experiments have been completed measuring the response of pigs to graded levels of nutrient input. Figure 11.1 shows the results of one such experiment to identify the requirement for an amino acid. The requirement is taken to be around the point of the diminishment of response; in the region of 5.0 g per day.

The problems of this approach are many, including:

1. a different requirement for each different criterion of assessment (feed efficiency, carcass quality, economic margin and so on);
2. a complex multi-graded experiment being needed for each nutrient, each environment, each moment in time and place, each type of pig (weight, sex, genotype) and for all the interactions between nutrients, pig types, times, environments and places;
3. the limiting factor often not being the achievement of the requirement, but rather a shortage of another nutrient (Figure 11.2).

The more appropriate approach, with general applicability, is to identify requirement in terms of constants and efficiency factors for each of the specific products.
required. The nutrient supply necessary to provide for any given level of product or function can then be calculated. For present purposes these are taken to be some combination of protein retention, lipid retention, the fetal load, lactation, cold thermogenesis and maintenance.

Chapter 8, in describing the energy evaluation of feedstuffs, discussed three related frameworks for energy: digestible energy (DE), metabolisable energy (ME) and net energy (NE). As concluded there, the highest system in the hierarchy (DE), was the most simple to employ, and the most widely used. However, advances in nutritional knowledge have now allowed development on NE systems, which are more accurate. Both approaches will be covered here, with the general principles being dealt with in the context of the DE system. From the animal requirement point of view the DE system is interpreted through the requirement of energy that is in metabolisable form (ME), that is DE minus the small amount of energy lost in the urine and gaseous escapes (which, being lost, is not metabolisable).

**Energy using a DE/ME system**

The ME of carbohydrate and lipid may be taken as 1.0 of (the same as) the DE. This is not the case for fibre, where small gaseous losses (and reduced efficiencies of utilisation) occur when volatile fatty acids are yielded from microbial fermentation of fibre energy in the large intestine (the effective ME of digested fibre may be taken as around 0.5 of the DE value). However, fibre levels are relatively low in most conventional pig diets (but not all).

The major controller on the relationship between DE and ME is the amount of energy yielded from protein. In order to obtain energy from protein, the protein must first be deaminated, which itself costs energy. While protein contains some 23.6 MJ/kg, ME yield from digested protein which has been deaminated is about 11.5 MJ/kg (deamination costing about 5 MJ/kg protein and 7 MJ/kg protein being voided in the urine in association with nitrogen moieties). ME is usually about 0.96
of DE, varying from 0.94 to 0.97; the lower value applying when there is a high rate of deamination and urinary N excretion due to either over-supply of diet protein or the supply of poorly balanced dietary amino acids.

**Maintenance, activity, cold thermogenesis and disease**

Energy for maintenance \( (E_m, \text{MJ ME/day}) \) is usually expressed as a function of \( W^{0.75} \) because larger animals have a smaller maintenance requirement in relation to body weight.

\[
E_m = 0.44 \, W^{0.75} \tag{11.1}
\]

remains the best-used of all estimates of the energy requirement for maintenance. The three-quarter exponent has no special biological meaning, and the United Kingdom Agricultural and Food Research Council Working Party [ARC (1981) *Nutrient Requirements of Pigs*. CAB, Farnham Royal, UK] found \( 0.72 \, W^{0.63} \) to give the line of best fit for growing pigs. There is a suspicion that the exponent for live weight is helpful merely in adjusting for the pig carrying more fat as it grows heavier; and, because much of the energy expenditure for maintenance is concerned with the turnover of body protein tissues, there may be some logic also in using a function based on protein mass \( (P_t) \), such as:

**Growing pigs**: \( E_m = 1.75 \, P_t^{0.75} \) \tag{11.2}

the exponent now accounting for larger pigs turning over their protein mass at a slower rate than smaller pigs. Equation 11.2 is suitable for growing pigs. For breeding sows the exponent in Equation 11.2 is also satisfactory at higher values for \( P_t \), and:

**Breeding sows**: \( E_m = 0.44 \, W^{0.75} = 1.75 \, P_t^{0.75} \) \tag{11.3}

The energy needed by the pig to ambulate and carry out normal pen behaviours may legitimately be seen as part of maintenance costs. It has been suggested that ‘activity’ is equivalent to about one tenth of the maintenance costs. To account for activity therefore, 10% can be added by multiplying the maintenance requirement by 1.1. More active pigs (such as those outdoors) justify a higher multiplier.

Ambient temperature \( (T) \) below the critical or comfort temperature \( (T_c) \) induces cold thermogenesis. The energy cost of cold thermogenesis \( (E_{th1}) \) may be estimated as \( 0.018 \, \text{MJ ME} \) for each kilogram of metabolic body weight \( (W^{0.75}) \) for each degree \( (C) \) of cold \( (T_c - T) \) for pigs housed singly, and 0.012 MJ for pigs housed in groups:

\[
E_{th1} = 0.012 \, W^{0.75} (T_c - T) \tag{11.4}
\]

\( T_c \) is itself modified by the level of metabolic activity of the animal. Higher food intakes and higher rates of growth or milk production will give a lower value for effective critical temperature and therefore a greater resistance to cold by creating an elevated rate of heat output. Critical temperature \( (C) \) may be estimated as:

\[
T_c = 27 - 0.6 \, H \tag{11.5}
\]
where $H$ is total body heat output, which is the sum of all the bodily work functions for maintenance, growth of protein and fatty tissues, lactation, fetal growth and protein deamination.

The quality of the environment modifies the effective environmental temperature, thus:

$$T = T(Ve)(Vl)$$

where $Ve$ is an estimate of the modifying effect of the rate of air movement and insulation, and $Vl$ is an estimate of the modifying effect of floor type.

Disease costs energy. Determining the energy cost of maintenance would, by virtue of its being measured in living animals, include an estimate of some of the requirement for combating disease challenge. There might be an expectation therefore that entirely healthy pigs have a lower maintenance requirement; and conversely that pigs in commercial environments have a higher maintenance requirement. How much higher is presently a matter of conjecture, but of little importance. The influence of disease upon energy requirement is complex. Gross effects will include reduction in feed intake, increase in metabolic rate and (in the case of enteric infection) a reduction in the digestive and absorptive function. It may be reasonable to separate the costs of maintaining immuno-competence (sub-clinical disease costs) from the costs of dealing with frank disease (clinical disease costs), and indeed to cost as realistic only the former. Model-fitting exercises (and indeed practical observations) of commercial herds would suggest that the presence of sub-clinical diseases may increase the maintenance requirement by at least a third.

### Table 11.1

Scores for $Ve$ and $Vl$ for use in calculating the effective environmental temperature ($T$) in the equation $T = T(Ve)(Vl)$.

<table>
<thead>
<tr>
<th>Rate of air movement and degree of insulation</th>
<th>$Ve$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulated, not draughty</td>
<td>1.0</td>
</tr>
<tr>
<td>Not insulated, not draughty</td>
<td>0.9</td>
</tr>
<tr>
<td>Insulated, slightly draughty</td>
<td>0.8</td>
</tr>
<tr>
<td>Insulated, draughty</td>
<td>0.7</td>
</tr>
<tr>
<td>Not insulated, draughty</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Floor type in lying area</th>
<th>$Vl$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep straw bed</td>
<td>1.4</td>
</tr>
<tr>
<td>Shallow straw bed</td>
<td>1.2</td>
</tr>
<tr>
<td>No bedding on insulated floor</td>
<td>1.0</td>
</tr>
<tr>
<td>Slatted floor with no draughts</td>
<td>1.0</td>
</tr>
<tr>
<td>No bedding on uninsulated floor</td>
<td>0.9</td>
</tr>
<tr>
<td>Slatted floor with draughts under</td>
<td>0.8</td>
</tr>
<tr>
<td>No bedding on wet, uninsulated floor</td>
<td>0.7</td>
</tr>
</tbody>
</table>

$Ve$ is an estimate of the modifying effect of the rate of air movement and insulation, and $Vl$ is an estimate of the modifying effect of floor type.
Production

One kilogram of retained protein (Pr) contains 23.6 MJ. On average, some 31 MJ/kg of Pr is required in addition to cover for the energetic work of protein tissue turnover associated with protein anabolism, and the energetic cost of tissue synthesis itself. This gives a total energy cost for protein retention ($E_{Pr}$) of 55 MJ/kg:

$$E_{Pr} = 23.6 \text{ Pr} + 31 \text{ Pr}$$  \hspace{1cm} (11.7)

the efficiency of protein retention ($k_{Pr}$) being 0.44.

This, however, is an inadequate descriptor. Although the cost of tissue synthesis – the joining together of the amino acids into body protein – is probably independent both of the rate of synthesis and the size of the pig and is around 5 MJ/kg of protein synthesised (estimates range from 4–8), the energetic cost of tissue turnover is likely to be positively related to both the rate of turnover and the mass of protein tissue (Pt). In younger pigs of about 20 kg W, the ratio of new protein retained to total protein turned over is about 1:5, while for older pigs at 100 kg W the ratio is about 1:8. The major part of the energy expenditure for protein synthesis may therefore be variable rather than fixed, and positively related to pig size. Where $P_x$ is the total mass of protein turned over in a day (including new protein deposited):

$$E_{Pt} = 5 \text{ Pt} + 23.6 \text{ Pr}$$  \hspace{1cm} (11.8)

The definitive estimation for the daily rate of body protein turnover, and the factors affecting that rate, are not yet well elucidated. It may, however, be assumed that there is a minimal value, probably in the region of 5% of the total body protein mass (Pt):

$$P_{x_{min}} = 0.05 \text{ Pt}$$  \hspace{1cm} (11.9)

It may further be assumed that turnover is some function of the degree of maturity, and the following has been estimated:

$$P_x = P_{r}/(0.23[P_{t_{max}} - \text{ Pt}]/P_{t_{max}})$$  \hspace{1cm} (11.10)

where $P_{t_{max}}$ is the mature total protein mass. It remains difficult to quantify the possibility that $P_x$ is also related in some proportional way to $P_r$, such that higher daily rates of protein retention may be associated with higher rates of daily protein turnover.

Values require to be assigned to Pt and $P_{t_{max}}$. Pt is accumulated as the pig grows and is therefore self-generated; usually it approximates to 0.16 W. $P_{t_{max}}$ is strongly influenced by pig type and may vary between 25 and 50 kg, but for modern genotypes is now usually accepted to be some 40–50 kg. As the daily rate of protein growth is strongly related to mature size, it may be possible to calculate $P_{t_{max}}$ from knowledge of the maximum rate of protein deposition ($P_{r_{max}}$) associated with any particular sex or genotype (the Gompertz growth coefficient, B, as described in Chapter 3):

$$P_{t_{max}} = e(P_{r_{max}})/B$$  \hspace{1cm} (11.11)
As at least some of the above remains conjectural and not well quantified, it may be forgivable to settle for a single fixed value for $k_{Pr}$ of 0.44. However, many nutritionists believe $k_{Pr}$ to have higher values of up to 0.54 for younger pigs, and to have lower values down to 0.35 for heavier pigs of 100 kg or more.

For sows, the calculation of $E_{Pr}$, with the involvement of estimates of turnover, has the unfortunate consequence that as maturity is approached the cost of the small remaining increments of $Pr$ approaches infinity – which is unacceptable – and a fixed value for $k_{Pr}$ of, say, 0.44 has much to commend it.

One kilogram of retained lipid ($Lr$) will contain 39.3 MJ. Most of the work energy associated with lipid retention is to do with the creation and linking together of appropriate fatty acids, and there is little energy cost of lipid turnover. Only some 14 MJ/kg $Lr$ is therefore suggested to be required to cover for the energetic work of fatty tissue turnover and tissue synthesis, giving a total energy cost for lipid retention of 53 MJ/kg:

$$E_{Lr} = 39.3 \times Lr + 14 \times Lr$$  \hspace{1cm}(11.12)$$

the efficiency of lipid retention ($k_{Lr}$) being 0.74. In contrast to the situation for protein synthesis, this is likely to be an entirely adequate descriptor because turnover of fatty tissue is much slower and less important. In the event of a significant proportion of the substrate for lipid synthesis being dietary lipid, $k_{Lr}$ may be greater than 0.75; the efficiency of direct transfer being high at up to 0.90.

**Reproduction**

Pregnancy involves the progressive development of the fetal load, the placenta and fetal membranes, fetal fluids, the uterus and the initial development of the mammary glands. The final total gravid uterus at term weighs around 25 kg and contains almost 3 kg of protein and 85 MJ of energy. The rate of energy deposition in the uterus ($E_u$) is slight in early pregnancy but rises exponentially. French and UK workers at Shinfield [Noblet, J., Close, W.H., Heavens, R.P. and Brown, D. (1985) *British Journal of Nutrition*, 53, 251–265] determined:

$$E_u (\text{MJ/day}) = 0.107 e^{0.027t}$$  \hspace{1cm}(11.13)$$

where $t$ is the day of gestation. The efficiency of use of ME for energy deposition in the uterus ($k_u$) is probably around 0.5. The energy cost of deposition in the gravid uterus therefore appears to be for days 20, 80 and 110 of pregnancy, 0.4, 1.9 and 4.2 MJ ME respectively (if $t = 110$, then $E_u/0.5 = 4.2$).

The rate of energy deposition in mammary tissue ($E_{mam}$) has been handled similarly to $E_u$ by the French/UK team:

$$E_{mam} (\text{MJ/day}) = 0.115 e^{0.016t}$$  \hspace{1cm}(11.14)$$

Efficiency of deposition ($k_{mam}$) is probably similar to $k_u$ at 0.5. Thus on days 80 and 110 of pregnancy some 0.8 and 1.3 MJ ME respectively is required.
Lactation level is highly dependent upon litter size. Because the energy cost of sucking piglet live weight gain is round about 22 MJ ME/kg and the energy value of milk is 5.4 MJ ME/kg (being 55 g protein, 50 g lactose and 80 g fat/kg), milk yield may be estimated as:

\[
\text{Milk yield} = \text{Daily piglet gains} \times \text{number of piglets} \times 4
\]

Individual sucking pigs may gain 200–400 g daily depending upon their age and size.

The efficiency of use of ME derived from dietary sources for milk production \( (k_i) \) may be taken as 0.70. The energy requirement for the formation of 1 kg of milk, inclusive of the energy retained in milk, is therefore 7.7 MJ ME/kg. During lactation, sows will lose significant quantities of lipid from the maternal body, and this is used to support milk synthesis – especially milk fat synthesis – with a high efficiency of 0.85 or more. One half kilogram of fatty tissue lost would therefore contribute 16.7 MJ \((39.3 \times 0.5 \times 0.85)\), which at 5.4 MJ ME/kg milk is enough to satisfy the requirements for 3.1 kg of milk (the same 3.1 kg of milk would require 23.9 MJ from dietary sources; in terms of diet equivalent, therefore, 1 kg of body lipid is worth 48 dietary MJ).

In the event of body protein being catabolised for purposes of providing substrate for milk lactose or milk fat (rather than milk protein), the efficiency of conversion will be much lower at 0.5.

**Protein**

Diet proteins are digested and absorbed as amino acids. Ileal digestibility values are an appropriate guide to the likely rate of appearance of amino acid in the body, although the efficiency factor \( v \) (Chapter 9), the proportion of absorbed amino acids available for metabolism, brings about a writing-down of the ileal digestible amino acids in order to achieve a true estimate of available amino acids.

The proteinaceous content of feedstuffs comprises amino acids and non-protein nitrogen. Of the 22 commonly found amino acids, 9 are essential to the pig. These cannot be manufactured in the body and must therefore be provided in the diet. Some non-essential amino acids can be synthesised from non-protein nitrogen, and the non-essential amino acids are interconvertible. Protein requirement is therefore usually expressed in terms of (1) the total protein supply as crude protein (CP) or digestible crude protein (DCP), and (2) the essential amino acids that must be supplied to the pig in the diet. Some amino acids are ‘semi-essential’. Although arginine can be synthesised in the body, the rate of synthesis is too slow for the rapidly growing young pig; and about half of the total requirement is recommended for dietary inclusion. Cysteine and tyrosine are also semi-essential, because they can support the essential methionine and phenylalanine in the event of a shortage of the latter.

Both these fractions (total protein and essential amino acids) must be supplied adequately for the pig to have an effective protein economy. It is taken for granted
that if the essential amino acid provision is adequate, then so also will be the non-essential balance. This will be true for pigs fed conventional feedstuffs, but the possibility of purchasing pure amino acids, and the fashion of presenting diet protein content in terms of the single amino acid lysine, may mislead. It is possible – but unlikely – for the key amino acids lysine, threonine, methionine and tryptophan to be supplied industrially from artificial sources well up to the level of dietary requirement, but for the pig to have a frank under-supply of digestible crude protein.

Protein is required in the body: (1) to replace losses consequent upon body protein tissue turnover which is highly active but not perfectly efficient, (2) for the manufacture of body enzymes, replacement of intestinal epithelial cells and synthesis of various gut secretions, and (3) for deposition and retention in lean tissue growth, the fetal load and milk.

**The utilisation of digested protein: ideal protein**

The amount of diet protein that is available for metabolism is dependent upon the level of essential amino acid supply. Special interest is often centred on those amino acids required at high levels by pigs but which are comparatively lower in feedstuffs: lysine, histidine, threonine, methionine and tryptophan.

Because the body does not use the amino acids supplied to it as individual entities, but rather for purposes of synthesising proteins from mixtures of essential amino acids and non-essential amino acids, the balance of the essential amino acids is crucial to optimum protein utilisation. Protein metabolism requires a supply of ‘ideal protein’; that is, essential amino acids balanced correctly for the various purposes of maintenance and production. Amino acids supplied outwith the necessary balance cannot be used for protein synthesis and must therefore be deaminated.

The value of a diet protein depends upon the relationship between the balance of essential amino acids required to make up ideal protein and the balance of amino acids supplied from the diet. This is not to suggest that pig diets should be purposely compounded in order to supply protein exactly in its ideal form – that would not only be extremely expensive but also waste the biological potential of the pig to turn lower quality cereal proteins into higher quality pig meat protein. The proposition, however, does allow knowledge of the proportion of the total diet protein that will be used by the pig for productive purposes. This latter is necessary both for the effective provision of requirement and for the proper economic evaluation of the worth of pig feedstuffs and mixed diets.

The ideal protein content of a diet is not the sum of the contributions of ideal protein from the ingredients. This is because the amino acids in the various feedstuffs can be complementary. A judicious mixture of feedstuffs, each lacking in a different amino acid, can produce a diet of a quality far in excess of its individual components. In short, the content of ideal protein in a mixed diet is not the weighted mean of the ideal protein contents of the ingredients.

The 50/50 combination of one foodstuff of which the protein is only 0.5 ideal because of shortage of lysine, with another that is only 0.4 ideal because of a short-
age of threonine is not a diet of which the protein is 0.45 ideal but one that is 0.6 ideal; because the essential amino acid falling short in the first foodstuff is complemented by excesses in the second (Figure 11.3).

Calculation of protein value requires a strict definition of the essential amino acid balance in ideal protein for pigs. Much painstaking work has gone into the determination of amino acid requirements for pigs. The spectrum of amino acids in ideal protein is largely that pertaining in the product for which the amino acids are required; namely, pig meat protein, pig milk or maintenance. If there are relatively small differences in the efficiency of utilisation \((v)\) of individual absorbed amino acids, then ideal protein should look rather like pig meat protein or sow milk protein; there being similarity between the two as shown in Table 11.2. Perhaps, because there is some inefficiency in collecting up sulphur amino acids during protein turnover, methionine + cysteine levels in ideal protein might be a little higher than in pig tissue. The essential amino acid composition of ideal protein is suggested in Table 11.3. The total of all the essential amino acids in ideal protein seems to be just less than half the total protein; the other half represents the non-essential amino acids.

Having provided the criterion for ideal protein, the amino acid spectrum of the protein in a mixed diet can now be compared with it and the value of the diet \((V)\) derived (Table 11.4). The effective value of the protein in the diet is that

![Fig. 11.3](image-url)
proportion of the dietary protein judged utilisable on the strength of the most limiting amino acid. In the case shown, lysine is the most limiting, and the maximum efficiency of use of the diet protein (V) for growing pigs is 0.64 or 64%; 0.64 of the ileally digested and subsequently utilisable protein will be available (although not necessarily all used) for maintenance and for protein tissue synthesis, while 0.36 will be deaminated and excreted via the urine. If there is over-supply, the rate of

### Table 11.2. Amino acid composition of pig meat protein and sow milk protein (g/kg).

<table>
<thead>
<tr>
<th>Amino acid</th>
<th>Tissue protein</th>
<th>Milk protein</th>
</tr>
</thead>
<tbody>
<tr>
<td>Histidine</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Leucine</td>
<td>75</td>
<td>85</td>
</tr>
<tr>
<td>Lysine</td>
<td>70</td>
<td>75</td>
</tr>
<tr>
<td>Methionine + cysteine</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Phenylalanine + tyrosine</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>Threonine</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Tryptophan</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Valine</td>
<td>50</td>
<td>55</td>
</tr>
<tr>
<td>Other, non-essential¹</td>
<td>500</td>
<td></td>
</tr>
</tbody>
</table>

¹ Cysteine, tyrosine and arginine are semi-essential; non-essential are glutamic acid, proline, serine, glycine, aspartic acid and alanine.

### Table 11.3. Ideal protein for growing pigs and pregnant and lactating sows. The required balance of amino acids is the balance of the utilisable ileal digested amino acids. Pregnant sows may require proportionately a little more methionine + cysteine, threonine and isoleucine, while lactating sows may require proportionately a little leucine, histidine and valine.

<table>
<thead>
<tr>
<th>Amino acid</th>
<th>(g/kg ideal protein)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Histidine</td>
<td>25</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>40</td>
</tr>
<tr>
<td>Leucine</td>
<td>75</td>
</tr>
<tr>
<td>Lysine</td>
<td>70</td>
</tr>
<tr>
<td>Methionine + cysteine</td>
<td>40²</td>
</tr>
<tr>
<td>Phenylalanine + tyrosine</td>
<td>75¹</td>
</tr>
<tr>
<td>Threonine</td>
<td>45²</td>
</tr>
<tr>
<td>Tryptophan</td>
<td>15²</td>
</tr>
<tr>
<td>Valine</td>
<td>50</td>
</tr>
<tr>
<td>Total essential amino acids</td>
<td>435</td>
</tr>
<tr>
<td>Total non-essential amino acids</td>
<td>565</td>
</tr>
</tbody>
</table>

¹ At least half as the first-named.
² As the requirements of methionine + cysteine, threonine and tryptophan are higher for maintenance than for tissue growth, these amino acids should be increased by some 10% in relation to the others when a higher proportion of the diet protein is being used for maintenance; as is the case for growing animals above 100 kg and for breeding sows and boars.
deamination will be proportionately higher. There is possibly further reason to believe that, in the case of some amino acids, over-supply may have a negative influence upon protein value.

The addition of artificial lysine to the diet shown in Table 11.4 could raise the lysine concentration in the protein to, say, 55 g/kg, in which event threonine and methionine + cysteine would become the limiting amino acids and the protein value (V) would become 0.75. However, there may be some doubt as to the efficacy of large additions of synthetic lysine to boost protein value. There is a view that the efficiency of its use may be lower than natural lysine if the total artificial lysine contributes more than about 2.0 g/kg of total food lysine. However, recent work from Eire appears to suggest that up to 4 kg lysine, 1 kg threonine and 0.5 kg methionine per tonne of food may be added efficaciously in the form of artificial amino acids to diets limiting in these amino acids from natural sources. In some circumstances nutritionists may force in an extra 1 kg of artificial lysine per tonne of feed where dubious or unusual feed ingredients are used. (Artificial amino acids may be assumed to be 100% digestible. L-lysine HCl contains 780 g lysine/kg, L-threonine contains 980 g threonine/kg, DL-methionine contains 980 g methionine/kg and DL-tryptophan contains 800 g tryptophan/kg.)

The proportion of ideal protein in cereal protein is usually about 0.45. For pig diets, protein supplements are added to raise the value of cereal-based diets (see Table 11.5), and these supplements are usually particularly rich in lysine (cereal proteins being particularly poor). Although lysine is often the first limiting amino acid in pig diets, and is usually the controller of protein value, this is not invariably the case.

The balance of essential amino acids in ideal protein and in pig tissue and pig milk protein is represented in Figure 11.4, while Figure 11.5 shows how only around half of unsupplemented cereal protein can be utilised by the pig because the proportion of the total cereal protein that is ideal is limited by lysine.

### Table 11.4. Derivation of the protein value (V) of a mixed diet. V is taken as the lowest score in the column A/B.

<table>
<thead>
<tr>
<th>Ileal digested and utilisable amino acid (g/kg diet protein)</th>
<th>Amion acid (g/kg ideal protein)</th>
<th>V (A/B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Histidine</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Leucine</td>
<td>70</td>
<td>75</td>
</tr>
<tr>
<td>Lysine</td>
<td>45</td>
<td>70</td>
</tr>
<tr>
<td>Methionine + cysteine</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Phenylalanine + tyrosine</td>
<td>65</td>
<td>75</td>
</tr>
<tr>
<td>Threonine</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Tryptophan</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Valine</td>
<td>40</td>
<td>50</td>
</tr>
</tbody>
</table>
In pig diets, dietary protein values (V) usually vary between 0.65 and 0.85. Even when the calculated number for diet protein value is in excess of 0.85, it is often best to take 0.85 as an assumed pragmatic upper limit for commercial diets. Deamination of a proportion of the absorbed diet protein is a proper function of efficient pig production. Pigs convert lower quality plant proteins into higher quality pig proteins; the unbalanced amino acids being excreted. To feed ideal protein in a diet would be grossly uneconomic, and it is appropriate to offer more of a lower quality. As the pig requires its protein in terms of daily mass, not protein proportion, one diet protein with half the biological value of another can provide the same requirement if given in twice the amount. Energy considerations aside, it only needs the second protein to be less than half the price of the first for the poorer quality to be worthy of consideration for inclusion in the diet.

With the capability of calculating V, the proportion of diet protein that is ideal, protein supply can be presented in terms of ileal digested and available essential amino acids supplied in ideal balance; namely, ideal protein. Figure 11.6 shows a complete flow diagram for protein absorption, use and efficiency.

Crude protein supplied in pig diets is usually in the range 140–240 g CP/kg diet. Ileal digestibility of protein (D\textsubscript{i}) may vary between 0.60 and 0.90, with a reasonably expected average of about 0.75, depending upon source and circumstance. The protein value V for conventional pig diets may range from 0.65–0.85; being around 0.75–0.85 for young pigs, 0.70–0.80 for growing pigs and 0.65–0.75 for finishing pigs and for sows. The potential (i.e. when not in over-supply) efficiency of use of ileally digested ideal protein (v) may vary from 0.70 or less up to 0.90, with a value of around 0.85 being realistic. It may be argued that, if the protein absorbed is ideal, then the efficiency of use of absorbed ideal protein should approach unity (rather than be around 0.80) if it is not supplied in excess of requirement. This would be to

Table 11.5. Some protein sources used in pig diets grouped according to their ability to impart high protein value to diets in which they are included.1

<table>
<thead>
<tr>
<th>Class 1 (good) protein sources</th>
<th>Class 2 (mediocre) protein sources</th>
<th>Class 3 (poor) protein sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish meals</td>
<td>Meat, meat-and-bone meals</td>
<td>Cereals</td>
</tr>
<tr>
<td>Milk products</td>
<td>Rapeseed meals</td>
<td>Cereal by-products</td>
</tr>
<tr>
<td>Single-cell proteins</td>
<td>Field peas</td>
<td></td>
</tr>
<tr>
<td>Soya bean</td>
<td>Field beans</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of diet</th>
<th>Approximate protein value (V)²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 3 sources alone</td>
<td>0.45–0.55</td>
</tr>
<tr>
<td>Class 3 + class 2</td>
<td>0.55–0.70</td>
</tr>
<tr>
<td>Class 3 + class 1 + class 2</td>
<td>0.55–0.80</td>
</tr>
<tr>
<td>Class 3 + class 1</td>
<td>0.65–0.85</td>
</tr>
</tbody>
</table>

1 This table refers to the quality of the protein in feeds. This is independent of the level of protein, although many feeds high in protein are in the class 1 category and many feeds low in protein in class 2 or 3.
2 The higher the inclusion level of any protein source, the greater its effect on dietary protein value. When lysine is first limiting, V can be calculated as: \( V = \frac{\text{lysine in diet (g/kg)}}{\text{CP (g/kg)}}/0.07. \)
ignore the substantial losses occurring upon protein turnover. The highest recorded measurement was for growing pigs at the University of Illinois, at 0.87. The British Society of Animal Science Nutrient Requirement Standards for Pigs [Whittemore, C.T., Hazzledine, M.J. and Close, W.H. (2003) Nutrient Requirement Standards for Pigs. BSAS, Midlothian, Scotland] presume \( v \) to be 0.82, setting their view of the upper limit for healthy pigs fed high quality feed ingredients. It is likely that the presence of disease will increase protein turnover and the losses therefrom. For commercial pigs under disease challenge, \( v \) may reduce to a value of 0.70–0.75.

![Fig. 11.4](image)

The similarity of balance of essential amino acids in ideal protein, pig tissue protein and pig milk protein. (In pig tissue methionine is 20 g/kg and phenylalanine is 40 g/kg.)
Where the total available ideal protein required daily to support the protein need for maintenance (IP$_m$), production (IP$_p$) or reproduction (IP$_u$ and IP$_l$) is represented as IP$_t$, then:

\[ IP_t = (F)(CP)(D_a)(V)(v) \]  

(11.16)

where $F$ is the feed intake, CP is the crude protein concentration, $D_a$ is the ileal digestibility of protein, $V$ is the protein value in comparison to ideal protein in terms of the amino acid balance and $v$ is the efficiency of use of absorbed ideal protein.

IP$_t$ is the source of supply of ideal protein for maintenance and production functions, thus:

\[ IP_t = IP_m + IP_p + IP_u + IP_l \]  

(11.17)

The above model is effective in estimating the supply of balanced amino acids (ideal protein) to satisfy the needs of maintenance and production, but falls short in desiring only a single value for $D_a$ and $v$ to represent all the amino acids; because the algorithm works on the base of protein (IP) and not the various constituent amino acids. Given that $D_a$ and $v$ both differ amongst the amino acids, an alternative approach is to describe protein supply in terms of each of the 9 (+2) essential amino acids; $aa(i)$ ($i = 1 - 9$):

\[ aa(i) \times F \times D_a(i) \times v(i) \]  

(11.18)

to give the supply of utilisable $aa(i)$ at tissue level. ($v$)($uaa(i)$) is then compared with the amino acid spectrum of ideal protein for maintenance ($m$), body tissues ($Pr$), milk ($l$) or conceptus ($u$). The amino acid in shortest supply on the strength of this comparison gives the value for $V$ for the diet protein supply, and the levels of product of $Pr$, $l$, $m$ and $u$ that can be created.

**Fig. 11.5** Only 0.43 of unsupplemented cereal protein can be utilised because of the particular imbalance and shortage of the amino acid lysine.
Fig. 11.6 Representation of protein absorption and use showing various influences upon efficiency.
**Maintenance**

Protein is required to replace amino acids lost via the urine and gut in consequence of the inefficiencies of protein turnover, and failure to reabsorb from the gut all the enzymic secretions and lost epithelial cells. Where apparent digestibility is used (rather than true digestibility), as is the case for the determination of the ileal digestibility of crude protein, then metabolic faecal losses are set against the diet and should not be double-counted. Maintenance, therefore, will accord with the obligatory losses in the urine following deamination. Ideal protein requirements for maintenance (IP_m) may be expressed on the basis of metabolic body weight:

\[
IP_m = 0.0013 W^{0.75}
\]  
(11.19)

or, more logically, as a function of the protein mass:

\[
IP_m = 0.0040 Pt
\]  
(11.20)

There is no reason to doubt that this estimate is as valid for the breeding sow as for the growing pig.

It may be surmised that the presence of sub-clinical disease will be evidenced as an increase in maintenance requirement, as a result of elevated turnover losses and decreased efficiencies of amino acid utilisation. (The consequences of clinical enteric disease for amino acid absorption and gut epithelial tissue turnover would, of course, be expected to be dramatic.) Fitting models to populations of healthy and sub-clinally diseased pigs suggests that the efficiency of protein turnover may decrease from 0.94 in normal pigs to 0.80 in those challenged by the presence of sub-clinical disease. Commercial pigs may therefore have effective protein maintenance requirements some 15% higher than suggested by Equation 11.19.

**Production**

Given that the supply is already calculated in terms of available absorbed ideal protein, all inefficiencies have been included in the estimate of IP_t, and it follows that the requirement for production (IP_pr) exactly equals the daily rate of protein retention:

\[
IP_{pr} = Pr
\]  
(11.21)

\[
Pr = IP_t - IP_m
\]  
(11.22)

This relationship will hold until Pr = Pr_max, the potential maximum daily rate (see Chapter 3). Beyond this position there will be excess ideal protein (IP_ex), and this adds to the pool of protein destined for deamination (Pm).

**Reproduction**

Protein deposition in the uterus over the course of the pregnancy (t, days) has been estimated from the data of the combined French and British research teams of Noblet and co-workers in the mid-1980s:
Pr\textsubscript{u} = 0.0036 e^{0.0261} \tag{11.23}

This equation gives a gravid uterus at term with some 3 kg of protein therein, and daily deposition rates at days 20, 80 and 110 of pregnancy of 6, 29 and 63 g respectively. As for Pr, the ideal protein (IP) required for Pr\textsubscript{u} is equal to Pr\textsubscript{u}.

The rate of protein deposition in the mammary tissue, Pr\textsubscript{mam}, has been described as:

Pr\textsubscript{mam} = 0.000038 e^{0.0591} \tag{11.24}

The product Pr\textsubscript{u} is, of course, lost at parturition. There is also a loss of nitrogen in urine after parturition associated with regression of the maternal uterine tissues. At weaning there is similarly regression of Pr\textsubscript{mam} and consequential losses of nitrogen in the urine.

The protein content of milk is around 55 g/kg, and daily milk yield can readily rise to 12 kg. The ideal protein (IP) required for Pr\textsubscript{1} is equal to Pr\textsubscript{1}. Where Pr\textsubscript{1} exceeds the availability of IP for Pr\textsubscript{1}, then maternal body protein catabolism will supplement the dietary supply. It may be assumed that efficiency of transfer of body tissue protein to milk protein would be in the region of 0.8–0.9, given the amino acid profiles and the likely values for v, as muscle protein and milk protein are so similar.

Example calculations for the energy and protein requirements of growing and breeding pigs

As may be gathered from the foregoing, a sophisticated calculation of requirement necessitates the use of a complex model to determine net energy and protein usages, and to deal with all the various interactions. Such techniques are dealt with later. For the present, a more simple approach with generalised factors is utilised.

**Naïve calculation of the energy and protein requirement of a young pig**

**Energy:**

\begin{align*}
W (kg) &= 10; \ Pt (kg) = 1.6; \ E_m (MJ ME/day) = 1.75 P_t^{0.75} = 2.5 \\
Bp &= 0.018; \ Pt_{max} = 45; \ Pr (kg/day) = 0.096; \ E_{Pr} (MJ ME; \ kg) = 55; \ E_{Pr} (MJ ME/day) = 5.3 \\
Lr (kg/day) &= 0.7 Pr = 0.067; \ E_{Lr} (MJ ME/kg) = 53; \ E_{Lr} (MJ ME/day) = 3.6 \\
H &= E_m + 31 Pr + 14 Lr = 2.7 + 3.0 + 0.9 = 6.6; \ Tc = 27 - 0.6 H = 23.0^\circ C \\
\text{if} \quad T(Ve)(Vl) &= 25(0.8)(1.0) = 20^\circ C \\
\quad \text{then} \quad E_h^1 (MJ ME/day) &= 0.012 W^{0.75} (Tc - T) = 0.2 \\
\text{Total energy requirement} &= 11.6 MJ ME = 12.1 MJ DE/day
\end{align*}
Protein:

\[
\begin{align*}
W (\text{kg}) &= 10; \ P_t (\text{kg}) = 1.6; \ IP_m (\text{kg/day}) = 0.0040 \ Pt = 0.0064 \\
IP_{pr} (\text{kg/day}) &= Pr = 0.096 \\
IP_t (\text{kg/day}) &= IP_{pr} + IP_m = 0.112 \\
\text{If} \ v &= 0.90, \ V = 0.80 (0.056 \text{ kg lysine/kg protein}), \ D_a = 0.80 \\
\text{then} \\
\text{the efficiency of use of protein} &= 0.58 \\
\text{Total crude protein requirement} &= 0.112/0.58 = 0.193 \text{kg CP/day}
\end{align*}
\]

Summary of daily requirements:

Energy: 12.1 MJ DE \\
Protein: 0.193 kg CP \\
Lysine: 0.056 \times 0.193 = 0.0109 kg \\
g CP/MJ DE: 16.0 \\
g lysine/MJ DE: 0.90

Where the pig eats 0.75 kg feed daily:

Dietary concentration of CP = 260 g CP/kg diet \\
Dietary concentration of DE = 16.1 MJ DE/kg diet \\
Dietary concentration of lysine = 14.5 g lysine/kg diet

Naïve calculation of the energy and protein requirement of a growing pig

Energy:

\[
\begin{align*}
W (\text{kg}) &= 60; \ Pt (\text{kg}) = 10.2; \ E_m (\text{MJ ME/day}) &= 10.0 \\
B_p &= 0.0125; \ Pt_{\text{max}} = 47.5; \ Pr (\text{kg/day}) = 0.196; \ E_{pr} (\text{MJ ME/day}) = 10.8 \\
L_r (\text{kg/day}) &= 0.7 Pr = 0.137; \ E_{lr} (\text{MJ ME/day}) = 7.3 \\
\text{Total energy requirement} &= 28.1 \text{ MJ ME} = 29.3 \text{MJ DE/day}
\end{align*}
\]

Protein:

\[
\begin{align*}
IP_m (\text{kg/day}) &= 0.041 \\
IP_{pr} (\text{kg/day}) &= 0.196 \\
IP_t (\text{kg/day}) &= 0.237 \\
\text{If} \ v &= 0.90, \ V = 0.80 (0.056 \text{ kg lysine/kg protein}), \ D_a = 0.78 \\
\text{then} \\
\text{the efficiency of use of protein} &= 0.56 \\
\text{Total crude protein requirement} &= 0.237/0.56 = 0.423 \text{kg CP/day}
\end{align*}
\]
Summary of daily requirements:

- Energy: 29.3 MJ DE
- Protein: 0.423 kg
- Lysine: 0.0237 kg
- g CP/MJ DE: 14.4
- g lysine/MJ DE: 0.81

Where the pig eats 2.2 kg feed daily:

- Dietary concentration of CP = 192 g CP/kg diet
- Dietary concentration of DE = 13.3 MJ DE/kg diet
- Dietary concentration of lysine = 10.8 g lysine/kg diet

Naïve calculation of the energy and protein requirement of a finishing pig

Energy:

- W (kg) = 100; Pt (kg) = 17.0; E_{m} = 14.7
- Bp = 0.011; P_{max} = 40; Pr (kg/day) = 0.160; E_{Pr} (MJ ME/day) = 8.8
- Lr (kg/day) = 0.9 Pr = 0.144; E_{Lr} (MJ ME/day) = 7.6
- Total energy requirement = 31.1 MJ ME = 32.4 MJ DE/day

Protein:

- IP_{m} (kg/day) = 0.068
- IP_{Pr} (kg/day) = 0.160
- IP_{l} (kg/day) = 0.228
- If v = 0.88, V = 0.78 (0.055 kg lysine/kg protein), D_{h} = 0.76 then
  the efficiency of use of protein = 0.522
- Total crude protein requirement = 0.228/0.522 = 0.437 kg CP/day

Summary of daily requirements:

- Energy: 32.4 MJ DE
- Protein: 0.437 kg CP
- Lysine: 0.0240 kg
- g CP/MJ DE: 13.5
- g lysine/MJ DE: 0.74
Where the pig eats 2.5 kg of feed daily:

- Dietary concentration of CP = 175 g CP/kg diet
- Dietary concentration of DE = 13.0 MJ DE/kg diet
- Dietary concentration of lysine = 9.6 g lysine/kg diet

**Naïve calculation of the energy and protein requirement of a pregnant sow**

**Energy:**

\[
W (kg) = 200; \ Pt (kg) = 31; \ E_m (MJ ME/day) = 1.75 \ Pt^{0.75} = 22.9
\]

Day of gestation (t) = 80; \ E_u (MJ ME/day) = 0.107 e^{0.016t}/0.5 = 1.9

Day of gestation (t) = 80; \ E_mam (MJ ME/day) = 0.115 e^{0.016t}/0.5 = 0.8

Parity = 3; \ Pr (kg/day) = 5/116 = 0.043; \ E_p (MJ ME/kg) = 55; \ E_p (MJ ME/day) = 2.4

Parity = 3; \ Lr (kg/day) = 7/116 = 0.060; \ E螺旋 (MJ ME/kg) = 53; \ E螺旋 (MJ ME/day) = 3.2

Replacement of 4 kg of lactation lipid loss = 4/116 = 0.034; \ E螺旋 (MJ ME/day) = 1.8

\[
H = E_m + 0.5 (E_u + E_mam) + 31 Pr + 14 Lr = 26.8; \ Tc = 27 - 0.6 H = 11°C
\]

If

\[
T(Ve)(Vl) = 15(0.8)(0.8) = 9.6°C
\]

then

\[
E_{h}^{1} (MJ ME/day) = 0.012 W^{0.75} (Tc - T) = 1.0
\]

Total energy requirement = 34 MJ ME = 35.4 MJ DE/day

**Protein:**

\[
W (kg) = 200; \ Pt (kg) = 30; \ IP_{m} (kg/day) = 0.0040 Pt = 0.120
\]

\[
IP_{pr} (kg/day) = 0.0036 e^{0.026t} = 0.029
\]

\[
IP_{pr} (kg/day) = 0.000038 e^{0.059t} = 0.004
\]

\[
IP_{pr} (kg/day) = 0.043
\]

\[
IP_{t} (kg/day) = 0.196
\]

If

\[
v = 0.87, \ V = 0.75 (0.052 kg lysine/kg protein), \ D_u = 0.75
\]

then

the efficiency of use of protein = 0.489

Total crude protein requirement = 0.196/0.49 = 0.400 kg CP/day

**Summary of daily requirement:**

- Energy: 35.4 MJ DE
- Protein: 0.400 kg CP
Lysine: \( 0.052 \times 0.400 = 0.0208 \) kg
\[ \text{g CP/MJ DE: 11.3} \]
\[ \text{g lysine/MJ DE: 0.59} \]

Where the pig is given 2.6 kg of feed daily:

Dietary concentration of CP = 154 g CP/kg diet
Dietary concentration of DE = 13.6 MJ DE/kg diet
Dietary concentration of lysine = 8.0 g lysine/kg diet

**Naïve calculation of the energy and protein requirement of a lactating sow**

**Energy:**

\[ W (\text{kg}) = 240; \text{Pt (kg)} = 36; E_m = 25.8 \]

Piglets = 10; milk yield = 12 kg

If

0.25 kg of maternal fatty tissue is lost daily

then

\[ 0.25 \times 39.3 \times 0.85 = 8.4 \text{MJ available for milk synthesis} = 8.4/5.4 = 1.55 \text{kg milk}; \]

leaving

\[ 12 - 1.55 = 10.45 \text{kg milk to be provided from dietary resources} \]

\[ E_l (\text{MJ ME/kg}) = 7.7; E_l (\text{MJ ME/day}) = 7.7 \times 10.45 = 80.5 \]

Total energy requirement = 106.3 MJ ME = **110.8 MJ ME/day**

**Protein:**

\[ I_{pm} (\text{kg/day}) = 0.144 \]

Protein content of milk = 0.055 kg CP/kg

If

maternal body protein tissue contributes toward the protein of 0.4 kg of milk

then

\[ 0.022/0.85 = 0.026 \text{kg body tissue protein daily will be lost} \]

and

this leaves 11.6 kg milk to be provided from dietary resources

IP for Pr1 (kg/day) = 0.055 \times 11.6 = 0.638

IP1 (kg/day) = 0.782

If

\( v = 0.90, V = 0.77 \) (0.054 kg lysine/kg protein), \( D_a = 0.78 \)

then

the efficiency of use of protein = 0.541

Total crude protein requirement = 0.782/0.54 = **1.45 kg CP/day**
Summary of daily requirement:

- Energy: 110.8 MJ DE
- Protein: 1.45 kg CP
- Lysine: 0.0783 kg
- g CP/MJ DE: 13.1
- g lysine/MJ DE: 0.71

Where the pig eats 8 kg of feed daily:

- Dietary concentration of CP = 181 g of CP/kg diet
- Dietary concentration of DE = 13.9 MJ DE/kg diet
- Dietary concentration of lysine = 9.5 g lysine/kg diet

It is evident that maternal tissues may well contribute in excess of that estimated above, or that the milk yield may well be curtailed.

The British Society of Animal Science (BSAS) Nutrient Requirement Standards

In 2003, BSAS published requirement standards for energy, amino acids, minerals and vitamins [Whittemore, C.T., Hazzledine, M.J. and Close, W.H. (2003) Nutrient Requirement Standards for Pigs. BSAS, Penicuik, Midlothian, Scotland]. The standards are presented in the form of Standardised Ileal Digestible Lysine (with the other amino acids presented as a balance to lysine) and Net Energy.

Although the Standards are presented in tabular form, the requirements are calculated factorially and all the necessary equations and algorithms are given in the text.

Growing pigs

Variations in pig potential for tissue gains are accommodated through variable values for parameters A (30–50), B (0.01–0.03) and b (1.1–1.3), where A = the asymptote for protein mass (Pt max) and B = the growth rate parameter in the equation:

\[
\text{Protein deposition rate (Pr, kg) = B} \times \text{Pt} \times \ln(\text{Pt max}/\text{Pt})
\]  
(11.25)

in which Pt is the present protein mass.

The potential for fatness, b, is the allometric exponent in the equation:

\[
\text{Lipid mass (Lt, kg) = a} \times \text{Pt}^b
\]  
(11.26)

in which a = 0.5.

BSAS gives three feed intake curves based on:

\[
\text{Feed eaten daily (kg) = F} \times [1 - \exp(-0.019W)]
\]  
(11.27)

where W is the live weight of the pig and F varies from 2.9–3.5.
The NE requirement of the pig (MJ/day) is calculated in the BSAS Standards as the sum of the energy content of the products [retained lipid (kg) × 39.3 + retained protein (kg) × 23.6] together with the net energy used in maintenance (as fasting heat production) and activity. Fasting heat production is taken as 0.750 MJ/kg W^{0.60}, and activity costs are taken (for pigs in intensive housing) as an additional 0.1 of the maintenance expenditure.

In order to allow comparison with previous estimates, the BSAS Standard is also given in terms of DE. This is calculated as the sum of the metabolisable energy requirement for maintenance, activity, protein retention and lipid retention, and assuming ME to be 0.96 of DE. DE (MJ/day) = [(0.444 W^{0.75}) × 1.10] + (23.6 Pr / 0.44) + (39.3 Lr / 0.74) / 0.96, where Pr and Lr are the daily rates (in kilograms) of protein and lipid retention.

The lysine requirement (and thereby that for all the other amino acids, as provided in the stated balance) is given as the standardised ileal digestible lysine requirement. As BSAS states: ‘It is determined as [(lysine in retained protein + lysine in protein used for maintenance) / (1 – obligatory turnover inefficiency)] + (basal intestinal endogenous lysine loss). For purposes of the calculation, the lysine content of retained protein and maintenance protein is 0.070 and 0.058 kg lysine/kg protein respectively. The maintenance requirement is 0.9 g protein per kg W^{0.75}. The efficiency of use of ileal digested amino acids absorbed in balanced proportions, and not supplied in excess, is 0.82, and the basal level of endogenous loss is equivalent to about 5% of the ingested lysine. The basal endogenous lysine loss is estimated as the difference between digestibility coefficients for lysine of 0.80 (ileal digestibility) and 0.84 (standardised ileal digestibility), and (although variable) is assumed constant. For maintenance and protein retention (kg standardised ileal digestible lysine daily) = [(0.0009 × (W^{0.75}) × 0.058) + (Pr × 0.07)] / 0.82 × 1.05.’ Although v is set at 0.82, this is considered a maximum value, and values between 0.74 and 0.82 are suggested.

Pregnant sows

BSAS allows for sows of different live weight and different rates and composition of the maternal gain. The following are the assumptions pertaining to their calculations.

The NE of maternal live growth is 15 MJ/kg when the protein retention and lipid retention are 0.20 and 0.25 of the live growth. The energy content of replacement lipid lost in the course of lactation is 39.3 MJ/kg. The mean daily requirement for the conception products is 0.5 MJ. The NE fasting heat production is 0.750 MJ/kg W^{0.60}. Digestible energy requirements were calculated from the sum of the digestible energy requirements for maintenance (0.463 W^{0.75}), live body growth (24.5 MJ/kg), replacement lipid (53.1 MJ) and conceptus (0.6 MJ/day).

The average daily deposition of lysine in the conception products is taken as 2.0 g. The equations used for calculating the remainder of the daily requirement for standardised ileal digestible lysine are those as similarly derived for the growing pig.
Lactating sows

Different sow weight (150–300), different feed intake (4.5–10.0 kg/day) and different levels of milk yield (6–14 kg/day) are allowed.

For their NE calculations BSAS states: ‘The energy content of milk is 5.4 MJ/kg. For catabolism in support of lactation 0.85 efficiency is presumed, making 1 kg of catabolised body lipid equivalent to 33.4 MJ of dietary NE. A daily rate of maternal lipid catabolism during lactation of 0.25 kg is assumed. Sows in body lipid balance will require 8.4 MJ NE (or 12.5 MJ DE) more than the daily Standard. Losses of 0.50 kg body lipid daily are not exceptional in lactating sows, reducing daily dietary requirement in lactation by 16.7 MJ NE (or 25 MJ DE). Fasting heat production is taken as 0.750 MJ per kg W^{0.60}. Activity costs may be accounted in terms of a proportion of the maintenance expenditure. A default value of 0.1 is assumed for pigs in intensive housing. Higher values may pertain for active pigs’. The requirement in terms of DE is ‘calculated as the sum of the metabolisable energy requirement for maintenance, activity, and milk yield, and assuming ME to be 0.96 of the Digestible energy. DE (MJ/day) = \left\{\left(0.444 W^{0.75} \times 1.10\right) + (5.4 \times \text{milk yield/0.70})\right\}/0.96. 1 \text{ kg of catabolised maternal body lipid is taken as equivalent to a saving of 50 MJ dietary DE’}.

Calculations for lysine follow the now established paradigms. Thus the daily requirement for standardised ileal digestible lysine is: \left\{\left(\text{milk yield} \times (0.054 \times 0.073)\right) + \left((W^{0.75} \times 0.0009) \times 0.058\right)/0.82\right\} \times 1.05. The standardised ileal digestible lysine requirement is determined as \left\{(\text{lysine in secreted milk protein} + \text{lysine in protein used for maintenance})/(1 – \text{obligatory turnover inefficiency})\right\} + (\text{basal intestinal endogenous lysine loss}). The protein content of sow milk is taken as 0.054 kg/kg and the lysine content of milk protein 0.073 kg/kg. The maintenance requirement is 0.9 g protein/kg W^{0.75}. The lysine in maintenance protein is assumed to be 0.058 kg/kg. An efficiency of 0.82 is used for obligatory turnover, and the obligatory endogenous losses are estimated as 0.05 of the requirement.

Recommended energy and protein concentrations in diets for different classes of pig

Recommended nutrient requirements expressed in terms of nutrient concentrations clearly have shortcomings in their generality of application (and hence a likelihood of being wrong) and their dependence upon the amount of the diet the pig may be consuming. Nevertheless, such guides to diet specifications are used world-wide as the basis of diet formulation, and their derivation remains the main preoccupation of both research and industrial nutritional scientists. Diet specifications and the recommendation of nutrient concentrations represent the culmination of the sciences of growth, reproduction and nutritional biochemistry, as has been demonstrated in this chapter. Recommended guide diet specifications are to be found in Appendix 2.
Energy and protein requirements of the breeding boar

The common factor associated with experimentation to determine the nutrient needs of working boars is the equivocal nature of the response. Results are often contradictory, some experiments showing positive response to the nutritional treatment and some negative, but usually there is no response at all. Even where response might be expected, there is bound to be a considerable lag-time due to spermato genesis itself taking some 4 weeks to complete and passage through the male tract to storage to await ejaculation a further 2 weeks more, giving a lag of almost 2 months for any nutritional effects on sperm formation to be seen through effects on fertility.

In general it may be assumed that there is little effect of energy or protein nutrition on the efficiency of the breeding boar, provided that diet protein levels are maintained at a reasonable level and amino acid quality. In this latter regard, one of the more consistent findings has been that long-term protein inadequacy will moderate sperm production. Enough feed should be given to maintain fitness while avoiding excessive leanness or – and possibly most important – excessive fatness. Libido and fertility are likely to be reduced should the boar become over-fat and over-heavy.

Maintenance requirements (E_m and IP_m) for breeding boars may be taken as the same as for breeding sows. There may frequently be a requirement for cold thermogenesis (Tc ≈ 20°C, and often boars may find themselves in a draughty environment with an inadequately insulated floor), the extent of the energy needed to support an effective reaction to a cold environment clearly depending much upon individual housing circumstance.

Post-pubertal growth could be assumed empirically to proceed at around 500 g daily to 150 kg live weight, 250 g daily to 250 kg live weight and 100 g daily thereafter until mature size of around 350 kg is attained.

While factorial calculations can be made for the growth of protein and fat, maintenance and cold thermogenesis, and indeed the work of mating itself and the production of sperm, such would be to imply a precision of nutritional knowledge which does not exist. Common practice would suggest that the energy requirements of working boars should be met by the provision of 30–40 MJ DE/day. This would normally be between 2.5 and 3.25 kg of feed, although lower density diets are likely to be the more preferable due to the benefits of greater bulk density for the satiation of physical appetite. Dietary energy is normally balanced with protein, amino acid, minerals and vitamins in a manner similar to that for the breeding sow (for example, 12 g CP/MJ DE; 0.6 g lysine/MJ DE).
Chapter 12

Requirements for Water, Minerals and Vitamins

Introduction

The body of the pig contains on average 16% protein, 16% lipid, 3% mineral ash and 65% water.

Water is a major structural element giving form to the body through cell turgidity. Water also acts as a transport medium, both in the intestines and in the blood and tissues of the body-proper. It is the medium at metabolic level for enzyme-aided biochemical reactions. Because of the crucial necessity for maintenance of body water balance, the system is set up on the assumption that water consumption will always be in excess of requirement.

The body ash is held in fairly strict ratio to protein; ash \(= 0.20 \text{Pt} \), which is not surprising in view of the support role that the skeleton has for the lean tissue mass. Of the mineral matter the vast majority (three quarters) is calcium and phosphorus as bone hydroxyapatite, and the remainder mostly sodium, potassium and chlorine in body fluids. Magnesium, iron, zinc and copper are measurable, while the other minerals and all the vitamins are to be found only in traces (Tables 12.1 and 12.2).

Proportionality of body content is not indicative of importance. Vitally important vitamins and minerals are used at trace levels acting as catalysts in enzymic reactions, and recycled. The low levels of daily need, the presence of internal buffer and storage mechanisms in the body, together with the often adequate background levels occurring naturally in feedstuffs in any event, result in a diversity of understanding of requirement for trace mineral elements and vitamins, and a breadth of opinion as to the exact quantities pigs may actually need. It is a noticeable feature of nutritional standard-setting for trace elements and vitamins that National Research Councils (NRCs) and public bodies often set requirements markedly lower than levels routinely added to pig diets by feed manufacturers (Table 12.3).

Fear of inadequate dietary supply of vitamins and trace minerals, together with their expense being a small proportion of total feed costs, leads to vitamin and mineral requirements being ‘talked-up’ to ever greater levels of dietary inclusion. Progressive increases in vitamin and trace mineral allowances are the more suspect because in many cases naturally occurring levels may be adequate, and considerable quantities of many of the vitamins can be biosynthesised in the pig’s gut. On the other hand, the discovery of the essential nature of dietary minerals and
vitamins, and the supplementation of diets accordingly, has been one of the most exciting advances of biological science in the twentieth century, and has led to the considerable enhancement of productivity. Further, nutritionists must allow for significant increases (of up to 25%) in diet energy and protein density, which must be matched by equivalent increases in mineral and vitamin density. However, most important of all, nutritionists must aim for dramatic increases in rates of growth and reproduction over recent years. These increases have often not been matched by equivalent (or any) improvements in appetite. All these forces conspire to demand increased concentration of dietary vitamins and minerals. A requirement of $n\text{ mg}$ of a vitamin per kilogram of lean tissue formation would calculate to a diet concentration of $0.1\text{n mg/kg diet}$ for a pig eating 2 kg and gaining 0.4 kg daily, of which half is fat, but $0.5\text{n mg/kg diet}$ for a pig eating 1.5 kg and gaining 0.8 kg daily, of which one eighth is fat. As this example is in no way an exaggerated claim for the change of fortune of growing pigs over recent years, increases in vitamin requirements should not necessarily be considered out of order. Last, vitamin potency may be lost with storage, both before inclusion into the diet and between diet manufacture and diet use. The threat of loss of potency may be realistically countered by an increase

<table>
<thead>
<tr>
<th>Table 12.1. Mineral composition of pigs (g/kg body weight).</th>
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<tbody>
<tr>
<td>(Protein 170)</td>
</tr>
<tr>
<td>Calcium 15</td>
</tr>
<tr>
<td>Phosphorus 10</td>
</tr>
<tr>
<td>Potassium 2.9</td>
</tr>
<tr>
<td>Sodium 1.6</td>
</tr>
<tr>
<td>Chlorine 1.1</td>
</tr>
<tr>
<td>Sulphur 1.5</td>
</tr>
<tr>
<td>Magnesium 0.4</td>
</tr>
<tr>
<td>Iron 0.060</td>
</tr>
<tr>
<td>Zinc 0.030</td>
</tr>
<tr>
<td>Copper 0.003</td>
</tr>
<tr>
<td>Molybdenum 0.003</td>
</tr>
<tr>
<td>Selenium 0.002</td>
</tr>
<tr>
<td>Manganese 0.0003</td>
</tr>
<tr>
<td>Iodine 0.0004</td>
</tr>
<tr>
<td>Cobalt 0.00006</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 12.2. Mineral composition of sows’ milk (g/kg milk).</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Protein 55)</td>
</tr>
<tr>
<td>Calcium 2.1</td>
</tr>
<tr>
<td>Phosphorus 1.5</td>
</tr>
<tr>
<td>Potassium 0.80</td>
</tr>
<tr>
<td>Sodium 0.35</td>
</tr>
<tr>
<td>Chlorine 0.20</td>
</tr>
<tr>
<td>Magnesium 0.10</td>
</tr>
<tr>
<td>Iron 0.0018</td>
</tr>
<tr>
<td>Copper 0.0008</td>
</tr>
</tbody>
</table>
in level of diet supplementation. Clearly, where experimental trial evidence is used to set vitamin and mineral standards rather than practical and field experience, it is essential that feed intake, vitamin potency and pig performance are properly accounted.

It should come as no surprise that factorial calculation to estimate requirements for trace elements and vitamins used in tiny amounts, primarily as catalysts in the body, is doomed to failure. The empirical approach, primarily through (1) deprivation and (2) dose-response experiments, is the only effective means of establishing level of need. However, for the major minerals – calcium, phosphorus, magnesium, potassium and sodium – estimates of net deposition rates and obligatory losses (maintenance, digestibility and subsequent utilisability) should provide factors from which requirement can be deduced. Many have been the attempts, and the results remain regrettably unconvincing. There are various problems with the factorial approach, even though the major elements are clearly readily determinable as predictable proportions of the growth of the skeleton (calcium, phosphorus, magnesium), the growth of the soft tissue (potassium, sodium) and the secretion of milk (see Tables 12.1, 12.2 and 12.4).

From Table 12.4 the expectation may be derived that a 60kg pig retaining 150g protein daily would require some 14g calcium and 9g phosphorus for purposes of deposition alone. With a daily consumption of 2kg of diet, and assumed combined
co-efficients for digestibility and utilisability of 0.7 for calcium and 0.6 for phosphorus, the diet supply would calculate to 10 and 8g/kg diet respectively.

It is the obligatory losses, digestibility and utilisability that have proved so difficult to predict, due mostly to the intrinsic control mechanisms for minerals which are not present for either energy or protein. Thus the digestibility of minerals, measured as their disappearance from the digestive tract, can fluctuate according to the relationship between supply and requirement. For calcium the intestine is a major route for endogenous loss and homeostatic control. Equally, the phosphorus content of urine will vary widely according to the discretion of the body; thus may phosphorus be absorbed in excess of need, only to be excreted with minimal metabolic cost. It is no surprise therefore that there is a building body of evidence supporting the contention that P (and also Ca) may have been oversupplied in the past. Expression of the requirement in terms of digestible, rather than total, phosphorus will help considerably in improving the accuracy of provision. Sodium and potassium are readily digested, and as readily excreted – such a system is essential if ionic balance is to be maintained in the body on the prerequisite short-term basis. Magnesium is poorly absorbed, but little is needed, so a status of luxus consumption is normal.

### Water

The water requirement for pigs is free availability at all times. The calculation of requirement is therefore one of expected rate of intake.

Water may be derived from the natural moisture of feedstuffs and from oxidative metabolism, which yields metabolic water. These sources, however, are trivial in comparison to the water supplied through drinking, or added to the feed.

The water content of the body of a pig can vary from 80% in the newborn to 50% in a fat adult. At any one time, however, the water content of soft body tissue and blood is quite stable; while water intake may fluctuate wildly. The kidneys excrete water via the urine in direct proportion to the intake. It is a confusing characteristic of the study of water requirement that liquid intake varies so widely amongst individual pigs, and across different times. Much of the variation in water consumption can be adjusted at the level of the digestive tract, but the main control

<table>
<thead>
<tr>
<th>Mineral element</th>
<th>Grams of mineral per kilogram of protein retained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>90</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>60</td>
</tr>
<tr>
<td>Potassium</td>
<td>15</td>
</tr>
<tr>
<td>Sodium</td>
<td>10</td>
</tr>
<tr>
<td>Magnesium</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 12.4. Deposition of minerals in pig gain.
mechanism is through the continuous excretion of water into the bladder for temporary storage prior to frequent voiding.

Water is needed by pigs as a means of maintaining a rigid but maleable body form (by giving rigidity to the muscle cells of the lean mass). Water upholds the ionic balance, forms the products of new growth, fetal tissue and milk, acts as a hydraulic fluid for conveying metabolites, endogenous biochemical moieties and waste through the body, comprises part of the thermoregulatory system by its evaporation from the lung surface, its specific heat maintains body temperature and prevents fluctuations, lubricates joints, and is the essential medium for the conduct of the biochemical reactions of the digestive and metabolic processes.

The initial stages of water depletion will increase withdrawal rate from the large intestine, and predispose to constipation. Loss of body fluids in the form of secreted milk and urine will diminish, reducing productivity and piglet growth in the former case, and in the latter reducing the ability of the body to clear toxins while also disrupting ionic balance and water-sensitive metabolic reactions. The consequences of diarrhoea are those of water shortage due to uncontrolled faecal losses, and dehydration of the essential tissues, with disruption of ionic balance and failure of the endogenous biochemistry to operate in the absence of an adequately fluid medium. It is self-evident that water requirements will be related to the level of lactation yield, the amount of food eaten, ambient temperature, the need to evaporate water from the lungs and the amount of toxic product to be cleared from the system via the urine. Water output is increased in proportion to the level of dietary un-ideal protein and dietary protein excess consequent upon the need to dilute the deamination product (urea) to a level of concentration appropriate for urinary excretion.

There is little logic in sophisticated calculation of water requirement, as any attempt to control supply to provide for a requirement would be counterproductive. In general, however, young pigs will need more water per kilogram of body weight than older ones, due to their greater surface area of body and lung in comparison to weight, and the tendency for the urine of younger animals to be more dilute. Using sows’ milk as a guide, piglets will prefer a ratio of water to dry matter of about 5:1, and early weaned pigs given a dry diet may readily exceed this. Growing pigs are conventionally (and erroneously) understood to desire a water to dry feed ratio of 2:1. Recent European data suggest that for growing pigs:

\[
\text{Minimum water need (litres) } = 0.03 + 3.6 \frac{I}{1} \text{ (kg)}
\]

(12.1)

where \(I\) is the feed intake. However, even this is marginal and, given free access, a water to dry feed ratio of 5:1 is common. Pregnant sows given water at any ratio of less than 3:1 are likely to be in deficit even at low environmental temperatures. As pregnant sows are often given their food dry, and access to water is restricted in order to prevent wastage, these animals – especially in hot climates – are prone to suffer chronic water shortage and this may often be evidenced by hot-weather constipation. Pregnant sows on restricted levels of feed may also show a desire to compensate for inadequate gut fill by enhanced intake of water. Current interest in
increasing the fibre content of pig diets, especially those for pregnant sows, is also likely to increase the required ratio of water to food. Lactating sows will require not merely the replacement of some 8–16 kg of secreted milk, but also enough water to void in the urine huge quantities of metabolic by-products; this, in the lactating sow, is in addition to a need to create an adequate fluid environment in the intestinal tract if effective digestion of up to 8 kg of food is to take place. A water to feed ratio of 5:1 is a reasonably likely absolute minimum.

It is self-evident that water needs will rise with increasing ambient temperatures.

Water usage for pigs is almost best dealt with independent of aspects of pig metabolism, which the pig can take care of more than adequately, provided that water is freely available at all times. The means of providing free availability for water is a more appropriate subject for systematic study than any factorial estimation of requirement. The presence in the pen of a water point, in the form of a trough, bowl or nipple-drinker, may not be taken to imply free availability, and careful siting of water points and maintenance of adequate flow-rate are necessary. It is estimated that one water point is needed for every 8 pigs in a pen; this ratio covering all pig types from young growers to adult sows. Lactating sows should have individual access to high-quality water flowing freely but at low pressure.

Recommendations for water-flow rates range from 1–2 litres per minute, the former for weaners and the latter for sows. It is especially important that lactating sows do not have to work hard to gain the ample supply of water that they need. In hot climates inadequate water intake is a common cause of constipation, and in young and growing pigs insufficient water is a common reason for reduced feed intake and slow growth.

Water is the most important of appetite stimulators. Young pigs given dry feed may be seen to alternate between feed hopper and water point during the course of a meal, and food intake will be directly proportional to the availability of the water. Neither should it be assumed that sucking piglets do not require an independent supply of water; whether or not they are eating creep-feed, piglets need water as well as milk. The simple expedient of adding water to food can increase the voluntary intake of pigs by at least 5–10%, and occasionally by up to 30%. Pigs with appetite-limited productivity, such as young pigs, growers and lactating sows, will benefit from being given their feed wet rather than dry, and it is well appreciated that three times daily provision of a wet meal will elicit markedly greater feed intake than the ad libitum provision of dry feed from a self-feed hopper. Additional benefits of wet feeding are the reduction of dust, and also of feed wastage; dry feeding systems may often waste 5–10% of the feed supplied, whilst wet feeding waste is normally 2–4%.

Automatic wet-feeding systems are one of the most effective means of both maximising intake and controlling nutrient supply to individual pig rooms and pens. The hydraulic medium is, of course, water and in this capacity water fulfils one of its important roles on the pig unit. Wet-mix pumping can be readily achieved at 15–18% dry matter; a water to feed ratio of 5:1. This may be considered overly dilute to maximise feed intake due to the limited volume capacity of both the intes-
tine of the pig and the feed trough. Optimum feed and water intake is facilitated by part of the water being ingested with the feed, and part drunk subsequently as pure water. Lesser ratios for the pumped feed, with top-up provision of water from independent water points, is therefore preferred. Few pumping capacities, however, can achieve a dry matter percentage exceeding 25% (a water to feed ratio of 3:1).

Given the modifying effects of feed intake and environmental temperature on water requirement, generalised approximations of water usages are given in Table 12.5. This level of provision will result in the consumption of 7000–10000 litres of potable water daily for every 100 sows and their progeny.

### Minerals

**Calcium and phosphorus**

The skeleton holds 98% of total body calcium and 80% of total body phosphorus in a ratio of just greater than 2:1 in the form of hydroxyapatite. Bone contains 45% mineral, 35% protein and 20% fat, while the bone ash comprises 40% calcium, 20% phosphorus and 1% magnesium. Bone is a dynamic and labile tissue, continuously in a state of balanced accretion and destruction. Calcium in soft tissue is found in muscle and plasma (blood contains around 10 mg calcium/100 ml), and soft tissue phosphorus is also mostly in the muscle mass and in blood. In addition to bone formation, ionic calcium is involved in cell permeability, muscle contraction, blood clotting, excitation of nerves and the activation of enzyme systems. Phosphorus is heavily involved in a wide range of metabolic processes, especially the release of energy and the formation of amino acids. Requirement, however, is mostly perceived in terms of that for skeletal deposition in the course of growth and mammary secretion in the course of lactation.

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Table 12.5. Water intake allowances for pigs.

<table>
<thead>
<tr>
<th>Type of pig</th>
<th>Water intake daily (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lactating sows</td>
<td>25–40</td>
</tr>
<tr>
<td>Pregnant sows</td>
<td>10–20</td>
</tr>
<tr>
<td>Growing pigs 20–160kg</td>
<td>Dry feed intake × 5</td>
</tr>
<tr>
<td>Young pigs</td>
<td>Dry feed intake × 6</td>
</tr>
</tbody>
</table>

1 Water should be freely available to all classes of pigs at all times, even when feed is given wet.

2 Water may be contaminated with disease organisms, when decontamination may be indicated.

3 The level of salts dissolved in water may have a significant effect upon its quality and the willingness of pigs to drink it. The total dissolved salt in water should be <3000 parts per million, of which the content of calcium should be <1000 ppm, sulphates <1000 ppm, nitrates <100 ppm and nitrites <10 ppm.
The digestibility of calcium is influenced by (1) the source of the element, (2) other diet components and (3) the physiological state and the physiological needs of the animal, as both endogenous calcium and phosphorus may be voided via the intestines (especially calcium, but also phosphorus which uses both intestinal and urinary routes). The ability of the gut to control rate of entry of intestinal calcium to the skeletal and plasma pool renders calcium digestibility a primary function of animal need, and the digestibility coefficient will fall with both increase in supply and decrease in demand. This system uses both active transport and diffusion processes, and is somewhat dependent upon the presence of ample vitamin D₃. Vitamin D also interacts with parathyroid hormone to encourage skeletal mobilisation of calcium and the maintenance of calcium homeostasis. The presence in the gut of dietary sugars, such as lactose, may enhance calcium digestibility, while oxalates will decrease it. Most important, however, is the consequence of dietary fats, which at high levels can mutually inhibit absorption of both the fat and the calcium by the formation of insoluble calcium soaps. Further interactions in the tract between dietary calcium and dietary zinc may result in the depression of either if one is consumed at excessive level. Most common and conventional sources of calcium will freely yield the element for absorption from the intestine; the order of relative digestibility being bone meal, calcium carbonate, di- and tri-calcium phosphate, mono-calcium phosphate; the potential rate of digestibility in all cases being above 70%. However, it is the level of diet calcium itself, together with the perceived calcium need, that is the primary control of the rate of both inflow (digestibility) and outflow (endogenous losses) fluxes across the gut wall.

The digestibility of phosphorus is reduced if diet calcium is in excess, due to the formation of insoluble calcium phosphates. The ratio of calcium to phosphorus should be maintained in the diet at 2:1 or less; the ratio being more critical in the absence of adequate supplies of vitamin D₃. Organic phosphorus forms, especially the phytates, are less readily digested than inorganic forms, which is important in terms of interpreting the general usefulness of total diet phosphorus, much of which (often half or more) will be in organic form from plant sources. Cereals will contain around 3–4 g P/kg, whilst cereal by-product phosphorus can rise to 5–10 g P/kg (cereal calcium, in contrast, is trivial at 0.5 g Ca/kg).

The digestibility of phosphorus from di- and tri-calcium phosphate and bone meal is greater than that from alumino ferric phosphate, fluorine rock phosphates or phytate phosphorus; the latter group being likely to be lower than 40% digestible, whilst the former group may be digested at levels better than 70%. While luxury absorption of calcium results in it being cycled back into the gut lumen for endogenous excretion, and thus causes a decrease in apparent digestibility, the major mechanism for endogenous loss of phosphorus is via the urine, so the effects of level of diet phosphorus intake in comparison to bodily phosphorus need are noted not at the level of digestibility, as for calcium, but rather more at the level of urinary phosphorus outflow; the diet supply and rate of urinary loss of phosphorus being directly and closely related.
Inadequate calcium and phosphorus supply will depress growth and milk yield and result in poorly mineralised bones. The pig’s requirement – as expressed in terms of dietary concentration – for fully mineralised bones of maximum strength is about 1 g/kg higher than normally recommended levels, but there is little reason to wish to achieve such a target. There is scant evidence to support any relationship between joint, leg or foot weakness and the diet supply of calcium and phosphorus provided these are within reasonable range. Serious deficiencies do, of course, result in osteomalacia, osteoporosis and rickets.

The recommendations given in Table 12.6 assume that most of the diet calcium is in the form of either bone meal, calcium carbonate or dicalcium phosphate, and that about half of the diet phosphorus is from bone meal or dicalcium phosphate, while of the other half some three quarters is organic phytate. The addition of phytase enzyme to the diet will release more of the (previously) indigestible plant phytate phosphorus and reduce the total requirement. Recent concern with phosphate pollution of the environment has called into question the need for such high levels of diet phosphorus in diets for pigs destined for slaughter.

Recent reductions in recommended provision of P have resulted from practical experience where recommended levels of dietary phosphorus for slaughter pigs were reduced from previous levels by 30% or more; without any apparent detriment, but with the benefit of much reduced excretion rates in faeces and urine. In using the lower levels of digestible P it is important that the digestibility coefficient used for the mineral source in question is correct.

**Sodium, chlorine and potassium**

Sodium, chlorine and potassium are major controllers of the delicate ionic balance in body tissues. Sodium and potassium salts are well digested, normally absorbed in excess of requirement, and excreted by the urine whose content of these elements is closely related to the rate of dietary intake. Sodium is supplied as salt, which is widely used as a diet appetiser and is usually included at supplementary levels of 1–3 g salt/kg diet, while ample potassium is available from normal diet ingredients. Dietary levels of common salt above 10 g/kg will predispose to salt toxicity if water...
supply is at all limiting. Requirement appears to be about 1.5 g/kg diet for sodium and about the same for chloride. This would be supplied in total by 3.75 g salt/kg diet. The sodium content of cereals is around 0.3 g Na/kg, while fish meal contains about or above 6 g/kg. The requirement for potassium seems around 3 g/kg diet. Cereals contain natural levels of greater than 4 g K/kg, whilst soya bean has 20 g K/kg. The sodium requirement is given in Table 12.6; the chloride requirement will be satisfied along with that of sodium, and potassium will normally be provided in excess from all but the most unusual of diets.

**Magnesium**

Magnesium is associated with calcium and phosphorus in the formation of bone, and is also an essential part of body enzyme systems. The requirement is around 0.4 g Mg/kg diet, and this is readily met from dietary sources. Cereals contain somewhat above 1 g Mg/kg, although the digestibility is probably at or below 50%.

**Trace mineral elements**

Zinc, manganese, iron, cobalt, iodine, selenium and copper are all required for normal metabolism as a part of the biochemical reactions catalysed by enzymes, or as a part of hormone systems. Their requirement is best expressed in terms of the amounts that might be expected to be needed as a dietary supplement. The supplement is usually pre-compounded to contain a given balance of all the trace minerals, and this supplement is then added to the diet at a single recommended level to provide for the whole of the estimated diet requirement. Recommendations vary hugely, due at least in part to a difference of opinion as to the extent to which trace elements contained naturally in the diet ingredients can contribute to the perceived requirement. Values given in Table 12.7 are formulated after reference to the United States National Research Council, the United Kingdom Agricultural Research Council and common practice.

**Vitamins**

The gross effects of vitamin deficiencies are spectacular, but rather difficult to reproduce with natural diets. Vitamins are involved in the widest possible range of normal body functions, especially the biochemical pathways of the metabolic processes, the immune response, co-factors in enzyme function, cell membrane activity, inheritance and tissue differentiation, and so on. Shortfalls in vitamin supply, such as may occur on rare occasion in the course of conventional pig production activities, will therefore bring about chronic and insidious consequences for growth rate, disease resistance and reproductive ability; all of which tend to be of a general rather than a particular nature. It is essential, therefore, to be satisfied that dietary levels of vitamins are entirely adequate.
For vitamins, the determination of adequacy is fraught. Even the criteria of assessment for the adequacy of vitamin supply is difficult to determine. It may be instructive to take the case of vitamin E as an example. There are eight chemical isomers of vitamin E, but alpha tocopherol is the only one acceptably bio-available. Vitamin E adequacy is highly dependent upon other dietary components, especially as being an anti-oxidant it is used up by unsaturated dietary fatty acids. After digestion and absorption dietary vitamin E is deposited in both cell wall and cell content, where it acts as an anti-oxidant by reducing the levels of free radicals in the tissues. (For a note on free radicals see footnote to Table 12.8.) The requirement for alpha tocopherol is around 10 mg/kg to avoid muscular dystrophy, heart and liver disease. It has been shown, however, that up to 200 mg/kg may enhance the immune system and assist in control of oedema, diarrhoea, sudden death, metritis and diseases of the mammary gland; whilst up to double that amount again can help to protect the fat of pork post-slaughter from fatty acid oxidation and drip-loss instability, this latter through its reaction in maintaining the integrity of cell membranes. Alpha tocopherol allowance must also accommodate for loss of potency, the influences of dietary polyunsaturated fatty acids, the deleterious effects of the presence of dietary mycotoxins and the possible antagonistic effects of vitamin A. How then is a requirement for a specific vitamin to be set?

The level of need for diet supplementation of vitamins is further complicated by the extent to which allowances should be made for the vitamin naturally occurring in feedstuffs. For example, barley and maize corn, which have been well stored, appear to contain all of the necessary level of vitamin E, half the requirement for pantothenic acid and all of the thiamine. The question here is about the bio-availability and suitability of form of the naturally occurring vitamins which may be variable and low. Many vitamins are also biosynthesised in the body of the pig; from other nutrients, from metabolites or through the medium of microbial synthesis in the intestine. Vitamin C (ascorbic acid), for example, may be synthesised by the pig

<table>
<thead>
<tr>
<th>Mineral element</th>
<th>Recommended requirement (mg) to add per kg of diet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>75¹</td>
</tr>
<tr>
<td>Manganese</td>
<td>30</td>
</tr>
<tr>
<td>Iron</td>
<td>75¹</td>
</tr>
<tr>
<td>Cobalt</td>
<td>0.5</td>
</tr>
<tr>
<td>Iodine</td>
<td>0.3²</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.3³</td>
</tr>
<tr>
<td>Copper</td>
<td>5⁴</td>
</tr>
</tbody>
</table>

¹ Zinc 125 and iron 125 if copper is included at growth promoter level.
² Two times higher if dietary goitrogens are present.
³ Selenium is an anti-oxidant, helps to mop up free radicals and is immunogenic. Grains are low in Se. Cell walls require lipoprotein for their integrity, and so oxidation of lipid causes cell walls to become leaky; a negative occurrence countered by selenium-containing glutathione peroxidase. Se and vitamin E can act complementarily in maintaining cell wall integrity.
⁴ For growth promoter levels up to 175 for young growers, and up to 100 for pigs above 60 kg.
from glucose, whilst both biotin and $B_{12}$ are open to synthesis with the help of gut flora in the lumen of the intestine. With regard to biosynthesis, the question is always one of the adequacy of synthetic rate possible within the body of the pig in relation to the level of demand for highly productive animals.
Recommendations for vitamins are therefore presented on the same basis as for the trace elements. The whole of the requirement is proposed as being supplied in the form of a supplement. The values in Table 12.8 are derived from a compendium of many sources, including the US NRC, UK ARC, UK BSAS and feed manufacturing practice. There is some temptation to present the full range of recommended and used levels of vitamin inclusions in diets obtainable from diverse literature sources. However, to do so would be to present ranges often spanning tenfold differences or more. Such a wide range in estimates for vitamin requirements makes recommendation most difficult, and the values given in Table 12.8 can only be taken as a guide based on best available current knowledge (note that Table 12.8 assumes no substantial loss of potency between manufacture and ingestion by the pig). As already pointed out for the trace mineral elements, diets of particularly high nutrient density should have vitamin inclusion levels raised pro rata. Concentrations given in terms of milligrams per kilogram of diet in Table 12.8 assume a dietary DE content of about 13 MJ/kg.
Chapter 13

Appetite and Voluntary Feed Intake

Introduction

Animal appetite – the desire for nutrients expressed in terms of feed consumption – is, by definition, a function of nutrient requirement. However, appetite must ultimately be limited by factors that arise from the animal’s environment and its capacity to deal with constraints that derive from it. Such constraints can be categorised into dietary, physical and social. The maximum capacity of the digestive tract to deal with the bulk contributed by the diet and the upper limit to the animal’s ability to dissipate into the environment the heat associated with feed digestion and metabolism are two very usual constraints operating on pig appetite. Although the quantitative estimation of actual voluntary feed intake achieved by a given pig in a given day may be complex, some progress has been made recently in arriving at predictions of voluntary feed intake under various physical and social conditions (see Chapter 19). The prediction of the pig’s voluntary feed intake and the reduction in its appetite during the presence of infectious pathogens that lead to disease, however, remains a significant challenge.

Appetite is a moderately heritable trait (0.2–0.4) and highly correlated with both growth rate overall (positively) and percentage lean (negatively), and somewhat positively correlated with lean-tissue growth rate. The relationship with feed-conversion efficiency is positive so long as maintenance costs are effectively offset by increasing lean-tissue growth rate, but this relationship tends towards the negative when fatty-tissue deposition becomes dominant. Pig responses to increasing daily feed intake are shown in Figure 13.1. The positive relationship between feed eaten and daily fatty-tissue growth accelerates at higher feed intake, whilst the even more positive relationship with daily lean-tissue growth is shown to plateau at higher feed intake. Unsurprisingly, daily live-weight gain is the sum of these two responses. Feed efficiency increases at first, and then has a tendency to stabilise or even decline. Optimum feed intake is that which maximises lean-tissue growth rate and provides additionally the level of fat desired; Figure 13.1 shows that this will occur at point X or beyond.

The central nervous system (CNS) is involved in appetite control through a series of sophisticated neural and endocrine interactions. In particular, the controlling roles of β-adrenergic agonists, serotonin, cholecystokinin, opioids and neuropeptides have been the subject of study but have not offered much elucidation of this
control. That the CNS may be open to direct communication with blood metabolites, and control feed intake through that mechanism, has been proposed for many years through the glucostatic and lipostatic theories; high blood levels of these metabolites giving negative feedback to appetite. It may readily be shown that glucose or lipid loading of the gastro-intestinal tract will reduce the size of an individual meal, but a systematic control mechanism has not been identified. The hormones insulin, glucagon and somatotrophin are clearly involved in nutritional response, but any linkage there may be between feed intake and nutrient need mediated through such hormone controls is as yet obscure. Somatotrophin has been implicated as often in appetite depression as in appetite enhancement; the illogically of such a finding suggests that understanding of the system is unlikely in the near future. The intestinal hormone cholecystokinin (CCK) is secreted in response to the presence of feed there, and through its action limits feed intake. If the influence of CCK can be suppressed by creating an immune response to it, then it appears that feed intake may be enhanced by 5–10%. Immunosuppression of CCK is not generally possible, and it might be fair to suggest that there are other ways of improving feed intake which should perhaps be more fully exploited first. It seems

Fig. 13.1 Growth rate and efficiency responses to increase in daily feed intake. Point A is an indicator of maintenance requirement. Between A and X, responses tend to be linear. Optimum feed intake is at X or beyond.
unlikely that such a vital process as feed intake would rely for its regulation on a single signal.

Taste and smell are important aspects of CNS-mediated feeding behaviour and the predilection of the pig for sugar and truffles is well known. However, whilst a flavour may mask an appetite-depressing unpalatability or enhance an appetite stimulator, these phenomena also remain mysterious. Pigs will prefer to eat a feed rich in sucrose when offered a choice, but often will not eat any more of such feed when offered no choice. Flavour technology is a novel science and it is possible that genuine appetite enhancers, acting upon the CNS, may be forthcoming. However, normally such flavours will at best merely ameliorate a problem of appetite depression, rather than lift appetite above the fundamental controlling forces of (1) gut capacity and (2) nutrient requirement. High ingredient quality and absence of unpalatable components remain the best route to appetite optimisation. Self-inflicted obesity (or the converse, anorexia) is likely to be consequent upon interaction of bodily and CNS forces and unlikely to be open to simple manipulation through taste.

To date there has been some manipulation of appetite through genetic selection, both high-appetite and low-appetite genotypes now being evident in improved pig populations. Whilst feed intake may itself be relatively simple to measure and manoeuvre through genetic selection, high appetite genotypes may be associated with fast lean-tissue growth rate, fast lipid-tissue growth rate or both. In the past, breeding for fatness created genotypes whose gluttony outstripped their requirement for maximum lean-tissue growth rate, thus creating an excess of nutrient supply and the accretion of depot fats. Reversal of the trend to fatness, and the breeding of lean pig types, initially went hand in hand with appetite diminishment. It remains the case that reduction in appetite is a most effective way of reducing fatness and improving percentage lean content. Between 1960 and 1990, in the UK, there was a reduction in backfat depth of about 0.5 mm P2 annually (from 28 to 14 mm P2 at 100 kg). Over the same time period, there is evidence that feed intake at 100 kg may also have been dramatically reduced, from about 4 kg to around 2.5 kg. Increased diet nutrient concentration can only account for some of this latter diminishment. On the other hand, given a population of adequately lean genotypes, there is a need to breed for increased appetite because only by elevating nutrient intake can genetic increases in potential lean-tissue growth rate be realised. The link between feed intake and obesity can be severed, but only while increased lean-tissue growth rate is selected for simultaneously with fatness control.

**Appetite as a consequence of nutrient demand**

The demands of a pig for energy may be itemised in terms of the digestible energy (DE) requirements for maintenance, protein and lipid deposition, lactation, etc., as has been described earlier. Where values for the optimum rates and compositions of growth and lactation are known, then:
where $E_H$ is the energy lost as heat through maintenance, metabolic and physical work and cold thermogenesis, $E_U$ is the energy lost in urine and $E_P$ is the energy retained in protein, lipid growth or produced as milk.

Sources of nutrients are multidimensional, comprising at least energy (such as starches, fats and sugars), amino acids and a range of minerals and vitamins. In domesticated circumstances pigs are usually disallowed any choice amongst these dimensions, being given a fully compounded diet. Where the ratio of nutrients in the diet is in accord with the ratio of nutrients demanded, then appetite will reflect a rational choice comprehensive in the extent of its satisfaction of requirement. If, however, diet nutrients are not balanced in relation to demand, then appetite is likely to become irrational:

1. The intake of the imbalanced diet may be reduced to the extent that follows from the perception of the level of its inappropriateness; that is, the diet will be discriminated against as a result of a nutrient being consumed above the level of need. This is frequently observed with diets grossly imbalanced in amino acids or minerals (and toxins). A pig may eat inadequate levels of energy because the diet supplies in excess a mineral that the pig wishes to avoid.

2. The imbalanced diet may be more avidly consumed to an extent that follows from the pig perceiving a limiting nutrient, and, through a desire to satisfy a need for that nutrient, eating others to excess. Pigs on a low protein diet often attempt to do this and as a consequence over-consume energy and become fat. Whether the pig achieves an intake that reflects its requirement for the deficient nutrients will depend on its ability to cope with the amounts of nutrients and/or energy that are over-consumed.

**Negative feedback: heat losses**

Negative feedback regulating appetite may come from elevated levels of blood glucose, blood lipids and plasma amino acids; all of which may be used to monitor adequacy of supply in relation to need. The same may arise from absorbed toxins and their products of metabolism and detoxification. Equation 13.1 implies no limit to the capacity of the pig to lose heat ($E_H$). However, this is often not the case and the avoidance of heat stress will limit energy intake where the environment fails to allow for adequate heat losses from the body. Consumed nutrients that have been used for metabolic work, together with energy not deposited in products, are actively lost as heat. This heat must be dissipated if stress and a body temperature rise are to be avoided. The more productive the pig, the greater is its nutrient need, and it follows that the greater also is the need to lose heat and therefore to find an environment of appropriate (reduced) temperature. Consumption of excess of any
of the energy-containing lipids, proteins or carbohydrates due to dietary imbalance will further exacerbate the need to dissipate heat (see above).

In the absence of ability to lose adequate heat, then reverse pressure is placed upon Equation 13.1 and feed intake must fall. It may be estimated that feed intake will be reduced by 1 g for every 1°C of heat above comfort level for every 1 kg of body weight of the pig:

$$\text{Feed reduction (g/day)} = W(T - T_c)$$

(13.2)

where W is the live weight (kg), T is the effective ambient temperature and Tc is temperature associated with optimum pig comfort.

The influence of rate of air movement (which is important in the avoidance of heat stress) may be accommodated somewhat on the assumption that a 10 cm/s increase in air movement is approximately equivalent to a 1°C reduction in air temperature. A more comprehensive approach to the effect of temperature on feed intake is given in Chapter 19.

**Positive feedback: relative productivity above maintenance**

Positive feedback (enhancing appetite) will come from demands for maintenance, cold thermogenesis and production exceeding the current rate of ingestion (Equation 13.1). If the most steadfast demand is for maintenance, then the basal energy intake, scaled according to live weight, would need to be amended upwards according to the rate of growth or level of lactation. Using a diet of 14 MJ DE/kg feed, maintenance intake measured in terms of kilograms of feed eaten daily would be around 0.03 $W^{0.75}$. During rapid growth of lean and fatty tissue, intakes may rise to 0.12 $W^{0.75}$ (four times maintenance) or above, while at peak lactation values of up to 0.15 $W^{0.75}$ (five times maintenance) may be achievable.

Entire males usually have appetites 10% lower than castrated males, with the female usually intermediate. Pigs of improved genotype, due to selection against percentage fat in the carcass, have lower appetites than unimproved pigs; although there is some dichotomy in the relationship as further genetic gains in lean-tissue growth rate are dependent upon appetite increase – not diminution.

**Influence of diet nutrient density**

A diet relatively low in energy presented to a pig with a nutrient demand that is relatively high in energy will induce a positive feedback and enhance appetite. In theory this will prevail until either the energy demand is satisfied or negative feedback occurs due to the retrograde effects of all the other nutrients which would now be consumed to excess. Pigs offered diets of increasing energy concentration will be seen initially to consume more, and then, once a balance has been achieved between intake and demand, to consume progressively less. This downward adjustment of
Feed intake with increasing diet energy concentration, and its converse upward adjustment with decreasing diet energy concentration, is rather exact and delicate, especially in pigs, such that equivalence of digestible energy intake is almost precisely attained. Feed intake and digestible energy responses to increasing concentrations of dietary energy are shown in Figure 13.2.

There is some evidence, that appetite may, in addition to the influence of energy, also be affected by the dietary amino acid level and amino acid balance. Negative feedback can be given by diets with imbalanced levels of amino acids, these being consumed less avidly than those whose amino acids are balanced more closely to the ideal, thus avoiding excess intake of unwanted nitrogen. Figure 13.3 indicates that feed intake will increase in response to increasing lysine to the point of achievement of ideal amino acid balance, whilst excess of lysine supply will bring about subsequent decrease in feed intake.

Positive feedback, on the other hand, may arise from diets with a frank shortage of (balanced) protein in comparison with protein requirements such that, as was the case of pigs ‘eating to energy’ above, they would seek an increased rate of ingestion of protein, and in this event ‘eat to protein’ with the possibility of consuming unwanted energy. This response tends towards attempts by the pig to satisfy the demands for lean-tissue growth rate, whilst unavoidably promoting the deposition of depot fatty tissue. As the pig’s response to dietary protein content will depend on its ability to cope with the other nutrients and energy that are over-consumed, in these instances the environmental temperature becomes of critical importance.
Appetite as a consequence of gut capacity

The classic ability of the pig to adjust appetite in response to progressive decreases in diet nutrient density (especially energy) has its limits when ultimate gut capacity (in terms of volume and throughput rate) is reached. Feed flows out of the stomach and down the duodenum of the pig at the rate of about 10 g dry matter per minute, beginning immediately after feeding. The rate of outflow is linear until the stomach is about half-cleared of the original feed inflow. After this, the outflow rate declines exponentially. Outflow rate is slightly lower for younger pigs than for adults, but it is relatively constant for much of the total dry matter moved and is not greatly affected by the absolute amount of feed eaten. So total stomach and intestinal volume will be the most important factor controlling the physical limits of feed intake in the pig, and it may be confidently supposed that the physical limits to feed intake will be related to some function of body size. This leads to the remaining elements of the scheme represented in Figure 13.2.

At diet concentrations below N (Figure 13.2), gut capacity limits feed intake and the rate of digestible energy ingestion must fall. In practical terms, pigs maximising their gut fill but failing to maximise their productivity due to inadequate intake of energy may have their performance increased by addition to the diet of fats and oils which provide maximum energy for minimum diet space. Artificial (synthetic) amino acids will serve a similar purpose for similar reasons. The exact position of N in Figure 13.2 – the point below which required energy intake is curtailed by diet bulk – is highly dependent upon pig gut capacity in relation to the rate of pig productivity and the pig’s prior experience of bulky foods. In young pigs, potential productivity is especially high but gut capacity especially low due to the small size of the animal. Bulk effects may begin to exert some limit on performance through appetite restraints at DE values below 20 MJ/kg for young piglets (sows’ milk has around 30 MJ DE/kg DM), 14 MJ/kg for young growers and lactating sows and 10 MJ/kg for other adults. These values will somewhat decrease if the pig has had the opportunity to adapt on bulky foods and increase the size of its digestive system. The potential productivity of lactating sows and young growers is greater in rela-
tion to their gut capacity than that of older growing pigs and pregnant sows and, because of this, the former require diets of higher nutrient density.

Although in wet-feed systems water may constitute an element of ‘bulk’, the bulking characteristics of feedstuffs are normally measured in terms of their fibre content; that is, their indigestibility. The relationship between fibre and DE concentration is, of course, highly negative. ‘Fibre’ not only occupies much space in the gut in its own right as an entity of low (or zero) energy value, but also attracts and holds water (which takes up further gut space). It may therefore be helpful to measure gut capacity in terms of either potential daily output of undigested food material in the faeces or the water-holding capacity of the food’s dry matter. For example, if it is surmised that the faecal organic dry matter output of a pig approximately equals 0.013 W, then values for 20, 100 and 200 kg pigs would be 0.26, 1.3 and 2.6 kg. Assuming dry matter digestibilities for pigs of these weights of respectively 0.80, 0.70 and 0.65, then these values equate to physical intake limits of 1.3, 4.3 and 7.4 kg. These limits are similar to those that would be estimated by the expression of $0.14 W^{0.75}$, a function mentioned earlier and equivalent to rather more than four times the maintenance requirement. If this argument is credible, then:

\[
\text{Physical limits to feed intake (kg/day)} = 0.013 W/(1 - \text{digestibility coefficient})
\]

The coefficients for W may be assumed to be relatively lower for pigs of a genotype selected for lower appetite, and relatively higher for pigs with a particularly strong propensity to consume fibrous feedstuffs.

**Estimation of feed intake in young and growing pigs**

It is conventionally, but not necessarily reasonably, assumed that until 20 kg, live-weight growth rate and feed intake of young pigs are limited by the physical capacity of the gut. Equation 13.3 would suggest physical limits for pigs of 5, 10 and 15 kg live weight of 0.65, 0.65 and 0.98 kg [if digestibilities of 0.90 (milk), 0.80 and 0.80 are used]. These values are realistic for the weaned pig, but for the 5 kg suckler consuming about 300 g dry matter daily there is a limit due to either the liquid intake or space available for the consumption of some 300 g of supplementary feed. It is interesting to note that at 3 kg live weight, gut limits and likely milk dry matter intakes are broadly similar.

Weaned pigs do not consume to their potential appetite until around 20 kg live weight, and sometimes not even then. Were they to do so, they would be more likely to achieve their growth potential which can be demonstrated in optimum conditions (see Chapter 3). Some of the reasons for young pigs failing to eat enough to satisfy their nutrient demands have been alluded to earlier. Specifically, ill health, stress, unfavourable ambient temperatures, unpalatable feed, feed of inappropriate ingredient composition or nutritional balance, inadequate water supply, insufficient space to live and eat and general mismanagement all conspire to ensure, for example, that the 400 g of high-quality feed required to be eaten by the 6 kg newly weaned pig in
order to attain growth rates equivalent to those already shown pre-weaning is comprehensively not attained, nor will it be until some 2 weeks later. Attempts to estimate pig feed intakes between weaning and 15 kg have therefore largely failed due to their overwhelming dependence upon individual management circumstance. Figure 13.4 shows estimates for daily feed intake in relation to physical limits, nutrient needs and the likely achievements at production level, the latter falling far short of the former.

From 15 kg onwards it is likely, all other aspects of production being satisfactory, that the appetite of growing pigs may be best estimated from their nutrient demand (Equation 13.1), within the constraints of gut capacity (Equation 13.3). Empirical estimates have been determined by many workers in various countries. The UK Agricultural Research Council (ARC) working party reported in 1981:

**Digestible energy intake = 4 × maintenance requirement** \hspace{1cm} (13.4)

or, where maintenance is estimated as 0.72 MJ ME/kg \( W^{0.63} \):

**DE intake (MJ/day) = \( 4(0.72 \ W^{0.63})/0.96 = 3.0 \ W^{0.63} \)** \hspace{1cm} (13.5)

In a similar vein, Irish workers found 4.0 \( W^{0.5} \). However, these relationships are unrealistic for pigs of higher values of \( W \) (e.g. a 160 kg pig would be expected to eat over 54 MJ DE/day) and for this reason the following relationship has been put forward:

**DE intake (MJ/day) = \( 55(1 - e^{-0.0204 \ W}) \)** \hspace{1cm} (13.6)

which has been supported by the US National Academy of Sciences–National Research Council (NAS–NRC) working party reporting in 1988.

Table 13.1 presents values from this equation together with a calculation of the intake of a diet of 14 MJ DE/kg and the prediction from the equation:

**Feed intake (kg/day) = 0.13 \( W^{0.75} \)** \hspace{1cm} (13.7)

which, as mentioned earlier, is a naïve expression approximating to just above four times maintenance, and therefore likely to approach the limits to appetite.

Values in Table 13.1 show how maximum feed intake is similarly estimated by Equations 13.3 and 13.7, the former based on faecal excretion of indigestible material and the latter on metabolic body weight. Both of these estimates are in
respectable agreement with the Agricultural and Food Research Council (AFRC) working party Equation 13.6 until 80 kg live weight, when divergence occurs. The idea that feed intake limits are asymptotic, and that for growing pigs that asymptote appears before 100 kg live weight, is well accepted and confirmed by many data sets (see, for example, Figure 13.5). However, known feed intakes achieved by lactating sows when 160 kg support the likelihood of gut capacities of 6 kg, which is closely in accord with Equations 13.3 and 13.7. Perhaps Equation 13.6 and the responses in Figure 13.5 are reflective not of maximum gut capacity but rather of a lesser nutritional need, and a following diminishment of growth rate subsequent to 100 kg live weight. However, caution must be exercised as to assumptions made for the asymptote to growth, which should occur at much higher live weights for improved than for unimproved genotypes. The causes of the apparent asymptote to appetite which seems to occur at around 100 kg are possibly in large part a function of systems of production and management and deserve greater investigation.

Whereas the expected appetite of growing pigs may be described by one or other of the alternatives in Table 13.1, or by a description such as in Figure 13.5, it remains the case that practical feed intakes achieved under ad libitum conditions on farms more nearly approximate to values predicted by:

Table 13.1. Limits to feed intake estimated by different methods.

<table>
<thead>
<tr>
<th>Live weight of pig (kg)</th>
<th>Equation 13.6¹ (MJ DE/day)</th>
<th>Equation 13.6² (kg diet/day)</th>
<th>Equation 13.7³ (kg diet/day)</th>
<th>Equation 13.3⁴ (kg diet/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>18.4</td>
<td>1.31</td>
<td>1.23</td>
<td>1.30</td>
</tr>
<tr>
<td>40</td>
<td>30.6</td>
<td>2.19</td>
<td>2.07</td>
<td>2.08</td>
</tr>
<tr>
<td>60</td>
<td>38.8</td>
<td>2.77</td>
<td>2.80</td>
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</tr>
<tr>
<td>80</td>
<td>44.2</td>
<td>3.16</td>
<td>3.48</td>
<td>3.47</td>
</tr>
<tr>
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<td>4.33</td>
</tr>
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<td>50.2</td>
<td>3.59</td>
<td>4.71</td>
<td>4.46</td>
</tr>
<tr>
<td>140</td>
<td>51.8</td>
<td>3.70</td>
<td>5.29</td>
<td>5.20</td>
</tr>
<tr>
<td>160</td>
<td>52.9</td>
<td>3.78</td>
<td>5.85</td>
<td>5.94</td>
</tr>
</tbody>
</table>

¹ DE intake (MJ/day) = 55(1 – e^{0.0204 W}).
² Equation 13.6, using a diet with 14 MJ DE/kg.
³ 0.13W^{0.75}.
⁴ 0.013W/(1 – digestibility coefficient); digestibility coefficient = 0.8, 0.75, 0.75, 0.70, 0.70, 0.65, 0.65 and 0.65 at each live weight, respectively.

or this latter being some 3.2 times maintenance. These estimates are shown in Table 13.2.

Practical feed intakes may be less than the maximum because the nutrient requirement is satisfied well within the limits of gut capacity. More realistic, however, is that production management circumscribes intake even below optimum nutrient needs. Negative factors may include feed palatability, inadequate trough space, between-pig aggression, ill-health, nutrient imbalance, ambient temperature, stocking density and so on. Some attempt can be made at quantification of the last two factors.

Temperature (T) above the comfort level (Tc) will diminish feed intake at the rate of 1 g per °C (T – Tc) per kg of pig body weight, and Tc is dependent upon heat output – that is, the metabolic activity of the pig. Figure 13.6 (relating to a pig of around 80 kg live weight) shows how the daily intake of feed is directly and nega-

### Table 13.2. Achieved feed intakes by pigs fed ad libitum under practical conditions.

<table>
<thead>
<tr>
<th>Live weight of pig (kg)</th>
<th>Equation 13.8</th>
<th>Equation 13.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.90</td>
<td>1.13</td>
</tr>
<tr>
<td>40</td>
<td>1.59</td>
<td>1.75</td>
</tr>
<tr>
<td>60</td>
<td>2.16</td>
<td>2.26</td>
</tr>
<tr>
<td>80</td>
<td>2.67</td>
<td>2.71</td>
</tr>
<tr>
<td>100</td>
<td>3.16</td>
<td>3.12</td>
</tr>
<tr>
<td>120</td>
<td>3.63</td>
<td>3.50</td>
</tr>
<tr>
<td>140</td>
<td>4.07</td>
<td>3.86</td>
</tr>
<tr>
<td>160</td>
<td>4.50</td>
<td>4.19</td>
</tr>
</tbody>
</table>

1 Feed intake (kg/day) = 0.10 W^{0.75}.
2 DE intake (MJ/day) = 2.4 W^{0.63}, using a diet of 14 MJ DE/kg.

![Fig. 13.6 Influence of temperature upon appetite. Increase in temperature first reduces intake due to reducing demands for cold thermogenesis; next, higher temperatures depress appetite as the pig responds to the need to avoid heat stress.](image-url)

Feed intake (kg/day) = 0.10 \ W^{0.75} \quad (13.8)

or

DE intake (MJ/day) = 2.4 \ W^{0.63} \quad (13.9)

this latter being some 3.2 times maintenance. These estimates are shown in Table 13.2.

Practical feed intakes may be less than the maximum because the nutrient requirement is satisfied well within the limits of gut capacity. More realistic, however, is that production management circumscribes intake even below optimum nutrient needs. Negative factors may include feed palatability, inadequate trough space, between-pig aggression, ill-health, nutrient imbalance, ambient temperature, stocking density and so on. Some attempt can be made at quantification of the last two factors.

Temperature (T) above the comfort level (Tc) will diminish feed intake at the rate of 1 g per °C (T – Tc) per kg of pig body weight, and Tc is dependent upon heat output – that is, the metabolic activity of the pig. Figure 13.6 (relating to a pig of around 80 kg live weight) shows how the daily intake of feed is directly and nega-
tively related to temperature. At low temperatures there is an energy demand for cold thermogenesis. As this demand diminishes with temperature rise, intake will fall pro rata (as indicated by Equation 13.1). In the comfort zone, daily feed intake is likely to stabilise. At temperatures above $T_c$ there is again seen to be a steep negative relationship as a progressive temperature rise induces intake depression according to Equation 13.2.

The influence of stocking density also merits further elaboration. Daily gain is adversely affected by increasing stocking density. Most of this response is due to a reduction in feed intake. Where the area occupied by the pig ($m^2$) is $k W^{0.67}$, a change in $k$ value of 0.005 below optimum may be taken to be associated with a 4% change in feed intake (when $k \approx 0.025$ there is just sufficient space for the pig to lie down – usually $k \approx 0.040–0.050$ in acceptable intensive housing systems). The relationship between change in $k$ and feed intake is likely to be universal for growing pigs. For a 60 kg pig eating 2.0 kg of feed, a change in $k$ value of 0.005 would give a reduction of 80 g daily, or about 0.1 kg of potential feed intake per pig per day lost for each 0.1 $m^2$ loss of floor space.

**Estimation of feed intake in sows**

From Equation 13.3 the physical limit to feed intake for a sow eating a diet that is 0.70 digestible is probably around 5 kg at 120 kg live weight, and 11 kg at 250 kg; which is, of course, much greater than the asymptote identified for growing pigs. Nutrient demand, given a reasonably balanced diet, during pregnancy and between weaning and conception will be within this limit. Indeed, sows given concentrated diets will readily consume a further 0.5 kg or more of straw daily, either to fill vacant space in the gut or perhaps to satisfy the motivation to forage. Appetite in the non-lactating adult sow is therefore likely to be a function of the various demands of maintenance, fetal load, cold thermogenesis, growth and (equally important) the replacement of fatty tissue catabolised during lactation; that is to say, as indicated in Equation 13.1.

The lactating sow is usually unable to satisfy nutrient demand within the limits of appetite, and will lose body fat to bridge the deficit. This problem is particularly acute in the first lactation where voluntary feed intake in gilts is invariably at least 1 kg per day lower than that for sows. This is probably due to a combination of lower body size and increased stress. Increasing sow appetite with parity number and live weight is frequently observed, and in general sow appetite is consistent with the ‘four times maintenance’ proposition, which can also be expressed as $0.12 W^{0.75}$. Many types of sow will indeed well exceed this intake and manage more than 10 kg of food daily in lactation. The propensity of many of today’s lean breed types, however, is to consume much less than that, and lactation feed intakes of 4–8 kg are the conventional expectations. These reduced feed intakes are probably not solely the result of selection against fat, and therefore against appetite. Amongst other things, modern farrowing and lactating rooms frequently place the sow under heat
stress. With a comfort temperature ($T_c$) of around 15°C, a room temperature ($T$) of 25°C will reduce the appetite of a 200 kg lactating sow by 2 kg (Equation 13.2). It may therefore be estimated that:

$$\text{Feed intake (kg/day)} = [0.013 W/(1 - \text{digestibility coefficient})] - [W(T - T_c)/1000]$$

which is an elaboration on Equation 13.3 and likely to be more general.

Low lactation feed intakes may be ameliorated by:

- feeding more frequently (maximum intake at a single meal is probably 3–4 kg, indicating benefit from three times daily feeding);
- feeding wet rather than dry (the simplest expedient of providing a water:food ratio of 3:1 will increase feed intake by 10–15%);
- allowing additional ample clean water separate from the food;
- reducing ambient temperature to 15°C;
- using high concentration diets (greater than 14 MJ DE/kg – increasing energy concentration by use of fats and oils rather than starches is helpful because fats are used more efficiently, and therefore produce less heat whilst being metabolised);
- feeding during cooler times of day, and using water drips and snout coolers (which may be worth 1–2 kg of extra feed intake daily in hot climates);
- provision of a balanced diet, with adequate protein.

There is a well known negative relationship between the level of pregnancy feed intake and appetite in lactation, but this is not especially strong and is probably mediated through sow body fatness at parturition as indicated by $P_2$ backfat depth (mm):

$$\text{Lactation feed intake (kg in 28 day)} = 240 - 0.20 (\text{feed intake in 115-day pregnancy})$$

or

$$\text{Lactation feed intake (kg in 28 days)} = 212 - 3.6 P_2$$

In addition to being negatively related to body fat, lactation feed intake is positively related to lactation yield; that is, the number of piglets sucking. Where capacity limits due to the physical size of the gut are not in play, it may be calculated that each piglet will demand about 1.2 kg of fresh milk daily, and this will require 8 MJ of dietary ME/kg of milk produced, or about 0.7 kg of feed per sucking piglet per day. So the feed intake of lactating sows could be described as:

$$\text{Feed intake (kg per day)} = A + 0.7x$$

where $x$ is the litter size and $A$ is the maintenance requirement (say, in kilograms of feed daily, 0.033 $W^{0.75}$). The consequence of the use of these propositions is shown in Table 13.3. As discussed elsewhere, it has been estimated empirically that lactating sows of average weight, with acceptable litter size and consuming less than 8 kg of an average diet are likely to lose body fat, a proposition in accord with Equation 13.13. Usually, the sow never achieves a rate of increase in feed intake of 0.7 kg for
each extra sucking piglet; more often a response in the region of 0.4 kg of extra feed intake per extra sucking piglet can be expected. Because this response is inadequate to maintain nutrient balance, there is an inevitable loss of maternal fatty (and lean) tissues which are catabolised and go towards supplying the nutrient needs of lactation. Lactating sows appear well aware of forthcoming difficulties of nutritional supply in lactation and, like most other mammals, are happy to deposit fat during pregnancy, in order to lose it during the subsequent lactation.

**Nutritional enhancers: supplements that may modify appetite and/or the nutritional value of feeds**

**Specific dietary ingredients**

There is ample evidence that pigs will eat, initially at least, more of feedstuffs that are sweet. Sugar itself is highly palatable, but it must not be assumed that sugar inclusion will necessarily overcome the unpalatable aspects of other diet ingredients. Cooked and flaked cereals, oils and fresh and dried milk are amongst the range of feedstuffs appreciated by pigs. On the other hand, appetite depression will result from dietary inclusion of ingredients such as poorly processed and conserved meat-and-bone meal, some fish meals, rapeseed meal (both high and low glucosinolate, but the former is rejected more vigorously than the latter), cotton seed meal and, to a certain extent, also some bean meals. Pigs are also averse and may show severe appetite depression to lectins, mycotoxins, glucosinolates, tannins, saponins, sinapines and such like toxic and anti-nutritional factors. Correct choice of ingredients is fundamental to appetite maximisation.

**Feed enzymes**

Feed carbohydrates are made up of sugars (few), starch and the structural carbohydrates or non-starch polysaccharides. The non-starch polysaccharides contain β-glucans and pentosans. The relative proportions of these differ between feedstuffs (barley endosperm is richer in β-glucans, and wheat in pentosans). β-glucans make up 2–8% of barley grain, depending on variety; the level and nature of the wheat
pentosan component is also variety dependent. Carbohydrates are digested not only in the stomach and small intestine, but also in the large intestine. In the pig, microbial fermentation is the only adequate system available for the hydrolysis and digestion of non-starch polysaccharides. Microbial fermentation will take place throughout the gut, but mostly in the large intestine and caecum. Bacterial carbohydrases will yield mostly the volatile fatty acids lactate, acetate, butyrate and propionate, which are utilised about half as well as glucose.

The addition of enzymes to the feed is purported to break down carbohydrates and improve digestibility. If this is so, then, according to Equation 13.3, at any given live weight, feed intake on bulky foods will increase. The yield of the nutrient from each unit of feed ingested will also increase. If the enzyme attacks the fibre components of the carbohydrate fraction and reduces the bulk loading in the gut, then there is potential for a third positive factor influencing nutrient intake. It is reasonable, therefore, that enzyme preparations should be considered for use in diets for young pigs; but their efficacy should not be taken for granted.

The enzyme system of the young pig is highly milk-orientated until around 4 weeks of age when the need to digest solid food becomes dominant (Figure 13.7). In-feed enzymes may therefore act beneficially in diets for young pigs whose own limited enzyme systems might be supplemented or whose natural enzyme secretions might be complemented by enzymes not normally occurring in the intestine – such as fibre-digesting cellulases.

Gastric pH in the empty stomach is around 2, which is below the working tolerance of most carbohydrases. However, the oesophageal part into which feed falls is maintained above that level, and after a meal the gastric pH rises significantly in any event. The possibility of exogenous enzyme action taking place in the stomach is supported by the finding that salivary carbohydrase itself (active at pH > 4.0) probably has 2–3 hours of action time there. Bacterial fermentation also occurs in the stomach, producing lactic and organic acids; Lactobacillus is mainly responsible in the sucking pig for lactic acid production.

The capacity of the small intestine to digest starch increases in direct response to the presence of starch in the gut. Within about 2 weeks of a significant challenge, ample carbohydrase is available for any conceivable need for simple starch hydrolysis; but this is to assume the absence of the protection of feed carbohydrate by
non-starch polysaccharide cell wall materials not attacked by intestinal carbohy-
drases. It is also apparent that whereas most of the cereal starches are relatively
simple, those in non-cereal vegetable feedstuffs such as bean meals may be more
complex and less readily digested. Perhaps most important of all, however, has been
the observation that not only is weaning associated with a massive change in nutrient
substrates (from milk to cereals, and animal to vegetable proteins), but also the
trauma itself appears to compromise the effective workings of the small intestinal
and pancreatic enzyme systems.

On the face of it, therefore, it is reasonable to propose, especially for newly
weaned and young growing pigs, the following:

(1) The use of in-feed enzymes may lend support to conventional starch digestion
by their action in the stomach.

(2) Enzymes may be especially helpful when used in diets containing high levels
of complex non-starch polysaccharides (NSP), such as lupin, sunflower, rape-
seed and bean meals, or where particular ingredients are known to contain
troublesome NSP, such as arabinoxylans in rye, triticale and some wheats.

(3) Supplementation of the endogenous system by exogenous in-feed cellulase
enzymes which may digest non-starch structural carbohydrates, and which may
be active both before ingestion and in the gut, will not only yield useful nutrients
from otherwise unavailable substrate, but also release starches and proteins
previously protected in plant material by indigestible cell walls.

(4) The potency of polysaccharide anti-nutritional factors will be reduced by
in-feed enzymes, and the problematic increase in digesta viscosity caused by
β-glucans will be diminished.

In the case of the non-starch polysaccharidases, however, it is well to remember
that there are between-ingredient differences in the type of non-starch polysaccha-
ride present, and the enzymes used require to be specific. Thus barley-based diets
might benefit most from β-glucanase and wheat-, rye- or triticale-containing diets
from pentosanase (arabino-xylanase).

The digestion of vegetable protein is known to be poor in young pigs immedi-
ately post-weaning, and the milk-based endogenous protease system takes some
time to build up to adequate levels to provide the daily nutrient needs from veg-
etable protein sources. In the frank absence of adequate protein digestion capabil-
ity, support from exogenous protease enzymes is a valid concept.

Commercial products containing cocktails of amylases, β-glucanases, pen-
tosanases, general cellulases (lipases) and proteases are available for incorporation
into dry pig diets. It is clear that these will result in active hydrolysis of starches,
non-starch polysaccharides and proteins, in both cereals and vegetable protein con-
centrates, upon addition of water and heat in the laboratory. Additions of a com-
prehensive enzyme cocktail to cereal-based diets appear to increase marginally the
digestibility of starch and non-starch polysaccharides in young piglets, but there is
not always any noticeable improvement in performance. While not all experiments
are reported, and there may be some bias toward positive results being reported
more often, there is a commercial perception (which may or may not be justified) that up to 2–3% improvement in daily gain may be achieved. This presumably comes from a combination of improved digestibility and enhanced appetite. Similar or slightly greater claims are made for the cooking, flaking and extrusion of cereals. It has been suggested that arabinans and xylans – especially in wheat, triticale and rye – can cause digestive disturbance, and in this eventuality their early enzymic digestion by in-feed arabino-xylanases might be beneficial, but no proof of this remedy yet exists.

Objective and safe proofs for the efficacy of in-feed enzymes for dietary carbohydrates are slow in coming, but that may change in the future.

*Environmental pollutants*

Ammonia and hydrogen sulphide are both toxic and low levels of around 10 ppm or more of either will reduce appetite. The effects increase with gas concentration. Ammonia levels in intensive pig grower houses may rise above 50 ppm, while levels of hydrogen sulphide above 5 ppm may occur following slurry agitation. Levels of ammonia above 25 ppm will result in significant reductions in growth rate. Environmental gases are clearly best controlled by effective ventilation, but difficulty may arise when outside air temperatures are low. Recent commercial interest has been shown in the possibility of placing additives in the pigs’ feed that, upon passing into the slurry, appear to reduce ammonia levels. This may be achieved through binding the ammonia and buffering the system to prevent an over-rapid rise in pH. Encapsulated (i.e. digestion protected) microbial and enzyme products may also be added to the feed, on the supposition that these may act on the slurry, aiding odour-free slurry digestion. It appears that use of this material may, by decreasing gaseous ammonia levels when they exceed 10 ppm, improve feed intake and thereby pig performance. However, as with some other such new biotechnology developments in pig nutrition, the forces of commerce are somewhat ahead of the validations and explanations of science. Neither should it be assumed that other methods of reducing gaseous ammonia, which would clearly be beneficial, might not be equally effective. Deep-litter (sawdust) systems providing bedding for pigs and using *in situ* composting techniques may be associated with special substances that, when added to the bedding, are claimed to reduce gaseous emissions and aid fermentation. Such systems in any event can only tolerate stocking densities 30–50% more generous than conventional systems; but even then, the extent of the benefit of the additive has yet to be quantified.

*Addition of dietary organic acids*

Gut acidity levels are normally between pH 2 and 4 in the stomach, and rise to pH 5–6 in the small intestine, and again up to 7 in the large intestine. At pH levels above 6, there is increasing likelihood of reduced efficiency of enzyme action and increased proliferation of pathogenic bacteria in the gut. For both these reasons there is a
close relationship between maintenance of optimum gut pH and pig appetite. Organic acids such as propionic, formic, citric, lactic and fumaric may readily be added to the diet, and these may help to counter the likelihood of pH rise in the stomach which can occur when young pigs are stressed. Diet organic acids may help the gut environment and through that assistance enhance feed intake and reduce the incidence of diarrhoea post-weaning. However, as organic acids tend to operate through helping to cover for the loss of lactic acid bacteria which would otherwise have been encouraged by lactic acid from ingested milk, then dietary additions of acids tend to operate best on cereal/soya-type diets containing no milk products.

It may also be important that individual feed ingredients have markedly different acid-binding capacities. The acid-binding capacity of liquid milk and cereals is low, but that for dried milk and for animal and vegetable proteins (and also limestone) is high. In the immediate post-weaning period there is particularly likely to be a predisposition to a rise in intestinal pH. There is little experimental evidence giving clear information about the mode of action of efficacy of in-feed organic acids in addressing the problem (if there is one) of elevated intestinal pH.

**Addition of micro-organisms – probiotics**

Various micro-organisms have been put forward as having beneficial influence within the environment of the gut, to ameliorate appetite depression after weaning and later to enhance appetite in young growing pigs. The objective of adding micro-organisms to the diet is to direct the gut flora away from abnormal or unhealthy species. Pathogenic organisms attach to the gut mucosa and from there produce toxins. Competitive attachment of non-pathogenic species at binding sites will therefore prevent toxin production. Cultures presumed beneficial, and often used, are special strains of *Lactobacillus*, *Streptococcus (Enterococcus)*, *Bifido bacterium* and various *Bacillus* species. *Lactobacillus* would, in the normal course of events, be encouraged by mother’s milk for the fermentation of lactose and the production of lactic acid. However, this natural population would rapidly diminish upon weaning. Loss of *Lactobacillae* may have negative effects for gut acidity and also, following their absence, they may be replaced in the flora with pathogenic species. The two major claims made for in-feed additions of micro-organisms are therefore that:

1. an optimum gut pH is maintained; and
2. by competitive and antagonistic effects, the growth of pathogens such as *Escherichia coli*, *Salmonella* and *Staphylococcus* is curtailed.

*Lactobacillus* and *Streptococcus* cultures may be combined with an appropriate yeast (*Saccharomyces*) culture, which is also purported to stimulate feed intake. Giving doses of benign *Bacillus* bacteria to sows has been ‘claimed’ not only to improve the reproductive performance of the sows, but also – by modification of the flora in the environment – to improve the performance of sucking and weaned piglets.
Yeast (*Saccharomyces*) may be used as a feed ingredient at low levels of inclusion as a source of nutrients (especially B vitamins), and at micro inclusion levels (1 g/kg) of live culture as a probiotic, where it is purported to regulate gut flora in a beneficial way, and/or ameliorate *E. coli* toxins, and/or be aggressive toward pathogenic organisms, and/or make a net contribution of enzymes to the system.

Improvements in feed intake and performance as a result of dietary microorganism additions are notoriously variable. It is a prerequisite that ingested cultures are first efficacious in maintaining pH and competing against pathogens and, second, are included at sufficient levels to multiply rapidly into viable gut populations. There is inadequate experimental evidence to date to show clearly that the theory is translated into effective practice. Bold claims are often poorly based on objective science and are difficult to substantiate. Reviews of many experiments completed in the 1980s and 1990s world-wide have shown that whereas antibiotics may be expected to improve growth rate by 5–10%, the expectations for probiotics are 0–5%. Some workers have been bold enough to report growth suppression in some cases of probiotic supplementation. In all cases it is evident that response to probiotics is certainly extremely variable and much more so than for antibiotics, for which a positive result is assured in some 60% of cases where they are used. The cost–benefit of a highly variable response, which may only be 2.5% when it is achieved, is doubtful. It would appear that much more needs to be understood about the mode of action of specific probiotic treatments in relation to specific pathogens before the verdict that probiotics are efficacious could be considered safe.

**Addition of antibiotics**

In-feed antibiotics at ‘growth-promoter levels’ enhance appetite and growth by combating the negative effects of gut pathogens (through suppression of the pathogenic microbial flora), and also by enhancing the absorptive capacity of the gut. Positive responses in healthy animals are more difficult to show than the clear benefits of antibiotics in the treatment of intestinal disorders. Antibiotic addition to the diets of newly weaned pigs especially has been common practice for many years, and the benefits to feed intake and growth are unequivocal and may be as great as 10%. Should additions also be able to prevent a frank outbreak of disease, the benefits are, of course, considerably greater. Benefits to young growers may be somewhat less (around 5–10%), whilst the response appears to reduce to something a little less than a 5% improvement when antibiotics are included in the diets of finishing pigs. These positive responses have been confirmed over a great many individual experiments and through years of production experience. The positive responses of antibiotic additions to the diet show relatively little variation, particularly when compared to the wide variation that is presently being found for response to dietary organic acids, in-feed enzymes and ‘probiotic’ microbial cultures. Some in-feed antibiotic/antimicrobial compounds derived from benign micro-organisms may also be employed not so much with a view to inhibiting pathogens but as enhancing feed intake directly – especially in younger pigs. However, concerns over the unrestricted
use of antibiotics which may increase the risk of bacterial resistance to them has recently led the EU to legislate for their complete ban from use in pig feeds. Although the benefits from in-feed antibiotics on appetite and performance of pigs is unquestionable the above risks may outweigh them.

**Flavours, flavour-enhancers and masking agents**

Positive flavour effects are assumed to increase feed intake (1) by heightening the pig’s appreciation of an acceptable taste in the diet, (2) by adding an acceptable taste or (3) by masking an unacceptable taste. Prevention of mould growth in feeds by proper harvesting and storage is basic to appetite maximisation. The use of mould inhibitors, such as propionates, could be interpreted, with regard to pig appetite, as a negative activity. Pigs are susceptible to diet fat oxidation and rancidity; appetite depression through loss of palatability is marked. Antioxidants include both synthetic (such as BHA and BHT) and natural (such as tocopherol) products.

Given the absence of a need to mask off-flavours, the concept of a dietary appetite enhancer is most attractive and has raised commercial expectation and speculation over many years. However, the idea that a pig might be encouraged to eat more poses the question of why that pig is presently eating less, and the search for a reason as to how a flavour compound might address that cause. It may be surmised that in the majority of cases the positive effects of feed flavours – where they are present – are more often due to the masking of negative palatability rather than the creation of positive palatability. Exceptions may perhaps be specific attractants that relate to the provision of positive cues for pig foraging and eating behaviour which would have had helpful evolutionary benefits. Even these attractants, however, may have only a transient effect in enhancing pig appetite. The pig very quickly learns to regulate its food intake on the basis of the diet nutrient content.

Spices have been usually associated with the masking of off-flavours, but this may be an inappropriate generality. Amongst other things, mixed spices may contain attractive aromatic oil essences which may be positive to palatability and also may stimulate enzyme production. Other – unsubstantiated – claims involve suppression of gut pathogens and feed mycotoxins. While all possibilities remain of interest, feed palatability is likely to be ensured first and foremost by provision of fresh and well-stored ingredients of high quality which are themselves found by the pig to be pleasant to eat.

**Form of feed and method of presentation**

There remains debate as to whether maximum feed intake is more likely to be achieved on pellets, crumbs or with meal. There is considerable interaction with feeding method. In general, medium-ground cereals are more readily eaten than those either coarse- or fine-ground. Small pellets or crumbs are preferred to large pellets or a fine meal. Fine meals may become pasty in the mouth and stomach and reduce both palatability and rate of outflow from the gut; they are also implicated
with gastric ulceration. Meals create dust in buildings which increases the likelihood of respiratory disease and reduces environmental acceptability. Meals are more costly to transport (being less dense) and are prone to being wasted at the point of consumption (comparative wastage rates for meal and pellets being around 6 and 2% respectively). Pellets are, however, more costly to produce.

All forms of feed are eaten in greater quantity if presented wet rather than dry. Some grower/finisher feeder designs incorporate water flow into dry feed systems, thus allowing moistening of the feed at the point of consumption. Pipeline feeding allows presentation of wet-fed ‘meals’ frequently through the day, and although the pigs are not fed ad libitum, feed intake per day is greater due to the pig’s preference for eating its food wet. However, if all the food presented at each meal is not eaten up, then there is a risk of spoilage as wet pig feed ferments quickly, and the type of fermentation cannot be easily controlled. This is especially relevant for weaners and young growers which, while being the most likely to benefit from wet feeding (due to appetite limitation of growth rate on dry-feeding systems), are also the most likely to suffer from loss of feed palatability due to spoilage of feed left over from the previous meal.

It is an essential part of appetite enhancement that fresh water is near at hand, trough space is ample and feeding opportunities sufficiently frequent. Ad libitum feeding from self-feed hoppers rarely, if ever, maximises feed intake. Often the flow is unduly restrictive (a necessity for wastage avoidance); but that notwithstanding, the feed is often presented dry and stale, while access may be curtailed for pigs lower in the social dominance hierarchy.

The realisation that appetite is one of the most important factors limiting productivity has led to much attention being given to the influence of diet nutrient content and of feed additives in appetite enhancement. However, in practice, the major factors influencing individual feed intake of pigs are management related; not least the presence of disease and inadequate space allowances in newly weaned, growing and finishing pigs, and high ambient temperatures and inadequate feeding arrangements in lactating sows.
Introduction

More expenditure is incurred in the purchase of pig feed than in all the other costs of a pig unit put together. Pig production is an exercise in turning animal feedstuffs into high-quality pig meat at the most beneficial cost:value ratio.

The pig producer may buy diets from feed compounders, or compound them himself. Any pig feeding programme will require at least seven pieces of nutritional information about the diets:

1. the energy concentration;
2. the concentration of essential amino acids;
3. the protein (amino acid) concentration or protein:energy ratio;
4. the efficiency of utilisation of energy;
5. the efficiency of utilisation of amino acids;
6. the quality of the protein used (or protein value);
7. the adequacy of vitamin and mineral levels.

Diets are made by mixing feed ingredients to achieve a given nutrient specification; that is, a predetermined requirement for the concentration in the diet of certain named nutrients [for example, 14 MJ DE (or 9.9 MJ NE)/kg, 10 g lysine/kg, 200 g CP/kg]. Pigs will eat a wide range of feedstuffs and those listed in Appendix 1 are merely representative. Diets high in fibre may, however, limit intake to the detriment of performance. Most conventional diets are formulated from grains (maize, wheat, barley, oats, rye, sorghum), supplemented with higher quality protein sources [beans, peas, oilseed rape meal, sunflower meal, meat meals (not presently in the EU), fish meals, but especially soya bean meal]. Other energy and protein contributions may come from roots (beets, potatoes, manioc) and by-products (fats and oils, human food industry by-products, milk products). Diets will often also contain, where appropriate, additives and growth-promoting agents.

For purposes of simplicity of expression of the concepts, this chapter will express energy primarily in terms of DE (and ME as 0.96 of DE) and amino acids in terms of total lysine, as these are presently the common usage. However, as earlier chapters have explained, the use of NE to express energy value of feedstuffs (and pig requirement) and standardised ileal digestibility of amino acids to express protein value adds substantially to the efficiency of compounding. It is recommended that
diet formulators who have not already done so benefit from the efficiency gains of moving to NE/standardised ileal digestibility systems of diet formulation as soon as practicable.

NE values and standardised ileal digestibility values for feeds and NE and standardised ileal digestibility requirements of pigs have been described in earlier chapters and the appendices. In addition, the reader is referred to the British Society of Animal Science (2003) *Nutrient Requirement Standards for Pigs*, BSAS, Penicuik, Scotland, and the British Pig Executive (2004) *Feed Formulations for Pigs*, MLC, Milton Keynes.

**Energy concentration of the diet**

The energy concentration of pig diets may range from as low as 11 MJ DE/kg for diets containing grass meal and other roughages, to more than 16 MJ DE/kg for diets formulated from high energy ingredients such as maize, full fat soya bean and added feed fats. Dietary energy concentration is negatively related to fibre levels and positively related to oil levels. Where NDF is the neutral detergent fibre (g/kg diet dry matter) and OIL is the content of total oils and fats (g/kg diet DM), then

\[
\text{DE (MJ/kg DM)} = 17.0 - 0.018 \text{NDF} + 0.016 \text{OIL} \tag{14.1}
\]

The nutrient concentration of a particular weight of diet depends, of course, upon its water content. Diets are usually prepared and offered to pigs in air-dry form; where water is added it being incorporated at feeding time. Some diet ingredients may, however, be available wet, such as root crops (10–25% DM), fish silage (15–25% DM) and liquid milk by-products (4–13% DM). There are many industrial wastes from the human food and drinks industries of high quality, and these may range from 2–30% DM.

Pig diets formulated from mixtures of cereals and soya bean are usually 85–92% DM, depending upon the moisture content of the cereals. The convention is to assume about 87% DM (13% water) in a pig diet unless otherwise stated, and nutrient concentrations for pig diets are usually, but not invariably, expressed on an air-dry basis assuming 87% DM (the National Research Council uses 90%).

Proper comparison of diets differing in water content requires correction to equal water content (Table 14.1). To provide a given quantity of energy, more feed needs to be offered if the diet is of low energy concentration, and less if the diet is of high energy concentration. To provide 30 MJ DE, 2.6 kg is needed of a diet with 11.5 MJ DE/kg, while only 2.2 kg is needed of a diet with 13.5 MJ DE/kg. For rapid growth or high production where substantial nutrient intakes are required, more concentrated diets are needed if the capacity of the gut for food is inadequate in relation to nutrient requirement – as is often the case with young growing pigs and lactating sows. Pigs of lower productivity with large appetites, such as growers above 80 kg and pregnant sows, are able to use diets of lower nutrient density (Table 14.2).
Any pig given a feed allowance that is less than its appetite could be given a diet of lower nutrient density; but it may or may not be economic to do this.

**Protein:energy ratio (g CP/MJ DE)**

Dietary protein is usually discussed in terms of crude protein (CP). This is less useful than digestible crude protein (DCP) because there may be a range of 0.4–0.9 in the digestibility coefficient of different dietary protein sources. However, it appears likely that differences in protein digestibility may be accommodated best by recognition in feed compounding of the importance of the level of the ileally digested amino acids; which have been discussed earlier, and of which there will be more later.

The concentration of protein required in the diet depends upon the total amino acid needs for lean tissue growth or for milk production in comparison to energy needs for body fuelling. Larger animals have higher energy demands for body maintenance and therefore need diets with a narrower protein:energy ratio. Pigs whose growth is destined to be low in lean content and high in fat have a lower protein requirement, and therefore do not need diets of high protein concentration. Smaller pigs with lower maintenance needs, pigs with high lean tissue and low fatty tissue

### Table 14.1. Comparison of diets of differing water content.

<table>
<thead>
<tr>
<th></th>
<th>‘Wet’ diet</th>
<th>‘Dry’ diet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry matter of diet (%)</td>
<td>32.8</td>
<td>87.0</td>
</tr>
<tr>
<td>DE content of diet (MJ DE/kg)</td>
<td>5.0</td>
<td>13.5</td>
</tr>
<tr>
<td>CP content of diet (g CP/kg)</td>
<td>75</td>
<td>180</td>
</tr>
<tr>
<td>DE content of diet corrected to 87% dry matter</td>
<td>13.3(^1)</td>
<td>13.5</td>
</tr>
<tr>
<td>CP content of diet corrected to 87% dry matter</td>
<td>199(^2)</td>
<td>180</td>
</tr>
</tbody>
</table>

\(^1\) \(\frac{5.0}{0.328} \times 0.87 = 13.3\).

\(^2\) \(\frac{75}{0.328} \times 0.87 = 199\).

### Table 14.2. Lower limits for energy density range appropriate to various types of pig\(^1\).

<table>
<thead>
<tr>
<th></th>
<th>MJ DE/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young piglet (5–15kg)</td>
<td>14</td>
</tr>
<tr>
<td>Grower (15–30kg)</td>
<td>14</td>
</tr>
<tr>
<td>Grower (30–100kg)</td>
<td>13</td>
</tr>
<tr>
<td>Pregnant breeders</td>
<td>11</td>
</tr>
<tr>
<td>Lactating breeders</td>
<td>13</td>
</tr>
</tbody>
</table>

\(^1\) The upper limit for the energy density range is not dependent on the type of pig, but on the feasibility of the diet. Thus all pigs could be given diets with 14 MJ DE if this was the most economic concentration (perhaps if maize was inexpensive compared to barley). Pigs offered higher density diets should have lower feed allowances *pro rata*.
growth rates and lactating sows need more protein and therefore diets with wider protein:energy ratios (Table 14.3).

Pig diets may be divided into three broad classes according to their protein:energy ratio. Diets with 13 g CP/MJ DE or less are appropriate to pregnant adult females and growers above 80 kg live weight. Diets with 13–14 g CP/MJ DE are appropriate to lactating females and growing pigs between 30 and 80 kg. Diets with more than 14 g CP/MJ DE are appropriate to pigs of less than 30 kg live weight, and to pigs of greater than that weight which have particularly high potentials for daily lean tissue growth rate.

Although diets may be usefully described by their protein concentration alone (g CP/kg diet), this value is of little use unless the DE concentration (MJ/kg diet) is also known – that is to say, unless the protein concentration is expressed in terms of the protein:energy ratio. Table 14.3 shows that to provide for the pig’s protein requirements a diet of higher energy density may also need to be of higher protein density. The range of possible energy densities for pig diets is wide, the upper limit being about 17 MJ DE/kg and controlled by the availability of high-energy ingredients. The lower limit depends on pig type and may go below 11 MJ DE/kg depending primarily upon animal appetite (Table 14.2). A concentration of 165 g CP/kg diet represents a high level of protein if the associated energy concentration is only 12 MJ DE/kg, but would represent a low level of protein if the associated dietary energy concentration was 15 MJ DE/kg.

The number of different diets (phases) found on a single pig unit depends much upon the number of differing classes of pig requiring either different dietary energy concentrations or different dietary protein:energy ratios. Sometimes management simplicity outweighs nutritional efficacy, and at the (absurd) extreme a single diet of about 14 MJ DE and with 13 g CP/MJ DE may be used for all pigs. Such an arrangement is straightforward, but not optimum in terms of efficiency of feed use and will incur costs of lost production and wasted nutrients. The other extreme is to use as many diets as there are pig classes, and to define the pig class as narrowly

<table>
<thead>
<tr>
<th>Class</th>
<th>DE density (MJ/kg)</th>
<th>CP density (g/kg)</th>
<th>g CP/MJ DE</th>
<th>Lysine (g/kg)</th>
<th>Lysine (g/MJ DE)</th>
<th>Protein value (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starter (up to 15kg)</td>
<td>15.5</td>
<td>250</td>
<td>16</td>
<td>14.8</td>
<td>0.95</td>
<td>0.85</td>
</tr>
<tr>
<td>Young grower (up to 30kg)</td>
<td>15.0</td>
<td>225</td>
<td>15</td>
<td>12.8</td>
<td>0.85</td>
<td>0.80</td>
</tr>
<tr>
<td>Finisher (up to 100kg)</td>
<td>14.0</td>
<td>200</td>
<td>14</td>
<td>10.5</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Finisher (up to 160kg)</td>
<td>13.0</td>
<td>160</td>
<td>12</td>
<td>8.4</td>
<td>0.60</td>
<td>0.70</td>
</tr>
<tr>
<td>Pregnant breeder</td>
<td>12.5</td>
<td>140</td>
<td>11</td>
<td>6.0</td>
<td>0.50</td>
<td>0.65</td>
</tr>
<tr>
<td>Lactating breeder</td>
<td>14.0</td>
<td>180</td>
<td>13.5</td>
<td>10.0</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Improved entire male grower</td>
<td>14.0</td>
<td>225</td>
<td>16</td>
<td>12.8</td>
<td>0.90</td>
<td>0.80</td>
</tr>
<tr>
<td>Unimproved castrated male grower (40kg)</td>
<td>13.0</td>
<td>160</td>
<td>12</td>
<td>7.8</td>
<td>0.60</td>
<td>0.70</td>
</tr>
</tbody>
</table>
as possible (ultimately one animal at one moment in time). This will maximise the efficiency of feed use, but programmes involving a substantial number of different diets are only likely to be feasible in larger production operations and where there are automatic mixing and feeding systems that may be modulated on a day-to-day basis. Larger units are usually able to handle a greater number of different diet specifications than smaller ones. A frequent solution to be found in practice is to have two special diets for young piglets up to 13 kg or so, a third diet for growers up to 30 kg or so, a fourth diet for finishing pigs, a fifth diet for pregnant sows and a sixth for lactating sows. Many units also use a seventh diet which is incorporated into the growing pig programme, and is especially appropriate if the pigs are finished at weights greater than 100 kg.

**Protein value (V)**

The value of feed proteins for pigs relates to the feed’s amino acid composition in comparison to the balance required by the pig. A perfect match between the amino acid balance in feed protein and the amino acid balance required may be expressed as a protein value of unity (V = 1.0). The proteins of some feed ingredients such as soya bean and fish meal impart high protein value to the diet, while others such as the protein of cereals (which is deficient in lysine) impart a lower protein value to the diet. Reduced protein value may result from a relative deficiency in any one of the essential amino acids, but in pig diets it is usually found that lysine, threonine, methionine or tryptophan are (in that order of importance) implicated. So often is lysine the first limiting amino acid that compounders may add up to 3 kg/t (or occasionally more) of ‘synthetic’ lysine hydrochloride if it is of reasonable price, together with around 1 kg/t of threonine and similar amounts of methionine. There may also be some insurance value in this if feedstuffs of unusual type or dubious quality are being used.

A high protein value (V), like a high energy concentration (DE), is not an objective necessarily to be sought after, but good information is needed about protein value (just as about DE) so that appropriate adjustments can be made to feeding level and appropriate judgements made as to monetary value. A given protein requirement can be satisfied by provision of a higher quantity of protein of lower value, or a lower quantity of protein of higher value. Some guide as to the lower limits that may be expected for dietary protein value for various classes of pig are shown in Table 14.4. Protein of high value will be utilised more efficiently by the pig, but it may not be cost-effective always to use less of a higher quality protein as compared to using more of a lower quality – but cheaper – protein. Using a protein of lower value requires the diet to have a wider protein:energy ratio, and thus a higher crude protein level.

Where information on the value of diet protein is not available then a statement of the dietary level of the amino acid lysine can be of help, as this is often the first limiting amino acid and the major controller of diet protein value. With the knowledge that the pig’s requirement, expressed in terms of ideal protein, is for 0.07 g
lysine/g of protein, then protein value can be calculated from the dietary lysine level as follows:

\[ V = \frac{[\text{lysine in diet (g/kg)}/\text{CP in diet (g/kg)}]}{0.07} \]

(14.2)

Example protein values, calculated according to the concentration of lysine in the protein, are shown in Table 14.3.

**Table 14.4.** Lower limits for value of dietary protein appropriate to various classes of pig.

<table>
<thead>
<tr>
<th>Protein value (V)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Baby pig</td>
<td>0.80</td>
</tr>
<tr>
<td>Grower</td>
<td>0.70</td>
</tr>
<tr>
<td>Finisher</td>
<td>0.65</td>
</tr>
<tr>
<td>Pregnant breeders</td>
<td>0.60</td>
</tr>
<tr>
<td>Lactating breeders</td>
<td>0.65</td>
</tr>
</tbody>
</table>

1 The upper limit for value of dietary protein is dependent on the feasibility of the diet.

**Response to dietary concentration of DE**

Higher concentrations of DE in the diet are appropriate where pig productivity is below potential but the animal is already eating to maximum gut capacity; this is often the case for young growers and lactating sows. If the more concentrated diet ingredients are more expensive, then the extra productivity in terms of growth or milk production must be weighed against this extra cost. For pigs whose appetites are greater than the productivity required of them, a decrease in DE concentration can lead to cost-saving; provided the extra quantities that are needed of the cheaper diet do not cancel out the benefit.

If the protein:energy ratio remains unchanged then an increase in DE concentration will be exactly matched by an equivalent increase in protein concentration. The effect upon the pig will therefore be similar to it having been given (or to have voluntarily consumed) more food. To maintain constant performance while changing to a diet of lower or higher energy concentration, the food allowance must be increased or decreased appropriately (Figure 14.1). If there is no change in feed allowance, then an increase in energy concentration will increase energy supply (Figure 14.2).

Response to energy supply made by a 60kg growing pig is depicted in Figure 14.3. The rate of lean tissue growth will increase until maximum daily lean growth is achieved. The absolute level of this maximum is dependent, amongst other things, upon sex and genotype. During this phase of linear lean tissue growth response to increasing energy supply, the pig is unlikely to fatten. After lean growth is maximised, however, further increases in energy supply will go to the growth of fat which from this point onwards now escalates. Pigs with higher lean tissue growth poten-
Intakes will use more dietary energy before becoming fat. Figure 14.3 also shows how the response to energy will relate to diets of differing energy concentration; 2.25 kg of a diet with 11.5 MJ DE/kg would fail to maximise lean tissue growth, whilst the same level of food supply of a diet with a concentration of 14.5 MJ DE/kg would actually exceed the requirements for lean tissue growth rate, and the pig would fatten.
Responses of breeding sows to changes in the concentration of dietary energy are as readily predicted as in the case of the growing pig. If the change in DE concentration is accompanied by an equivalent and contrary alteration to the amount of feed supplied, then the nutrient intake effectively remains unaltered and there will be no change in productivity; although there may be a change in sow behaviour! If the intake level (or appetite) remains stable while the DE concentration of the diet alters, then the sow will respond to a decrease in energy supply by becoming thinner or lactating less, and to an increase in energy supply by becoming fatter or lactating more. In the case of breeding sows already thin, pregnant animals given more energy will produce heavier young, lactating sows will produce more milk and weaned sows will have improved conception rates. Over-fat sows given more food will both waste it and become even less productive.

Response to protein: energy ratio

Given sufficient dietary energy, an increase in the supply of diet protein (of adequate amino acid balance) will increase lean growth linearly until the maximum potential for lean tissue growth is attained. Additional increments of dietary protein cannot raise lean growth above that maximum. It should not be assumed that pigs that are not maximising their lean tissue growth potential would do so if they were given more protein. This would be to assume that lean growth was limited by a dietary protein deficit, and this is by no means always the case. Lean growth may be just as readily limited by an energy deficit (or indeed by environmental factors such as disease).

Figure 14.4 illustrates the type of growth responses that might pertain to a 60kg pig of relatively poor genetic merit and relatively low lean tissue growth potential. The example shows the pig to have been given one or other of three intake allowances of a diet with 12.5 MJ DE/kg, but with protein:energy ratios varying between less than 10 and more than 14 g CP/MJ DE. An intake of 1.5 kg daily (A) of a diet with only 10 g CP/MJ DE does not supply sufficient protein for lean growth. Increasing the protein concentration to 12 g CP/MJ DE corrects the situation and the lean growth rate improves. Dietary energy and protein are in balance at this point, and a further increment of protein to 14 g CP/MJ DE does nothing to alter the position, and although there is some 200 g of potential lean tissue growth yet to be made, no enhancement of lean tissue deposition occurs because lean growth is limited by a deficit of energy (an inadequate level of food supply). The excess protein is now an embarrassment to the pig, because its disposal uses up precious energy.

A protein concentration of 12 g CP/MJ DE maximises lean growth and minimises fat growth only within the confines of the overall feed intake allowance, which in case (A) is meagre. Lean growth is shown to be well below potential. If the feed allowance is now increased to 2.0 kg (B) then there is a general improvement in performance level. However, with less than 12 g CP/MJ DE there is again insufficient protein to maximise lean growth, and there is excess energy which induces fatness.
Maximum lean gain is achieved when 2 kg of diet with 12 g CP/MJ DE is given. This diet also minimises fat deposition. At protein levels above 12 g CP/MJ DE lean growth is limited by the pig’s potential (500 g daily). The situation in case (B) may be contrasted with that in case (A) where the limitation was due to energy shortage. Increasing protein concentration continues to decrease the amount of fat in the pig; so although at levels above 12 g CP/MJ DE there may be no further increase in daily lean tissue growth rate, there is continuing increase in the carcass lean percentage.

In case (B) the pig has not fattened because there is no excess energy. If, however, the feed intake allowance is raised to 2.5 kg of feed daily (C) then not only is maximum lean tissue growth reached at a lower level of protein concentration (10 g CP/MJ DE), but also the excess energy now present causes the accumulation of surplus fat in the carcass at all protein concentrations.

Figure 14.4 has demonstrated that if the protein:energy ratio is too narrow then lean growth may be retarded, particularly at lower levels of feed intake. Widening the ratio has a positive effect upon the rate of lean growth, and only when the correct ratio is attained can lean growth be maximised. Fatness is readily induced by either (1) inadequate protein supply or (2) excess feed allowance. Fatness also may be corrected by either (1) widening the protein:energy ratio or (2) reducing food supply. Figure 14.4 shows unequivocally that pigs can become fat at any protein:energy ratio if the feed intake level is greater than the pig requires. Excess protein cannot enhance lean growth above either the limit set by available energy or that set by the inherent potential of the pig. ‘Inherent potential’ in this regard may be defined as the genetic capability of the animal, but in practical circumstances the ‘inherent potential’ should also include other non-nutritional constraints such as the pig’s environment and the presence of disease.
The classical interaction between protein supply, the supply of energy and pig potential may also be described as in Figure 14.5. This often elegantly demonstrated phenomenon shows how the slope of response to diet protein is dependent upon the utilisability of the protein, while the asymptote is dependent upon a variety of possible factors.

The lactating sow can produce 400–700 g of protein in her milk daily. Milk production in the sow is a similar body process to growth and requires copious amounts of both protein and energy. A reduction in the protein:energy ratio below 12 g CP/MJ DE is likely to cause a reduction in milk yield and an increase in the rate of lean tissue loss from the maternal body (Figure 14.6). Widening the ratio will correct any protein deficiency, but above 13 g CP/MJ DE there is not likely to be much further positive effect upon milk yield.

The pregnant animal is relatively frugal in its protein needs. Increasing diet protein concentration may slightly increase live weight gain during pregnancy, but within the normally feasible range of 10–14 g CP/MJ DE there will be little effect on number of pigs born or upon their birth weight. The needs of the fetus are modest until the last 20–30 days of pregnancy. It has been proposed that 10–12 g CP/MJ DE is adequate for the pregnant female. There is evidence that lower protein levels than this may reduce conception rate and litter size, particularly if the protein is of low value. With this possibility in mind the diet prepared for lactating sows can be used for weaned females until they are confirmed pregnant.
Response to protein value (V)

Protein value governs the effective utilisability of the dietary crude protein (CP). A change in protein value therefore changes the effective CP content of the diet. Thus a reduction in protein value can be countered by an increase in protein level. It follows that response to change in protein value is similar to that for a change in effective CP supply. The protein level chosen for any diet must allow for the value of the proteins used in the mix, or errors will arise from a CP supply being assumed adequate when it is not.

Relating feed ingredients to pig requirement

The formulation of a satisfactory pig diet calls for consideration of:

1. the absolute levels of nutrients required daily by the pig (requirements);
2. the daily feed intake of the pig (intake);
3. the concentration of the nutrients in the diet (concentration);
4. the nutrient content of feedstuffs; that is, the diet ingredients;
5. the suitability of available feedstuffs for diets destined to be fed to different pig classes.

The first three are related by the equation

\[
\text{Concentration} = \frac{\text{requirement}}{\text{intake}} \quad (14.3)
\]

Requirement for energy, protein, vitamins and minerals is determined as the needs for maintenance, production (growth of lean and fat) and reproduction (pregnancy and lactation), and has been described in earlier chapters. Energy requirement is best expressed in terms of DE and protein requirement in terms of balanced and available ileally digested amino acids. Lysine, often being the first limiting amino acid, can be used as an indicator of the level of balanced amino acids in the mix. However, where a computer is used in diet formulation there is benefit from com-
pounding each and all the essential amino acids to the required level of provision, and as a minimum expectation the requirements for lysine, methionine, threonine and tryptophan, and possibly histidine and valine, should each be considered in their own right as likely to be potentially limiting in conventional pig diets.

Example nutrient requirements are given in the upper sector of Table 14.5. The means by which a requirement may be derived has been described earlier. In order to create a nutrient specification for a diet in terms of nutrient concentration to satisfy a given requirement, the feed intake must be known. The assumed feed intakes for the five example classes of pig are given in the middle sector of Table 14.5, and will result in the nutrient specifications shown in the lower section of that table.

The example diet specifications for nutrient content in Table 14.5 may be expanded to include all the amino acids, minerals and vitamins. For computer formulation such expansion is expected. The precise nature of the values shown accord with those calculated in the earlier chapter dealing with nutrient requirement, but their precision would not be a realistic basis for practical diet formulation because they relate to a particular individual pig at a particular moment in time. There is variation amongst individual pigs in terms of their performance (and therefore requirements), and also variation amongst pigs in terms of their feed intake. Guide nutrient specifications for practical usage are given in Appendix 2, which also identifies appropriate concentrations for all the essential amino acids, vitamins and minerals.

Given a target nutrient specification, a diet can be formulated by the appropriate combination of feedstuffs (diet ingredients). Ways of determining the nutritional value of feedstuffs have been discussed earlier and guide values for some example ingredients are given in Appendix 1. The mechanics of constructing a diet of given specification from combinations of ingredients of given value is shown in Table 14.6.
In columns 1, 3, 5 and 7 of sector A of the table the available ingredients and their nutrient contents are specified. The target nutrient specification for the final diet is shown in columns 4, 6 and 8 of sector C as 14.0 MJ DE/kg diet, 180 g CP/kg diet and 9.0 g lysine/kg diet. In sector A of Table 14.6 a combination of 200 kg/t of wheat, 550 kg/t of barley and 200 kg/t of soya bean (leaving 50 kg/t of space for binders, vitamins, minerals, synthetic amino acids and so on) is found to provide in the diet 12.8 MJ DE/kg, 167.8 g CP/kg and 8.3 g lysine/kg. The contribution to the diet DE from wheat is calculated as 14.0 ¥ 0.2 = 2.8 MJ, that from barley is calculated as 12.9 ¥ 0.55 = 7.1 MJ and that from soya bean is calculated as 14.5 ¥ 0.2 = 2.9 MJ. These sum to a total of 12.8 MJ DE/kg diet. The same mechanism is used to calculate the contributions of these feedstuffs to the crude protein and lysine in the diet. It may be seen from Table 14.6 that the initial calculations shown in sector A produce a diet mix that is not adequate to satisfy the targets given in sector C of the table, falling short in DE by 1.2 MJ/kg, in CP by 12 g/kg and in lysine by 0.7 g/kg. Sector B of Table 14.6 adjusts the levels of the various diet ingredients, and uses in addition fish meal and feed-grade fat. The combination of available feedstuffs offered in sector B now more nearly meets the target nutrient specification. Perhaps a little more fish, or wheat + soya, would improve this further, but an exact matching with all aspects of the target specification is highly unlikely. The degree of unlikelihood increases with the number of different elements in the target specification, and with the narrowness of the limitations to the range of ingredients available.

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Inclusion rate (kg/t)</th>
<th>DE (MJ/kg)</th>
<th>CP (g/kg)</th>
<th>Lysine (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>200</td>
<td>14.0</td>
<td>110</td>
<td>3.0</td>
</tr>
<tr>
<td>Barley</td>
<td>550</td>
<td>12.9</td>
<td>105</td>
<td>3.5</td>
</tr>
<tr>
<td>Fish meal</td>
<td>15.0</td>
<td>14.5</td>
<td>440</td>
<td>29</td>
</tr>
<tr>
<td>Soya bean meal</td>
<td>200</td>
<td>32.5</td>
<td>650</td>
<td>22.0</td>
</tr>
<tr>
<td>Feed-grade fat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>950</td>
<td>12.8</td>
<td>167.8</td>
<td>8.3</td>
</tr>
</tbody>
</table>

| Target specification        | 950                   | 14.0       | 180.0     | 9.0           |
Variety and number of feed ingredients

The greater the range of available feed ingredients the more likely is the target nutrient specification for a diet to be met for the full range of energy and amino acid demands such as are shown minimally in the guide nutrient specifications of Appendix 2. However, the greater the range of ingredients used in diet formulation the more complex is the compounding operation at the mill and mix unit, and the more difficult is quality control and assessment of the veracity of the assumed nutritive content and physical quality of each of the feedstuffs. So it is that many smaller operations will create their diets from perhaps only five or six main ingredients (or two in the case of a basic maize + soya diet!), and a mineral + vitamin supplement. Substantial feed compounding mills on the other hand may routinely have 20 or 30 ingredients available, some of which may readily be included in diets at quite trivial levels but which help to meet the target specification and optimise the diet cost. Fat, for example, is quite difficult to store and handle in the context of an on-farm mill and mix operation but is used widely by feed compounders to achieve adequate DE concentration in diets when cereals of lower energy concentration (such as barley), or by-products, are inexpensive and desirable to use.

Small-scale mixing facilities often have advantages of intimate local knowledge of ingredients, and may use long-standing tried and tested fixed formulae. However, the larger compounding mills achieve a greater precision in meeting exact nutrient specifications and are also able to minimise diet price as a result of extensive (world-wide) buying and storage opportunities when particular ingredients are cheap.

Farmers who also grow cereal grains may compromise by the purchase of a concentrate mix from a large compounder which is high in protein and includes a comprehensive mineral and vitamin supplement. This concentrate is then added to the milled cereal grains. However, concentrate purchases have in the past depended to some extent upon the availability of low priced concentrated protein sources (such as meat-and-bone meal) and synthetic amino acids. As the availability of these reduces, and/or the price rises, then the likelihood of cereal growers purchasing ‘straight’ ingredients (such as soya bean meal) increases.

The range of pig feed ingredients whose nutrient contents are given in Appendix 1 is by no means comprehensive, but most pig diets world-wide are made out of a relatively restricted range of preferred cereals, by-products and protein concentrates.

Choice of feedstuff ingredients for particular diets

Some animal feedstuffs may not be considered fit for use in pig diets because they:

- are unpalatable to pigs;
- contain factors toxic to pigs or substances that may otherwise cause ill-health or discomfort;
- do not show a cost-effective response in relation to their price;
- restrict appetite by undue bulk;
• fail to satisfy appetite by undue concentration;
• cause taints or off-flavours in the meat;
• reduce the physical quality of the meat (such as by creating soft fat);
• are likely to cause health difficulties in staff operating mill and mixing units;
• are difficult to handle through milling, mixing and pelleting machinery;
• are too costly or difficult to transport;
• are variable in nature and require excessive quality control systems in order to
ensure the correct identification of the true nutrient content of various feedstuff
batches.

Many of these criteria are not absolute and some ingredients may not be disallowed
altogether, but restrained to within certain maximum limits. These limits will natu-
really be more severe in the case of diets for young pigs than for finishing pigs. Sugg-
gested inclusion restraints for starter, grower, finisher and sow diets for a range of
ingredients may be found in the lower sections of the tables given in Appendix 1.
It is not possible to identify appropriate restraints on the basis of the physical quality
and wholesomeness of ingredients, even though this is a most vital aspect of feed-
stuff assessment. In this case the appropriate restraint is dependent upon the degree
of competence of feedstuff processing and the efficacy of storage. Soya bean meal
and potatoes are both toxic if not adequately heat treated; animal protein sources
can be rendered useless by over-heating; cereals may become toxic and unpalatable
as a result of improper storage; feedstuffs containing high levels of sugars and lipids
may be highly suitable and palatable for young pigs if of high quality, but when
poorly handled can be the worst of ingredients in a starter diet.

The importance of ingredient quality and wholesomeness as factors separate
from, and additional to, nutrient content cannot be over-stressed in the creation of
a successful diet formulation for pigs. Individual nutritionists are likely to place
restraints upon the inclusion level of various feedstuffs in diets for each of the
various classes of pig, according to knowledge of the quality and source of the feed-
stuff. This knowledge cannot be identified in the same way as can chemical analy-
isis; more usually these decisions depend upon local knowledge and individual
experience.

Sometimes doubtful feed ingredients are restrained (constrained) in diet formu-
lations as a result of feeding experiments which have shown no deleterious effects
below a certain inclusion level, but some evidence of reduced performance above
that level (as, for example, in the case of rapeseed meal). It is conceivable that in
the case of some feedstuffs there is indeed an inclusion rate below which the ingre-
dient is satisfactory, but above which it becomes problematic due to toxic or other
factors. However, it is more likely that the deleterious effects of the dietary ingre-
dient only appear to become less as the inclusion rate falls because the experimen-
tal procedures are unable to measure with statistical certainty progressively smaller
effects. This does not mean that the effect is not present. By the same token, combi-
inations of ingredients, each of which may be within a presumptive ‘safe’ level of
inclusion, may sum to an ‘unsafe’ level.
Limitations to inclusion rate can also offset the tendency for a particular feedstuff to be variable in its nutritional value. A poor batch of an ingredient will have a relatively trivial impact on a diet when included at levels of less than 5%, but would have a most serious impact if the rate of inclusion was above 20%. There is some degree of safety in a large number of ingredients being included in diets at low rates.

Too high an inclusion level of finely ground cereals may increase the apparent digestibility but predispose the pig to gastric ulcers and digestive disturbances (thus reducing digestibility). High fibre feedstuffs may need to be limited; because of potential disruptions to protein digestion (as discussed earlier), because of difficulties in accurately predicting response and because of problems of low bulk density.

There is frequently a strong case for the inclusion of some feedstuff ingredients in diets at a stated minimum level. This would ensure continuity of diet palatability and familiarity. Some compounders may feel that some ingredients such as fish meal may have attributes that impart special qualities to the diet. This gives rise to minimum inclusion rates regardless of price. Similarly, a given cereal may be included in all diets, again regardless of price, at a level of 25–35%, in order to maintain continuity between formulations.

There is some evidence that, especially for younger growing pigs and lactating sows, dramatic changes (swings) in diet formulations can affect feed intake due to an alteration in taste, texture and gut flora. Large changes in formulation are therefore not advised within any particular diet specification, and changes in diet formulation from one specification to another should be as gradual as possible. This is especially important for young pigs changing from creep to starter diets and from starter to grower diets. Many feed formulation packages have the ability to set ‘swing’ constraints.

Although some ingredient restraints for feedstuffs are given in Appendix 1, these are forwarded as guides and not recommendations. Where diet ingredients are cheap, the more courageous feed compounder may be well rewarded. Equally, in some countries individual feedstuffs may be considered especially good, whilst in others the same feedstuff may be especially poor. What constitutes an appropriate ingredient restraint is often as much opinion as biological reasoning.

Example ingredient compositions of diets for various classes of pig are given in Appendix 3. The propositions contained therein are compatible with those already forwarded in Appendices 1 and 2. Clearly, however, a multiplicity of other ingredient compositions would achieve the same compatibilities. Diets for younger pigs contain more higher quality products and the range of ingredients used are often more restricted in number in order to maximise knowledge of ingredient quality and source. No ‘doubtful’ ingredient is included as the cost–benefit would be likely to be negative. Finishing pigs, however, may be offered a much wider ingredient choice, and some move towards the use of less expensive ingredients and by-products is to be expected.

Nutrient density is an important component of ingredient choice. The needs of young pigs and lactating sows for diets of greater energy concentration on the
grounds of productive potential being high in relation to gut capacity, and the similarly important need for high ratios of lysine and protein to energy, results in nutrient specifications (Appendix 2) that can only be met from the use of certain ingredients such as wheat, maize, full-fat soya bean, milk and animal proteins, and feed oils and fats (Appendix 3). For finishing pigs and pregnant sows, however, these considerations are less important as gut capacity may usually accommodate the nutrient requirement when the latter is provided – at least in part – from less dense feedstuffs and by-products. Provided that the appropriate ratios of nutrients one to the other are observed, and that the feed allowance or voluntary intake can accommodate a lower nutrient density, then overall cost–benefit may accrue by creating diets of lower nutrient concentration from a wider range of ingredients.

The nutritional specification for dietary concentration of energy is often given great weight in the formulation procedure; the other nutrients following according to the appropriate ratio. It will have been apparent from the values given in Appendix 2 that whilst recommended ratios of essential amino acids to lysine, lysine to energy and crude protein to energy are indeed closely specified, the energy density itself is described in terms of a DE range. For pigs with appetite limitations it is of vital importance to formulate diets of high energy concentration (and of high concentration of other nutrients also). However, it is of equal importance that, when appetite limitations do not apply, the DE concentration of the diet is allowed to vary within as wide limits as possible. This will encourage maximum opportunity to be taken of feedstuffs of either particularly high energy density or particularly low energy density, when one or the other is especially beneficially priced. It is necessary only to know with reasonable precision the energy concentration of the diet (for example, as described in Equation 14.1), and to allow for more of a lower density diet to be consumed by the pig (Table 14.7). The two pricing situations shown in the table may readily occur over a 6-month period; in the first the high density diet is most cost-beneficial, whilst in the second case the low density diet is the better option.

The density restraint is often used in practice, and a definitive target (rather than a wide range) for MJ of DE per kilogram is given for the feed compounder to

<table>
<thead>
<tr>
<th>Diet</th>
<th>Cost (#/kg)</th>
<th>Intake allowance (kg) to provide 28MJ DE and 420 g CP</th>
<th>Feed conversion ratio (feed:gain)</th>
<th>Cost (#) to provide 1 day’s nutrient requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>A High density</td>
<td>15.0</td>
<td>1.8</td>
<td>2.4</td>
<td>27.0</td>
</tr>
<tr>
<td>B Medium density</td>
<td>14.5</td>
<td>2.0</td>
<td>2.7</td>
<td>29.0</td>
</tr>
<tr>
<td>C Low density</td>
<td>13.0</td>
<td>2.2</td>
<td>2.9</td>
<td>28.6</td>
</tr>
<tr>
<td>A High density</td>
<td>16.9</td>
<td>1.8</td>
<td>2.4</td>
<td>29.7</td>
</tr>
<tr>
<td>B Medium density</td>
<td>14.7</td>
<td>2.0</td>
<td>2.7</td>
<td>29.4</td>
</tr>
<tr>
<td>C Low density</td>
<td>13.0</td>
<td>2.2</td>
<td>2.9</td>
<td>28.6</td>
</tr>
</tbody>
</table>

Table 14.7. Relative values of three diets of differing density.
achieve. This facilitates exact feeding recommendations along with the particular diet to be fed, and it avoids the confusing issue of needing to change feeding level every time diet concentration is changed. Nevertheless, however valid the reasons for strict adherence to a stipulated energy concentration for a given diet, real savings in feed cost per unit of pig growth may be lost by unnecessary rigour.

On some pig units the policy for the amount of feed to be given to pigs is rigidly adhered to. Management rules are expressed in terms of daily allowances for growing pigs of given weight (or in given pens), and for pregnant and lactating sows. Such values are of little use when quoted independently of the nutrient concentrations of the diets that are to be offered, because pigs require quantities of this or that nutrient daily, not quantities of feed. There is therefore a certain safety in having a pig diet always of a known standard energy density. This obviates problems of feeding management. Particular feeding allowances for particular classes of pig become familiar to the feeder, and these may even be an integral part of a recording system. There is plenty of scope for confusion where a change in nutrient density could even require a reduction in the daily feed allowance in order to effect an increase in nutrient supply.

Over the years the nutrient concentration of pig diets has tended to rise and fall in response to market circumstances. This has been for a number of good reasons:

- The unit cost of energy in energy dense feedstuffs such as maize, wheat, full-fat soya and feed-grade fats varies in relation to less energy dense feed sources such as barley and cereal by-products.
- The appetite of many hybrid pigs has been reduced and become a factor limiting the achievement of potential growth up to 80 kg live weight and of potential lactation yield in milking sows.
- The industry is more aware of the growth possibilities of young pigs and the benefits of giving young animals diets of the highest nutrient density and palatability. If a growing pig is not yet up to the maximum rate of protein deposition then any further increment of nutrient will be used primarily for lean tissue growth. A premium can therefore be justified for a quality, energy-dense, protein-dense diet specially formulated for this class of pig.
- The types of feedstuffs used in the more concentrated diets are of more consistent quality, and the response is more predictable. Conversely, feedstuffs of low nutrient density tend to be more unpredictable. High density diets can therefore be formulated more precisely.
- The more concentrated the diet, the more likely there is to be savings in transport and handling costs. These savings are achieved as a result of the same weight of diet carrying more nutrients within it. Cost savings start at the mill, continue through storage and haulage, and are also achieved by the producer, who has less material to feed to the pig and less slurry to remove from the pen.
- On the other hand, there has been a move, based on pig well-being, toward provision of lower energy dense and higher fibre diets; even if this results in a higher unit cost for energy.
There is a direct relationship between the concentration of nutrients in a diet formulation and the efficiency of conversion of food to live-weight gain. Containing more nutrients per unit weight of food, a diet of higher concentration will have a better feed conversion efficiency. A high efficiency of conversion (gain per unit of feed) or a low feed conversion ratio (feed per unit of gain) is intrinsically attractive, but it may not necessarily be most cost-effective (see Table 14.7).

**Unit value of nutrients from feedstuffs**

It is evident that:

- feed ingredients with higher concentrations of the required nutrients are more valuable per unit weight than feed ingredients of lower nutrient concentration;
- some feed ingredients have a worth far above that which may appear from their own nutrient content and price alone; this is because they may provide (albeit at high price) a specific nutrient lacking in an ingredient that otherwise provides other nutrients at a specially low price, the overall mix being more cost-effective;
- where there is no disadvantage in meeting the nutritional specification of a diet by use of low priced ingredients rather than higher priced ones, then this should be done. Conditions of no disadvantage should prevail if (1) feedstuffs are correctly evaluated according to quality, wholesomeness and nutrient content, and (2) maximum and minimum limits (restraints) to the inclusion of particular feedstuffs in particular diets are correctly set. Doubts about (1) and (2) often, correctly, constrain feed compounders to not necessarily minimising diet costs at all times. Thus each new diet formulated in consequence of a change in ingredient price (and therefore value per unit nutrient) will be considered by the nutritionist on a basis of informed, but qualitative, judgement as to whether or not that formulation should go forward for manufacture and feeding to pigs. This last step, where the nutritionist’s knowledge, experience and caution can over-ride the mathematical and mechanical processes of diet formulation is most important. It arises not because subjectivity and prejudice should be allowed to supersede objectivity and science, but rather because the science is often not adequate to cover all eventualities at a quantitative level.

Table 14.8 shows three cereals at three prices and compares the unit values of the energy and protein that they contain. In this example the cheapest source of energy is maize, whilst the cheapest source of protein and lysine is barley. The cost for 1 MJ DE, 1 g CP and 1 g lysine is calculated on the basis of the whole of the feed-stuff price being apportioned to each nutrient. This serves for purposes of comparison and to help identify the most cost-effective ingredient, but it is not a true reflection of reality because for a single price each feed contains all three nutrients, albeit at different levels of importance. These three cereals are usually considered primarily as energy sources, so the cost per unit energy would tend to be the most
important. Maize appears most opportune even though the cost per unit lysine is high. However, again, such simplicity is spurious as in most pig diets at least half of the protein comes from the cereal fraction (see Table 14.6), and the cost per gram of protein and per gram of lysine is important. Whether maize or barley is the more cost-effective cereal is not clear until the unit values for all nutrients are compared simultaneously. To provide both 15 MJ DE and 3 g lysine from barley alone would cost 12.8\# (energy being limiting), whilst to provide the same from maize alone would cost much more at 14.1\# (lysine being limiting). Neither strategy is correct; buying both and mixing them together at a rate of 0.25 units of barley and 0.75 units of maize will provide both 15 MJ DE and 3 g lysine for the price of 12.6\#. This logic can be developed further to the realisation that the relative value that should be ascribed to the different grain proteins depends not only on comparison between the two grains, but also on the relative cost of protein which might be available from alternative protein sources. The calculation comparing barley, wheat and maize does not therefore approach realism until a feedstuff such as soya bean meal is added into the set of equations for simultaneous solution. Say the price of soya bean meal was 15.0\#/kg. Containing 14.5 MJ DE, 440 g CP and 29 g lysine/kg the unit costs of 1 MJ DE, 1 g CP and 1 g lysine in soya bean meal are respectively 1.03, 0.034 and 0.52\#. The unit cost of energy is therefore higher than that for cereals, but the unit cost of protein and lysine is very much less. The fact that barley lysine was cheaper than maize lysine now becomes irrelevant, and a maize/soya mix becomes the preferred option. This is not to say that barley, even at the example prices quoted, could never be competitive to maize; that would depend upon the relative costs of other energy sources such as feed fats.

In order to judge the relative economic worth of different feedstuffs, it is true that the unit values for energy, in ingredients included primarily for their energy content, are useful comparators. Equally useful are the unit values for protein and amino acids in feedstuff ingredients included primarily for their protein content. However, it will now also be evident that full optimisation of a diet formulation requires many simultaneous comparisons and a complexity of calculation that can be handled only by a computer.

### Table 14.8. Unit values of nutrients in three feedstuffs.

<table>
<thead>
<tr>
<th></th>
<th>Barley</th>
<th>Wheat</th>
<th>Maize</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Price (#/kg)</strong></td>
<td>11.0</td>
<td>12.0</td>
<td>12.2</td>
</tr>
<tr>
<td><strong>DE (MJ/kg)</strong></td>
<td>12.9</td>
<td>14.0</td>
<td>14.5</td>
</tr>
<tr>
<td><strong>CP (g/kg)</strong></td>
<td>105</td>
<td>110</td>
<td>90</td>
</tr>
<tr>
<td><strong>Lysine (g/kg)</strong></td>
<td>3.5</td>
<td>3.0</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>Cost (#)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 MJ DE</td>
<td>0.853</td>
<td>0.857</td>
<td>0.841</td>
</tr>
<tr>
<td>1 g CP</td>
<td>0.105</td>
<td>0.117</td>
<td>0.136</td>
</tr>
<tr>
<td>1 g lysine</td>
<td>3.14</td>
<td>4.00</td>
<td>4.69</td>
</tr>
</tbody>
</table>
Number of different diets required

The nutrient requirement, the balance of protein to energy and the appetite of the pig all change daily. Ideally, therefore, a different diet formulation should be offered day by day. Individual pigs also vary in their requirements and appetites, which should be accommodated by diet formulae customised to each pig. These ideals are entirely realisable, either with self-choice feeding arrangements or better with automated feeding systems allowing diet formulations to be modulated on a pen-by-pen and day-by-day basis. Integrated Management Systems using automatic measurement of gain in pig size add to the efficiency and precision of feed provision.

Different diet formulations will tend to be required in circumstances when:

- the specification becomes sufficiently over-generous that the excess of nutrients supplied above need is wasteful in economic terms;
- the specification is sufficiently under-generous that there is economic loss of potential production;
- a particular class of pig has particular ingredient restraints not common to the next class;
- one class of pig requires a diet of different nutrient concentration because of appetite constraints;
- a diet requires fortification with growth promoters or medicines appropriate only for a particular group or class of pigs.

Table 14.9 presents good reasons for five diets being used in a pig feeding programme, but contraction to three would be feasible if a single diet were used for both lactating and pregnant sows, and two diets were used to cover the young, growing and finishing stages. Equally appropriate might be a more sophisticated – and potentially cost-beneficial – programme of an even greater number of diets. A starter creep of high palatability and quality with especially chosen ingredients could be used from 14 days of age through weaning and up to 10 kg or so; a reduced

<table>
<thead>
<tr>
<th>Table 14.9. Some diet characteristics for different classes of pigs.</th>
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<tr>
<td><img src="https://example.com/table14.9.png" alt="Table" /></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy concentration (MJ DE/kg)</th>
<th>Young pigs (up to 15 kg live weight)</th>
<th>Growing pigs (up to 50 kg live weight)</th>
<th>Finishing pigs (up to 100 kg live weight)</th>
<th>Lactating sows</th>
<th>Pregnant sows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protein:energy ratio (g CP/ MJ DE)</td>
<td>14–17</td>
<td>14–16</td>
<td>13–15</td>
<td>13–15</td>
<td>11–14</td>
</tr>
<tr>
<td>Lysine:energy ratio (g lysine/ MJ DE)</td>
<td>1.0</td>
<td>0.90</td>
<td>0.75</td>
<td>0.75</td>
<td>0.50</td>
</tr>
<tr>
<td>Appetite factors</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Special feedstuffs</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Special additives</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
</tbody>
</table>
specification would follow on until the pigs were 20 kg live weight, after which would follow first a grower, then a finisher diet. For pigs growing on to weights above 100 kg a final (fifth) diet may be cost-effective.

The final number of diets chosen will depend greatly on the size of the plant mixing the diets, the potential for storage of different feedstuffs, and the ability of the machinery and management on the pig unit itself to cope with a wide variety of different diets. In dry-feeding systems, often a particular feed may be associated with a particular bulk feed bin which is used to hold the mixed feed formulation prior to delivery to the pigs. These may relate to one, or a number, of houses – but never to individual pens of pigs. The maximum flexibility for diet number in this case is therefore controlled by the number of holding bins available. In this latter respect the use in diets of feed additives, medicines and growth promoters which require withdrawal periods of weeks or days before dispatch for slaughter causes considerable problems in the finisher stages by creating the need for an additional diet from which these additives are excluded, and which is used only for the latter part of the finishing period.

Wet feeding systems allow the use of a wide range of by-products, such as those from the human food manufacturing industries, whey, skimmed milk, root crops, distillery wastes, liquefied fish, starch and so on. Further advantage accrues if the dry and wet diet components are mixed, as may readily be done to maximise the number of different dietary options. Through the wet feeding system individual diet formulations may be readily created to match more closely the nutritional requirements of pigs in particular parts of the production unit. Because each diet is mixed within a few hours of feeding, automatic wet-feeding systems can cope with a substantial number of different diets being offered through the growing phase.

Enhancement of the precision of formulation

The better the closeness of fit between animal nutrient requirement and diet nutrient provision, the more likely will optimum performance be achieved and the greater will be the efficiency of conversion of food into pig product.

However, the statement of diet nutrient specification is not an end in itself; rather it is only an interim point toward the ultimate objective of animal requirement and production response. It is implicit that the defined requirement should bear a reasonably close relationship with growth and reproductive response. Nevertheless, the nutrient specification is not itself the response; even though it may be confused as such by some feed compounders, on account of satisfaction of the nutrient specification being the primary objective of the diet compounding mill-and-mix unit. Only in a fully integrated operation is the response to the diet seen as the ultimate target of the diet formulator. It is for this reason that some feed compounders were in the past (wrongly) more preoccupied with provision of a recommended nutrient requirement given in terms of diet concentration than with nutrient requirement expressed in terms of achieved production response.
Better definition of dietary utilisable energy

The major variation amongst feedstuffs with regard to their content of utilisable energy is a result of variation in digestibility. Definition of energy content of feedstuffs – and the complementary definition of energy requirement – in terms of digestible energy (DE) rather than gross energy (GE) clearly enhances accuracy of diet formulation. The next step in precision improvement is to use metabolisable energy (ME) which allows for the energy losses in urine associated with protein deamination. Some diet formulation procedures do indeed express pig requirement and diet nutrient specification for energy in terms of ME, and the various available feedstuffs are described in terms of their ME rather than their DE content. The improvement in accuracy of formulation is, however, trivial: first, because most ME values for feedstuffs have been assessed simply as a fixed proportion (0.96, usually) of the DE, and there is therefore no effect upon the relative energy values of the various ingredients; second, variation in the relationship between DE and ME is as much a function of the animal and its circumstance (for example, potential rate of protein accretion in relation to protein supply) as of the feedstuff itself. Use of ME thus gives an appearance of increased formulation precision, but one that is largely spurious. Diet formulation is indifferent to the use of either DE or ME because constant factors require to be assumed in both the animal and in the feed elements of the formulation activity.

The ultimate requirement of the animal is for net energy (NE) and this would effectively account for differences in the efficiency of utilisation of diet energy for various different productive functions and classes of pigs. Some of these have been discussed earlier and are of considerable significance. Thus the contribution of total ME requirement made by diet protein which is accreted is twice that made by protein which is deaminated; while diet lipid is used much more efficiently for growth of body lipid than for energy fuelling. The ME of feedstuffs is contained in feedstuff protein, feedstuff carbohydrate and feedstuff lipid; the carbohydrate can be in the form of sugars or non-starch polysaccharides. All these various sources of energy may be used with different efficiencies for different purposes. It is not true, therefore, to assume that all the energy measured as ME from one feed source has the same value as another. This being the case it follows that feedstuffs could be better assessed in terms of their comparative values (cost per unit of utilisable nutrients) if NE values rather than DE or ME values were used. Diet formulation on the basis of NE is the norm in some countries and requires only that the energy value of feedstuffs (Appendix 1) and the nutrient specification of the diet (Appendix 2) be given in terms of NE. The calculation of NE requirement is not an issue because the proper expression of requirement in terms of DE or ME requires first an understanding of body energy metabolism in net terms. Equally pertinent is that the description of the value of a diet in terms of its response (rather than in meeting a given nutrient specification) explicitly involves a measurement of NE response. It is not such issues as these that create difficulties in diet formulation. Rather the problems of using NE for practical diet formulation in the conventional sense of
compounding to a given nutrient specification, as is being addressed here, are two-fold:

1. It is necessary to define clearly and closely the way in which the pig that is eating the diet will use it. This is often not possible if a single diet is to be used over a range of appetites, genotypes, environments and pig weights.

2. A single NE value cannot be ascribed to a single feedstuff. The value will change *inter alia* according to the way it is used by the pig. However, variable NE values are difficult to accommodate in tables of nutritive value and, of course, in conventional analytical procedures, which are usually made in the laboratory and not with optimally performing animals behaving in a similar way to those about to be given the compounded diet. NE systems require computer simulation modelling to take the variable nature of achieved energy value into account.

Substantial advances have been made in dealing with these issues in very recent times. The outcomes are well described in the following two companion publications which present both the background and the practicalities of feed formulation using the NE system. These are: British Society of Animal Science (2003) *Nutrient Requirement Standards for Pigs*, BSAS, Penicuik, Scotland, and British Pig Executive (2004) *Feed Formulations for Pigs*, MLC, Milton Keynes.

There is now clear evidence to show that the greater precision of energy formulation and predictability of response follows from the use of an NE system, particularly when it is combined with fully variable factors and a simulation model. However, if only fixed factors and fixed assumptions are used, the system becomes indifferent as to whether DE, ME or NE is used, simply because those factors that should be variable in the NE system are in fact fixed and thereby their beneficial effects nullified.

In some cases an NE system is used within the context of a conventional DE descriptor at both feedstuff and nutrient specification level. It is known, for example, that the efficiency of utilisation of DE from fibrous foods is less than that from starch. This is because of differences in relative difficulty of metabolism of VFAs as the end-products of fibre digestion as against glucose as the end-product of starch digestion. DE values of fibrous feeds containing complex non-starch polysaccharides (and feeds whose starch is fermented in the large intestine rather than digested in the small intestine) *may* therefore be written down to accommodate these phenomena. It is probably reasonable to surmise that most of the benefits of using a part-NE system come from:

1. writing-up determined DE values for dietary unsaturated lipids;
2. writing down determined DE values for fibrous foods – especially for young pigs;
3. the correct expression of the energetics of protein usage;
4. the accommodation of variable efficiencies of utilisation of fibre by different classes of pigs.
It is germane to note that in the previous edition of this book (1998), the following was stated: ‘Given the ease of routine determination of DE in feedstuffs, and the possibility of making realistic adjustments for lipids and fibres, it is doubtful if any greater precision would result from formulation on any other than a DE basis; unless and until a complete (not partial) NE system is invoked and properly utilised, as described earlier. This is likely within the next 5 years’. The 5 years have passed, and the predicted arrival of effective and usable NE systems is indeed with us, and offer feed formulators and pig feeders considerable benefit.

**Better definition of dietary utilisable protein**

Individual feedstuffs differ quite widely in the digestibility of their protein (see Table 9.1). Fish meals have an apparent faecal digestibility coefficient for protein up to 0.95; for soya bean meal this is around 0.85, while for other vegetable proteins such as wheat feed and cottonseed it may be as low as 0.60. To ascribe the same value to protein emanating from wheat feed as to protein emanating from soya bean is therefore to greatly over-value the former in comparison to the latter. It is remarkable therefore that for so many years pig diets have traditionally been compounded on the basis of the crude protein (CP) requirement, that the nutrient specification for diets has been given in terms of CP, and that a CP (N × 6.25) analysis of feedstuffs has stood as being an adequate descriptor of protein content (in passing, this also is in error; the multiplier for N to derive CP should vary according to the amounts of NPN in feedstuffs, but convention has never accommodated this despite true multipliers ranging from 6.25 for animal tissue to between 5.75 and 6.25 for most cereals and soya bean meal, and down as low as 5.5 for some low-quality protein sources).

There would be considerable benefit to expressing protein needs in terms of digestible protein, and the protein content of feedstuffs similarly. This may be readily achieved by using the digestibility coefficients given in Appendix 1 and setting up feed descriptor files with the more accurate protein definition of digestible crude protein (DCP). Complementary expression of requirement and nutrient specification in DCP rather than CP terms equally presents no problem of either concept or mechanism, and existing knowledge is more than adequate to allow this simple process of improvement in compounding precision.

It remains mysterious how nutritionists may insist upon the expression of the energy system minimally after accounting for at least variation in digestibility between feedstuffs, but be willing to ignore the same logic for protein. In practice, formulators now tend to skip the DCP step and account for digestibility through the medium of formulating to digestible amino acids.

Most authorities would now consider the issue of formulation to protein requirement to have been largely superseded by the issue of formulation to essential amino acid requirement; and this is indeed so. It is necessary for a diet to provide for both the protein requirement overall and the requirement of the individual essential amino acids. The nutrient specification for minimum levels of dietary essential
amino acids has been set up in the present case in terms of balance to the amino acid lysine; all the other essential amino acids given are required in the diet at least at the level of the given ratio (that is, the ratio required for ideal protein; see Table 11.3 and Appendix 2) if a further reduction in the protein value (V) is to be avoided.

It is therefore simple to formulate diets to the provision of nutrient specifications for the nine essential amino acids. It is often the case that, with conventional ingredients, once adequate lysine is provided in a diet then the other amino acids are adequately provided for as well; this is because lysine is usually the first limiting amino acid in pig feedstuffs. In order of likelihood of limitation, next comes threonine, and then methionine, and then tryptophan and histidine or valine. The liberal use of artificial lysine in the diet will, of course, cause some other amino acid to be first-limiting. Artificial sources of threonine, methionine and tryptophan are now also available as dietary ingredients, and they should be evaluated in the same way as any other potential feed ingredient; in this case, probably by comparison with the unit cost of amino acids in soya bean protein.

Satisfactory formulation of pig diets requires, of necessity, provision of the nutrient requirement of all the essential amino acids. To fail to provide for all the essential amino acids in the diet specification, and to fail to ensure that the final ingredient mix meets the minimum specification in terms of all the essential amino acids, is seriously to fail to achieve adequate accuracy of formulation. Information for compounding to amino acid requirements is to be found in Appendices 1 and 2.

Formulating diets to a nutrient specification detailing the essential amino acids in addition to total protein avoids the possibility of a shortfall in the expected efficiency of utilisation which might happen as a result of the inadequate supply of one or other amino acid. However, this does not deal with differences in digestibility of amino acids which are quite evident amongst feedstuff; as has been witnessed in Table 9.5 and detailed in Appendix 1. It is clear that the expression of the diet nutrient specification in terms of ileally digested essential amino acids (and, better, standardised ileal digestibility as described in earlier chapters) and the description of feedstuff ingredients in terms of the same ileal digestible essential amino acids are significant steps forward in increasing the precision of diet formulation and allowing greater flexibility of ingredient choice. Only when compared on the basis of the ileal digested amino acids can, for example, the cost–benefits of the use of cottonseed protein, wheat offal protein, lupin meal protein and soya bean protein be properly assessed (Table 9.5).

There is no good reason why feedstuffs should not be defined in terms of DCP and ileal digestible essential amino acids, nor any good reason why the nutrient requirement, expressed in the same terms, should not be best matched through these means in the routine formulation of diets. The determination of nutrient requirement for ileal digestible amino acids is the simple sum of the amino acids deposited in lean tissue growth and the amino acids used for maintenance, divided by the factor v (the utilisability of the ileally digested amino acids) \((IP_m + IP_n)/v\), as has been shown in Chapter 11. The necessary dietary concentrations of digestible amino acids may be determined (just as for the dietary concentration of digestible energy)
with knowledge of expected feed intake. Formulation of pig diets on the basis of ileal digested amino acids is now becoming common practice amongst many progressive feed compounders. Until recent times there remained two outstanding problems which slowed advances in the precision of amino acid formulation:

1. The use of ileal digestible essential amino acids improves upon total amino acids in the same way as DE improves upon GE; but equally, optimum precision could not in the past be achieved until a view of net utilisation is obtained. Although it was appreciated that absorbed amino acids may be used with different efficiencies for body processes (v, Chapters 9 and 11), effective quantification of this character has only recently been achieved. As the reason for the inefficiency at the level of v is now known to be the cost of recycling, and has been quantified (as described in earlier chapters), and as utilisation is well described by the use of the standardised ileal digestibility system, there is no reason to gainsay the benefits of the now available net systems.

2. The determination of ileal digestibilities is arduous, and there is still a great range of values being proposed for individual feedstuffs. It is therefore difficult to state with any degree of certainty exactly what the ileal digestibilities of the amino acids in the protein of a particular feedstuff may actually be. This means that the apparent increase in precision of formulation by use of ileal digestible amino acid values can be somewhat exaggerated. Work on ileal digestibility has shown that particular feedstuffs can have especially poor digestibility values for their amino acids (see Table 9.5 and Appendix 1), and this information is vital if feedstuff protein is to be credited with its true worth, and feedstuffs are to be objectively and correctly compared with each other. Fortunately, the science of the determination of amino acid value of feedstuffs has moved forward rapidly over recent years, and is with some confidence that improved feedstuff valuations are now forwarded by the likes of Premier Nutrition Products’ Premier Atlas Ingredients Matrix and INRA Editions A F Z’s Tables de Composition et de Valeur Nutritive de Matières Premières Destinées aux Animaux d’Élevage.

In many instances feed compounders will allow for reduced values for ileal digestibility of amino acids in some feedstuffs by only permitting their inclusion in diets at strictly limited levels. This tendency is also evident in the recommendations found in the lower sections of the tables in Appendix 1. Conventional pig diets tend to try to avoid dubious feedstuffs, but in so doing might be missing opportunities for cost beneficial ingredients of lower nutritive value, and also of lower price.

**Benefits from enhanced precision of formulation**

The objective of the progression:

- identification of nutrient content of feedstuffs;
- formulation of feedstuff ingredients into a compounded diet to satisfy a nutrient specification;
• consumption by the pig of its diet at an adequate level of intake to provide for its daily nutrient requirement;
• achievement of required daily production response; and
• obtaining adequate accuracy at each point in this programme

is to enable flexibility (1) in the face of changing feedstuff availability, price and nutrient content according to time and source, and (2) in the face of changing market demand for product type, and the changing abilities (through genetic, environmental or health improvement) of pigs to grow and reproduce.

In the absence of the need for flexibility the whole procedure is rendered unnecessary. Where a given feedstuff combination may be depended upon (when eaten at a given rate) to result in a predictable growth or reproductive response, and where feedstuff prices and availabilities are not capricious, and where that response is considered entirely satisfactory by both producer and ultimate consumer, then a fixed diet formulation is all that is required. Even knowledge of the nutrient concentration of that formulation is an uncalled for sophistication. It is adequate to know that two or three feedstuffs of repeatable quality, when mixed together in a certain ratio, result in an output of acceptable and repeatable quality. Such was the basis of pig feeding regimes over many years in the USA using only maize-corn and soya bean meal, and in parts of northern Europe using only barley, wheat feed and fish meal (or barley, wheat feed and skimmed milk). However, fixed formulae for pig diets were unable to allow minimisation of cost because cheaper sources of energy and protein were precluded (such as the use of maize and soya bean in European pig diets), and changes in pig genotype or customer requirements (such as greater lean tissue growth rate and a demand for leaner meat) could not be accommodated. Fixed ingredient formulations, however, remain potentially beneficial in the following circumstances:

(1) A limited range of ingredients are available, and these are of known quality. This case would apply to diets based on home-grown ingredients provided from mixed and integrated farming operations with both livestock and arable interests.

(2) Ingredient quality, and therefore knowledge of ingredient source, is of paramount importance. This would apply in the case of diets formulated for young piglets and young growing pigs.

(3) The definition of value of production response is not likely to change, and is expressed in terms of performance rather than cost–benefit. This is invariably the situation in the case of post-weaning diets where the primary requirement is for a high level of feed intake and the avoidance of diarrhoea.

In most other circumstances, cost–benefit will result from the widest possible range of ingredients being available for formulation in as wide as possible a range of combinations. If such flexibility is to be combined with effective precision of prediction of the pigs’ response to nutrient supply it is essential that:
the relationship between nutrient supply and animal response be understood and precisely quantified at the level of the animal; and
(2) there is precise identification of the nutritional contents of feedstuffs in terms that relate to the final utilisability at animal level.

These aspects of diet formulation demand the further attention of nutritionists, and enhancement of diet formulation precision will result from:

- a better definition of utilisable energy;
- a better definition of utilisable protein;
- a better definition of utilisable vitamins, minerals and trace elements.

However, before these are considered it is proper to reiterate that all attempts at greater precision in the definition of animal requirement and in the analysable nutrient content of feedstuffs are quite fruitless – indeed ludicrous – if either:

(1) the feed intake of the pig is compromised or significantly different to that assumed; or
(2) the assumed nutrient contents of feedstuffs are invalidated by poor storage, inadequate heat treatment, excessive heat treatment, the presence of toxins and the like.

It is a self-evident truth, which is all too often ignored, that it is irrelevant to try to increase the accuracy of nutrient provision in a diet if the feed intake is compromised, and equally irrelevant to reduce the price of a diet if the response is reduced by a greater financial margin.

It is frequently the case, world-wide, that further improvements in diet formulation by better nutrient specification and better feedstuff definition are unlikely to be worthwhile unless and until optimum pig feed intakes can be attained and the feedstuffs can be certified as free from negative factors not readily identified by simple chemical analytical procedures.

**Least-cost diet formulation by computer**

Although the same rules apply as for the hand calculation of a diet formulation, the computer has no effective limit to the number of ingredients that can be examined with a view to dietary inclusion. Neither is there any limit to the nutritional characteristics that may be taken into account, so it is possible to adjust ingredient inclusions to get close to the nutrient concentrations specified for a diet.

The linear program for least cost demands not only that the available ingredients are mixed to provide the diet nutrient specification requested, but also that this is done for the minimum cost. A particular balance of energy, protein, amino acids and minerals can be reached by a number of different ingredient combinations. However, only one particular ingredient recipe will achieve the nutrient specification at the least possible cost. This least-cost formulation will change as frequently as the relative prices of feedstuffs, just as has been shown earlier.
The greater the freedom of choice given to the computer the better will be the chance of reducing the price of the diet as far as possible. The efficiency of the program will be improved if the limits to the lower and upper inclusion levels allowed for the various feedstuffs are wide apart. Minimum inclusion rates for a particular ingredient can prove restricting on a computer formulation. It is not just that this ingredient has to be included at a particular stated minimum level, but with that ingredient goes a particular balance of energy, amino acids and minerals, and this balance influences the other ingredients that can be placed into the mix. Again, a low maximum inclusion rate for a feedstuff that is currently advantageously priced can be expensive. The fewer the restraints, the more efficiently the program will run and the cheaper will be the final diet. The great beauty of the linear programming methodology for least-cost diet formulation is that it is able to look at the cost–benefit of all the various nutrients in all the various feedstuffs simultaneously, and can therefore calculate in the optimum way alluded to earlier but found to be too complex to handle by hand calculation.

Appendix 3 shows examples of minimum and maximum inclusion restraints, and further guidance is given in Appendix 1.

Nutrient specification targets, as has been seen from Table 14.6, are also difficult to meet with exactitude, particularly when there may be many of them. Again, a target with some width is helpful to the optimisation process. Thus targets for a DE concentration of 13.0–13.3 MJ/kg and for a lysine concentration of 11–12 g/kg will result in a lower cost diet than would exact specifications of 13.2 and 11.5. It follows, however, that whereas in the latter case there will be 0.88 g lysine/MJ DE, in a former case the lysine:energy ratio can range from 0.92 to 0.83. It is important that the ratio does not stray outside realistic maximum and minimum values.

In practice it is remarkably easy to restrain a least-cost computer program to producing diets little different from what may be calculated simply by hand, and no cheaper. It is quite possible to produce an apparently innocent set of constraints which are mutually incompatible and for which no solution is obtainable. Occasionally an unusual ingredient may be forced in at a very high price simply to adjust for some trivial imbalance of a minor amino acid or mineral. As a general rule therefore all constraints (both of ingredients and nutrient specification) should be kept to as few as possible and based on hard evidence.

**Description of raw-material feedstuff ingredients**

The computer files require precise descriptions of the nutrient contents of available feed ingredients. These nutrients will be called up by the computer from the ingredients in order to satisfy the various aspects of the diet nutrient specification. There must be a complete match between the elements specified as required within the diet and these elements described for each of the individual feedstuffs. The matrix of nutrient content descriptors for feedstuffs, together with their recommended maximum and minimum inclusion levels for the various diets to be formulated, with a statement of the current price of each feedstuff, comprise the necessary informa-
tion files for the least-cost diet formulation package to draw upon in the course of
the formulation process. Appendix 1 is an example of an appropriate source for
some of the information needed in an effective feed descriptor file. Example files
for a particular source of barley and a particular source of soya bean meal are to
be found in Appendix 4, which in this case shows an adequate, but not compre-
hensive, analysis. The same information file also, of course, gives the price for each
potential diet ingredient.

**Description of the nutrient specification for the diet**

Appropriate nutrient specifications for various pig diets may be found from sources
such as Appendix 2, and it is at this point that maximum and minimum levels should
be set for the concentrations of the various nutrients required. Maximum (and
minimum) inclusion limits for the various feedstuffs (which naturally differ for
different diets) have already been suggested in the lower parts of the tables in
Appendix 1.

**Computerised least-cost diet formulation**

The simple example described here used a computer program prepared by Format
International (Singlemix). The output shown in Table 14.10 describes in columns 3
and 4 the target nutrient specification to be achieved in the diet. The formulation
specification is not comprehensive for vitamins and minerals as it is assumed that
the vitamin and trace element supplement will provide fully for the dietary require-
ment (Appendix 2 refers). It may be seen from Table 14.10 that the minimum and

<table>
<thead>
<tr>
<th></th>
<th>Analysis achieved</th>
<th>Limit</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Volume)</td>
<td>100.0</td>
<td>(max)</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>DE</td>
<td>14.0</td>
<td>(min)</td>
<td>14.0</td>
<td>14.5</td>
</tr>
<tr>
<td>CP</td>
<td>208.5</td>
<td></td>
<td>200.0</td>
<td>240.0</td>
</tr>
<tr>
<td>DCP</td>
<td>179.6</td>
<td></td>
<td>150.0</td>
<td>200.0</td>
</tr>
<tr>
<td>Lysine</td>
<td>11.3</td>
<td></td>
<td>11.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Methionine + cysteine</td>
<td>6.8</td>
<td></td>
<td>5.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Methionine</td>
<td>3.2</td>
<td></td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Threonine</td>
<td>7.0</td>
<td></td>
<td>6.6</td>
<td>10.0</td>
</tr>
<tr>
<td>Tryptophan</td>
<td>2.7</td>
<td></td>
<td>1.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Linoleic acid</td>
<td>10.6</td>
<td></td>
<td>10.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Calcium</td>
<td>10.2</td>
<td></td>
<td>9.8</td>
<td>11.5</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>6.5</td>
<td>(min)</td>
<td>6.5</td>
<td>9.0</td>
</tr>
<tr>
<td>Sodium</td>
<td>1.5</td>
<td></td>
<td>1.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Oil</td>
<td>40.3</td>
<td></td>
<td>40.0</td>
<td>56.0</td>
</tr>
<tr>
<td>Fibre</td>
<td>45.0</td>
<td>(max)</td>
<td>25.0</td>
<td>45.0</td>
</tr>
<tr>
<td>Ash</td>
<td>65.4</td>
<td></td>
<td>49.0</td>
<td>70.0</td>
</tr>
<tr>
<td>Neutral detergent fibre</td>
<td>142.8</td>
<td></td>
<td>100.0</td>
<td>200.0</td>
</tr>
</tbody>
</table>
maximum levels for DE requirement are quite narrow (14.0 to 14.5), but those for protein quite wide. The lysine minimum is set to give at least 0.75 g lysine per MJ DE (11.0/14.5), and the other essential amino acids (three others are identified) are balanced to lysine in the appropriate ratio as described earlier. Such a set-up might be expected to formulate on the basis of energy and lysine, possibly being modified by phosphorus fibre, oil and even protein. In the event, as seen in column 1, the final analysis of the mixed diet gives the minimum value for DE and phosphorus and the maximum for fibre, showing that energy and phosphorus were relatively expensive (and therefore to be minimised). The cheapest ingredient mix was also associated with an analysis at the maximum level of fibre. Releasing the restraints of minimum energy and phosphorus and of maximum fibre would allow a cheaper diet, but being of lower energy and mineral concentration, more of it would have to be eaten per day.

Often lysine is the most expensive nutrient to find from conventional feedstuffs and least-cost diet programs often formulate to the minimum limit for lysine. This is not the case here, however, as energy is at the minimum, and the program is looking to maximise energy from fat supplementation. This particular program was not set up to offer any synthetic amino acids as possible feed ingredients. If artificial amino acids are available (as they often are) it is beneficial at least to offer them as available feedstuffs. Their inclusion would, of course, depend upon the relative prices of synthetic amino acids and amino acids found within conventional feedstuffs such as soya bean meal and fish meal. The inclusion of synthetic amino acids will certainly alter the least-cost solution.

Table 14.11 shows the least-cost mix of feedstuff ingredients that will provide a nutrient specification within the limits detailed in columns 3 and 4 of Table 14.10. When formulated, the feedstuff combination in columns 1 and 2 of Table 14.11 will provide a compounded diet of the nutritional analysis shown in column 1 of Table 14.10. From Table 14.11 it is seen that the optimal currency cost is 136.17; achieved only by including the ingredients as shown in columns 1 and 2 of the table. The major cereal used is wheat, but there is also some barley and wheat feed. Column 2 gives the exact percentage of each ingredient and column 3 the amounts to make a 2500 kg mix. Column 5 shows which limits were operational in this particular formulation, while columns 6 and 7 show respectively the minimum and maximum inclusion levels to be allowed. Wheat is limited to a maximum of 40% and at a currency cost of 120 per t is clearly favourably priced as it is included up to the maximum limit allowed. Similar comments are appropriate for the fat supplement. Additives, vitamins and minerals are forced in at exact quantities regardless of price. Fish meal appears expensive, but is forced in at 4% on the basis of the judgement of the feed compounder. A cheaper diet would result if more wheat and fat were allowed in, and fish meal were less strongly insisted upon. There may be an (understandable) fear, however, that there would be a consequential uneconomic fall in performance.

Many ingredients available for inclusion have been rejected on the grounds of price per unit cost of their nutrients. These are listed in the lower section of column
1 of Table 14.11. Reductions in the costs of these latter feedstuffs or increases in the costs of included ingredients (column 4) would, of course, change the optimal mixture of feedstuffs in the least-cost diet formulation. Most linear programming packages will give estimates of the prices that would need to prevail before a rejected ingredient is likely to be included.

### Changes of ingredients

The least-cost diet formulation process infers that pigs will respond to analysed nutrients such as given in column 1 of Table 14.10. This is to suppose that pigs do not notice, or react to, the tastes or textures of different feed ingredients, such as given in column 1 of Table 14.11. It is further to suppose that pigs do not notice differences in diets compounded from either few or many ingredients. Although in general the desire for nutrients by pigs does seem to over-ride matters relating to ingredient taste, this is not likely to apply so strongly to younger pigs and lactating sows. These classes of pigs may have their appetites noticeably disrupted by the appearance in their diets of new ingredients, or ingredients included at unfamiliarly high levels. This being the case it is undesirable to allow the dramatic fluctuations in ingredient level that may follow from changes in comparative prices of the major

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**Table 14.11.** Output from a least-cost linear programming formulation package (Format International – Singlemix).

<table>
<thead>
<tr>
<th>Name: Pork Diet</th>
<th>Currency Cost: 136.17</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Included</strong></td>
<td></td>
</tr>
<tr>
<td>%</td>
<td>kg</td>
</tr>
<tr>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>1</td>
<td>12.7</td>
</tr>
<tr>
<td>2</td>
<td>40.0</td>
</tr>
<tr>
<td>3</td>
<td>5.5</td>
</tr>
<tr>
<td>6</td>
<td>25.2</td>
</tr>
<tr>
<td>12</td>
<td>0.6</td>
</tr>
<tr>
<td>19</td>
<td>5.0</td>
</tr>
<tr>
<td>27</td>
<td>5.0</td>
</tr>
<tr>
<td>37</td>
<td>4.0</td>
</tr>
<tr>
<td>59</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rejected</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>kg</td>
</tr>
<tr>
<td>4</td>
<td>194.0</td>
</tr>
<tr>
<td>5</td>
<td>217.0</td>
</tr>
<tr>
<td>7</td>
<td>246.0</td>
</tr>
<tr>
<td>8</td>
<td>165.0</td>
</tr>
<tr>
<td>10</td>
<td>125.0</td>
</tr>
<tr>
<td>11</td>
<td>35.5</td>
</tr>
<tr>
<td>13</td>
<td>91.0</td>
</tr>
</tbody>
</table>
ingredients. Restraint should therefore be imposed on the formulation to ensure that dramatic and abrupt changes (swings) in diet ingredients do not occur. It has to be accepted that such restraints will move the formulation away from optimisation achieved solely on the basis of consideration of price per unit of nutrient.

The computer output of a least-cost diet formulation is best used as a guide for the nutritionist toward appropriate diet construction. Whilst the exact suggestions of a linear program may indeed be implemented, it is not appropriate to allow the computer to over-ride all human judgement. Least-cost diet formulation is particularly helpful in showing up both the real costs of nutritional decisions that may be made regarding the degree of appropriateness of various feedstuffs and the assumptions that are made regarding nutrient requirements and target diet nutrient concentrations.

**Sensitivity analysis**

Least-cost linear programming allows a financial sensitivity analysis. This report gives the cost of any nutrient or raw material constraints that are hitting minimum or maximum. Thus, for example, in the Table 14.11 wheat is on its maximum inclusion limit of 40%; and the sensitivity report would indicate the reduction in feed cost that could be attained by increasing this limit. Normally this is given as a cost per unit increase – thus it might be that the currency cost of the diet decreases by 0.1 for each 1% additional wheat above 40%. This will challenge the nutritionist as to the reason for the 40% maximum constraint. As a second example, energy concentration is the most costly nutrient in pig feeds. The example (Table 14.10) has a minimum DE of 14 MJ/kg, and the sensitivity analysis (Table 14.11) gives the cost of this energy. It is for the nutritionist to judge whether that cost per unit MJ DE/kg is reasonable. Perhaps a feed of lower energy density might be proportionately cheaper. There is therefore a cost implication attached to the energy constraint which should have its worth seriously questioned. A specification should be seen as dynamic rather than fixed. Most commercial nutritionists understand the value of energy and other nutrients and routinely check sensitivity values after each formulation.
Chapter 15

Optimisation of Feed Supply to Growing Pigs and Breeding Sows

Introduction

Control of the feed allowance remains the most biologically, financially and managementally effective way of optimising pig performance. Feed control is simple in the mechanical sense through the medium of feed-supply engineering systems. These may range from computer-controlled pipeline feeding, through auger-supplied individual pen (or pig) volume-controlled metering devices, to self-feed continual access *ad libitum* hoppers. The influence of feed supply upon the rate and composition of growth, and upon reproduction, is both substantial and direct (see Figure 15.1). There is a close relationship between feed allowance management and financial management which comes from (1) the influence of feed supply upon the level and quality of pig production output, and (2) the cost of feed being by far the greatest single element of total production costs (usually about 75% of all costs, including fixed costs).

Growing pigs

The pig production manager has many points at which his operation may be controlled, but six are especially important: health control, environment control, diet formulation control, feed intake control, genetic control and product quality control (Figure 15.2). As the figure shows, feed intake control is pivotal to the effective usage of both feedstuffs and pig inputs. Through interaction with both genotype and diet nutrient specification, feed intake control determines the quantity and quality of the end-products. This is well illustrated by the case history shown in Figure 15.3. The grow-out unit concerned was showing a loss. Upon investigation, the following aspects of management, amongst others, were noted:

- The pigs were fed twice daily to appetite with a computer-controlled pipeline wet-feeding system.
- The carcasses were unacceptably fat.
- Growth rate was adequate, but not particularly impressive.
- Health and environment were satisfactory.
- The diet used was of relatively low nutrient concentration.
### Optimisation of Feed Supply to Growing Pigs and Breeding Sows

<table>
<thead>
<tr>
<th>Feed intake restricted</th>
<th>Feed intake to appetite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pigs less than 40 kg</td>
<td></td>
</tr>
<tr>
<td>increasing feed allowance</td>
<td>increasing growth rate</td>
</tr>
<tr>
<td>much more lean</td>
<td>more lean</td>
</tr>
<tr>
<td>no more fat</td>
<td>little more fat</td>
</tr>
<tr>
<td>increasing growth rate</td>
<td></td>
</tr>
<tr>
<td>Pig more than 80 kg</td>
<td></td>
</tr>
<tr>
<td>increasing feed allowance</td>
<td>increasing growth rate</td>
</tr>
<tr>
<td>more lean</td>
<td>no more lean</td>
</tr>
<tr>
<td>little more fat</td>
<td>more lean</td>
</tr>
<tr>
<td>increasing carcass value</td>
<td></td>
</tr>
<tr>
<td>Pregnant females</td>
<td></td>
</tr>
<tr>
<td>increasing feed allowance</td>
<td>increasing growth rate</td>
</tr>
<tr>
<td>some lean loss</td>
<td>no lean loss</td>
</tr>
<tr>
<td>much fat loss</td>
<td>some fat loss</td>
</tr>
<tr>
<td>Lactating females</td>
<td></td>
</tr>
<tr>
<td>increasing feed allowance</td>
<td>increasing milk production</td>
</tr>
<tr>
<td>some lean loss</td>
<td>no lean loss</td>
</tr>
<tr>
<td>much fat loss</td>
<td>some fat loss</td>
</tr>
<tr>
<td>increasing growth rate</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 15.1** Influence of increase in feed allowance upon pig productivity.

**Fig. 15.2** Flow diagram of a grow-out unit for pigs, showing inputs, outputs and points of decision-making and operations control.
The obvious remedial action might have been to suggest that a diet of higher nutrient specification should be used, but this would have increased input costs at a time when such would have been financially hard to bear, and when other circumstances – such as feeding level – would have conspired to ensure that the positive effects of improving the diet would have been minimal. Rather, the recommendation was that the feed allowance be reduced. This had the apparently negative effect of reducing growth rate, but input costs were reduced and carcass quality improved; thereby raising output value and margin. This helpful response was indicative of (1) the stock being of relatively low genotype in terms of potential daily lean growth rate, and (2) the particular market for which these pigs were destined discriminating strongly against fat and meriting an improved genotype. A pig of improved quality alone, however, would not have maximised the response. Further actions need to be taken with regard to both diet quality (concentration of nutrients) and feeding level. Given an improved genotype with a high lean tissue growth rate potential, the longer-term strategy recommended was not only to move to the use of a higher quality diet but also to re-introduce the original high level (appetite) feeding system (Figure 15.3).

**Interactions with level of feed supply**

**Slaughter weight**

Product quality control (Figure 15.2) has many elements but a major aspect is the interaction between feed supply and slaughter weight. Pigs may usually be despatched from the production unit at a weight that will target a particular market; for example, 120–160 kg live weight for heavy pigs, 85–120 kg for conventional processing and manufacture, or 60–80 kg for light, fresh pork. Even within these bands, more rigorous dead weight limits might be set (for example, 65–72 kg dead weight which would require a live weight despatch range of only 85–95 kg). The manager must therefore decide which pigs should be despatched at what weight, and to which market outlet, in order to maximise profitability. However, the quality of the carcass and the quantity of carcass can be counteracting forces. The heavier the weight of the individual pig at sale, the greater will be its individual value and the lower will
be the fixed costs as a proportion of total costs; but the heavier pig at sale is likely to be fatter, and this will reduce the value per unit weight of pig sold. This means that where carcasses are likely to be at risk of being judged unacceptably fat, there is impulsion not only to reduce daily feed input by rationing but also to reduce the weight at slaughter. If a range of 62–75 kg dead weight is allowed, it is probable, all other things being equal, that pigs of 73–75 kg will have a lower value per kilogram when a premium is paid for leaner pigs. This may be countered by giving a lower level of feed to those pigs that are more likely to fatten, or by selecting them for earlier despatch. Figure 15.4(a) shows the relationship between weight at slaughter and subcutaneous P2 backfat depth, and the interaction with pig genotype; while Figure 15.4(b) shows the equivalent relationship between feed allowance and backfat depth. It may be inferred that lower feed intakes – by encouraging a lower P2 backfat depth – may allow a higher live weight at slaughter. Disbenefits in terms of carcass value due to pigs being unacceptably fat will be more evident when less improved genotypes are allowed to eat higher quantities of feed [Figure 15.4(b)]. In the absence of any price penalty for fat pigs (all pigs are equally acceptable regardless of fatness), the highest levels of feeding and the heavier slaughter weights will tend toward being more economic.
Feed conversion efficiency

The contrary pressure to the conclusion that heavier (and fatter) pigs are to be preferred in the absence of any quality discrimination against fat is primarily the efficiency with which the most expensive input commodity (feed) is used. Feed conversion efficiency will inevitably decrease at higher slaughter weights due to the progressively greater costs of maintenance. Maintenance costs result in no product yield, and are related to the body mass of the pig. Thus at 60 kg live weight there is a fixed maintenance cost of about 0.7 kg of feed, at 90 kg about 1.1 kg of feed, and at 120 kg 1.3 kg of feed. Feed conversion efficiency will also inevitably decrease at the highest levels of feeding when this brings about excessive fat deposition. It is salutary to note that reducing the feed input may not always improve feed conversion efficiency; this will usually happen only when extremes of fatness are restrained. More usually reducing feed intake will – by reducing growth rate – worsen the efficiency of utilisation of feed for growth. As the amount of feed eaten increases, there is a beneficial reduction due to progressive savings in maintenance costs (Figure 15.5). Ultimately, however, efficiency deteriorates due to the deposition of excess fat at the higher feed intakes, and the fact that a unit of fatty tissue growth requires more than three times as much feed as a unit of lean tissue growth. Importantly, the figure also shows that there is relatively little change in the amount of feed required for each kilogram of live weight gain over quite a wide range of amounts of feed eaten; changes in feed conversion ratio tend to be more evident at the extremes than in the middle of the range.

Response to an increase in feed intake

Optimisation necessitates quantification of response. Empirical measurements would suggest that a 100 g increase in daily feed intake (approximately 1.5 MJ DE daily) from 20–100 kg live weight will bring about an increase of 30–40 g daily live weight gain, 1 mm or so in P2 backfat depth, 10–15 g in the daily lean tissue growth rate, 20–25 g in the daily fatty tissue growth rate and a marginal deterioration in
feed conversion ratio (Figure 15.6). Such statements of empirical response, although often much beloved, are dangerous. The nature of the response to an additional increment of feed allowance is dependent – _inter alia_ – upon the absolute feed level, the lean tissue growth potential of the pig, the weight range over which the response was measured and the environmental conditions. In the extreme, it is possible for a 100 g feed increment to be used infinitely inefficiently to achieve no growth, or to be used for the single purpose of the growth of 100 g of straight lean tissue (1 kg lean tissue uses 15 MJ of balanced DE), or to be used for the single purpose of the growth of 30 g of straight fatty tissue (1 kg fatty tissue uses 50 MJ DE); and, of course, any combination of these three extremes is entirely feasible.

**Fig. 15.6** Responses to increasing average daily feed intake. The diet contained 14 MJ DE, 200 g CP and 11 g lysine per kilogram. Pigs were fed from 20–100 kg.
Interaction with genotype and sex (potential lean tissue growth rate and predisposition to fatness)

Increasing feed allowance will in general increase growth rate and fatness (Figures 15.4 and 15.6). The extent of these increases is highly dependent upon genotype and sex. Thus the same level of feeding that would induce inefficient fattening in a castrated male could give beneficial lean growth in a female. Castrated males and unimproved genotypes of lower lean tissue growth potential will justify feed allowance restriction to a greater extent, and imposed at a lighter weight, than will females (or entire males) and improved genotypes. The later on in the growing period that restriction is imposed, the faster will be the average rate of growth; with those animals of higher lean tissue growth potential benefiting the more from delaying the live weight at which the feed allowance restriction occurs [Figure 15.7(a)]. Similar growth responses may be expected consequent upon the severity of restriction imposed [Figure 15.7(b)].

Figure 15.8 remains the most useful paradigm for considering the appropriate level of feed to be supplied to any pig in any given day. The first principle is that the overall growth response of fat plus lean is always positive to increasing increments of feed. The more feed that is given, the faster the pigs will grow. Second, at lower feeding levels this response is particularly steep and efficient because the next increment of feed is going toward growth of equal composition (i.e. equal fat:lean ratio) as the last increment; and this composition is primarily of lean tissue. Third, the response becomes broken and the slope less steep with higher levels of feeding when fattening is induced. The fourth principle, and of paramount significance, is that the point at which the reduction in efficiency occurs, and at which fattening begins, is dependent upon the lean tissue growth rate potential of the pig (as may be seen by comparison of pig types a and b). Feed supplied to the amount X (Figure 15.8) will maximise lean tissue growth rate. Above X growth rate will

![Graph](image-url)
continue to increase but the pig will fatten. Below X lean tissue growth rate is not maximised. The absolute amount of feed represented by X is highly dependent upon the type of pig (sex, genotype and lean tissue growth potential). The absolute amount of feed represented by X will also increase as the pig grows. For a 40 kg live weight pig, X may be at a feed supply level of 1.75 kg, for a 60 kg live weight pig at 2.25 kg and for an 80 kg pig at 2.75 kg. For pigs not required to fatten, the ideal ration scale will be one that allows for each pig on each day exactly the amount of feed represented by X. This is not to suggest that feed levels higher than X should never be chosen. Not at all; feed levels above the break point may be readily justified where there is a desire to increase the level of carcass fat, or where the relationship between feed price and carcass price is such that even the lower efficiencies achieved at higher levels of feed supply are nevertheless economic, and the benefits of more rapid pig growth rate are perceived to outweigh the benefits of a leaner product.

There are also important and substantial differences between pigs in their inherent predisposition to lay down fatty tissue even during nutrient-limited growth (at feed supply levels less than X). While the normal expectation may be a ratio of around 1 of fat to 4 of lean, this may be both better (1 of fat to 5 of lean) or worse (1 of fat to 2 of lean); and this characteristic is open to the influence of both sex and genotype. Thus castrates will be inherently fatter than entire males at any level of feeding. Pigs selected for their capacity to be lean will be less fat than unselected pigs at any level of feeding. This phenomenon is depicted in Figure 15.9. As illustrated, the pig type that inherently discriminates against fat deposition (d) will be more efficient and require a lower level of feeding for a given growth rate response than the pig type that has a predisposition to fat (c). Maximum lean tissue growth rate is also reached at a lower level of feed intake.
Ration scales for growing pigs

Feed can be supplied to growing pigs in a rationed amount once, twice or many times daily; in an unrationed amount when the pig is allowed to eat to appetite as much as it wants but does not have access to feed 24 hours per day; or in an unrationed amount where feed is continuously available. It should not be assumed that these systems are mentioned in ascending order of feed intake achieved. Maximum feed intake will probably occur when pigs are fed high levels of rationed amounts three to four times daily.

Most feeding scales that ration the feed allowance do so in the knowledge that:

- young pigs, because they convert efficiently and grow mostly lean tissue, are unlikely to be overfed;
- as pigs grow bigger they can use (and need) more feed;
- as pigs grow bigger, their appetites catch up with their lean growth potential and they will tend to fatten.

The pig live weight at which feed restriction is imposed, and that extent of the restriction will depend upon the strength of the desire to achieve a lean carcass. It can be assumed that few circumstances merit feed restriction in pigs of below 40 kg live weight. Some fattening scales based on pig live weight are exampled in Figure 15.10. Those in section (a) are smoothly curved, whilst those in section (b) bring about abrupt restriction. In practice, pigs are rarely weighed as they grow; but because the relationship between feed intake and growth rate is both close and direct, weight can be estimated readily from knowledge of feed intake and time. There is some danger in this procedure if it is assumed that pigs are lighter than they really are, for the pigs will be restricted more than is the intention and growth will be slowed below potential. It is good policy always to challenge the grow-out unit every 6 months or so with an increased feeding scale to determine the response.

![Diagram](image.png)

Fig. 15.10 Ration scales for pigs based upon their live weight: (a) smooth transitions from appetite to restricted regime; (b) abrupt transitions. Scales (i), (ii) and (iii) represent progressive degrees of feed restriction, (iii) being extremely restrictive for most modern genotypes.
of the pigs. On the other hand, assuming the pigs to be heavier than they really are will cause them to be fed more than originally intended. This may be no bad thing if the reason for underweight has been some degree of illness, because some catching up may be called for; but if the potential of the pig has been overestimated the scale will be excessive and the carcasses will become fatter than intended.

Realistically, the weight-based scales in Figure 15.10 will actually be operated on the basis of feeding either ad libitum (self-feeding systems) or to appetite (controlled feeding systems) up to the point at which the restriction is imposed, which will occur consequent upon a decision relating to the time passed since the pigs entered into the pen at a known starting weight. The restrictions themselves may be imposed either gradually (a) or abruptly (b). The figure shows three levels of restriction – (i), (ii) and (iii) – indicative of increasing severity which would relate to the relative quality of the genotype (propensity to become fat) and the need to achieve leanness (severity of price penalty for unacceptably fat carcasses).

Time-based scales for rationing pigs are shown in Figure 15.11. Part (a) shows weekly steps of different size from 20 kg live weight onwards, while (b) shows a system of appetite feeding up to a given time after entry into the grow-out pen, after which the time-based restriction is imposed. Scales (i) and (ii) in Figure 15.11 represent progressive degrees of feed restriction.

Ration scales may be usefully employed in automatic feeding systems, but not necessarily with the objective of restricting feed supply, reducing growth and controlling fattening. Rather feed intake may be increased above ad libitum levels if feed is provided fresh in discrete and limited meals three or more times daily, and offered in amounts that challenge the pig’s natural appetite. It should not therefore be assumed that pigs with limited appetites or known to yield lean carcasses are always best fed through an ad libitum dry self-feed hopper system.

The choice of scale, whether it be purposely limiting or purposely generous, is highly dependent upon the following:
(1) the nature of the product required (carcass fatness);
(2) the importance (in financial terms) of growth rate;
(3) the nutrient concentration of the feed used (a given response following from a lower quantity of a more concentrated feed);
(4) the inherent potential of the pig for lean tissue growth (pig sex and genotype).

As has been explored previously, it may be presumed that:

(1) young pigs should be encouraged to eat to the maximum of their appetite;
(2) improved genotypes may have lower appetites;
(3) improved genotypes may eat more feed without the likelihood of becoming fat;
(4) at any given feed allowance, castrated males will fatten more readily than females, and females more readily than entire males.

Simplistically, the point at which lean tissue growth rate is maximised but fattening avoided (X, Figure 15.8) may be empirically determined by trial and error. If the scale exceeds X, the pigs will fatten and this will be evident in fatter carcasses at the point of slaughter. On the other hand, if the ration scale provides feed at a level of less than X, then the pigs will not be maximising their growth. This latter position can be made evident by an increase in the level of feeding being shown to bring with it improved daily growth rate without an increase in carcass fatness. The appropriate method for selecting a correct ration scale is therefore to increase feed allowance until an unacceptable proportion of the pigs are judged to have carcasses that are over-fat, and then to reduce the ration scale to the point at which acceptable carcass fatness is achieved.

Many growing pigs are fed ad libitum world-wide right through to the point of slaughter, and no ration scale is imposed. This is because either genotypes of high quality are being used which do not require to have their feed restricted in order to be acceptably lean, or high fat levels in the carcass are not considered to be unacceptable. The imposition of rationing scales becomes especially relevant for pigs slaughtered at higher weights and/or where there is a desire for a lean carcass.

**Breeding sows**

The appropriate feed supply for breeding sows to achieve optimum performance will be that which:

- maximises the number of piglets per litter;
- optimises the weight of individual piglets at birth;
- maximises the number of litters per year (minimises the weaning to conception interval);
- maximises sow lactation yield (maximises piglet growth from birth to 28 days);
- optimises longevity and lifetime productivity.
General pattern of live weight and fatness changes in breeding sows

Sows gain body weight in pregnancy and lose it during lactation. In addition, at parturition, they produce (and lose) the combined weight of the fetal load plus a further 50% of placenta and fluid (Figure 15.12). As is the case for body weight overall, sows also grow fatty tissue in pregnancy and lose it in lactation, but for fat there is not the same overall positive gain as the sow increases in age and body size. Rather, under well-managed sow feeding programmes, average sow body fatness will remain between 15 and 20% or so (being lowest at weaning and highest at parturition) throughout breeding life (Figure 15.13). As a result, sows that are properly fed will become bigger as they age, but not necessarily fatter.

The greater the feed allowance in pregnancy, the greater will be pregnancy gains. The less the feed consumed in lactation, the greater the lactation losses. Figure 15.12

Fig. 15.12 Expected pattern of sow weight change.

Fig. 15.13 Changes in lipid content of the body of female pigs consequent upon fatty tissue losses after weaning in early life and during lactation while breeding.
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shows 25 kg of maternal gain, parity upon parity, up to the fourth pregnancy. During the early parities the sow is making maternal gains to achieve her target mature lean mass, and gains should be in excess of the 25 kg average. Over this period of breeding life pregnancy gains may be assumed to be of both lean and fat. Later, however, pregnancy gains are likely to be almost entirely of fatty tissues. In all parities (regardless of sow age) lactation losses should most likely be of fat alone, as this is the prime substrate for which there should be a likely shortfall in relation to the requirements for milk synthesis. There may also be some lactation losses of protein, but this will only occur in a protein-deficient diet, or to yield energy if the sow has used up most or all of her energy reserves. Table 15.1 shows maternal body weight gains achieved by adequately fed sows mated for the first time at 125 kg live weight, and maintaining a pattern of body fat change of the sort indicated in Figure 15.13. The composition of the pregnancy gains in terms of chemical protein and lipid are given in Table 15.2. Figure 15.14 shows how weight gains (in this case in the first two parities) can take place at the same time as significant fat losses. In this case the feeding regime used was inadequate for both lactation feeding (being only 4.8 kg per day) and the necessary fat recovery in pregnancy (the sows being fed only 1.8 kg per day in the first pregnancy and 2.3 kg per day in the second). This figure shows how in pregnancy both weight and fat can be gained, but more weight than

<table>
<thead>
<tr>
<th>Parity</th>
<th>Live weight gain conception to conception (kg)</th>
<th>Live weight at next conception (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>160</td>
</tr>
<tr>
<td>2</td>
<td>28</td>
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<td>23</td>
<td>211</td>
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<tr>
<td>4</td>
<td>18</td>
<td>229</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>243</td>
</tr>
</tbody>
</table>

Table 15.1. Maternal body weight gains of breeding sows mated at 125 kg live weight and growing to maturity under adequate nutritional conditions.

<table>
<thead>
<tr>
<th>Parity</th>
<th>Pregnancy gains of protein (kg)</th>
<th>Pregnancy gains of lipid¹ (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>11</td>
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<td>3</td>
<td>6</td>
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<td>4</td>
<td>4</td>
<td>7</td>
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<td>5</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 15.2. Chemical composition of maternal body pregnancy gains of protein and lipid for adequately fed sows.

¹ These gains do not allow for replenishment of any fatty tissue lost in the course of lactation, following the presumption that lactation feeding levels are adequate to provide for lactation needs.
fat; whilst in lactation both weight and fat are lost, but more fat than weight. In this case gains of 11 kg of live weight in the course of a single parity appear to have taken place despite absolute losses of more than 3.5 mm of P2 backfat depth, which is equivalent to losses of 4 kg of fat. The responses shown in Figure 15.14 should not be interpreted to mean that sow weight gains and fat losses of this order are natural expectations; in fact, it has been clearly demonstrated that P2 backfat depths of less than 12 mm are likely to be associated with reproductive inefficiencies.

Figure 15.15 shows the distribution of P2 backfat depths throughout the population of pigs on the same trial as that referred to above. Three distribution curves are depicted. The middle distribution is that which prevailed upon the entry of the pigs into the breeding unit when they were around 90 kg live weight. The pigs had an average P2 backfat depth of 15 mm, and this was mostly distributed between 12 and 18 mm. At parturition (the distribution curve to the right of the figure) the average fatness had increased to about 20 mm P2. By the time of weaning at the end of the second parity (as shown by the left-hand distribution curve) not only the
backfat depths had decreased to a dangerous average of below 10mm P2, but also
the variation in P2 backfat depth had spread to a range of between 6 and 18mm.
Because sows are likely to show rebreeding difficulties at P2 backfat depths of below
12mm, a large proportion of these sows were clearly at risk. The degree of varia-
tion that has been created in the herd is a further and independent cause for serious
concern. The standardised feeding regime [4.8kg per day in lactation and 1.8kg
(parity 1) or 2.3kg (parity 2) per day in pregnancy] over all the sows has created not a standardised population of pigs but instead a highly variable and diverse one.
It is evident that to achieve a standardised level of sow fatness at any point in the
breeding cycle sows must be fed individually a non-standardised ration allowance
calculated according to their needs. The optimum feed supply will therefore be sow-
specific, individual and variable within the breeding herd.

If young breeding females start with about 20% of fat at mating, and subse-
quently increase this to 25% of fat at parturition parity 1, then designing fat losses
into the feeding regime may be tolerable. However, the newer – leaner – hybrid
strains may have fat levels nearer 15% at parity 1 mating and 18% at parturition;
so pursuit of a fat-depleting regime would be intolerable. For young breeding sows
coming to first mating essentially lean, sow feeding strategies must maintain fatness
throughout breeding life. This means that lactation fat losses must be minimised and
pregnancy fat recovery encouraged.

**Feed supply to first mating**

The appropriate weight and age at first mating is much dependent upon the geno-
type of the pig. Asian breeds and unimproved European types are likely to be ready
for breeding at a younger age and lighter weight than modern improved hybrid
genotypes with high lean tissue growth rate and greater sow productivity potential.
For improved genotypes, a mating weight of around 130kg live weight and an age
of 220 days appear most appropriate for optimum subsequent fertility and longevity.
It is also important that at the start of breeding life there are adequate fat stores
available to facilitate a good lactation and a short weaning to conception interval.
It appears that adequate body composition may be that which has more fat than protein (i.e. greater than 17% lipid) and a P2 backfat depth measurement probably in excess of 18 mm. Figure 15.16 shows that modern hybrid sows tend to be much less fat than their predecessors, and the required combination of fatness and age at sexual maturity is unlikely to be readily achieved by the same feeding techniques that would optimise growth rate and carcass quality of pigs grown for meat production. The slaughter generation of hybrid pigs, if fed for maximum lean tissue growth, will achieve 125 kg live weight in less than 180 days, and the P2 measurement at that time may be little more than 16 mm! High levels of high-protein diet are not best suited to the rearing of breeding stock which should more properly be given a more conservative diet of adequate protein and average energy. The formulation used for the lactating sows (170–190 g CP/kg diet) might be ideal. Low protein rearing of breeding gilts may well be counter-productive as protein status may be of equal importance to fat status in determining age at first conception and in its success. The level of feeding would normally be somewhat lower than that encouraged in finishing pens of slaughter pigs. Some rationing is likely to be needed if the growth rate is to be restrained to the required average of around 700 g daily between 30 kg and mating. It is difficult to generalise about what level of feeding will achieve optimum growth for breeding pigs up to the point of first mating (nor even to generalise about optimum age and weight at first mating), as so many other factors interact. The ultimate objective, however, is to mate pubertal gilts at a heat subsequent to their first, at which time they should have an adequate but not excessive cover of fat. Age and live weight are not themselves targets with respect to the right time for first mating. They arise as a consequence of the age pattern of puberty, the weight pattern of fatty tissue growth, and the relationship between ultimate mature size and the appropriate proportion of mature size that needs to have been reached before the phase of reproduction is initiated.

There is no evidence to support the idea of short-term ‘flushing’ before first mating, but a level of feeding adequate to support positive fatty tissue gains (as well
as positive lean tissue gains) throughout the period prior to mating is essential. Particularly important is the status of the body fatty tissues between the first pubertal heat and the first conception. This is interpreted by some to mean an elevated feeding level at this time; and this is not itself a bad thing.

**Feed supply in pregnancy**

The influence of feed allowance in pregnancy was the subject of a series of classical experiments by Professor F. W. H. Elsley. At feeding levels below 2 kg it was found that the maternal body would need to be catabolised for purposes of supporting fetal gain; litter size was reduced and individual piglets were of lower birth weight than those from dams that had received more appropriate levels of pregnancy feeding (Figure 15.17). The figure shows that the effect of feed allowance (ration) upon the live weight of the pigs at birth is significant but small. Average birth weight should be 1.2–1.4 kg. Individual piglet birth weight will increase by around 0.2 kg in response to an extra 1 kg of feed given daily throughout the 115 days of pregnancy.
days of pregnancy; which is a feed:gain ratio of about 50:1. Nonetheless pig birth weight does have significance when pigs of particularly low birth weight die simply because they are small; this often happens to piglets born at less than 1 kg live weight. Percentage survival can be approximated as 

\[ 55 \times W_b^{1.3} \]

where \( W_b \) is the weight at birth.

It has been suggested that birth weight can influence subsequent growth performance (Figure 15.18). Researchers at the Royal Veterinary College, London, in noting that the number of muscle fibres is broadly decided around the time of birth, and that larger numbers of muscle fibres result in greater subsequent lean growth and lean mass (growth after birth mostly being through an increase in the size of muscle fibres rather than their number), are also now suggesting that restricted feeding of sows at any time during pregnancy will, either through compromising the placenta itself or by reducing the flow of nutrients to the fetal load, result in piglets at birth with less than their potential number of muscle fibres. These suggestions would point to disadvantage in feeding sows at a low level through any stage of pregnancy, and an advantage in more generous pregnancy feed provision. It is far from clear whether this effect is real or supposed, or what the differences might be between feed levels defined as ‘restricted’, ‘adequate’ and ‘excessive’. There will, of course, also be indirect effects of birth weight upon subsequent growth mediated through factors such as post-natal health and position in the dominance order.

Because the growth of piglets \textit{in utero} is exponential, dramatic increases in fetal weight can take place in the last 3 weeks of pregnancy. Increasing the feed allowance at this time is therefore likely to be more efficient in terms of feed use for fetal piglet growth than increasing the allowance over the whole of the pregnancy. Whereas increased feed level over the whole of the pregnancy will tend to support mostly maternal gains, feeding subsequent to day 90 of the pregnancy will be more likely to support mostly fetal gains. This is especially the case for sows carrying inadequate body fat reserves at this time (as suggested by the propositions in Figure 15.19).
Figure 15.17 shows that the relationship between feed allowance and maternal live weight gain is almost linear, and may be broadly represented by an efficiency of between 0.2 and 0.25. Positive responses to pregnancy feed intake in terms of maternal and piglet live weight do not, of course, continue to be linear at extreme levels; over-fat females waste feed and are also likely to have fewer young and problems at parturition.

The experiments of Elsley confirmed pregnancy feeding as needing to:

- establish the fetal number (ultimately litter size);
- grow the fetal load (ultimately piglet birth weight); and
- grow maternal lean tissue mass (ultimately mature size).

Additionally, pregnancy feed is required to:

- grow mammary tissue (ultimately a relatively minor factor in milk yield); and
- replenish maternal fatty tissue mass lost during the previous lactation (ultimately a major factor in subsequent lactational milk yield and in the weaning to conception interval).

Fatty tissue deposition appears to be most active during the first three quarters of pregnancy, whilst in the last quarter some fat may even be catabolised if the sow goes into negative energy balance on account of the rapidly developing fetal load. Whether this loss of fat during late pregnancy is an unavoidable biological phenomenon or the result of under-feeding in the final trimester is not clear. The picture of fat loss from the 85th day of pregnancy was particularly evident in the young gilts that generated the data depicted in Figure 15.14.

Weight gains in pregnancy are closely related to pregnancy feed intake (Figure 15.20). Due to individual sow variability there is a broad band of response. Maternal body gains of 40 kg or so may be associated with a daily feed intake of 3 kg, while 1.5 kg could achieve approximate maternal weight stasis. The total weight gain

![Fig. 15.20 Response of maternal live weight gain to feed intake in pregnancy. The diet is assumed to contain about 13 MJ digestible energy (DE) per kg.](image)
Optimisation of Feed Supply to Growing Pigs and Breeding Sows

(maternal body weight gain plus the fetal load and the other products of conception) will be about 20 kg greater than the maternal gains alone. Maternal gains of 25 kg will therefore relate to overall body weight gains of 45 kg. A guideline regression relating maternal live weight gains in pregnancy ($\Delta W$) to daily feed intake ($F$) might be:

$$\Delta W \text{ (kg)} = 25 F \text{ (kg)} - 27 \quad (15.1)$$

This equation points to a daily feed allowance of 2.2 kg in pregnancy giving maternal weight gains in pregnancy of 28 kg, and confirms that the rate of live weight gain in sows may be increased with an efficiency of feed use of 0.22; or a rate of feed usage of 4.6 kg feed for every kilogram of live weight gain.

The relationship between maternal pregnancy fatty tissue gain ($\Delta T$) and daily pregnancy feed intake ($F$) is shown in Figure 15.21. The corresponding guideline regression for this illustration is:

$$\Delta T \text{ (kg)} = 15 F \text{ (kg)} - 30 \quad (15.2)$$

The relationship between fat change and feed intake may also be given in terms of backfat depth (P2) change in pregnancy:

$$\Delta P2 \text{ (mm)} = 4.60 F \text{ (kg)} - 6.90 \quad (15.3)$$

by which equation a daily feed allowance of 2.2 kg in pregnancy would give maternal gains of 3.2 mm P2 backfat.

The broad approximations contained within the regression coefficients in Equations 15.1, 15.2 and 15.3 imply that (1) depth of fatty tissue is a large component of weight gain in pregnant sows, and (2) weight gains can proceed at lower feed intakes than those that would support fatty tissue gains. A daily intake of 2 kg of an average diet (which is often quoted as a feeding level appropriate for pregnant sows) can be associated with maternal gains of around 23 kg, total body weight gains of about 43 kg and little fatty tissue gain or replenishment. This response might well be considered appropriate for adequately fat sows with no requirement for maternal
growth or replacement of lipid catabolised during lactation, but will be inadequate for sows in their first three parities (and which are therefore still growing) and for sows with fatty tissue levels that are sufficiently low, unless replenished, to put at risk subsequent reproductive success. Where inadequate pregnancy feeding results in sows carrying insufficient fatty tissue at parturition, the subsequent milk yield is likely to be adjusted downwards by the mother and the growth of the sucking pigs prejudiced. A recent experiment showed the necessity of allowing for losses of body fatty tissue and body weight in the subsequent lactation:

Litter weight (kg) at 28 days of age = 57 + 1.5 sow fat loss (mm P2) + 0.46 sow weight loss (kg)  

Sows that are thin will also react to their unacceptable state by delayed rebreeding. This will show as an increase in the number of days that lapse between weaning and next conception. Days between weaning and conception have been found to be consistently negatively related to both sow fatness and sow live weight at weaning; that is, sows that are too lean and too light rebreed less soon after weaning.

Although the fatness of the sow at weaning is more to do with lactation feeding level than with pregnancy feeding, it is nevertheless true that the chance for reinstating lost fat stores comes only in pregnancy. It is therefore relevant to pregnancy feeding, as well as lactation feeding, to note the crucial effect of sow body condition upon readiness to rebreed. Figure 15.22 shows the relationship between the interval from weaning to oestrus and the P2 backfat depth of the sow at weaning. Usually there are 3–5 unproductive days between weaning and oestrus. However, these escalate dramatically as sows become thinner and have backfat depths below about 12 mm P2. The effect seems to be more serious for primiparous gilts at the end of their first lactation than for more experienced multiparous sows. Sows becoming too fat may exhibit similar problems. Whilst more attention may justifiably be given to the problem of sows that are too thin, there can on occasion be an equally important problem with sows that become too fat. There is no benefit in the breeding pig attaining backfat depths in excess of 25–30 mm P2.
The relationship between fatness and reproduction shown in Figure 15.22 is pivotal to the success of the breeding sow herd:

- Pregnancy feeding must allow sufficient fat accumulation during the pregnancy minimally to (1) facilitate the expected fat losses that will occur in lactation, and (2) support adequate fat depth at the time of subsequent weaning (at least 12 mm P2).
- Sows weaned in poor condition and with inadequate fat levels will show reluctance to rebreed, and it is also likely that the next litter will be reduced in both number and birth weight.

The pattern of feed supply through pregnancy has long been as much the subject of fashion as a science. Suffice to identify the following overriding principles:

1. Overall feed supply in pregnancy, related to the condition of the sow, is the most important factor prevailing upon sow productivity.
2. Reduced feeding levels in early pregnancy may be beneficial to ova implantation in the first month of pregnancy if sows are fat; but there is little or no evidence for this in modern genotypes, and some evidence for the reverse – namely that higher levels in early pregnancy increase subsequent litter size in sows that have suffered lactation weight loss, as most sows now do. Work at the Swedish Pig Centre, Svalöv, is not alone in showing improved litter size to result from feeding higher levels after mating (3 kg) and for the first 3 weeks of pregnancy, as similar results have come recently from a number of countries, including Australia.
3. Higher feeding levels in late pregnancy may be beneficial to fetal growth if in the last month of pregnancy sows are thin; but there is also some evidence that high late lactation feeding will predispose to agalactia in some herds.
4. The overriding principles of sow feeding are the consideration of lifetime performance and lifetime feeding strategies (not part-parity performance and feeding tactics), and to secure from the outset an adequate body condition for the breeding sow at the earliest opportunity, and subsequently through breeding life, by feeding to body condition. Feeding to body condition effectively targets the vital relationships between feed supply and sow body lipid content and sow body lipid content and breeding success.

**Feed supply between weaning and conception**

At one time or another, there has been reason to suppose that, after weaning, both a generous ration and a restricted ration might enhance the number of ova released and the number of embryos safely implanted into the uterine wall. It would now appear that extremely heavy feeding before conception and in the first 3 weeks of the pregnancy may be counter-productive; but very high feeding levels after weaning are in any event rather difficult to achieve. It would also appear that if problems of
embryo implantation were to be relevant, they would only arise with feeding levels in early pregnancy that are more than 3 kg daily, and probably greater than that. A sow already thin at the point of weaning will not benefit from being further embarrassed by a restricted feeding regime. It may be concluded therefore that between weaning and conception sows may be fed to appetite for the duration of this 3–5 day period; and they will eat 3–4 kg daily. If ad libitum feeding results in feed intakes greater than this, then for sows that have lost weight in lactation the consequences are likely to be beneficial. If conception is delayed, some restriction will become necessary and the level of feed supply should relate to the condition of the sow but would normally be between 2 and 3 kg daily. The first 3 weeks of pregnancy are sensitive because this includes the period of embryo implantation that has a large effect on ultimate litter size. It would appear that both particularly high and particularly low feeding levels at this time may compromise the number of fetuses that will settle into the uterine wall. Feeding levels in early pregnancy therefore usually range between 2 and 3 kg daily – the higher levels for sows in poorer body condition.

Lactation weight losses may have involved loss of both fatty and proteinaceous body tissues. This being the case, logic would suggest a high quality, high nutrient dense (both protein and energy) diet as appropriate for the weaning to conception interval in order to replenish lost tissue and return the body to rebreeding condition; the lactation diet might also be considered for use in the first trimester of pregnancy, especially for first and second parity sows.

**Feeding in lactation**

Lactation feed allowance needs to be provided at adequate level to:

- maximise milk yield (ultimately to maximise piglet weaning weight);
- minimise maternal fat and protein losses (ultimately to minimise the time between weaning and conception, and maximise subsequent litter size).

It is well recognised that the breeding sow will gain both fatty tissue and lean tissue in pregnancy and lose them (but mostly fatty tissue) in lactation. There will be a relationship between these two phases of the reproductive cycle. Sows of greater weight and fatness at parturition have more tissue available to be volunteered toward lactation and rearing of the young. Post-partum appetite is negatively related to pregnancy feed intake. A 0.5 kg increase in daily allowance during pregnancy may result in as much as a 0.5 kg decrease in daily appetite during lactation, but usually the relationship is much weaker. Lactation feed intake is linked to the status of the sow’s fat stores. The fatter the sow at parturition, the greater the appetite depression.

Under ad libitum conditions, the daily feed intakes of lactating sows may vary between 3 and 12 kg daily. It is often stated that sows should be fed according to the size of the litter; for example, 4 kg for the sow plus 0.4 kg for each piglet over 6, or perhaps 2 kg for the sow plus 0.4 kg for each and every piglet in the litter. However,
more usually lactating sows are fed according to appetite, regardless of litter size. The idea that a lactating sow should be rationed is a contradiction in terms; lactating sows needing to eat as much as they can, and often even that is not enough.

In warm climates and in farrowing houses where ambient temperatures are high, adequate feed intake in lactation presents a severe problem. It may be estimated that the appetite of lactating sows will be reduced by about 0.1 kg/day for each degree Centigrade above comfort temperature (normally around 15°C for a lactating sow). In these circumstances a maximum feed consumption of 4 kg per day or less is quite common. Reducing the heat output from the body by providing energy in the form of fat rather than carbohydrate can be helpful in maintaining appetite in the face of high ambient temperatures. Other methods to reduce the likelihood of appetite loss by heat stress are to increase ventilation rate, provide sprays and wallows, and enhance conduction through the floor by use of solid rather than perforated flooring. All these devices will increase the effective comfort temperature by facilitating a more rapid removal of heat from the body surface. Removal of heat from the body at a faster rate has the same effect as reducing the level of heat production in the first place, and thereby forestalls feed intake depression. The total effect of all these factors combined can offset appetite depression by as much as 1.5 kg daily at an ambient temperature of 25°C, and therefore represents most important considerations for the breeding herd manager.

Some large sows kept under cool conditions may eat 7–8 kg (up to 12 kg) daily, but most sow appetites rarely exceed 6.5 kg during lactation. On the first day after parturition relatively little can be consumed (1–2 kg), but this can rise by about 1 kg daily to reach 6–7 kg or so at the end of the first week of lactation. In order to avoid loss of appetite in early lactation, a rise of 0.5 kg daily is often recommended. Some reduction may occur after 21 days of lactation as yield falls. Primiparous sows often only eat 4 kg or less in lactation, some larger and more highly productive multiparous sows may eat more than 9 kg daily. Sows fed the diet wet will eat 10–20% more feed than when the diet is given dry.

Fig. 15.23 Influence of feed intake in lactation on sow body weight and body fat change.
Lactation weight and fat losses are directly related to lactation feed allowance (Figure 15.23). At the higher feed intakes maternal body weight gains of more than 10 kg may be achieved in the course of a 28-day lactation, but at the lower intakes 20 kg of sow maternal body weight may be lost. Fat losses as measured by the change in ultrasonic P2 measurement show similar trends. The less the feed, the greater the rate of fat loss, with lower feed allowances causing P2 losses in excess of 5 mm over a 28-day lactation, whilst the higher feed allowances may almost achieve fatty tissue balance.

The linear regressions for Figure 15.23 are:

\[
\text{Weight loss during 28-day lactation (kg)} = 48.8 - 9.60 \times \text{feed intake (kg/day)} \tag{15.5}
\]

\[
\text{Fat loss during 28-day lactation (mm P2)} = 11.1 - 1.37 \times \text{feed intake (kg/day)} \tag{15.6}
\]

An average feed intake in lactation of 6 kg daily will therefore result, in the course of a 28-day lactation, in a weight loss of 9 kg and a reduction in P2 backfat depth of 3 mm.

These equations suggest that:

- lactation weight loss may be largely prevented at feed intakes of above 5 kg per day, which may be quite readily achieved;
- lactation fat loss may be largely prevented at feed intakes of above 8 kg per day, which are less readily achieved;
- at weight stasis significant quantities of body lipid are lost;
- an extra 1 kg of feed per day over a 28-day lactation will save about 10 kg of maternal body weight loss and about 1.4 mm of P2 maternal subcutaneous fatty tissue loss.

Feed intake in lactation has a positive effect upon milk yield and the weight of piglets at weaning. Putative responses are shown in Figure 15.24. The sigmoid curve suggested is a consequence of early increments of feed supply going primarily to satisfy the priority shortfall in maternal requirement. Sow milk yield, of course, is also highly dependent upon litter size. Further, large sows will have less feed available for lactation than smaller sows eating the same amount of feed, on account of differences in maintenance requirement. Moreover, as is the case with all responses expressed in terms of feed weight (rather than energy or amino acid intake), lactation responses are highly dependent upon the concentration of nutrients in the ration consumed.

Sows that are either unacceptably thin or unacceptably fat have less desirable reproductive performance. As has been presented in Figure 15.22, there is now clear evidence of negative relationships between sow body condition at the end of lactation and readiness to rebreed (days between weaning and oestrus). There are also negative relationships with conception rate (percentage of mated oestrous females conceiving) and ovulation rate (potential litter size)(Figure 15.25). It has been pro-
posed that for each 1% of fat lost from the body of the sow in the course of lactation there will be 0.1 piglets less born in the next litter. This is consistent with the view that, for thin sows, delaying conception by 21 days can give an extra piglet per litter. Australian workers are unequivocally in support of evidence from a variety of sources that the greater the extent of fatty and lean tissue losses during lactation, the longer will be the weaning to conception interval. Figure 15.22 represents these propositions.

Figure 15.26 may be used to depict the relationship between body weight losses during lactation and the weaning to conception interval. Average intervals are generally about 10–12 days because although sows would usually be expected to show oestrus 3–5 days after weaning, some of these will return in the normal course of events. From the figure it is apparent that rebreeding problems are likely to become evident with maternal body weight losses in lactation that are greater than 10 kg per sow for sows with little fat or 20 kg for sows with ample fat. The implication here is
that the adverse effect of weight loss upon rebreeding proficiency would be mitigated by the presence of adequate fatty tissue stores. Figure 15.22, alluded to earlier, is seminal to the understanding of the importance of fatty tissue losses in lactation to subsequent reproductive efficiency. Failure to achieve at least 12 mm P2 of backfat depth at the time of weaning will result in a significant increase in the weaning to oestrus interval. Similarly failure to restrain backfat depth to levels of below 25 mm P2 will have like negative effect.

Recent work from Hughes and colleagues in Australia has confirmed that the increased rate of weight and fat loss resultant from low feed intake during lactation results in lower subsequent litter size (weight loss in lactation of <11 kg gives 11.7 piglets born alive whereas weight losses of >30 kg in lactation gives 9.8 born alive; while fat losses in lactation of 2 mm P2 give 10.5 born alive, and losses of >4 mm in lactation give 9.2 born alive). Marked effects were also noted for the absolute level of fatness at weaning where, if the P2 backfat depth at weaning was >13 mm, days from weaning to oestrus were 5.8, the proportion of anoestrous sows was nil and the total born alive was 11.4; whereas if the P2 backfat depth at weaning was <10 mm, days from weaning to oestrus were 8.1, the proportion of sows showing anoestrus was 0.22 and the number born alive was 8.9.

It is now quite evident that the major causes of low feed intake in lactation are high ambient temperature and the presentation of feed in a dry state. Sows suckling large litters can eat more than 10 kg feed daily. It is also evident that low level lactation feed intake may cause protein catabolism as well as fat catabolism. Whilst body fat losses are known to be detrimental to subsequent rebreeding success, body protein losses are catastrophic. The greater the rate of daily overall body weight loss, the greater the chance of body protein losses occurring in addition to losses of body fat. The UK Meat and Livestock Commission has developed on its Stotfold Research Unit a sow feeding regime which is reported to minimise lactation weight loss and days to oestrus. After parturition, 2.5 kg/day is given of a nutrient dense diet (14 MJ DE and 185 g CP/kg), and this is increased daily according to animal appetite but at a rate never exceeding 0.5 kg/day. Feed offered is raised in this way until the maximum amount of 1 kg for each piglet in the litter is realised. Increasing feed intake is planned to coincide with increasing milk yield and maximum feed intake is usually achieved around 15 days post-partum. The ambient temperature of a lactating sow house is held down to 16°C (the suckling piglets themselves are of course warmed by separate heaters). After weaning, these sows are offered as much as they might wish to eat of a high energy, high protein diet.

**Condition scoring**

The measurement of P2 backfat depth in pregnant sows is entirely feasible and relatively simple, but may not always be convenient. In this case sow condition may be used as a good indicator of sow body fatness. It is well established that there is an optimum breeding fatness which is the most vital component of the feeding regime. This is more important than live weight or the slavish adherence to some
generalised rationing scheme which stipulates given feeding levels at given times regardless of individual sow requirement. Feeding to sow body condition, because it focuses on sow body fatness, is thus an entirely reasonable concept. Feeding to condition demands that when a sow is seen to be in lower body condition than she should be, her feed allowance needs to be increased; but if the sow is in higher body condition than she need be, the feed allowance should be reduced. It therefore remains to define only what optimum body condition might be at the various stages of the reproductive cycle; but especially at the beginning and at the end of pregnancy because it is during pregnancy that feed level adjustments can most readily bring about changes in body condition. It is equally as important that sows do not become over-fat, as it is that they do not become over-thin.

As 70% of the fat in the bodies of pigs is in the subcutaneous fatty tissue depots, it is relatively easy to judge the fat status of the sow – her body condition – by external appearance. A visual assessment may be compared with a photographic or diagrammatic standard (Figure 15.27). Physical assessment may also be made by manual palpation of those parts of the sow’s body that are particularly indicative of fat change, such as the areas over the spinal processes and hips.

Visual condition score (using a 10-point scale) is well related to P2 backfat depth as measured with an ultrasonic probe. As a generalisation, the backfat depth at P2 (mm) is about three times the numerical value of the condition score. The use of sow fatness, through the medium of condition scoring, as a monitor of nutritional adequacy for breeding proficiency has the great advantage of being independent of feed level, health, environment and management. Proposals for feeding strategies made in the form of target condition scores surmount the problems of sows in different environments reacting in a variable way to the same standard feed level. The condition score target demands that the animal be fed what it takes; not fed any previously predetermined amount. In consequence, a sow judged too thin but already on a high feed level will be identified as requiring to be given more; whilst
a sow judged to be too fat but already on a low feeding level will be identified as requiring to be given even less.

Usually a condition score of 6 is an appropriate target for the end of pregnancy, and one of 4 is acceptable at the end of lactation. Under normal circumstances these targets can be achieved by relatively minor adjustments to feed levels. Sows that are thinner than a condition score of 4 or fatter than a condition score of 6 merit special attention. It is evident that many modern hybrid sows are being weaned at condition scores of less than 4 consequent upon an inadequate level of feed supply during lactation; with inevitable negative results. Condition score at weaning is, of course, highly dependent upon both condition score at farrowing (influenced by the pregnancy feeding rate) and the rate of condition loss during lactation as a result of lactation feed intake. Problems with sow fertility should not, however, invariably be seen as solvable by nutritional means. Other vital factors are health, the hormone status of the sow, environmental conditions and, of course, the fertility of the boars.

An example of a feeding procedure for use on breeding units employing condition scoring techniques is given in Table 15.3.

Condition scoring is clearly the most appropriate base for determining the adequacy of sow nutrition, but no system is without some shortcomings:

1. Condition scoring measures fatness only indirectly, and can be prone to error consequent upon variation in sow size and shape.
2. Condition score is dependent upon the subjective opinion of the scorer and standards can drift. Individuals often have different views about adequate condition states through the reproductive cycle.
3. The response of condition score to change in feed intake is not well documented and is variable. Values given in Table 15.3, for example, should be treated as guidelines and not rules.

**Rationing scales for breeding sows**

Sow feeding is mostly about long-term strategy and long-term trends in body weight, fatness and condition. It is the general status of the sow that requires to be maintained to a satisfactory level, and sow fatness changes are probably more important than sow weight. It has been established that young, modern hybrid gilts should be mated at live weights in excess of 130 kg and ages in excess of 220 days. They should have been fed sufficient to make gains of around 700 g daily from 30 kg live weight onwards, and to gradually increase their levels of body fat over this time. Feeding in the 3-week period immediately prior to mating may well be accommodated by a generous (*ad libitum*) rationing regime.

It has further been established that pregnancy feeding should be adequate to allow gains of sow maternal body weight and fatness to achieve a condition score of around 6 or more by the time of farrowing. This will be approximately equal to a P2 fat depth of 20 mm and a *total* body gain from conception to farrowing of about 50 kg. Under normal circumstances, feeding levels in pregnancy will vary, according to sow condition, around a mean of 2.3 kg daily.
In lactation, sows will invariably lose fatty tissue and may also lose some lean tissue. If losses are severe not only will the lactation be compromised but also the success of the next parity. Lactation feed intakes may often average only 6 kg of feed daily, which will require some degree of fatty tissue replenishment in the course of the subsequent pregnancy. The lactation feeding regime should be one of intake encouragement and not intake limitation.

Over-fatness will also result in both diseconomies and reproductive inefficiencies. Sows of condition score much greater than 6 can be restricted. Generous levels of feeding in pregnancy should be avoided by ensuring the correct general strategy,

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**Table 15.3.** Feeding pregnant sows according to body condition.

1. Using all the sows in the breeding herd that are pregnant or empty (that is, all sows not lactating), determine the average daily feed allowance per sow. Record this number.
2. Determine the condition score of all the sows in the herd that are pregnant or empty. Use whole numbers on a 10-point scale, with 1 as emaciated and 10 as grossly obese. The target average condition score for the whole herd should be about 5. Usually young sows should have a condition score of rather more than 5, while old sows could be tolerated at rather less than 5. Newly weaned sows should score about 4, while sows due to farrow should score around 6.
3. If the average condition score for all pregnant and empty sows in the herd is above 5, then the average daily feed allowance (as per paragraph 1) should be reduced. If the average condition score is less than 5, then the average daily feed allowance for the sows should be increased. In the first event, increases and decreases in the average daily feed allowance should not be greater than plus or minus 0.2 kg per sow per day.
4. Although the average condition might be satisfactory, this average can be made up of sows that are thin and sows that are fat. To deal with this, individual animals must be fed according to their individual condition scores.
5. For each individual sow, determine the condition score immediately after weaning the piglets. Feed according to the table below until a condition score of 6 is reached for the particular individual in question. Upon reaching condition score 6, the sow should be returned to the average daily feeding level (as per paragraphs 1 and 3).
6. At weaning the sow should be changed immediately from her lactation feed allowance to a suitable regime to prepare her for mating. Feed allowances between weaning and conception are likely to involve feeding at least 3.0 kg of lactating sow diet, but it is usually best to feed to appetite. It is unnecessary to present more than 3.5 kg of food daily.

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<table>
<thead>
<tr>
<th>Sow body condition score</th>
<th>Likely feed requirement in addition to the average daily feed allowance for sows in pregnancy (kg/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>+0.6</td>
</tr>
<tr>
<td>3</td>
<td>+0.4</td>
</tr>
<tr>
<td>4</td>
<td>+0.3</td>
</tr>
<tr>
<td>5</td>
<td>+0.2</td>
</tr>
<tr>
<td>6</td>
<td>Average daily feed allowance¹</td>
</tr>
<tr>
<td>7</td>
<td>−0.2</td>
</tr>
<tr>
<td>8</td>
<td>−0.3</td>
</tr>
</tbody>
</table>

¹ On exceptional units, or where a highly concentrated diet is used, average allowance may be around 2 kg per sow daily. More usually, however, the average feed allowance is around or in excess of 2.2 kg per sow daily.
which ought to obviate the need for short-term crash-course tactics to fatten sows up or slim them down. Because sows will unavoidably lose fat during lactation, they should gain fat in pregnancy to compensate. Fat level minima are probably in the region of 18 mm P2 at the end of pregnancy and about 12 mm P2 at the end of lactation. Sows much over 25 mm may be considered too fat.

Finally, it has been established that attempts to define general nutritional requirements and to prescribe general blueprints for feeding all the breeding sows in a herd will be disappointing. Sow variability in response to nutrients means that each sow must be rationed according to her own individual condition. General guidelines to ration scales for sows are to be found in Figure 15.28. The figure allows for a pattern of pregnancy feeding that is lower than average in the first 3 weeks and higher than average in the last 3 weeks. However, unless there is reason to believe that there is a problem of embryo mortality caused by extremely high feeding levels to over-fat sows in early pregnancy or of low piglet viability due to inadequate birth weight, then a single feeding level based on condition score and perceived needs for fatty tissue replenishment should be applied throughout pregnancy. There is no benefit in prescriptive reduction of feed level in early pregnancy or increase in late pregnancy. Overall, the pattern of feeding should reflect sow need according to body condition, and feed strategies should target lifetime feeding rather than tactical adjustments within the breeding cycle.

In practice:

- Sows should be condition scored frequently during pregnancy and appropriate adjustments be made to the ration.
- Feeding allowance in pregnancy will normally range between 2 and 2.8 kg, and should depend upon body condition.
The appropriate feed allowance during lactation is *ad libitum*. Should the litter size be particularly small (less than 8 piglets), the feed allowance may be limited to 6 kg daily. Nevertheless, the near-impossibility of over-feeding the lactating sow means that control of feed allowance is centred during lactation not upon feed restriction but upon appetite enhancement, and the maximisation of feed intake by all possible devices.

At weaning, feed supply may be set to a standard rate that is just below appetite, say 3.5 kg daily.

As a general guide, a good sow producing 2.3 litters per year will use annually *at least* 1.2 tonnes of feed of conventional nutrient concentration \[ (115 \times 2.5 \times 2.3) + (13 \times 3.5 \times 2.3) + (28 \times 6.5 \times 2.3) \].

It will readily be appreciated that breeding sows, as also growing pigs, respond to quantity of nutrient, not weight of feed; the feed being potentially quite widely ranging in its nutrient concentration. The above estimates for optimum levels of feed supply refer in general to diets with around, or above, 13 MJ DE and 150 g CP (pregnant sows) or 13.5 MJ DE and 175 g CP (lactating sows) per kg fresh weight.

By use of Equations 15.3 and 15.6, it may be calculated that a sow farrowing at condition score 4, with a P2 backfat depth of 14 mm and predicted to eat 5 kg of feed daily over the period of a 28-day lactation will come to weaning with an inadequate P2 measurement of 10 mm and a condition score of less than 3. Feeding 2.8 kg daily in pregnancy would raise P2 fat levels to 16 mm and condition score to around 5 by the time of the next farrowing.

Farrowing at condition score 6, with 18 mm of P2 backfat and eating 6 kg daily will result in the loss of 3 mm of P2, 9 kg live weight and a condition score of 4 by the time of weaning. A feed allowance of 2.2 kg in pregnancy will replace the 3 mm of fat lost and allow a pregnancy gain of maternal body weight of 28 kg; or a net gain (conception to conception) of 19 kg. The latter regime would appear just adequate for sows later in breeding life, but clearly marginal for those in their first three parities who would benefit from a higher level of feeding.

Table 15.4 provides a simple résumé of the effects of pregnancy and lactation feeding on the efficacy of breeding in the sow.

### Feeding the sucking pig

Solid feed is usually offered to young piglets from 14 days of age as a supplement to mother’s milk. Noticeable quantities are rarely eaten before 25 days of age. If
weaning is at 28 days of age, it is beneficial to piglet growth for the same diet to be used before weaning as afterwards, and to continue until the weaned pig attains 10 kg live weight.

In addition to being dependent upon the lactational ability of the sow, the actual milk received by an individual piglet is a function of the number of piglets sucking, the size and vigour of those piglets and the stage of lactation. Vigorous sucking pigs in smaller litters may readily attain live weights of more than 10 kg at 28 days of age, showing the potential for growth when milk is in ample supply. However, usually most sucking pigs from litters of 10 or more weigh only 7–8 kg at 4 weeks, indicating that there is a shortfall in milk supply at the udder. The potential for growth and the availability of sow’s milk begin to diverge at about 20 days of age, and it may be assumed that from this point on supplementary feeding is beneficial. Should the litter be greater than 8 piglets or the sow be yielding less than expected, then earlier feeding of sucking pigs is warranted – usually from 14 days of age (earlier, of course, in cases of milk shortage).

In many studies, piglets sucking sows of good milk yield have been shown to ingest little or no supplementary feed before 18–21 days of age. Generally, sucking pigs may begin to eat trivial amounts of supplementary feed at around 10 days of age, and 10–30 g daily between 14 and 21 days. By the 4th week of life, intake may have risen to 60 g or so. The increasing relationship between the intake of supplementary feed and sucking piglet age could be expressed as:

\[
Y = 0.0044 X^{2.80}
\]

where \(Y\) is feed per day per piglet (g) and \(X\) the age of the piglet (days).

Sucking pigs have different digestive systems to those of pigs eating solid feed, and the change-over at weaning represents a considerable digestive trauma. This period is counter-productive, and it is helpful if young pigs are persuaded to eat solids before they actually need them in order that they are acclimatised to the post-weaning diet. This requires frequent provision of a highly palatable diet offered to the sucking pig in appealing form. Unless the highest levels of management skills are employed, the consequences can be lost growth, poor feed conversion efficiency and diminished pig throughput in the post-weaning phase.

There are therefore two good reasons for offering solid feed to sucking piglets. First, for litters of reasonable size, supplementary feed will help to attain the greatest possible growth rate during the sucking phase. Second, all piglets (regardless of the litter size) are helped if they are accustomed to the nature of solid feed before they are abruptly weaned at 3, 4 or even 5 weeks of age.

The overriding requirement of a supplementary solid feed for sucking pigs is that it be readily eaten. The diet must therefore be interesting to the young piglet in non-nutritional (taste, texture and smell) as well as nutritional terms. For young piglets to avoid a post-weaning growth check, they should consume around 300 g of solid feed on the day following their removal from the sow. Such intakes are rarely, if ever, achieved by sucking pigs less than 30 days of age; even under the best conditions. Ad libitum feeding, indeed appetite encouragement to maximise voluntary
feed intake, should continue from weaning through to the need for feed intake limitation and rationing, which is unlikely to occur until around 40 kg live weight at the earliest.

There is a substantive body of evidence to show that rapid growth achievement before and after weaning (through the use of high quality diets and excellent management) will have a positive residual effect throughout the remaining growth period through to slaughter. Compensatory growth following poor post-weaning performance is not evident under practical production conditions, and investment in maximising early growth is handsomely returned at slaughter in terms of superior daily gain and feed efficiency through the grow-out period.

**Ration control by diet dilution**

Nutrient intake is the product of feed nutrient concentration and level of feed supply. Where appetite is limiting, nutrient intake can be enhanced by increasing nutrient concentration. Equally, a decreasing diet nutrient concentration can be countered with an increasing level of feed supply. However, when the feed allowance meets the bounds of appetite further decrease in nutrient concentration will result in a decrease in nutrient supply; *de facto* an effective restraining ration scale is imposed. The possibility of allowing pigs to eat to appetite but controlling nutrient supply by means of diet dilution has some attractions – especially with respect to the simplicity of management. All pigs would be fed *ad libitum*. Where control of the allowance is needed, the diet is diluted *pro rata*. This apparently enviable scheme has been tried many times but invariably foundered because:

- the diluent itself is not free of charge, although nutritionally inert;
- a diluted diet is more expensive to mix, to transport, to store and to convey;

<table>
<thead>
<tr>
<th>Pigs appropriate for feeding to appetite (diet dilution contraindicated)</th>
<th>Pigs appropriate for feed intake limitation but level of diluent required likely to be too high to be economic (diet dilution contraindicated)</th>
<th>Pigs appropriate for feed intake limitation and for which the level of diluent required may be economic (diet dilution feasible)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lactating sows</td>
<td>Pregnant sows</td>
<td>Finishing pigs and castrated male pigs with conventional appetite but a predisposition to being unacceptably fat</td>
</tr>
<tr>
<td>Weaned sows</td>
<td>Finishing pigs of high appetite and low genetic merit</td>
<td></td>
</tr>
<tr>
<td>Sucking piglets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weaned piglets</td>
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<tr>
<td>Growing pigs</td>
<td></td>
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<tr>
<td>Finishing pigs of high genetic merit</td>
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</tbody>
</table>
the amount of diluent needed can be extraordinarily large before appetite restraint is achieved, as with a pregnant sow, for example, whose requirement can be met by 2 kg of a concentrated diet, but whose appetite limit is probably three times that.

Relatively few classes of pig fall within the range appropriate to being nutrient-restricted by means of diet dilution (Table 15.5).

**Conclusions**

Optimisation of feed supply for growing pigs and breeding sows is a hands-on activity requiring constant reappraisal and adjustment, managerial dexterity and a clear view of the relative benefits. Rationing scales and recommended feed allowances are not open to generalised rules or blueprints, but are highly specific to individual production circumstances.

While broad guidelines as to expected feed regimes can be helpful, it is through knowledge of the likely responses to changes in nutrient supply that the optimum level of feed allowance will best be set.

Maximum appetite is sought in young piglets, young growing pigs and lactating sows. Effective control of the production process through rationing the feed supply is achieved primarily with only two classes of pig: (1) pregnant sows and (2) meat pigs in the grow-out stage. However, effective control of feed supply at these points in the production process is crucial to efficient production in both grow-out and breeding herds.
Chapter 16

Product Marketing

Introduction

Marketing starts with the creation of a differentiated product followed by an effective description of its characteristics that make it desirable to potential consumers. In developed countries marketing has a second phase in which the delivery of the product and the satisfaction of customer needs are essential to obtain a repeated order. The marketing of pig meat therefore involves many segments of the production chain, including compound feed, breeding stock supplies and transforming pigs into meat cuts and processed products. In this chapter, most of the discussion will be dedicated to pig meat marketing and sales in developed countries.

Total world production of pig meat for 2003 was about 96 million tonnes; an amount that has increased steadily by 2.4% annually for the last 10 years. China, the USA, Brazil and the European Union (EU-15) are the main pig producing countries of the world, accounting for more than 80% of total pig meat production. Main export countries worldwide are the EU-15, Canada and Brazil whereas the main importers are Japan, Mexico and the former USSR. Pig production in the EU-15 for 2004 was estimated at around 205 million pigs (18 million tonnes of pig meat) and per capita pig meat consumption is close to 44 kg per year. Pig meat, comprising 46% of total meat consumption, occupies first place as preferred meat by European consumers thanks to the diversity of the offer that includes fresh and processed products. Over the past decade, pig production in the EU-15 has increased by more than 8% and currently about 5–7% is exported. Pig meat circulates freely within the EU countries and intra-community exchanges represent more than 24% of total production. The main export countries are Denmark, the Netherlands and Spain whereas the main importers are Italy, Germany, the UK and Portugal. Pig production in the USA and Canada is estimated at 9.9 million tonnes of meat. However, consumption in these two countries is only about 30 kg per person; less than either beef or poultry.

The market conditions in the EU-15 and North America are becoming increasingly challenging. In the EU-15 stringent rules on animal welfare, environmental constraints and an alerted public in terms of food safety pose difficulties and an economic burden on the swine sector. In the USA, food safety is also an issue that requires a reassessment of the existing safeguards. In both cases, the investments
required for proper assurance will have a significant impact on the final cost of the meat.

The objectives of the pig meat production industry have changed over time since 1960. In the 1960s and 1970s the objective was to meet the requirements for protein of animal origin and the key issue was to produce more meat at the lowest possible cost. In the 1980s and early 1990s a more conscious consumer appeared and the efforts of the pig meat supply chain were aimed at improving the quality of the meat at a competitive cost. The new strategy resulted in the production of meatier pigs with a reduced amount of subcutaneous fat. In the last decade, the pig meat chain, under consumer pressure, has had to adapt to a new situation in which meat safety and the need to produce while taking into account issues related to animal welfare and environment protection are emphasised. New challenges have to be met at a competitive cost in a world market where leading countries such as the EU-15, USA and Canada face strong competition from Asian and South American countries.

Changes in the pig meat supply chain

Traditionally, price was the market driving force in the pig meat supply chain and, because of the high potential for pig meat consumption, the main objective was to achieve more volume through efficient production systems. The supply chain was producer-oriented, with only a small share of the market belonging to the packers and a limited regional influence of processors and retailers. Commercialisation was focused on selling pig meat as a commodity whichever quality was produced. Connections among the different segments of the supply chain were quite loose, usually through traders. The transaction system, as for many other commodities, was characterised by its high volatility, and margins were unstable and fluctuated throughout the years (Figure 16.1). Fixed benefits were unusual and long-term planning of the business was an objective that was difficult to achieve.

New challenges have dramatically changed the market situation, and integration, food safety and quality are the driving forces of the current largest pig meat processors in the world (Table 16.1). Pig production, as for many other rural activities,

<table>
<thead>
<tr>
<th>Traditional</th>
<th>Modern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply driven production (push)</td>
<td>➔ Demand driven production (pull)</td>
</tr>
<tr>
<td>Commodity and mass production</td>
<td>➔ Differentiation of products</td>
</tr>
<tr>
<td>Transaction system: daily, risky and volatile</td>
<td>➔ Relation system: long-term, fair profit and stable</td>
</tr>
<tr>
<td>Loose connections: objective is price</td>
<td>➔ Fixed partnership: objectives are price and consistency of quality</td>
</tr>
</tbody>
</table>
depends on good husbandry conducting to high meat output, but the importance of marketing and trading needs to be emphasised. The relatively high incidence of health scares in recent years has reduced the confidence of the public in the meat supply chain and has obliged the distribution companies to modify their strategies. One of the major changes has been the search by food retailers for partners within the production and packer segments to produce identified meats (certified, conformed, branded). A summary of the strengths and weaknesses and of the opportunities and threats for the European pig meat supply chain is offered in Tables 16.2 and 16.3, respectively.

The main driving forces of recent changes in the pig meat supply chain are grouped in the following categories:

- Changes in the habits of the consumer.
- Changes in the distribution channels.
- Changes in the pig meat supply flows.
- Sector verticalisation.

**Consumer habits**

Evolution in society has driven changes in consumer habits and expectations. Affluent families spend less of their total income on food, but are more conscious of quality and become more dependent on issues such as product information, buying convenience and emotions. They spend less time cooking and shopping for
food but dedicate more time to obtaining information on what they eat. Thus, the
way meats and processed foods are presented and distributed in the western hemi-
sphere has changed. There is a clear trend to purchase pre-sliced, ready-to-cook,
packed meat products and the objective of the pig meat industry is to achieve con-
sumer loyalty based on a satisfactory price to quality relationship. Consumers
demand products derived from healthy pigs raised in a healthy environment and
expect them to be ‘natural’, fresh tasting and nutritious. The attributes of pig meat
needed to meet such consumer demands are shown in Table 16.4.

**Distribution channels**

Retailers are consolidating at both national and international levels. In many coun-
tries, such as Denmark and the Netherlands, the market share of the top five retail-
ers represents more than 50% of total production, a trend that is expected to
continue in the near future. Merging among producing and packing groups and the
need to supply larger volumes to food companies change the type of agreements
within the pig meat chain, and long-term agreements with stable prices are preferred
to traditional short-term deals. Supply, logistics, marketing and management stra-
gies (category management) require the implementation of new models to facilitate
the relationship between producers and suppliers. As a consequence, there has been

### Table 16.2. Strengths and weaknesses of the pig meat supply chain in the EU.

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verticalisation of the supply chain</td>
<td>Cost of production</td>
</tr>
<tr>
<td>Technical skills</td>
<td>Disease control across borders</td>
</tr>
<tr>
<td>Whole chain assurance</td>
<td>Herd health</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Lack of prepared labour</td>
</tr>
<tr>
<td>Proactive associations</td>
<td>High population density</td>
</tr>
<tr>
<td>Differentiation of products</td>
<td>Concentration of production areas</td>
</tr>
<tr>
<td>Quality control</td>
<td>Cost of labour</td>
</tr>
<tr>
<td>High average consumption</td>
<td>Image of the meat because of religious concerns and fat content</td>
</tr>
<tr>
<td>Export nets</td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td></td>
</tr>
</tbody>
</table>

### Table 16.3. Opportunities and threats for the pig meat supply chain in the EU-15.

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product image abroad</td>
<td>Disease outbreaks</td>
</tr>
<tr>
<td>Offer of added value products</td>
<td>Ingredient cost</td>
</tr>
<tr>
<td>Diversification of the production</td>
<td>Globalisation</td>
</tr>
<tr>
<td>Improve collaboration with customer associations</td>
<td>Retailer power</td>
</tr>
<tr>
<td>Increase consumption in some countries (the UK)</td>
<td>Preferences of wealthy consumers for vegetable proteins</td>
</tr>
<tr>
<td>Improve health image</td>
<td>Contamination and environmental concerns</td>
</tr>
</tbody>
</table>

...
Table 16.4. Attributes of meat quality.

<table>
<thead>
<tr>
<th>Category</th>
<th>Attributes</th>
</tr>
</thead>
</table>
| Food safety       | Microbiological safety: including absence of *Salmonella*, *Campylobacter* and *Listeria*  
|                   | Absence of residues: including antibiotics, heavy metals and pesticides |
| Technological quality | Uniformity and consistency  
|                   | pH  
|                   | Water holding capacity  
|                   | Firmness of fat and meat without tissue separation  
|                   | Oxidative stability |
| Eating quality    | Colour  
|                   | Tenderness and juiciness  
|                   | Flavour and smell  
|                   | Quantity of visual fat and marbling |
| Nutritional value | Fat content  
|                   | Fatty acid profile  
|                   | Protein content  
|                   | Nutrient enrichment |
| Social value      | Animal welfare  
|                   | Environmentally friendly |

A reduction in the number of suppliers and a new set of requirements for pig production has been set by the retailers. The end result is a further concentration of production sites and processing plants. Tighter linkages among producers, packers and retailers become more important when increased quality demands are being placed on the system. At the same time, large food companies are putting pressure on their suppliers to develop production chains that add more safety and quality to the commercial products at competitive prices. Traceability of food products has become essential and the implementation of credible quality assurance programmes is a must in order to respond to this demand.

**Pig meat supply flows**

The market strategies of the producers and packers of specific countries are closely related to the pig self-sufficiency ratio. When domestic production does not meet internal demand, the main concern of the slaughterhouses is to use as much of their capacity as possible. Producers can sell pigs at an attractive price without fixed contracts or long-term supply agreements. Quantity prevails over quality, and commercialisation is focused on selling what is produced. In this context, the need for a vertically integrated production system is limited.

When supply is greater than internal demand, part of the production has to be sold abroad, and the sector needs to be competitive in terms of quality and price, especially when the target is a market that demands high standards (e.g. Japan and Hong Kong). A change in objectives from meeting internal demand to increasing
exports forces the pig meat chain to adapt its marketing expertise. It needs to be consumer oriented and willing to adjust production, cutting and packaging systems to new demands. A continuous over-supply and growing competition lead to restructuring of pig meat production systems and facilitate the development of vertical chains. Food safety, meat quality, cost optimisation and product uniformity are the driving forces of vertically organised systems.

The main pig meat producing countries in the world and their self-sufficiency rate in 2002 and the international pig meat exchanges in 2003 are shown in Tables 16.5 and 16.6, respectively. Production, exchange and consumption of pig meat in the EU-15 are shown in Figure 16.2. The top seven countries (Germany, Spain, France, Italy, the UK, the Netherlands and Belgium) consume 14.2 million tons, which

### Table 16.5. Countries producing over 1 million tons of pig meat annually, 2002 (data from Ofival, Eurostat, FAO, Meat and Livestock Commission).

<table>
<thead>
<tr>
<th>Country</th>
<th>Production (thousand tons/year)</th>
<th>Consumption (kg/person/year)</th>
<th>Self-sufficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>43,000</td>
<td>34</td>
<td>101</td>
</tr>
<tr>
<td>USA</td>
<td>8,948</td>
<td>30</td>
<td>108</td>
</tr>
<tr>
<td>Germany</td>
<td>3,912</td>
<td>52</td>
<td>92</td>
</tr>
<tr>
<td>Spain</td>
<td>3,105</td>
<td>64</td>
<td>117</td>
</tr>
<tr>
<td>France</td>
<td>2,370</td>
<td>37</td>
<td>107</td>
</tr>
<tr>
<td>Brazil</td>
<td>2,534</td>
<td>12</td>
<td>106</td>
</tr>
<tr>
<td>Denmark</td>
<td>1,866</td>
<td>64</td>
<td>527</td>
</tr>
<tr>
<td>Canada</td>
<td>1,856</td>
<td>32</td>
<td>128</td>
</tr>
<tr>
<td>Poland</td>
<td>1,816</td>
<td>39</td>
<td>105</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>1,625</td>
<td>40</td>
<td>225</td>
</tr>
<tr>
<td>Italy</td>
<td>1,395</td>
<td>36</td>
<td>69</td>
</tr>
<tr>
<td>Japan</td>
<td>1,215</td>
<td>18</td>
<td>56</td>
</tr>
<tr>
<td>Mexico</td>
<td>1,065</td>
<td>12</td>
<td>93</td>
</tr>
<tr>
<td>Belgium</td>
<td>1,051</td>
<td>43</td>
<td>229</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>From:</th>
<th>↓</th>
<th>To: →</th>
<th>Japan</th>
<th>USA</th>
<th>The former USSR</th>
<th>Far East</th>
<th>Central America</th>
<th>Eastern Europe</th>
<th>Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU-15</td>
<td></td>
<td></td>
<td>300</td>
<td>80</td>
<td>350</td>
<td>230</td>
<td>10</td>
<td>400</td>
<td>290</td>
<td>1660</td>
</tr>
<tr>
<td>China</td>
<td></td>
<td></td>
<td>—</td>
<td>—</td>
<td>90</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>188</td>
</tr>
<tr>
<td>Far East</td>
<td></td>
<td></td>
<td>—</td>
<td>10</td>
<td>30</td>
<td>50</td>
<td>—</td>
<td>—</td>
<td>29</td>
<td>1079</td>
</tr>
<tr>
<td>Canada</td>
<td>230</td>
<td>740</td>
<td>30</td>
<td>50</td>
<td>180</td>
<td>—</td>
<td>175</td>
<td>50</td>
<td>122</td>
<td>735</td>
</tr>
<tr>
<td>USA</td>
<td>320</td>
<td>—</td>
<td>20</td>
<td>40</td>
<td>180</td>
<td>—</td>
<td>175</td>
<td>50</td>
<td>122</td>
<td>232</td>
</tr>
<tr>
<td>Eastern Europe</td>
<td></td>
<td>10</td>
<td>50</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>50</td>
<td>76</td>
<td>476</td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>—</td>
<td>—</td>
<td>400</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>76</td>
<td>450</td>
<td>778</td>
<td>4549</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>977</td>
<td>842</td>
<td>960</td>
<td>327</td>
<td>215</td>
<td>450</td>
<td>778</td>
<td>4549</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Whittemore’s Science and Practice of Pig Production
represents 87% of the total EU-15 market. Denmark, the leading net exporter of pig meat in Europe with 622,000 tons (from a total of 1,500,000 tons), is an example of a well organised, vertically integrated production system with an effective quality management control programme with the capability to customise a product from farm to table. A good example in this respect was the development, 10 years ago, of the Europe Pig project, targeting among other countries Germany. The Danish industry conducted a series of studies in which consumers and experts were involved to determine the needs of the European market that were not fulfilled by pig meat products available at that time. The outcome was that the industry started to produce a higher percentage of pigs that were heavier and had greater marbling. The organisation of the Danish pig meat chain allows delivery of large amounts of pig meat portions to any demanding country in the world with a guarantee of uniformity, quality and attractive price.

One example of evolution from being an importer to becoming an exporter is that of Spain. Spain has increased per capita pig meat consumption from less than

![Fig. 16.2 Production (million pigs/year) and pig meat exchange (x 10^3 tonnes) in the EU-15. Exporting countries are indicated by hatching, importing countries by grey shading (Marché du Porc Breton, 2003).](image-url)
45 kg in 1995 to over 68 kg per year in 2003. Also, pig meat production has increased accordingly from 2 million tonnes in 1985 to 3.3 million tonnes in 2003. In fact, in the 1980s pig meat production was based on small farms producing carcasses to be sold by local butchers. Most slaughterhouses and further processing plants were small and family owned. Production was based on entire Large White × Landrace pigs of non-selected genetic background slaughtered at 95 kg, and more than 60% of the production was dedicated to producing low cost processed and cured products. The low cost and wide range of products offered to the market led to an increase in consumption in a population with a limited income per capita. In the late 1980s and 1990s the average income of Spanish consumers improved sharply and the pig meat industry adapted to the new situation by increasing the number of added value products and improving the quality of the meat. Pietrain and Duroc male lines were introduced in the production chain according to objectives: to improve percentage of meat of the carcass for the fresh pork industry and to increase meat quality and percentage of intramuscular fat for the cured ham industry. Also, the percentage of castrated males fattened and the final body weight at slaughter increased, aiming to improve carcass meat quality. On the other hand, the production of high added-value native Iberian pigs, reared under free-range conditions, increased to cover the demand of affluent consumers. Currently, many Iberian pigs are produced under less extensive conditions, allowing the production of high quality products, but at a moderate cost. The wide range of production and husbandry systems allowed segmentation and product differentiation with a pricing structure that fitted most of the economies of a developing country. In the late 1990s Spain was self-sufficient in pork and the industry had to focus on exports to sustain its growth. Under these circumstances, excessive product differentiation based on a myriad of husbandry systems and of further processing and cured products was a handicap. Thus, there was a need for producing uniform products better adapted to the export markets. As a consequence, there was a sharp growth in vertically integrated groups, producing increasing volumes of pig meat under the same husbandry and processing conditions. The changes in the production system allowed the Spanish pig meat chain to fit new demands, capture new markets and raise domestic and international sales. In general, the industry needs to develop systems to effectively communicate the requirements of the export customer to all the segments of the pig meat chain. Integrated pig meat production systems enable the information flow.

**Sector verticalisation**

Historically, pig meat production has been organised locally with production expecting to meet the local demand. Today, it is a multi-billion euro industry targeted at global markets, with major and minor players exporting and selling their products around the world. Therefore the pig meat chain needs a global strategy. Demanding markets (large retailers and exports) require safe and high quality products at a competitive price. Consequently, pig meat producers need a high level of organi-
sation to meet the demand and optimise cost. Vertically integrated structures have the distinct advantage over traditionally organised groups of reducing cost at all stages of the pig meat chain because of economy of scales and are better prepared to fulfil the demand for cost-effective, safe, consistent and top quality pig meat products. Figure 16.3 indicates the different stages of a vertically integrated system, and the important aspects within each stage. Networking is essential in the sense that working with others will allow the achievement of what individuals could not accomplish alone.

Figure 16.4 is a simple diagram of the pig meat food chain that identifies the major links in the chain. Each segment has several dimensions. The old pig meat food chain was producer-oriented and each segment of the chain worked separately, with strong competition among companies within the same segment and very little communication with companies of the preceding or subsequent segments. Under these circumstances the pig meat industry was organised as a horizontal network,
i.e. producer to producer and packer to packer. The companies within each segment in the old chain took steps towards vertical networks, signing contracts and long-term agreements among producers, packers, processors and retailers. In the future, pig meat food chains have to be consumer-oriented without strict separations or walls among the different segments. A good understanding and coordination with mutual trust and respect among partners is imperative in vertical networks. The type of products to be produced must come through market signals diligently detected by the chain network. The desirable characteristics of a vertically integrated chain are detailed in Table 16.7.

Networking is a must in order to achieve excellent pig meat quality. The pig meat industry has to go vertical to reach the consumers, fulfil their needs, capture opportunities and overcome the challenges without recapitalising the industry. Currently, two models for verticalisation coexist, although in some instances a mixed model is followed:

- Each stage of the supply chain belongs to a different group, but all of them are extremely well coordinated. An example is the cooperative approach, frequent

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**Fig. 16.4** Organisation of traditional and modern pig meat supply chains.
in many European countries such as Denmark, France, Sweden and the Netherlands.

- All stages of the supply chain belong to a single economic organisation. Examples of this model are the large corporations in the USA (i.e. Smithfield Foods, Premium Standard Farms, Seaboard) and within the EU, the Spanish pig meat sector.

A good model of the cooperative approach is represented by the Danish pig sector. Danske Slagterier (DS) is the umbrella organisation for Danish Crown and Tican, two cooperatives involved in pig slaughter and packing, and the farmers who own them. A number of companies related to the pig industry are also members of DS. The directions of DS in terms of quality systems, flow of information and marketing approaches are followed by all participants in the production chain. The Danish model provides insights into the importance of addressing quality and customer service issues on a national rather than on a farm-to-farm or plant-to-plant basis. Increased cooperation between industry segments is a key factor in the development of pig production in Denmark. Pig meat associations and large corporations in the USA and Canada, specialised in exports to high demanding markets such as Japan, Hong Kong and Singapore, have adopted many of the concepts developed for pig meat marketing by the Danish industry. The North American pork industry needs to continue developing production and processing methods to give more flexibility in manufacturing and sales. The industry needs to improve its ability to customise products for different market segments and exports while maintaining its cost advantage over other developed countries. A comparison of different production chains in Europe and the USA is depicted in Figure 16.5. Although organisational structures might differ among countries, all of them face similar challenges to a different extent (Table 16.8). Achievement of the objectives is fundamental to ensuring in all cases an effective management and the success of future developments in the pig meat chain.

Table 16.7. Characteristics of successful vertically integrated supply chains.

- Sound, well-structured and organised.
- Good relationship and trust among all stages of the chain.
- Close interlink between breeders, producers, retailers and final consumers:
  (a) exchange and rapid flow of the information throughout the system;
  (b) identification with the end-product;
  (c) transparent verification systems.
- Optimisation to achieve the lowest cost:
  (a) increased efficiency by economies of scale;
  (b) avoidance of duplication.
- Acceptance and easy adaptation to changes.
- Proactive communication.
- Win–win mentality.
- Ultimate commitment to quality.
Fig. 16.5 Examples of vertically integrated organisations in the USA and selected European countries (million pigs/year).

Table 16.8. Challenges of the pig meat production chain: the importance of key pig meat requirements in selected markets.

<table>
<thead>
<tr>
<th></th>
<th>UK</th>
<th>Germany</th>
<th>Italy</th>
<th>Spain</th>
<th>USA</th>
<th>Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traceability</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>TQM – HACCP¹</td>
<td>***</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Uniformity</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>**</td>
<td>*</td>
<td>****</td>
</tr>
<tr>
<td>Lean percentage</td>
<td>**</td>
<td>***</td>
<td>****</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Meat pH (PSE)</td>
<td>***</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>****</td>
</tr>
<tr>
<td>Meat colour</td>
<td>**</td>
<td>***</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>****</td>
</tr>
<tr>
<td>Antibiotic residues</td>
<td>****</td>
<td>****</td>
<td>****</td>
<td>****</td>
<td>****</td>
<td>****</td>
</tr>
<tr>
<td>Salmonella control</td>
<td>**</td>
<td>***</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Animal welfare</td>
<td>****</td>
<td>***</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
</tbody>
</table>

¹ Total quality management (TQM) system – ¹Hazard Analysis and Control of Critical Points (HACCP).

Importance in market: * low, ** medium, *** high, **** very high.
Requirements in pig meat marketing

Meat quality

The main categories of meat quality attributes accepted by the industry are shown in Table 16.8. The current perception of meat in developed countries is paradoxical in the sense that food is better than it has ever been and yet it is a cause of growing concern to affluent consumers. Eating involves emotion and consumers do not base their decisions on what to eat on scientific reasons alone. Warnings of the risk of food-borne disease and health hazards have been frequent in recent years in Europe. Improvement and consistency of the attributes, such as food safety, is required to achieve consumer confidence and fidelity. Issues such as bovine spongiform encephalopathy, dioxin and medroxy-progesterone acetate contaminations together with animal disease outbreaks (swine fever and foot-and-mouth disease), which have attracted high media attention, have emphasised the importance of food safety attributes in this respect. Hygiene and absence of pathogenic bacteria and residues in the meat are of paramount importance to the consumer, and demonstrable and transparent programmes for their control in the meat chain constitute the minimum requirement to obtain a ‘licence to produce’. The need applies both to the commodity market and to the added value market. In added value products, the objective is to assure consistently the specific requirements of the specialty. Retailers rely increasingly on standards and certifications by outside organisations to fulfil consumer expectations. Some examples of food safety standards and quality assurance programmes are the British Retailer Council (BRC), the Global Food Standard, the European Food Safety Inspection Service Standard (EFSIS), the Danish Quality Guarantee (DQC), the IKB in the Netherlands, the Filière Qualité du Porc Breton in France and the Consorzio del Prosciutto di Parma in Italy. In North America, actions are essentially focused on the food safety aspects of a commodity product, with special emphasis on antibiotic residues. The producers associations have played a leading role in these certifications. In the USA, the Pork Quality Assurance Program was introduced at farm level in 1989 by the National Pork Board as a three-level management education programme. The programme emphasises good management practices in the handling and use of animal health products, and encourages producers to review their herds’ health programmes for food safety reasons. A similar type of programme has been introduced in Canada (the Canadian Quality Assurance Program) by the Canadian Pork Council. These sector programmes are the basis of many private schemes throughout the world, e.g. Murphy-Brown LLC Antibiotic Usage Policy.

Consistency in organoleptic and technological attributes of pig meat is an area that needs further improvement in many markets. Most of the attributes that determine the technological quality and the eating value of pig meat are strongly interrelated and affected by numerous factors along the production chain. For example, genetics play a significant role in many quality attributes, and often interrelate with other production processes including animal feeding and handling at slaugh-
ter. Pre-slaughter handling and transport have received considerable attention recently, not only because of animal welfare concerns, but also because of their implications regarding meat quality and financial impact. Mortality losses due to transport and lairage have been estimated in the Netherlands and the UK to be about 0.07%, but can reach up to 0.3–0.5% for stress-susceptible strains of pigs. Poor handling and transport conditions also have a significant impact on carcass and meat quality. Bruises and bone trauma lead to downgrades of carcasses and stress associated with handling and transport results in physiological changes that may increase the incidence of pale, soft and exudative (PSE) meat in swine. Deviations in pH value and variability in colour score and water-holding capacity of the meat are highly costly to the industry, especially in the case of PSE and dark, firm and dry (DFD) meats. PSE meats are unacceptable due to poor appearance and palatability of the meat. DFD results in a tender meat, but its stability is poor and food safety becomes jeopardised. Incidences of 10–25% of PSE and DFD meats have been reported in the USA and Spain. Even higher values can be evident where poor pig handling is combined with use of meaty PSE-susceptible parent stock. In particular, stress should be minimised during the pre-slaughter period by improving handling practices and facilities for loading, transportation, lairage and stunning. Besides, suitable corrective measures at other stages of the production process are required to reduce incidences and achieve optimal meat properties of the final product. Information, understanding of the physiological mechanisms involved in each attribute, coordination and cooperation in all processes occurring throughout the chain are essential to develop strategies at each critical point in the pig meat chain in order to maximise quality. Integrated planning within the same vertically coordinated organisation will enable the implementation of an effective meat quality improvement programme.

**Quality guarantee systems**

Implementation of a sound quality assurance programme is needed in the pig meat chain to adjust the production to the specific requirements of available markets. Different specifications require distinct actions along the production chain (Figure 16.4). The implementation of total quality management (TQM) systems should cover the entire chain of production including: (1) the rearing conditions of the pigs on own farms and on contracted farms, (2) the quality and nature of the feeds, and (3) the packing and delivery of the final products. There should be clear definition of responsibilities throughout the chain. The implementation of TQM to meet production goals is facilitated by vertically integrated organisation. Close monitoring of all aspects of the production chain results in the collection of detailed, accurate and up-to-date information, which is the base to develop realistic strategies for continuous improvement across the industry. However, since exhaustive analytical controls are not feasible, tighter linkages with the suppliers are essential to establish a joint quality target. The primary sector needs to adapt the HACCP (hazard analysis and control of critical points) and good manufacturing practices (GMP)
principles to its own facilities as is done by other industries. The implemented programme must be demonstrable and transparent in such a way that can be certified and audited at any moment by external third parties. A summary of the most important aspects of a typical quality assurance programme is given in Table 16.9.

**Traceability systems**

Implementation of a traceability system is compulsory for all food-chain businesses in the EU-15, USA, Japan and in general for all developed countries. Both mandatory requirements and consumer demands have led to the need to trace live animals and pig products along the food chain and it is a requirement in all production systems. Retailers have found that they can obtain a commercial advantage over competitors if there is a verification system available for the processes occurring in the pig meat chain. Traceability is multi-disciplinary because many departments of the company are involved in its implementation (quality, logistics, information technology). In this respect an important issue is to define who has the internal responsibility.

In general, traceability systems fulfil several purposes:

- They ensure a quick withdrawal from the market or recall of a given product if the case is needed, protecting the consumer’s rights.
- They minimise the financial impact of a recall by limiting the amount of products implicated.
- They enable companies to demonstrate that the remainder of their products are not implicated when a given, single product is recalled. Ensuring proper segregation and clear identification of all the products is required in this respect.
- They provide information on internal logistic and product quality, improving the overall efficiency of the company.
- They establish the responsibility and liability for any existing problem.
- They facilitate protection for the company and product brand names.

The implementation of traceability systems requires vertically coordinated networks along the different links of the pig meat production chain, in particular when

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**Table 16.9.** Key aspects of a guarantee system for meat quality.

- Integrated production system.
- Quality control of inputs:
  - (a) certified suppliers;
  - (b) quality specifications.
- Process control:
  - (a) hazard analysis and control of critical points (HACCP);
  - (b) good management practices;
  - (c) implementation of an adequate traceability system.
- Documentation:
  - (a) certified;
  - (b) audited by internal and external controllers.
several specialised companies in more than one location are involved in the multiple steps of the meat production process. Complex tracing situations may occur when pigs change ownership several times from birth to slaughter, when they are fed diets produced by different feed mills or when large numbers of transactions are involved in the production process. Also, pig meat end-products can be produced from a large number of meat batches originating from different slaughter plants. In all cases, integrated planning within the same organisation facilitates effective traceability.

The identification and registration of all pigs is the foundation for any quality assurance system. An organised traceability system must provide different sets of information on the original pigs that have yielded the meat used in the final product (Figure 16.6). Among others, the following information is important:

- origin of the pigs;
- type of animal and rearing location;
- health and welfare status of the farm;
- list of positive medication;
- feeding programme, including the origin of the raw materials used in feed manufacturing.

Tracing pigs from the farm to the slaughter plant requires a sound documentation system including the origin of the pig and the transportation system used. Current EU regulations set the basic rules for proper pig identification. Ear tags and tattoos are commonly used to identify officially the farm by a number, which is
unique nation-wide. The identification devices and the written documents provide
details on the batch of pigs and the farm and location in which the animals were
kept. The complexity of the information to be recorded depends on the type of
production and the marketing process. In farrowing-to-finish operations, tracing pigs
from the slaughter plant back to the farm is simple. However, complications arise
when piglets are produced in a breeding farm and are moved twice before reaching
the fattening farm. Pigs from several sources can be mixed before being dis-
patched to another location or even sent abroad. In addition, livestock markets and
traders add complexity to the animal flow and two or more partners may partici-
pate in the trading process. Complicated animal flows require enhanced standards
of pig identification and associated documentations from owners, locations and
transports. All these legal requirements, together with problems related to disease
transmission and animal welfare, will minimise pig flows in the future.

The documentation system must include all farm management practices applied
to each particular batch of animals. Records of all health treatments are essential
and have to include general prophylactic measures as well as individual treatments,
especially when applied in the late stages of the production life. Information on feed
deliveries needs to be linked to the recording system of the feed mill to ensure
full traceability of all raw materials used in feed manufacturing. A total quality
management system should integrate and link all inputs to the pig meat production
process from birth to delivery to the slaughter plant, and also from slaughtering to
marketing of meat products.

Traceback of carcasses and primal cuts to the slaughter plant in the EU is always
possible because a mark with the EU reference number for each carcass is required
at veterinary inspection. In addition, a system to assess the individual carcass value
(weight, yield, lean percentage) is needed for subsequent payment to the supplier.
Therefore, implementation of a system that correlates a carcass number with on-
farm identification is fairly easy. The problem arises when trying to correlate meat
cuts and carcass batch. In this situation systematic labelling, rational encoding and
appropriate computer usage are required. A batch of products, usually sorted by
homogeneity and quality parameters, must have a code number that links to the
carcass codes or numbers. Implementation of effective traceability systems is
realistic for fresh meat, but further efforts are needed to develop systems for prod-
ucts in which meat from many carcasses are combined, mixed and cooked. As in
previous stages, a large number of meat transactions are usual, especially in a com-
modity market which may add complexity to the traceability of end-products. In any
case, processing within an integrated organisation will enable and facilitate the
tracing of final products.

From farm to slaughterhouse, the European system for traceability does not
differ to a high extent from the current USA system in which pigs can be traced
back to the original farm for pig payment. The situation may differ in the last stages
of the pig meat chain. In the USA some segments of the pork industry do not feel
that the need for traceability and quality is good enough to off-set the costs and
management problems associated with implementing the new system. However,
some major companies have recently implemented source verification programmes that are verified by the US Department of Agriculture (USDA). The USDA Process Verified Program provides suppliers of agricultural products or services with the opportunity to assure customers of their ability to provide consistent quality products or services. This is accomplished by having their documented manufacturing or service delivery processes verified through independent, third-party audits. Therefore, implementation of traceability programmes will probably be of growing importance in the USA market, especially for those companies active in international trade.

New technologies currently available to the pig meat industry facilitate the traceability process. Bar-code systems at feed manufacturing, electronic identification (transponders) at the pig farm, electronic trolley tracking systems at the slaughter plant and specialised data handling software are available and used. DNA fingerprinting and antibody profile testing data could also be used. However, many of these tools are still at proof of concept stage and require further efforts in research and development before becoming practical cost-effective methods of traceability.

**Animal health status: control of Salmonella spp.**

Control of *Salmonella* spp. prevalence is important for at least three reasons:

1. Salmonellosis is the most common zoonotic disease in developed countries and plays an important role as a food-borne illness in public health programmes and food safety campaigns.
2. Food safety issues have a growing relevance in international trading.
3. *Salmonella* plays an important role in animal health status and may affect the long-term economic viability of many swine production systems.

Food safety issues can be used as a marketing tool to increase sales in demanding and competitive markets. An improvement in food safety standards allows product differentiation if the remaining competitors do not adopt the attribute as a mandatory requirement. An example of this approach is the *Salmonella* control programme implemented in Denmark, a net exporting country, since 1993. The Danish *Salmonella* surveillance programme for pigs has reduced the prevalence of the bacteria in fresh pork to less than 1.5% (2002 data). The number of Danes affected by the food-borne disease of pig origin was reduced from 1100 in 1993 to only 77 in 2002. The programme implemented in Sweden since 1961 does not allow for the commercialisation of *Salmonella* positive carcasses and was used as the basis for demanding additional requirements on pig meat imported from other members of the EU-15. Therefore, *Salmonella* control is important from a trading standpoint because health status can be used to create trade barriers between countries.

The number of reported cases of salmonellosis in Europe in 2000 was estimated at 73 per 100,000 inhabitants, with a wide range among countries depending on diagnostic methods, data communication and cooking habits. The official data probably
underestimate the real incidence of the disease because minor infections are not reported and go unrecorded. In the USA between 400 and 800 people die each year due to salmonellosis (Center for Disease Control, 2001). The 1999–2000 MAFF/MLC survey of food-borne pathogens in slaughter pigs in Great Britain isolated *Salmonella* spp. from 23% of pig faecal samples but from only 5.3% of carcass swabs (Table 16.10). Although pig meat products have rarely been associated with outbreaks of *Campylobacter, Salmonella* or other food poisoning cases, pig producers and processors should be active in reducing any potential threat to consumers.

Contamination by *Salmonella* spp. may happen at any stage of the pig meat production chain including during storage of raw materials, animal feed manufacturing, transport, commercial farms, slaughter and deboning plants, meat processing and also while preparing food at home. Paramount, however, is that the control of food-borne zoonoses must include a reduction of their prevalence in the animal population. The chain is as strong as the weakest of its links. Therefore, a sound *Salmonella* control programme requires efforts at every stage of the production chain. The epidemiological mechanisms involved in the introduction and control of *Salmonella* transmission on swine farms are shown in Figure 16.7. The combination of adequate feeding strategies and good husbandry practices before, during and after slaughter can help to control the incidence of *Salmonella*. The necessary pre-harvesting actions include (1) control of raw materials and feed manufacturing, (2) minimising stress due to long fasting periods, mixing, loading and transportation of pigs, (3) separate lairage spaces and programme for the slaughtering of pigs according to *Salmonella* prevalence, and (4) application of adequate hygienic procedures at slaughter and during processing and distribution of the pig meat. In summary, to achieve maximum food safety, the control of critical points should be extended to all stages of the farm-to-table cycle (Table 16.11).

An improvement in general health results in increased production efficiency, cost competitiveness, product homogeneity, meat quality and better food safety standards. Large differences in costs of production are observed in the commercial operations of low- and high-health-status farms because in most production systems, diseases limit the genetic potential of the pig. Also, a low-health status is associated in practice with high use of antibiotics on the farm, with potential problems of

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**Table 16.10.** Percentage positive faecal samples in the red meat species (data from a 1999–2000 survey in Great Britain).

<table>
<thead>
<tr>
<th>Species</th>
<th>Cattle</th>
<th>Sheep</th>
<th>Pigs</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Salmonella</em> spp.</td>
<td>0.2</td>
<td>0.1</td>
<td>23.0</td>
</tr>
<tr>
<td><em>Salmonella</em> typhimurium</td>
<td>0.2</td>
<td>0.1</td>
<td>11.1</td>
</tr>
<tr>
<td><em>Campylobacter</em> spp.</td>
<td>24.5</td>
<td>17.0</td>
<td>94.5</td>
</tr>
<tr>
<td><em>Campylobacter</em> jejuni</td>
<td>11.2</td>
<td>11.3</td>
<td>3.4</td>
</tr>
<tr>
<td><em>Yersinia</em> enterocolitica</td>
<td>6.6</td>
<td>13.7</td>
<td>26.1</td>
</tr>
<tr>
<td><em>Escherichia coli</em> 0157</td>
<td>5.4</td>
<td>2.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>
finding residues in meat. Indiscriminate use of antibiotics at farm level also increases the survival of strains resistant to antibiotics used in human medicine. This issue has attracted increasing public and scientific concern and EU-15 legislation is restricting the use of many drugs in animal production.

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**Table 16.11.** Critical points to control *Salmonella* prevalence.

<table>
<thead>
<tr>
<th>Breeding farms</th>
<th>Animal feeding</th>
<th>Pre-slaughter handling</th>
<th>Slaughtering and cutting</th>
<th>Processing and retailing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect on nursery and grower–finisher pigs</td>
<td>Safety of meat from culled sows</td>
<td>Effects of shipping stress on faecal shedding by carriers</td>
<td>Cross-contamination at scalding, evisceration and polishing</td>
<td>Hygienic procedures</td>
</tr>
<tr>
<td>Bacterial contamination of raw materials</td>
<td>Feed manufacturing</td>
<td>Cross-contamination in the lairage</td>
<td>Decontamination</td>
<td>Maintenance of cold chain</td>
</tr>
</tbody>
</table>
**Social values**

Pig production and pig meat processing must be conducted in a way that satisfies the expectations and concerns of urban consumers. In a society where information flows openly, the pig sector must be prepared to pass information to the public on the overall conditions and practices of the sector. Failing to meet these rules results in a negative image of the end-product. Today, the aim of any leader company that wants to keep its position is to reconcile productivity with sustainable production practices that preserve the future availability of resources and provide optimal satisfaction of the environmental, economic and social requirements of the society. This strategy needs to implement the following actions:

- Ensure food safety and quality by improving processes and processing conditions.
- Secure adequate food supplies that meet existing and future food demands, keeping external input requirements as low as possible.
- Protect and improve the natural environment and resources by minimising any adverse effects from pig production on soil, water, air and biodiversity.
- Care for animal well-being.
- Support economically viable and responsible farming systems.

Two major areas of concern in this respect are the maintenance of a clean environment and the protection of animal welfare. In the environmental issue, the pig meat industry has a clear social responsibility. Concentration of production sites reduces costs because of economies of scale, but creates problems related to conservation of the environment, especially in those regions with a high density of human population. The pig density in countries such as the Netherlands, Belgium and Denmark is over 250 pigs/km², and is even further concentrated in specialised areas such as Brittany, Lombardy, Jutland, the Netherlands, Renania and Catalonia. An excess of animals in these specific areas disrupts the equilibrium between manure production and available arable land, and slurry becomes a contaminant rather than a fertiliser. Concentration of nitrogen, phosphorus, copper and other minerals in the soil is an issue to be solved with short- and long-term strategies. Sound management programmes involve the calculation, control and record-keeping of manure production and soil needs. Manure must be spread and stored according to standard regulations. Implementation of good practices, adequate manure treatment systems and fulfilment of current legislation have become hot topics in the key pig producing regions of the EU-15. In most cases, there is a high cost associated with the maintenance of a clean environment which affects competitiveness among regions, and in fact, in some areas, environmental protection measures may include a ban on increasing pig population. In consequence, to ensure the profitability of the business, the geographical placement of pigs is changing in order to adapt production sites to manure loading.

Animal welfare is an important issue in developed societies and might become a new non-tariff barrier among developed and under-developed countries. Tradi-
tionally, the industry has kept in mind the need to maintain high standards of animal welfare because of its negative effects on animal productivity, health and meat quality. New concepts and ideas on animal welfare have been developed in recent years, driven in many cases by an urban vision of the agricultural production systems. New long-term regulations by the EU establish minimum requirements in terms of weaning age (at least 3 weeks), tail docking and general animal management including sow housing (use of farrowing crates, floor type, environmental enrichment, bedded groups) and transport conditions (density, floor type, duration, food and water availability). With the present scientific and practical knowledge, not all welfare issues have a simple solution. Besides, the sensibility of the urban consumer to animal welfare issues differs among countries, with lower appreciation by Americans and southern Europeans probably due to differences in cultural idiosyncrasy. In consequence, the auditing programmes related to welfare schemes by retailers may differ substantially not only among European and non-European countries but also among countries within Europe. An additional problem are the difficulties of measuring animal welfare and suffering. New techniques such as the measurement of acute phase proteins and other blood metabolites might help in this respect.

The introduction of minimum standards related to food safety, staff health, environmental protection and animal welfare is an ongoing process that continuously increases production costs and reduces the competitiveness of European producers in international markets and might even result in a loss of market share within Europe. Therefore, the pig meat industry needs to maintain an effective and proactive dialogue with national governments and EU bodies in order to know what is demanded by the society. At the same time, the conflicting interests of the different segments in the meat chain must be resolved within the industry to protect its long-term interest because government bodies prefer to hear a single opinion from the whole pig chain. In conclusion, society requires from the pig sector systems of farming that are environmentally sound and welfare friendly. In this respect, a key issue is to achieve realistic interpretations of what society demands in both areas because this has an important impact on production costs.

**Type of products**

Many different products can be obtained by combining the different elements involved in the production system (Table 16.12). When standard elements are used, a commodity product is obtained. Commodities by definition deal solely with the product and do not offer special eating quality, or emotional security or ‘intangible’ benefits to potential customers. A market remains commodity driven if products fail to differentiate in the eyes of the demanding consumers. In the last decade commodity markets have become over-saturated, resulting in price decreases. Added value is limited in some stages of the pig meat production chain (Figure 16.8) and, therefore, small increases in margin are essential for business profitability in
commodity-oriented markets. Margin growth can be pursued downwards (lower costs) or upwards (higher prices). As mentioned above, the production of pig meat in certain areas is associated with high production costs (raw material availability, labour and energy costs, environmental and welfare issues), and thus the potential for cost reduction is limited. Competition with low-cost meat producing countries such as Brazil, the USA and Canada in a commodity market is tough and undesirable. Pig producers recognise that to maintain their future economic prosperity they need to switch from commodities to offering differentiated products. Differentiation offers an alternative to producers with high costs of production. Product differentiation involves the combination of several elements at different stages of the whole pig meat production chain.

Table 16.12. Elements of production determining pig meat attributes.

<table>
<thead>
<tr>
<th>Genetics</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Leanness</td>
</tr>
<tr>
<td>• Meat quality (pH, colour and water-holding capacity)</td>
</tr>
<tr>
<td>• Marbling</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nutrition</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Dietary ingredients</td>
</tr>
<tr>
<td>• Level of fatness</td>
</tr>
<tr>
<td>• Fatty acid profile</td>
</tr>
<tr>
<td>• Enrichment with antioxidants and nutrients</td>
</tr>
<tr>
<td>• $n - 3/n - 6$ fatty acid ratio</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Production system</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Final body weight</td>
</tr>
<tr>
<td>• Castration (boar taint)</td>
</tr>
<tr>
<td>• Husbandry (outdoor/indoor housing)</td>
</tr>
<tr>
<td>• Flooring and pig density</td>
</tr>
</tbody>
</table>

![Diagram of the pig meat production chain](image)

**Fig. 16.8** Added value in the pig meat chain (courtesy of L. Cerdan).
Amongst all the various means of product differentiation, the most important remains that of eating quality. The result must be the offer of a tangible differentiated product of high quality for which the consumer is willing to pay an extra price. One of the fundamental methods of differentiation involves branding and to be successful requires that the branded product delivers consistently a clearly defined, appealing offering that sets it apart from its competitors. Examples of successful differentiation within Europe are the production of Parma ham based on heavy white pigs and the production of Iberian pigs based on heavy dark pigs kept under free-range conditions. Iberian pig production, either free-range or under semi-extensive conditions, has increased sharply in the last 10 years, and currently there are more than 350,000 sows in the western part of the Iberian Peninsula (Figure 16.9).

Elements of production

Several elements of production can be combined in a differentiated product. Genetics is one of the main tools used to achieve a tangible differentiation in pig meat. For example, the use of pure Duroc boars increases intramuscular fat and results in more tender and tastier meat whereas the use of Pietrain boars yields heavy-muscle, well conformed carcasses. However, Pietrain crosses, especially in the presence of the halothane gene, might present problems related to meat quality (Figure 16.10). Animal nutrition can also be used effectively to improve the quality of the end-product and the offer of enhanced meat products. Of great interest is the implementation of methods to modify the composition of pig meat fat and improve the
nutritional quality of the meat. The fatty acid profile can be adjusted to human health requirements by increasing the monounsaturated fatty acid content and manipulating the ratio of \( n-6/n-3 \) polyunsaturated fatty acids in pig meat. Enrichment of meat with conjugated linoleic acid, vitamin E, \( \gamma \) tocopherols and other natural antioxidants has also been extensively tested with a view to improving the health quality, the oxidative stability and the sensory properties of fresh meat and processed products. Management is also important in order to improve pig meat quality. For instance, a profitable way to raise the standards for quality of cured products is to increase slaughter weight from 95 kg to above 120 kg.

**Differentiated products**

Development of differentiated products has many advantages for the pig production chain and results in added margins. Also, as the latest food safety crises have shown, differentiation allows for the segmentation of the market and shields producers from the effects of price crises. However, it is often difficult to establish the limit between a commodity and a differentiated product. Large volumes of pigs are produced under a set of controlled conditions related to breeding, nutrition and management; however, they are considered only as a semi-commodity product.

Examples of segmentation and pig meat differentiation schemes that involve large production volumes are evident in France, Italy and Spain. In 2000, pig meat production under official quality designations represented 20% of French output. From the over 25 million pigs slaughtered in France in 2002, 26% corresponded to certified pigs, 19% to branded pigs, 2% to label pigs and 0.1% to organic pigs. Today, with the increase in certification and the new specification ‘Viande Porcine Française’ (VPF), more than 85% of total French pig meat production is produced under specifications. In north Italy, the production of pig meat is based on specially fed pigs slaughtered at heavy weights to produce high value dry-cured hams, of

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**Fig. 16.10** Effects on carcass and meat quality of the type of boar used.

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<table>
<thead>
<tr>
<th>Percentage lean/conformation</th>
<th>Iberian</th>
<th>Duroc</th>
<th>Large White</th>
<th>Pietrain</th>
<th>Hal +</th>
<th>pH ⇒ PSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meat quality</td>
<td>Marbling ⇒</td>
<td>Juiciness/taste</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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which Parma and San Daniele are the most famous. Another example of special breeding, management and nutrition in order to supply a differentiated product is the production of dry-cured Iberian hams, shoulders and loins in Spain (close to 2.5 million pigs per year). Iberian pigs are typically produced in the ‘Dehesa’ area, located in the southern and western parts of the Iberian Peninsula from local, indigenous, black-haired, dark breeds with a large capacity for fat deposition. The pigs are kept under extensive production systems based on the consumption of grass and of a minimum amount of acorns (at least 460 kg/pig). In the traditional system, pigs are slaughtered from December to March when more than 160 kg in weight. The carcasses are dedicated to the cured product industry, with drying processes that last at least 14 months for hams and 11 months for shoulders. The final product is characterised as having a specific fatty acid profile (more than 54% oleic acid, less than 9.5% stearic and linoleic acid and 21% palmitic acid) and, in the case of the ham, may reach in the market a price of over 100€/kg.

Many other domestic schemes involving a smaller number of pigs have been developed in different countries to market fresh meat or processed products under differentiated labelling schemes. In all of them, besides the associated marketing aspects, a tangible differentiation is essential. Differentiated pig meat production must take into account the marketing of not only fresh pork but also meat products, as high-quality fresh pork generally means better raw material for meat processing.

**Conclusions**

Pig meat production has undergone profound changes in the last decade. The industry needs a comprehensive understanding of consumer habits and expectations in order to produce pig meat products that fit the requirements of an urban society. Uniformity, food safety, meat quality, traceability, convenience and social and ethical requirements are key issues. Customers require the production of high quality pig meat that is safe and produced under farming systems that are environmentally sound and welfare friendly. And all of this at value-for-quality prices. The requirements set by the large internationally trading retailers and the high-demanding export markets have accelerated the changes in the pig meat supply chain. Growing demands and decreasing margins have resulted in the verticalisation of the sector. To increase profits, the industry needs to maximise income through customer loyalty, increased product quality and product differentiation, and to minimise cost through economies of scale and production in convenient locations. Achievement of these objectives is fundamental to ensuring the success of a pig meat marketing system.
Chapter 17

Environmental Management of Pigs

Introduction

Feral pigs frequent neither thick forest nor open range, but rather the intermediate ground of open woodland, scrub and the forest margin. They build nests of sticks, grasses and rushes which are used for shelter. It may be assumed that pigs will benefit from being protected from the elements of wind, sun and rain, and the provision of a warm, dry bed. In providing for these requirements, and in providing also for an individual supply of feed, housing systems are many and various. Housing for pigs also fulfils functions other than the provision of shelter and feed. Included amongst these are the prevention of bullying, the protection of sucking piglets, the facilitation of mating, the prevention of physical trauma whilst pregnant, the handling and the removal of excreta, and the allocation of quarters in which pigs may rest and grow, free of predators, parasites and disease. These provisions, being costly, tend to encourage intensive livestock systems in which the pigs must be, to a greater or lesser extent, densely stocked into relatively small spaces and restrained in enclosures and buildings. This consequence may be seen as having some disadvantages in terms of welfare, population-density disease and capital cost.

Provision of housing for pigs cannot ignore other aspects of pig production, which now feature strongly in building design and management. These include pollutants of the air, soil and water, biosecurity and working conditions for stockmen. Environmental management of pig production clearly aims to satisfy the pig’s requirements but must also address these other interests. No longer does environmental control mean an insulated building with a ventilation system governed by a thermostat.

It is remarkable that pigs thrive in the barren, unnatural environment of a piggery. Olfaction, vision and audition are keen senses in the pig and each may be affected by the physical environment. Environmental perception in the human is so different from the pig – what would it be like to see, hear, smell and feel the world from the pig’s perspective? An appreciation of the sensory modalities of the pig is not just an imaginative exercise but shows an understanding of the pig’s view of its environment. The greater the degree of environmental control in a building, the greater the responsibility of the farmer to understand the pig’s requirements if the pig is to be denied the opportunity to use its abilities. For example, heat stress is
ameliorated by wallowing in feral pigs but this means of cooling is not available to
the housed pig and alternatives must be provided.

**Physical environment**

The physical environment of a building is specified in terms of temperature, atmosphere (or air quality), light and sound. These, in turn, affect various physiological processes and specifications can be given for environmental optima, normally using financial criteria. The link between thermoregulation and feed utilisation is so strong that control of building temperature has been the traditional aim of environmental management.

Pig buildings may accumulate heat by radiation through the roof, the drawing in of warm outside air, internal supplementary heating and from the pig occupants themselves. Pigs lose heat to their environment through radiation, conduction (mostly through contact with the floor), convection (from the body surface) and latent heat (through the medium of evaporative water loss from the lungs). The removal of heat – and water vapour – from the internal environment of the building is aided by ventilation, but there can also be some control of conductive and radiant heat losses through insulation.

**Temperature**

Ambient temperatures at which pigs are comfortable are related strongly to body weight (Table 17.1). These values are much affected by the heat that has been generated in the course of energy metabolism, and which must be dissipated from the animal body. This heat helps to combat the exigencies of a cold environment. Indeed, there is a necessity for the heat to be carried away from the body if heat stress is to be avoided. The dependence of comfort temperature (Tc, degrees Celcius) upon heat output (H, MJ daily) from the body can be broadly expressed for pigs of 10kg or more as:

$$T_c = 27 - 0.6H$$  \hspace{2cm} (17.1)

The value of H is generated from within the pig as the sum of the work energy used for maintenance, the growth of protein and fatty tissues and the production of milk. H will therefore be lowest for smaller pigs growing slowly; intermediate for smaller pigs growing faster and for larger pigs; and highest for heavy pigs growing fast and lactating sows. The relationship between feed intake and comfort temperature is shown in Figure 17.1.

Once estimated, Tc must be modified by those factors that may materially influence the rate of heat loss from the body of the pig, especially conduction and convection, and pig behaviour.
Table 17.1. Comfort temperatures (Tc) for pigs of different body weights. The comfort zone will usually range 1°C above and below the values given. The pigs are assumed to be fed to appetite and able to lie on a floor with a thermal resistance that is not different to that of air.

<table>
<thead>
<tr>
<th>Live weight of pig</th>
<th>Comfort temperature (Tc) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sucking pigs:</td>
<td></td>
</tr>
<tr>
<td>&lt;2kg</td>
<td>32</td>
</tr>
<tr>
<td>&lt;5kg</td>
<td>28</td>
</tr>
<tr>
<td>Weaner pigs:</td>
<td></td>
</tr>
<tr>
<td>&lt;8kg</td>
<td>28</td>
</tr>
<tr>
<td>&lt;10kg</td>
<td>26</td>
</tr>
<tr>
<td>10–15kg</td>
<td>22</td>
</tr>
<tr>
<td>Growers: 15–30kg</td>
<td>20</td>
</tr>
<tr>
<td>Finishers:</td>
<td></td>
</tr>
<tr>
<td>30–60kg</td>
<td>18</td>
</tr>
<tr>
<td>60–120kg</td>
<td>16</td>
</tr>
<tr>
<td>Pregnant sows:</td>
<td></td>
</tr>
<tr>
<td>Feed restricted</td>
<td>18</td>
</tr>
<tr>
<td>In groups on straw</td>
<td>15</td>
</tr>
<tr>
<td>Lactating sows</td>
<td>16</td>
</tr>
<tr>
<td>Boars</td>
<td>18</td>
</tr>
</tbody>
</table>

Floor surface

A major influence upon effective comfort temperature is mediated through the nature of the floor surface upon which the pig may lie and heat be conducted away. All substances have some degree of resistance to thermal transfer (including air). Table 17.2 shows that losses of heat through deep bedding will occur at a much slower rate than through a concrete floor. The ambient comfort temperature on bedding is therefore much lower than on solid concrete.
Pig behaviour

Pig behaviour is not without its further moderating influences upon $T_c$. Pigs can lie recumbent, and by maximising the body surface in contact with the floor maximise the rate of heat loss through it. Equally losses can be minimised by pigs lying on the sternum. Pigs in groups have lower comfort temperatures than individuals; this is because they can lie together to conserve warmth. $T_c$ is about 5–6°C cooler for a group of 15 20-kg pigs on straw compared with single animals. The lying position of pigs in pens can give a good indication of the acceptability of the ambient temperature. Pigs should normally not be huddled together (too cold), nor all laid apart and recumbent (too hot).

Convection

The rate of air movement across the body controls the movement of heat from the body surface to the air. At low air speeds this effect is not great, but at higher air speeds (draughts) of above about 0.5 m/s the consequences for comfort temperature can be significant, and in this range every 0.2 m/s increase in air speed adds about 2°C to $T_c$. It is not surprising that when not in heat stress, pigs will volunteer to lie away from draughts.

Taking full quantitative account of the influence of the quality of the environment upon comfort temperatures has proved difficult, and the solution appears not to lie (yet, at any rate) in ever-increasing levels of mathematical sophistication and implementation of the detail of the laws of physical science. Meanwhile a pragmatic approach may be to offer a score for environmental quality along the lines of Table 17.3. The factors $V_e$ and $V_l$ may be used to modify the ambient temperature ($T$) and allow calculation of the effective environmental temperature ($T_e$), which may be estimated as:

$$T_e = T(V_e)(V_l)$$

where $V_e$ is the rate of air movement and degree of insulation in roof and walls and $V_l$ is the floor type in the lying area.

The effective temperature $T_e$ can now be compared with $T_c$ to assess any disparity there may be between what the pig requires and what the house provides.

### Table 17.2. Thermal resistance of flooring materials in comparison to air = 100.

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>100</td>
</tr>
<tr>
<td>Wire mesh floor</td>
<td>100</td>
</tr>
<tr>
<td>Deep straw bed</td>
<td>550</td>
</tr>
<tr>
<td>Concrete slats</td>
<td>50</td>
</tr>
<tr>
<td>Solid, wet, concrete floor</td>
<td>25</td>
</tr>
</tbody>
</table>
Cooling and heating (Table 17.4)

It may be surmised that pigs can be cooled by:

- decreasing the number of pigs per pen – not only to allow recumbent lying but also to reduce the total number of pigs in the total air space of the house and thus reduce the total heat output (H); rule of thumb suggests that half a dozen average-sized growing pigs will throw off energy at the rate of about 1 kW;
- providing flooring with low thermal resistance (high ability to draw away heat);
- increasing the rate of air movement.

Also helpful would be the protection from radiant heat (by the provision of an insulated roof), presentation of the food in wet form, provision of water sprays and drips, and wetting floors and providing wallows. Pigs are relatively indifferent to changes in relative humidity between 60 and 90%, although the structure of the building will not be indifferent to condensation which may take place at high relative humidities during cold temperatures. Pigs do not sweat, but evaporative heat losses are possi-
ble from the lung surface and pigs in heat stress may pant; at this point cooling strategies have most certainly failed.

Warming pigs up may be achieved by tactics contrary to the above, plus the actual input of energy into the house by means of supplementary heating. Pigs are themselves a ready source of heat, as witness the equation:

\[ H = ME - (23 \text{ Pr} + 39 \text{ Lr}) \]  

(17.3)

which is simply to say that feed metabolisable energy (ME, MJ daily) will end up as heat (H, MJ daily) to be lost from the body, with the exception of that which is retained as protein or lipid accretion (Pr and Lr, kg daily). The amount of heat generated from body metabolism (that is, the effective ME yield from energy digested) is dependent to a small extent upon the form in which dietary energy is provided. Dietary fibre has an especially high heat of fermentation, while dietary fat can be used particularly efficiently. High fibre diets will therefore be heat creating, whilst high fat diets will aid cooling.

Regardless, the ambient temperature of a pig building can be most effectively increased by increasing the number of pigs in it (increasing the stocking density) and/or by increasing the amount of feed given to the pigs (raising the allowance; encouraging appetite). However, the former will be accompanied by a greater concentration of aerial pollutants, unless the ventilation rate is increased pro rata.

Supplementary heat from oil, electricity or gas may be provided by conventional means, including convectors, floor heating systems, overhead radiant heaters and the like. Hot-water radiators may be found in sophisticated pig buildings in cold climates, while overhead gas or electric heaters are normal for sucking pigs, weaners and some young growers. The great disparity between the comfort temperature for a newborn sucking pig (about 30°C) and its suckling mother (about 15°C) exemplifies the impossibility of providing an ambient room temperature ideal to widely differing classes of pig. In the case of the sow and her litter, a local source of heat to create a warm micro-climate for the sucking piglets is prerequisite. The consequence for growing pigs is that different house types maintained at different ambient temperatures, and requiring different degrees of sophistication in their control systems, are required for weaners, young growers and finishing pigs.

An intermediate step in relation to heat input to a building between the utilisation of pig heat and the introduction of supplementary energy is to do all that is possible to conserve the heat already present. Insulation, recirculation and heat exchange technology may be readily adapted to pig buildings and can make a material contribution to energy saving in cold environments.

**Metabolic response to cold and heat**

Pigs are cold when the effective environmental temperature is less than the comfort temperature. The pig’s response to cold is to direct ingested energy from productive functions into the creation of heat (that is, cold thermogenesis). The energy cost of cold thermogenesis (E_{h1}) for each degree of cold may be estimated as:
where $W$ is the live weight (kg), $T_c$ is the comfort temperature and $T_e$ is the effective environmental temperature ($°C$).

Thus although body temperature is maintained, the pig will grow more slowly and the feed conversion efficiency will fall. As an approximation, 50 g of feed can be used up in this way by a 100 kg pig per °C of cold ($T_c - T_e$). There may, however, be more cost-effective means of inputting energy into the environment than the conversion of pig feed into heat – heat conservation certainly, but in many circumstances also the direct input of energy from (non-renewable) fossil fuels. The balance of benefit is dependent upon the comparative costs of pig feed (plant carbohydrate) energy and fossil fuel energy. It will be recalled that a higher feed intake decreases $T_c$ (Figure 17.1), and fortunately there is also an appetite response to an environmental temperature that is less than the comfort temperature. This latter response may go some way to offsetting the extent of the reductions in productivity due to diversion of energy away from the accretion of protein and lipid and toward the generation of heat.

Pigs are hot when the effective environmental temperature ($T_e$) is greater than the comfort temperature ($T_c$). The pig is embarrassed by its inability to dissipate heat into the environment and in consequence appetite falls by about 1 g for each kilogram of pig live weight per °C of heat above comfort ($T_e - T_c$). Growth rate and feed conversion efficiency fall.

The influence of environmental temperature upon growth rate mediated through the metabolic responses of cold thermogenesis and appetite depression is depicted in Figure 17.2.

**Influence of building insulation**

The degree of building insulation influences both the rate of heat loss and the rate of heat gain by a building. Given conventional densities of stocking with pigs and an outside air temperature of 0°C, an uninsulated building would be unlikely to be able to maintain an internal air temperature much above 12°C, and in addition surface condensation would occur. However, effective insulation (especially of the roof) would allow both a satisfactory internal air temperature of 20°C and prevent
surface condensation. This could be provided by 42 mm of polyurethane foam sprayed on the walls and roof, 50 mm rigid boards such as expanded polystyrene or 75 mm of glass fibre mat in a roof cavity: the overall target is a U value of 0.5 W/m²/°C or lower. A vapour check must be placed on the warm side of the building to prevent entry of vapour into the insulant, where it may condense and cause deterioration. Some insulants, for example expanded polystyrene, provide their own check because of their closed cell structure, while a 0.15 mm PVC sheet is needed for others.

Equally an outside air temperature of 20°C would be associated, in an uninsulated building, with an internal temperature in the living quarters of the pigs of above 25°C. However, when insulated, excellent ventilation could restrain the internal temperature to no greater than 3° above that outside.

**Air quality**

The air within a pig building seethes with a dense miasma of bioaerosols and gases. Both composition and concentration of the miasma vary according to animal husbandry and the building’s design and management. In Europe, inhalable dust concentrations vary widely, but levels of 1–2 mg/m³ are not uncommon in sow houses, and twice that (2–5 mg/m³) in grower pig accommodation. Inhalable endotoxins can range from a few tens of nanograms per cubic metre to many hundreds. Ammonia levels are rarely below 5 parts per million (ppm), but also rarely above 20 ppm. Amongst all classes of pigs, the mean mass concentration of dust and endotoxin was highest in weaner buildings with slats.

Dust can be characterised by its physical, chemical and microbiological properties, though most workers restrict themselves to mass concentration, presumably because of the tedium and expense involved in identifying and classifying individual dust particles. The main sources of pig dust are feed, faeces, bedding and skin squames; the predominant fine and coarse dust particles are faeces and feed, respectively. Most studies of noxious gases in piggeries have focused upon ammonia, partly because it is toxic but also because of its role in acid rain. However, over 100 gaseous compounds have been identified in the air of piggeries; most are simple odourants – which may still give rise to complaint amongst neighbours – while some are greenhouse gases. The concentrations of most of these gases are usually in the parts per million range or lower, with the exception of carbon dioxide where the concentration can be 5–10 times higher than ambient when the ventilation rate is slow. The mean concentrations of ammonia may mask the short-term fluctuations of hourly concentrations in weaner buildings which can readily be double the mean rate.

The final category of aerial pollutants in pig buildings is that of micro-organisms and their components. The majority of these will be non-pathogenic Gram positive bacteria at a concentration of approximately 10⁶ colony forming units (cfu) per cubic metre. Smaller numbers (less than 10⁵ cfu/m³) of Gram negative bacteria and fungi will also be found. The majority of airborne microbes will be non-pathogenic: some
opportunistic pathogens, such as *Pasteurella multocida*, and primary pathogens, e.g. African swine fever virus and *Bordetella bronchiseptica*, can be isolated from the air in numbers that depend on the shedding rate from the host and their viability whilst airborne. Endotoxins arise from the breakdown of the outer cell wall of Gram negative bacteria and have been implicated in occupational respiratory disease in pig stockworkers.

The variety of aerial pollutants in pig buildings poses several problems for abatement. It is not clear whether attempts to control the burden of one pollutant may exacerbate exposure to another. The development of abatement techniques is a topic of active research. Good progress has been made in the use of oil spraying to reduce airborne dust, which works by minimising the resuspension of dust after it has settled within the building. Although its adoption is less advanced, one promising technique to reduce ammonia emissions from pig buildings and waste stores is dietary manipulation to lower excretion of urea and proteins.

**Avoidance of aerial pollutants**

The ancestors of the domestic pig evolved in a woodland habitat in which pollutant gases were not present at concentrations typically found in modern pig buildings. There can be no reason *a priori* for the pig to have developed adaptive behaviour when faced with these gaseous pollutants. On the other hand, as the pig roots through the woodland soil, it is likely to be exposed to a heavy burden of inhaled dust particles which are filtered effectively by the turbinates in the snout, thereby offering some protection.

Ammonia gas is an irritant, which in humans is detectable at 5–50ppm, causes irritation of mucous surfaces at 100–500ppm after 1 hour and is rapidly lethal after exposure to 10000ppm. Although the UK occupational exposure limit for humans is 35ppm for a short-term exposure of 15 minutes or less and 25ppm over 8 hours, the initial reaction of most people to such atmospheres is avoidance followed by habituation if the exposure is prolonged.

A similar avoidance of ammonia has been observed in juvenile pigs by workers at the Silsoe Research Institute [Wathes, C.M., Jones, J.B., Kristensen, H.H., Jones, E.K.M. and Webster, A.J.F. (2002) Aversion of pigs and domestic fowl to atmospheric ammonia. *Transactions of the American Society of Agricultural Engineers*, 45, 1605–1610]. In a free-choice preference test, weaned pigs made fewer visits of shorter duration to ammoniated atmospheres (nominally either 10, 20 or 40ppm) versus fresh air (effectively, 0ppm). Overall, 80% of their time was spent in an atmosphere of 10ppm or lower, indicating a clear preference for fresh air. Although only a small proportion of time was spent in 20 or 40ppm ammonia, the shorter length of each visit (30–40 minutes) suggested a delayed aversion to ammonia. In subsequent experiments, either single or pairs of juvenile pigs were given a forced choice between either thermal comfort or fresh air. Thus heat was provided along with 40ppm ammonia in one compartment while the other was unheated and contained fresh air. As the air temperature fell below the animals’ lower critical tem-
perature, the single pigs became increasingly motivated for warmth rather than fresh air. The mean duration of the visits to the atmosphere with 40 ppm ammonia was six times longer than to fresh air over an air temperature range from 0–15°C. Paired pigs given choice also increasingly preferred a higher level of atmospheric pollution over fresh air as the air temperature fell.

These findings demonstrate that juvenile pigs prefer to maintain thermal comfort rather than endure a cold environment of fresh air. The reasons for the delayed aversion are unknown, but clearly sudden exposure to such high concentrations of ammonia was not sufficiently aversive for the animals to leave immediately. Perhaps the animals gradually developed a sense of malaise, which eventually drove them to seek fresh air: presumably, the domestic pig has not evolved a set of behavioural and physiological mechanisms that would allow it to make the necessary adaptive responses in the presence of noxious atmospheres of ammonia. Using the pig’s preferences, then, a cautionary limit of 10 ppm can be set for the maximum concentration of ammonia in a weaner shed. Pending similar work on neonates or adults, this limit can be used, thereby giving the animals the benefit of any doubt.

**Aerial pollutants and respiratory disease**

The effects of aerial environment on pig productivity are difficult to quantify, and experiments in this discipline difficult to interpret. This is in no small part due to the following: (1) the tolerance limits for aerial exposure have not been sufficiently well defined (or measured); (2) potential interactions between aerial pollutants have rarely been examined; (3) dust levels interact with other pollutants in precipitating disease; (4) dusts and gases may reduce productivity directly, or indirectly by affecting health; (5) respiratory diseases are variable in their effects upon production; (6) the key features of building design and management to control pollutant exposure are not fully understood.

There is good clinical evidence that poor air quality affects the incidence and severity of common endemic respiratory diseases, such as porcine reproductive and respiratory syndrome, swine influenza, pneumonia, atrophic rhinitis and enzootic pneumonia. The mechanisms by which dust affects respiratory disease are likely to be different from those for ammonia. Organic dusts will be immunogenic while inorganic dusts may block mucociliary clearance.

The mechanisms by which aerial pollutants are involved in the aetiology of porcine respiratory disease are complex and require consideration of specific pathogens, commensal respiratory microflora and host-specific factors as well as the nature of the pollutants themselves. Simply put, it seems clear that the incidence and severity of respiratory disease in pigs are greater when combined with chronic exposure to aerial pollutants. Recently evidence has, however, warned against putting anything simply when it comes to the production and economic consequences of low level aerial pollution. The Silsoe group and the MLC’s Stotfold Pig Development Unit addressed this question for dust and ammonia. This work was careful to use natural infection and mimick conditions on farm. Although the puta-
tive pathogens of most respiratory diseases were present, there was no effect of 5.2 weeks’ exposure to dust and ammonia at concentrations over the range recorded on UK commercial farms on the incidence and severity of respiratory disease. Performance was depressed at inhalable dust concentrations of 5 mg/m³ and higher, but there was no response to graded concentrations of ammonia. Given the scale of the experiment (960 pigs) and the extensive measures of health and performance, this is a surprising finding that, at first sight, flies against conventional wisdom, but may only have been a result of the excellence of the prevailing level of stock care at the unit concerned. Under less benign conditions, different results might have been obtained.

**Light**

Little is known about the importance of light in pig buildings. Light is characterised by its intensity, photoperiod and spectrum. Compared with humans, pigs have poorer visual acuity. They are dichromates with a similar sensitivity to blue light as humans but find it difficult to distinguish red from green light, which reflects their major pre-occupation with resting. They are not seasonal breeders and so photoperiod has no effect on reproduction. However, vision is used in social behaviour and dim lights in piggeries may hamper the effective transmission of visual cues. In the UK, the recommended minimum light intensity is 40 lux, which must be provided for at least 8 hours per day.

**Sound**

The pig has a well developed sense of hearing and can perceive frequencies from 40–40000 Hz. Sound levels (on a linear scale) in pig production were reported in 1998 by Talling and colleagues [Talling, J.C., Lines, J.A., Wathes, C.M. and Waran, N.K. (1998) The acoustic environment of the domestic pig. *Journal of Agricultural Engineering Research, 71*, 1–12]. They found the following:

- Naturally ventilated piggeries – 63 dB.
- Mechanically ventilated piggeries – 73 dB.
- During road transport – 91 dB.
- Abattoir lairages – 76–86 dB; and pre-stun pens – 89–97 dB.

The loud sound levels during transport and prior to stunning are likely to be highly aversive to pigs, because of their loudness and the unfamiliarity of their source. However, in the reassuring, familiar environment of the farm, pigs readily adapt to sudden noise and some farmers even play radios in piggeries for this purpose. Perhaps of greater concern is masking by the cacophony of noise within a piggery that may hinder normal social recognition via acoustic cues. Also pig stockworkers are at risk from occupational hearing damage, e.g. during feeding in dry sow houses.
or routine husbandry tasks, such as weighing, when stockworkers should avail themselves of the benefit of protective equipment. In the UK, noise levels above 85 dBA should be avoided.

**Ventilation systems**

**Principles of ventilation**

Pigs need a minimum air space of around 0.1 m³/kg metabolic weight ($W^{0.75}$). This air must be refreshed regularly if:

1. oxygen is to be replenished and carbon dioxide removed (in temperate climates there is usually a balance to be struck between the freshness of the air and its temperature);
2. evaporative moisture losses from the lungs and building surfaces are not to cause a build-up of relative humidity and hence condensation;
3. pigs are to lose heat from their bodies as is required;
4. the air is to be kept fresh and free of noxious pollutants. Desirable levels of gases are 3000 ppm carbon dioxide, 0.1 ppm hydrogen sulphide, 10 ppm ammonia and 5 mg dust/m³. Levels above these are indicative of inadequate ventilation, although levels may reach 5000 ppm CO₂, 5 ppm H₂S, 20 ppm NH₃ and 10 mg dust/m³ without undue alarm; but levels higher than these may be cause for concern owing to unwelcome environmental pollutants, hazards to stockpersons and the exacerbation of respiratory disease.

**Design of ventilation systems**

The design of a ventilation system is specified by its minimum and maximum rates of ventilation and the pattern of airflow within the building. The performance of a ventilation system affects air speed, temperature and humidity, and the concentration of gases and airborne micro-organisms and dusts. Each of these can vary over time and space: an average is normally calculated on a building basis but, of course, the pig responds to the micro-environment that it experiences in its pen. This distinction is rarely appreciated and control systems normally position a single sensor, usually a thermostat, at a ‘representative’ location. Naturally, the pig will exploit any spatial variation in the physical environment to its benefit.

Successful design and operation of a ventilation system requires (1) clear targets for the environmental variables and (2) an effective control system, comprising sensors, a controller and actuators. For temperature control, either mechanical or natural systems controlled by a thermostat(s) will satisfy these requirements. Practical sensors for aerial pollutants are not yet available and air temperature is the only variable that can be said to be controlled in a piggery.

In order to be effective, a ventilation system must be able to do the following. First, the gross or average building air temperature must be controlled by varying
the ventilation rate in a well insulated building, using supplementary heating if the contribution from the animals is insufficient. Second, the ventilation rate itself must be capable of control, which implies that either it must be measured or empirical relationships must be assumed between either fan speed settings and ventilation rate in a mechanically ventilated building or the number and size of inlets and outlets in a naturally ventilated building. On-line measurement of ventilation rate is feasible but normally only used in the most modern buildings. In practice, the empirical approach is the most common and can suffer from inaccurate calibration when the system is first installed. Third, control of building air temperature by using an appropriate ventilation rate does not guarantee control of either airflow pattern or temperature distribution within the piggery. Since sensors for airflow pattern are not available, little can be done in this regard. The final step is to control the three-dimensional temperature distribution. Here two philosophies prevail: some seek to provide a uniform thermal environment that is deemed optimal, usually according to financial criteria; others tolerate a heterogeneous thermal environment because it allows animals an individual choice. Given the difficulties in controlling ventilation rate and airflow pattern, the latter view normally prevails, if only because of the practical difficulties in achieving thermal uniformity.

Natural vs mechanical ventilation

Natural ventilation [Figure 17.3 (a)] relies upon the prevailing breeze and stack effect; the inlets may be manually or automatically controlled. The size of the inlets are dependent upon outside temperature; requiring in hot climates to be as much as 20% of the floor area, with a ridge vent of an area equivalent to 10% of the floor area. Proportionally smaller openings will suffice in temperate climates. This is normally achieved with a wide gap at the apex of the roof, and sides to the house which may be rolled up and effectively removed. The ridge vent may not be required with

![Fig. 17.3 Patterns of ventilation: (a) natural ventilation; (b)–(e) different configurations for fan ventilation systems (preferred circulation systems are depicted to the left of the buildings).](image-url)
houses whose side ventilation is generous. In any case, the roof should be well insulated.

In mechanically ventilated houses, air movement is usually achieved by electric fan, activated according to the temperature of the house. The fans operate when the upper end of the comfort temperature zone is reached and run at a minimum rate when ambient temperature reaches the lower end of the comfort zone. Thermostat sensitivities therefore require to be plus or minus around 1°C. Temperature fluctuations can be as counter-productive to pig health and well-being as can low or high temperatures themselves – especially in the case of weaner pigs. Variable speed fans or a mix of smaller and larger fans can be helpful in achieving smooth temperature transitions.

General examples of fan ventilation systems are shown in Figure 17.3(b)–(e). Airflow patterns depicted on the left hand side of the drawings are to be preferred over those depicted on the right. The latter allows cold air to fall directly upon the pigs, while the former encourages faster air movements along the roof line and slower more general air mixing in the body of the building and around the pigs. The preferred pattern can be achieved under most ambient conditions by varying the size of the inlets according to the ventilation rate, aiming for minimum air speed of 5 m/s at the inlets. The high-speed jet that issues from the inlets will entrain a slow moving circulation of air, avoiding draughts on the pigs. The slow secondary currents will gather heat as they move across the floor, so that there is a slight thermal gradient from the centre to the wall [Figure 17.3(b)] or vice versa [Figures 17.3(c) and (e)]. Pigs will tend to lie in the warmest part of the pen and urinate and defecate in the cooler. Thus, if the floor is part-slatted, the slats should be placed in the pen centre in Figures 17.3(b) and (d) and adjacent to the wall in Figures 17.3(c) and (d). However, in hot weather the pigs may defeat this aim by lying over the slats in an attempt to cool themselves in the manure, leading to random defecation and urination and dirty pigs.

Usually a minimum ventilation rate of around 0.2 m³/hour/kg pig live weight is needed in pig houses, even when the exterior temperature is low; although in cold weather there is a temptation to reduce this minimum further in the interests of pig warmth – this should be avoided. Maximum ventilation rates for warmer weather in temperate climates require to be around 2.0 m³/hour/kg live weight of pig. For hotter climates even more than this rate of air movement may be needed at peak.

Table 17.5 shows examples of the capacity of fans to deliver air. Fans have to overcome the resistance of the inlets and outlets if air is to be moved through a building. The fan capacities are based on a typical resistance of 50 Pa; nominal capacities are much greater if zero resistance is assumed and will be inadequate in a working building. Knowing the maximum and minimum needs of air movements and maximum and minimum stocking densities of the room to be ventilated, a profile of the fan requirements of individual pig rooms can be determined. Ventilation characteristics may be described in terms of ‘air changes’. A minimum of 5 per hour may often be specified for young pigs and low outside temperatures, while for
larger pigs and high outside air temperatures, peak short-term capacities of 50–100 air changes per hour may be needed.

Air speeds across the bodies of pigs are normally maintained at between 0.2 and 0.5 m/s; 0.2 m/s is considered suitable for smaller pigs maintained at higher room temperatures or for larger pigs maintained at lower temperatures. Faster speeds are needed for convective cooling as the effective temperature rises above comfort levels. At speeds above 0.5 m/s the movement of air becomes quite apparent. Air speeds along the roof line and near inlets may, of course, reach levels of 1–2 m/s or faster. Fans deliver air at speeds of up to 10 m/s. Avoidance of draughts in conditions of high density stocking and the need for positive ventilation may be assisted by diffusing the air before it enters the pigs’ living space. This may be achieved by provision of a false roof or a ducting system, both of which give spaces into which the fresh air is drawn and from which the air is spread through many smaller apertures. Air speeds above 0.5 m/s constitute a draught, whilst speeds of 1.0 m/s will give a high likelihood of significant local and intermittent temperature reductions. Work in the Netherlands has shown quite clearly that pigs subjected to intermittent draughts and temperature falls grow slower and are more susceptible to both respiratory and intestinal diseases.

Ventilation of buildings remains an imperfect science, and practical experience of effective systems is invaluable. It is difficult to maintain temperature and achieve adequate air movements in colder climates, and equally difficult to achieve adequate cooling in hotter climates (even where water spray systems are fitted). Forced (fan) ventilation is expensive in terms of both equipment purchase and recurrent energy costs. More expensive still is the evident need to put energy into pig houses to keep them warm, whilst simultaneously moving the air out in the interests of proper ventilation. Minimum ventilation rates almost invariably require supplementary heating to operate in all houses where young pigs are to be kept.

**Space**

The linear dimensions of pigs are found to have the following relationships with their weight (W, kg):

- Pig length (m) approximately equal to 0.30 $W^{0.33}$.
- Pig height (m) approximately equal to 0.15 $W^{0.33}$.
- Pig width (m) approximately equal to 0.06 $W^{0.33}$.
The volume of a pig may thus be expressed with reasonable accuracy as a function of its weight. A pig lying recumbent with its legs outstretched [Figure 17.4 (a)] occupies a space of $0.045 W^{0.66} \text{m}^2$, accepting that some free space is found particularly under the jaw and between the legs. If it is lying on its sternum (or standing) [Figure 17.4(b)] the space occupied is $0.018 W^{0.66} \text{m}^2$.

From these simple elements it may be surmised that if pigs are each allowed a space in a pen of $0.05 W^{0.66}$ then they may all lie recumbent simultaneously and about one third of the floor will remain uncovered (vacant). This calculates to about $1 \text{m}^2/100 \text{kg}$ of pig weight in the pen. If the pen floor is fully slatted or of suspended wire mesh and the house is closely environmentally controlled, this may be considered adequate. The industrial standard for intensive housing of pigs may even be as low as $0.025 W^{0.66} + 25\%$, which is $0.032 W^{0.66}$. In other circumstances, as for example for solid floored and straw bedded pens, an extra allowance of 25% may be added to the more generous standard of $0.05 W^{0.66}$ to facilitate further movement and for specially designed areas to be used only for excretion.

Use of pig dimensions in the above way to determine pen space allowances must be modified by the number of pigs in the pen. The fewer the pigs, the more space required per pig – and vice versa. Minimum lying area requirements are given in Table 17.6 which assumes a group size of 8–15 pigs per pen and the relationship $0.032 W^{0.66}$. To this lying area allowance will require to be added a further 20–60% of space for movement and excretion depending upon house type. The lower addition is for fully slatted floors and the higher for pens with bedded dunging areas. In warmer climates or for pigs with especially high levels of heat output, such as rapidly growing pigs with high appetites, the greater space allowances are beneficial. Adult sows kept in groups in straw yards may use $2–4 \text{m}^2$ of total space per sow.

**Table 17.6.** Minimum space requirements for lying areas.

<table>
<thead>
<tr>
<th>Description</th>
<th>Lying area (m²) per pig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sows</td>
<td>1.5–3.0</td>
</tr>
<tr>
<td>Piglets 5–20 kg</td>
<td>0.10–0.20</td>
</tr>
<tr>
<td>Growing pigs 20–60 kg</td>
<td>0.20–0.40</td>
</tr>
<tr>
<td>Finishing pigs 60–120 kg</td>
<td>0.40–0.80</td>
</tr>
</tbody>
</table>

Fig. 17.4  Physical space occupied by pigs (a) lying recumbent and (b) standing or lying on sternum.
There is a significant influence of space allowance on feed intake and growth rate – and a further interaction with disease. In general, raising the total space allowance in a fully slatted pen from 0.5 to 1.0 m²/100 kg of total pigs live weights will increase growth rate by about 10% in a broadly linear manner (Figure 17.5). In a recent experiment with 10 kg commercial pigs, an increase in space allowance from 0.14 to 0.22 m² per pig (0.031 to 0.048 W^{0.66} m²) was associated with a 10% increase in feed intake (from 440 to 481 g per pig per day). Some authorities recommend for optimum growth in weaner pigs 0.4 m² per piglet and 40% of the floor area solid.

The influence of group size upon pig performance is difficult to quantify independently of the effects of stocking density, the environment, pig behaviour and disease. It would appear, however, that performance will begin to deteriorate when the number of pigs in a group exceeds 12 for weaner pigs, 15 for growers and 20 for finisher pigs. Pregnant sows are best kept in groups of less than 10, but straw-based electronic feeding systems may have sows in groups of 20–60 animals. Presently, however, there is commercial value perceived in very large mobs (hundreds and up to a thousand) of growing pigs and of pregnant sows (hundreds) in equally very large barns. Good management may control reduction performance such that overall benefits of scale accrue.

Space required for feeding differs with the feeding system. Solid floors may accept food dropped from above and thus no special space allocation for feeding is made. Floor feeding is, however, both dusty and wasteful, it does not help to maximise appetite or decrease pig variability. Self-feed hopper systems for the delivery of dry meal or pellets will normally be 300–400 mm in width, and hopper length should be allowed to the extent of about 75 mm for each weaner piglet, 60 mm for each growing pig and 70 mm for each finisher pig. Pens with 10–20 growing pigs in them will normally have 4–6 feeder spaces provided in the hopper. Single-space feeders (usually one for 8 pigs) naturally require a lesser area of floor space to be provided. When pigs are fed from a long trough and all pigs in the pen require to eat simultaneously, it is evident that the absolute minimum allowance would be in excess of pig shoulder width (0.06 W^{0.33}), whilst the optimum would probably be twice that amount. Usual recommendations fall between these limits at 150 mm per pig for young growers, 250 mm for growers between 25 and 75 kg live weight and 300 mm for finisher pigs. Sows each need a trough of around 500 mm in length.
Manipulable materials

Straw-based systems have similar levels of disease problems overall, as do slatted and part-slatted systems. However, it has been noticed that pigs will spend 16% of their time manipulating straw, but only 1% of their time playing with chains and toys in slatted systems. Tail biting is also less frequently found on straw systems. These sorts of observations have led to recommendations that all pigs should have access to ‘manipulable’ materials such as straw. Where these materials have unacceptable repercussions for pig health or for waste disposal systems using slats and slurry, provision of toys is a suggested second best.

Waste management

The 60 million breeding sows of the world, together with their progeny, each generate 20 tonnes of excreta per year, or 1.2 thousand million tonnes of pig excreta in total. This may be seen as a serious source of nitrate, ammonia, oxides of nitrogen (NOx), phosphorus and aroma pollution; or alternatively as a source of nitrogen, phosphorus and potassium organic fertiliser which can be returned to the land which grew the crops which provided the pig’s feed ingredients in the first place.

Through pig excretion mineral elements are systematically moved into the environment as a result of the activities of pig farmers. Loss of ammonia (NH3) from excreta brings about non-trivial levels of aerial pollution in pig-rich areas. Over 50% of N in animal slurries is ammonium-N, and at alkali pH this converts to gaseous ammonia. About 30% of total excreta N may readily be lost through ammonia emissions. Losses of nitrogen in this way are problematic on four separate counts:

1. Ammonia is an aerial environmental pollutant causing a noxious aroma in the immediate surroundings.
2. The ammonia may be returned rapidly from the atmosphere to local land areas, encouraging in the natural environment the growth of high N-demanding plants, such as grass, and discouraging the growth of low N-requiring natural vegetation associated with poor soils, these latter becoming lost.
3. Gaseous losses of N preclude its utilisation as a fertiliser and therefore represent a loss of biological efficiency.
4. Gaseous ammonia in animal houses above 20 ppm is uncomfortable for human workers and animals, and reduces the performance of both.

There are losses of nitrogen especially, but also of phosphorus from agricultural land after animal slurries have been spread upon it, resulting in (1) elevation of nitrate concentration in water and reduction in drinking quality, and (2) nitrate and especially phosphate enrichment of water, causing eutrophication. The European Union Directive on the Quality of Water Intended for Human Consumption sets a limit of 50 mg nitrate per litre in drinking water. Sensitive areas are those where water drains into sources that are used ultimately for human drinking water and where there is
also a high concentration of livestock. Nitrate pollution can be controlled by reducing N (protein) levels in pig feeds, by limiting the number of animals per unit of land mass available to handle the excreta, and by avoidance through the physical transportation of N (and P) in animal slurries from intensive livestock areas to areas bereft of livestock. This may require some means of N (and P) concentration. A recently fashionable alternative is to use the organic matter in the slurry to generate bio-gas in fermentation units.

The ability of agricultural land to assimilate applied N relates directly to the extent of crop cover and the rate of growth of that crop. Grassland can utilise twice as much pig slurry as cereal crops, and growing plants in summer have maximum uptake, while there is a minimum uptake from winter arable stubble (from which 50% of N applied may be leached out before it can be fixed or used). The UK regulations indicate a maximum application rate to grassland for organic manures of 250 kg N/ha, but the EU Directive limits the rate of application to 170 kg N/ha.

In some European regions the behaviour of pig farmers has been considerably moderated already by legislation following EU Directives. Controls of N and P importations to farms have led to reductions in the N and P contents in animal feedstuff, and enhancement of the efficiency of livestock feed utilisation. Impending environmental pollution control (the EU Directive, IPPC – Integrated Pollution Prevention and Control) demands that gaseous emissions of ammonia from livestock buildings and stored slurries be reduced from present levels, even though beef cattle and dairy cows, not pigs, are the dominant sources of ammonia emissions in the UK. Controls over application rates for excreta to agricultural land have led to limitations on the size of intensive farms, and the enforcement of relationships between the number of animals kept and the area available for the spreading of their excreta. This becomes especially critical where (1) livestock units are geographically concentrated, as is so often the case for pig production, (2) farms with intensive pig units are associated also with substantial hectarage of arable (rather than grass) crops which can receive the slurry, as is so often the case with pig production, and (3) many livestock units use imported concentrates and are therefore open to net influx of N and P into the system, often the case with pig production.

The most severe consequence of pollution from pig waste would be the (enforced) dispersal of agglomerates of intensively housed livestock; but legislative pressures regarding maximum N application rates for organic manures may well bring this about over time in any event. Less dramatic moderations of farming practice would be: the avoidance of application of animal excreta to land not covered by growing crops; limitation of application rates to a maximum of 150 kg N/ha/year from livestock excreta sources; restrictions on gaseous ammonia emissions from livestock housing and slurry storage systems; consideration of construction of biogas plant; and export of animal manure from the intensive livestock units to farms where livestock are not abundant. (Current technology is able to separate the liquid and solid phases of animal excreta, leaving an N-rich liqueur and a fibrous low-N solid. This is satisfactory for short-range pumping of liqueur as a fertiliser, but not
as export to other farms. If excreta is to be exported from the farm it would be necessary to separate the water from the slurry, creating a solid phase rich in N and P, and a purified liquid phase.)

Excreta in the form of mixed faeces and urine comprises about 10% dry matter (DM), and the average production per pig on a unit which both breeds and rears the pigs up to slaughter weight is about 5 kg per pig space per day (1.8 t/year). The rate of excretion is less for younger pigs and a great deal more for lactating sows; 2, 6 and up to 25 kg for pigs of 30 and 100 kg and lactating sows respectively. At 4–8% DM the excreta is a readily pumpable slurry (a 250-sow breeding and grow-out unit will use 20 000 litres of water daily). At 20% DM or above it can be handled as a solid. Slurry can be stored under the slats within the house, or extracted for storage in tanks and lagoons. It can be aerobically and anaerobically digested before disposal to the land. Anaerobic digestion will yield methane as a useful energy source. The solids separate naturally from the liquids in a lagoon. The latter is pumpable directly to land, whilst the solids can be extracted for mechanical spreading. Solids and liquids may also be separated mechanically by centrifugation or sieving, whilst the solids may then be even further dried to a friable material. Pig excreta contains high levels of N, P and K and this can be both a useful fertiliser (when used judiciously) and a serious pollutant (when used to excess). In the normal course of events some 30% of the N is lost to the atmosphere but only 10% of P and K.

At 10% DM pig slurry contains about 4.2 g N/kg, 1.7 g P/kg and 2.5 g K/kg. As such it is a highly valuable plant fertiliser rich in essential minerals and able to substitute directly for manufactured NPK fertilisers. One hundred growing pig places on the farm (the output from 10 sows) will produce in a year some 180 000 kg of slurry; 750 kg N, 300 kg P, and 450 kg K. On the basis of the average rates of application acceptable to a mixture of arable and grassland, without causing run-off or excessive losses through the soil, 1 ha of farm land can handle the waste output of 50 growing pigs per year; or 2½ sows and their progeny to slaughter weight. The amount of land required per pig does, however, depend greatly upon what is considered as an acceptable application rate. Only if 150 kg N/ha is considered acceptable can 1 ha receive annually the waste output from 2 sows and their progeny taken to slaughter. Equally evidently, the calculation is sensitive to the amount of N and P excreted by pigs which is highly dependent upon the correctness of the amino acid balance and amino acid supply (N), and the availability of the minerals (P) supplied.

In terms of volumes to be spread, the output of slurry is calculated at 6.8 t per sow place and 1.8 t (1.8 m³) per year per growing pig place, and it is estimated that arable land can accept a slurry volume dose of about 25 m³/ha, while grassland can accept repeated doses up to a maximum total delivery of 100 m³/ha. Physical limits for annual slurry spreading therefore vary between 15 pig places/ha (arable) to 60 pig places/ha (grassland). It has been suggested that in northern Europe permissible levels of P (kg/ha) might be required to be as low as: land of lower productivity, 60; grassland and productive arable, 100; rapidly growing and demanding crops such as intensive grassland or maize, 120.
Possible legislation in some countries relating to the maximum applications of nitrates and phosphates to the land could bring embarrassment to large intensive pig farms on small land holdings; their waste would require expensive treatment and/or transportation. Were this to be the case then it may bring a move towards smaller sized units, and these located on arable and grassland farms as part of a mixed farming enterprise. In the Netherlands, 60% of total manure production from pigs is surplus to the requirements of the immediate farm vicinity upon which it was produced. Of this surplus material it would appear that more than a third is nevertheless distributed within the surplus area (adding to an already known problem situation), whilst a further third requires (environmentally unhelpful) transportation upon the road network. Pollution control is organised through a quota per farm on N and P input. This has already resulted in a reduction in the diet specifications for P and N, and a trend toward increasing proportion of dietary ideal protein by supplementation with artificial amino acids (lysine, methionine, threonine, tryptophan). Using criteria of growth rate and feed efficiency (not bone strength), phosphorus requirements can be almost halved. The availability of P in wheat and barley is 30–50%, in maize 20% and in most supplementing vegetable protein sources less than 30%. When reducing the phosphate content of pig feed, with a view to environmental protection, the lower phosphate inclusion levels must be of available phosphate – that is, from inorganic sources such as mono-, di- and tri-calcium phosphate and, of course, bone meal. Use of phytase enzyme can also reduce excretion rates by increasing the digestibility of plant phytin phosphorus. Levels of digestible mineral have been suggested to be 35 g P/kg diet for growers and 25 g P/kg diet for finishing pigs. Phytase enzyme is, unfortunately, expensive.

**Tactics for reducing nitrogen production from pig units**

Farmed animals in the European Union produce annually 1.2 thousand million tonnes of excreta with 8 million tonnes of straight N. If there is an intention to limit the average annual N application rate to land to 170 kg/ha, then the following commend themselves as ways in which N excretion rates per pig may be reduced without undue loss of performance:

- Reduce N supply to achieve that which exactly meets (or just fails to meet) the requirement. Because N requirement changes as the animal grows, the more frequent the change in input, the less likely it is that there will be an excess of N supply. Ultimately this implies exact knowledge of requirement (lean tissue growth rate potential) and a different diet every week during growth (phase feeding); and certainly different diets for breeding sow lactation and gestation.
- Compound diet protein to be as close as possible to the ideal. As non-ideal dietary protein is excreted, then the closer the match achieved between the amino acid balance in the diet and the amino acid balance needed by the pig, the less will be the rate of N excretion; any given amino acid requirement can be satisfied at a lower level of dietary N. A higher proportion of total diet protein
as ideal protein may be achieved by adding to the diet those amino acids that are in short supply. Artificial sources are particularly useful to achieve this (especially lysine, threonine, methionine and tryptophan).

- Faecal excretion of N is directly related to the indigestibility of the diet protein. Using more digestible feedstuffs in compounded diets will reduce the rate of N excretion.
- Pig lifetime N excretion rates will be reduced if the ratio of N retained to the N expended on maintenance is improved. Faster growing animals reach slaughter weight in fewer days and are therefore more efficient, excreting less maintenance N per unit mass of lean meat produced.

**Feed delivery systems**

**Sucking pigs**

Feed freshness and ingredient palatability are paramount to encourage intake, while the utilisation of investigative behaviour demands that the feed be placed where the piglets would normally expect to find it – on the floor. A clean dry area is required in the creep upon which feed can be scattered frequently throughout the day. Meal, pellets or crumbs may be used. Various shallow dishes might help to avoid excessive wastage, but troughs can be counter-productive if they encourage feed to be held for – at most – 9 hours, during which time it will become stale and unpalatable. Equally important is to disallow the possibility of feed to be contaminated with excreta. Sucking piglets usually eat supplementary creep feed immediately after they have been suckled; access is therefore required for all the pigs in the litter to eat simultaneously. *Ad libitum* self-feed hoppers, even of reduced size, are not appropriate for offering creep feed to sucking pigs as they fail on most, or all, of the above criteria. Best are shallow troughs, mats or simply a clean area of floor from which uneaten food can readily be brushed away. Water is prerequisite to the consumption of dry feed and may be provided by nipple drinkers or in special water troughs.

**Weaned pigs**

The weaner is delivered its feed invariably from a self-feed hopper in the form of a dry pellet or a crumb, or sometimes a ‘high fat’ meal. Because of the need to encourage intake to the maximum possible extent, the early feeds after the moment of weaning should be delivered by hand into the bottom of the trough, and preferably also onto a solid base-plate covering the floor to the fore of the hopper trough itself. Three or four times a day meal feeding in this manner may continue for 1, 2 or 3 days until the piglets are all eating enthusiastically. Even then the hopper should not be filled with more than a 24-hour supply of feed. Any contamination by excreta must be completely removed. The need for constant attention tempts the placement
of the bulk feed receptacle (trolley or bag) into the weaner room itself ready for immediate use. This will, however, be self-defeating as the food – being in the pig’s environment – will become stale. Creep and weaner diets in particular should be stored cool and dry, and away from pig odours.

After 10 kg live weight weaners will likely change on to a less expensive diet, and this can be provided in the hopper in a more conventional way. Automatic delivery to hoppers by auger and down-pipe is helpful in ensuring feed freshness as delivery can be twice daily and the pipe placed low into the trough to avoid excess supply.

The self-feed hopper principle assumes feed to be available *ad libitum*, that is 24 hours daily. In the early stages this is to be avoided, and the trough should be cleaned and empty for at least 1 hour every day. Neither must it be assumed that because feed is available it is always accessible to the pigs. Young pigs would prefer to eat and lie together; there is a tendency therefore for the more timid pigs in the group to not get their fair share. At a provision 75 mm of trough length per piglet and a shoulder width for an 8 kg piglet of 120 mm, it is evident that at best only half of the pigs could access the trough at any one time.

Water is usually provided through nipple drinkers provided at the rate of one every 8 piglets, or if a bowl is used, one for every 16 piglets. The flow rates should be in the region of 1 litre/minute.

Weaners will happily eat their food wet, and intake may even be encouraged in this way. The problem, however, is one of feed freshness and contamination. It is unavoidable that wet feed supply will exceed that which the piglets can eat up immediately. Between meals wet feed tends to become unpalatable. If, however, very frequent feeding is possible, and the piglets are eating vigorously (normally when they are 10 kg or more in live weight), then a wet feeding system might be usefully employed.

**Growers and finishers**

Dry pellet or meal feeding through *ad libitum* self-feed hoppers is the most widespread feed delivery system for growing pigs. It is usual to provide a trough length allowance of 60 mm for younger pigs and 70 mm for those that are heavier. The system lends itself to automation with auger and down-pipe delivery from a bulk feed hopper situated outside of the house. Some degree of feed intake restraint can be achieved by allowing only a small gap at the base of the hopper through which the feed can flow only at a limited rate. Feed intake can also be limited by increasing the number of pigs per hopper and raising the level of between-pig competition. *Ad libitum* self-feed hoppers have their trough length divided into individual pig feeder places by bars or solid divisions. These help the pigs to stand close together, but feed individually. Usually, one place is allowed for every three pigs in the pen (or more for larger pens). Feed intake encouragement is more problematic and predisposes to loss of feed from the trough at the base of the hopper and consequent
wastage. The trough may also be readily contaminated with excreta if not regularly inspected and cleaned.

Floor feeding systems dispense with any trough and deliver dry feed (pellets or meal) directly onto the floor of the pen. This can be done either by hand or by an over-head auger and hopper system. In both cases the amount delivered can be controlled, and the pig's daily feed allowance allocated as required. The floor must be clean and dry, and the feed presented frequently (4–8 times) throughout the day to ensure its rapid clearance. The advantages of floor feeding systems are their cheapness and the saving of both equipment (trough expenses) and pen space (allowing another pig or two per pen). The disadvantages are that the wastage is high, the house atmosphere tends to become dusty and it is difficult to arrange for all pigs to eat their fair share, so that between-pig variability in growth rate tends to be increased.

Feed given damp will be more readily eaten than that given dry, and wastage will also be reduced. *Ad libitum* feeders (both single space – one space for every 8–12 pigs – and multi-space – one space for every 3 pigs) can be provided with nipple drinkers over the trough. This mechanism will allow pigs to drink and eat at the same time, and to mix their feed with water.

Full-blown wet feeding systems deliver the feed into the trough at dry matter contents ranging from 15–25%. It is self-evident that for meal feeding all the pigs in the pen must eat simultaneously. This is usually arranged by providing for each pig in the pen a trough length of 150 mm (young growers) to 300 mm (pigs up to 100 kg). Feed may be placed into the trough in dry form, to have water added on top, or it may be mixed at some more central point and then pumped. Central wet mixing and pumping is a highly flexible system which lends itself to the utilisation of wet feed sources such as milk products, brewery waste, vegetables and by-products from the human food industry. Feed ingredients are compounded according to required nutrient specification, and a pumpable wet mix is created. Here the mix may be held until pumped out to the chosen pig house site.

The feed allowance to each pen within the house can be controlled manually or automatically. For manual systems there may be a tap controlling the flow of wet feed from the main pipe into the trough. This tap may be turned open for a given time consistent with the delivery of a known quantity of dry feed, or consistent with what the pigs are known to be able to eat up within 30 minutes or so of having been fed. Feeding is usually twice daily. Computer-controlled delivery allows each tap to be set at the central control point and to deliver a given amount of feed to any particular trough (pig pen). Scale feeding by weekly increment is thus simple and automatic, and adjustable down to the level of an individual pen of pigs. Automatic systems can of course deliver the feed as frequently as is wished. Pipeline wet feeding systems have many advantages in addition to those of freedom of ingredient choice and infinite diet formulation alternatives. The system can be used either to restrict feed intake (where this is deemed necessary to avoid over-fatness) or to encourage feed intake (where growth rate is to be maximised). Given full access to the trough, a palatable feed, a dry matter above 18% and at least twice daily feeding,
delivery of wet feed up to the level of appetite (that which the pigs will clear up) will achieve daily nutrient intakes considerably in excess (up to 10–20%) of dry *ad libitum* self-feed hopper systems.

**Lactating sows**

Individual feeding is essential to maximise the intake of lactating sows and prevent extremes of fatness and emaciation which rapidly occur when lactating sows are housed and fed as a group. Dry feeding, twice daily, of meal, pellets or nuts is common; delivered by hand or auger and pipe to a trough situated at the front of the individual feeder or sow farrowing crate. Feed allowance control is an essential part of encouraging intake without over-supply of feed and creating – by provision of excess – inappetence. Because the voluntary feed intake of lactating sows is highly variable it is difficult to achieve automatic control, and manual delivery remains the optimum system. Wet feeding will increase feed intake (as will three times daily feeding) and this may be achieved by delivery from a pipeline or by the simple expedient of adding water onto the top of the dry feed once placed in the trough. Sow feed troughs need to be capacious to hold 3–4 kg of feed plus water added at a ratio of about 2:1.

**Pregnant sows**

Stalled sows may be provided with an individual allowance in a trough about 500 mm wide placed to the fore of the pen. As there is no impulsion to maximise intake, dry feeding systems are common. Feed may be delivered by hand or automatically by auger into temporary containers above each sow trough. These may be adjusted to allow delivery of variable quantities and the provision of a different allowance to each sow – which facilitates allocation of individual feed supply. As pregnant sows are often fed only once daily, and they may be especially hungry before the daily feed becomes due, noise can be reduced if all the pigs are fed instantaneously and simultaneously. Accumulation of the feed allowance in a small (1.5–3.5 kg) container above the trough allows the activation of a release mechanism to feed at the same time all the sows in any given row of stalls. Alternatively, all the sows can be given a single flat rate level of feeding; those needing extra being given it by a manual top-up. Stall-housed pregnant sows can also be fed through wet feeding systems; but where the trough is not divided between each stall, care must be taken to ensure equality of supply.

Alternatives to tethers and stalls for pregnant sow housing have led to a variety of novel feed delivery alternatives. However, it was at least in part because previous feeding systems were found not to satisfactorily supply the individual nutrient needs of pregnant sows that first the individual feeder and next the sow stall came into being.

Pregnant sows can be fed by provision of cobs or nuts directly onto the ground or into the straw bedding. Groups of sows fed in this way tend to become variable
in body condition due to between-sow aggression. It is difficult to make individual adjustment to feeding level other than through the creation of smaller groups of sows drawn out for special treatment. The same aggression in loose-housed sow groups may also bring about a further reduction in reproduction efficiency due to physical damage.

Groups of sows in yards may be provided each with an individual feeder. Sows entering these may be fastened in, and there can receive (and consume) their due feed provision. This system remains the most effective way of ensuring the individual feeding of sows kept in groups. Automation may be achieved with an auger and a holding container above each feeder. However, as the occupant of each stall is not known before entry, a flat rate must be allowed, and individual rationing achieved by a subsequent manual top-up. Volunteer feeding stalls in which the sows are not fastened suffer from problems of fast eaters exiting and attacking the rear of the slower eaters. This problem may be alleviated by ‘trickle feed’ delivery. In this latter case all the sows are fed at once when feed is trickled via an auger and down-pipe system to a trough at the front of each voluntary stall. Pellets are delivered at the rate of 100g/minute over a period of 10–15 minutes, twice daily. The slowness of the delivery ensures that all the pigs remain at a single feeding place for the period of the feeding session – thus ensuring equality of provision and prevention of between-sow aggression. All sows receive the same flat rate ration. Some individual feeding stalls into which sows needing special provision can be fastened may be a useful adjunct to a trickle feeding system.

Individual identification of sows by means of an electronic tag and the provision of a central electronically controlled sow feeder appear to offer the best of all worlds. Sows may be kept in groups of 20–40 in yards (preferably strawed). The sows can be allocated, through the computer control system, any individual level of daily feed allowance as may be required. Thin sows can therefore be readily given a more generous allowance and fatter sows restricted. The level of daily allowance can be adjusted according to the stage of pregnancy. Changes in diet nutrient density (and thereby the required level of feed provision for all of the sows) can be automatically accommodated through the computer control panel. The computer printout will give information on how much feed each sow has eaten in the course of every day. Upon visiting the feeding station the sow is identified and the allocation, specific to herself, is dropped into the trough for her to eat. The drop may be only one each day, or it may be divided over a number of possible visits to the feeding station. Appropriate entry and exit mechanisms to the station can prevent other pigs attacking whilst one is feeding.

Electronic sow feeders (ESF), although an excellent feed delivery system, are unlikely to be the universal method of feeding pregnant sows, for they are not without disadvantages. However, in the absence of sow stalls, ESF stations are likely to play a major role in pregnant sow housing systems. Training is needed before a sow can join a group. A constantly altering group composition predisposes to agonistic behaviours, and this is particularly stressful for sows newly entering. There can be high levels of between-sow encounters. Pigs may spend a significant amount of
time queuing for access to the feeder. During this queuing time sows are hungry, impatient and aggressive – vulva biting being an outward sign. Sows may queue and visit the feeder having already eaten their full allocation for the day. Sows may wait for long periods in the feeder, preventing access by others. Dominant sows may occlude the entrance to the feeder and discourage sows lower in the social order from visiting. The feeder station and associated equipment can be expensive to buy and requires sophisticated mechanical and computer maintenance. The system benefits greatly if group size is relatively low, ample space is provided per sow and there is a copious allowance of forage (or straw) in addition to the concentrate feed, so that hunger can be alleviated and excessively aggressive encounters avoided.

**Summary of housing requirements**

A summary of temperature, ventilation and space requirements is to be found in Tables 17.7(a) and 17.7(b).

**Table 17.7(a).** Summary of housing requirements (quantitative).

| Space | Total area for pigs in groups, about 0.8–1.6 m²/100 kg of pig
| | Fully slatted or mesh floors, 0.5–1.0 m²/100 kg of pig
| | Adult pigs loose-housed, 1.0–3.0 m²/100 kg of pig
| | Young weaned pigs loose-housed, 1.0–2.0 m²/100 kg of pig
| | Suckling adult with piglets, 4–7 m²
| | Breeding males 9–12 m²
| | Crates for adult females, 2200 × 600 mm (approx)

| Air speed | About 0.1 m/s at pig height; 0.5 m/s constitutes a draught

| Ventilation | A minimum of around 0.2 m³/hour/kg of pig weight. Maximum about 2.0 m³/hour/kg of pig

| Humidity | 60–80% relative humidity

| Temperature | In the region of:
| 30–34°C for pigs of <5 kg
| 26–30°C for pigs of <10 kg
| 22–26°C for pigs of 10–15 kg
| 18–22°C for pigs of 15–30 kg
| 16–20°C for pigs of 30–60 kg
| 14–20°C for finishing pigs and adult females

| Air quality | Desirable | Acceptable
| Ammonia (ppm) | 10 | 20
| Carbon dioxide (ppm) | 3000 | 5000
| Hydrogen sulphide (ppm) | 0.1 | 5
| Dust (mg/m³) | 5 | 10

| Feeder space | 0.15 m/pig when <25 kg
| 0.25 m/pig when 25–75 kg
| 0.30 m/pig when >75 kg

| Excreta | Average of about 5 litres/pig/day for a mixed breeding/growing unit

| Housing insulation | To prevent more than 0.5 W passing through the walls or ceiling per m² per °C difference in temperature between one side and another
Pen requirements depend upon house type selected, the weight at which the pigs move from one type to the next and the performance of the pigs. Nevertheless, the various housing requirements are readily calculated for each individual set of circumstances. Example calculations are laid out in Table 17.8 which deals with a unit of 100 sows. Allowing 115 days for pregnancy, 12 days for weaning to conception, 28 days for lactation, 10 pigs of 8 kg weaned per litter and 9.6 pigs per litter surviving through to the point of slaughter, some 2200 pigs will be sold per year, or something over 40 per week. The sows would produce 2.3 litters per year \(\frac{365}{(115 + 12 + 28)} = 2.3\), and from these will come the 2200 grown pigs \((2.3 \times 9.6 \times 100)\). Where the pregnant sows are housed in cubicles then 75 of these should be provided \(\frac{(115 + 560)}{118}\).
2.3)/365 = 0.72], together with another four for replacement gilts. Mating pens may be either in the form of loose housing or cubicles. Some 15 sows will need to be accommodated in the mating pens for about 22 days (12 + 10).

If the replacement rate for the herd is 40%, then some 40 gilts will come in annually. They will probably arrive in batches of 8 every 2 months (to allow a safety margin). These will need quarantine quarters and then additional loose housing pens or stalls whilst they are awaiting mating. Boars are best used around three times weekly. On the basis of 5 sows being weaned per week, and each sow perhaps needing to be mated as much as three times, one may calculate a minimum requirement of 5 boars per 100 sows. However, the farrowing rate will not be 100% (more likely 80%), and 20% of sows will return and need to be remated. The minimum requirement is therefore for 6 boars for every 100 sows.

There are a plethora of mix and match systems to take growers on from weaning through to slaughter. In the example shown in Table 17.8 the flat-deck weaner pens are followed by a short stay grower pen (20–40 kg). Often this is omitted.

Table 17.8. Example calculations for housing requirements (per 100 breeding females); allowing 115 days for pregnancy, 12 days for weaning to conception (5–20 days, as appropriate to circumstance), 28 days for lactation (21–56 days, as appropriate to circumstance) and 10 pigs of 8 kg weaned per litter, with a further loss of 0.4 pigs/litter during growth. Some 2200 pigs will be sold per year, or just over 40 per week.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Calculation</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of litters/year/sow</td>
<td>365/(115 + 12 + 28) = 2.3</td>
<td></td>
</tr>
<tr>
<td>Number of pigs/year</td>
<td>2.3 × 9.6 = 22 × 100 = 2200</td>
<td></td>
</tr>
<tr>
<td>Stalls for pregnant females</td>
<td>(115 × 2.3)/365 = 0.72 = 72 (allow 75)</td>
<td></td>
</tr>
<tr>
<td>Farrowing pens (4.5 farrowings/week)</td>
<td>28 + 10 (safety margin) = (38 × 2.3)/365 = 0.24 = 24 (allow 25)</td>
<td></td>
</tr>
<tr>
<td>Mating pens</td>
<td>12 + 10 (safety margin) = (22 × 2.3)/365 = 0.14 = 14 (allow 15)</td>
<td></td>
</tr>
<tr>
<td>Boar pens and hospital pens</td>
<td>6 boar pens and 4 hospital pens = 10</td>
<td></td>
</tr>
<tr>
<td>Replacement females</td>
<td>10 pig places or 3 group pens and 4 sow stalls</td>
<td></td>
</tr>
<tr>
<td>Quarantine quarters</td>
<td>3 group pens</td>
<td></td>
</tr>
<tr>
<td>Weaning to 20 kg: 0.4 kg gain/day</td>
<td>20 – 8 = 12/0.4 = 30 days</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30 days for 2200 pigs = 66,000/365 = 180 pig places at 10 pigs/pen = 18 pens (allow 20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Or 30 days = 365/30 = 12.1 batches per year at 10 pigs/batch, 2200/(12.1 × 10) = 18 pens</td>
<td></td>
</tr>
<tr>
<td>20–40 kg: 0.6 kg gain/day</td>
<td>40 – 20 = 20/0.6 = 33 days</td>
<td></td>
</tr>
<tr>
<td></td>
<td>33 days for 2200 pigs = 72,600/365 = 200 pig places at 16 pigs/pen = 13 pens (allow 15)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Or 33 days = 365/33 = 12.2 batches per year at 16 pigs/batch, 2200/(12 × 16) = 13 pens</td>
<td></td>
</tr>
<tr>
<td>40–100 kg: 0.8 kg gain/day</td>
<td>100 – 40 = 60/0.8 = 75 days</td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 days for 2200 pigs = 165,000/365 = 452 pig places at 16 pigs/pen = 28 pens (allow 30)</td>
<td></td>
</tr>
</tbody>
</table>
Pigs may be kept from weaning through to 30kg in weaner pens, and then moved straight into finishing accommodation. In either case the method of calculation is the same, and the number of pens required is dependent upon the daily weight gain that is assumed for the pigs and the number of pigs to be placed into each pen.

The major confusion factors in allocating housing are:

- bunching;
- variation in growth rates and reproductive performance between batches;
- variation in growth rates and reproductive performance within batches.

Bunches of breeding females reaching the end of pregnancy simultaneously cause accommodation shortages in the maternity ward. Avoidance of peaks and troughs in pen usages is an essential part of the efficient utilisation of expensive capital buildings. Serious problems can result when, for one reason or another – usually disease – young growers which have been allowed a 30-day stay in a rearing house take 50 days before they are ready to move on. This will mean that pigs ready to be weaned will have nowhere to go, while places in the finishing house remain unfilled. Pen planning must allow for some peaks and troughs in production.

Because of individual differences in performance, pigs in a batch will reach slaughter weight at different times. The manager must choose between emptying the pen all at once (accepting that the biggest pig might be much heavier than the smallest) or waiting for each pig to come up to correct weight (which might take a spread of some time). Sale contracts that allow pens to be emptied all at once and accept variable pig weight have much to commend them.

It is self-evident that pigs grow but their pens do not. This incompatibility means that pens are normally either too empty or too full. In order to reduce this problem to a minimum pigs are either moved from one pen size to another or the number of pigs in the pen is adjusted. In most systems all three of these things happen (the pens are not optimally filled, the pigs are moved, the number of pigs in the pen are adjusted). Pens that are insufficiently densely stocked predispose to the pigs being cold, whilst pens that are stocked too densely will bring about reductions in growth rate and efficiency. Each time a pig is moved, however, there is a growth check consequent upon that move. The greater the change in circumstances the greater the check. Thus the solution to one inefficiency can readily lead to the creation of another. Growth checks upon moving and remixing pigs will usually be equivalent to losses of 1–5 days in time through to slaughter; but sometimes lost days can add up to weeks. Pig mixing is encouraged by the need for matched batches of growing pigs and efforts made to try to reduce pen emptying spread. In many systems it is particularly during early growth that pigs tend to be mixed with strangers. This causes an especially high level of tension, confusion and quarrelling; with consequent reduction in performance.

Mixing and moving pigs is a managerial convenience, but one that reduces efficiency and is best kept to a minimum.
Housing lay-outs

Accommodation for pigs must be laid out in such a way as to facilitate control of temperature and ventilation, to control disease, to allow adequate space, to deal with waste and to deliver feed. Means toward these ends are legion. It is remarkable, given the few definitive requirements of pig accommodation, how often the building actually constructed fails to meet one or other of the basic tenets (although perhaps meeting less important – if fashionable – criteria).

Effective pig housing is most likely to result from local experience and expertise, together with rigorous application of basic principles and knowledge of successful designs operating in other regions and countries. Examples of some house lay-outs that have been found to operate effectively are shown in Figures 17.6 to 17.45. (All measurements are in metres.)

Fig. 17.6 Pregnant sow stalls: (a) metal framework to confine newly weaned and pregnant sows [access to water is usually through a nipple (b) located over the feed trough – if there is spillage the pipeline may be opened for limited periods only]; (c) feed trough; (d) gate to rear of stall to confine the animal, or a tether may be attached to the neck or girth of the sow and fastened to the floor or the metalwork; (e) slats through which excreta falls into a slurry chamber. Boar pens are also located in the house (g), to which sows may be walked to be mated, or from which boars may be walked to the sows. Straw is not provided for bedding but may be given as a forage into the feed trough. Pregnant sow stalls and tethers were made illegal in the UK in 1999, and sow tethers will be illegal in the EC from 2006.
Fig. 17.7 Loose housing for pregnant sows: (a) covered kennels providing both individual lying and feeding places for pregnant sows held in batches of four (access to feeders is through a hinged lid in the kennel roof – the kennel may or may not be strawed); (b) yard from which excreta may be scraped automatically into a slurry tank (c). Sections may be arranged in every third position (d) for the boar or for sows in need of special care. Water is best provided by nipple drinkers in the yard to avoid spillage over the lying area.

Fig. 17.8 Loose housing for pregnant sows: (a) deep straw bed with covered kennel over; (b) yard, which may be strawed and the excreta removed as a solid, or left unbedded and scraped off; (c) individual feeding stalls. Each section is designed to hold four animals. Water bowls or nipple drinkers may be placed in the yard. If sows are moved here immediately after weaning, an adjacent pen may be given over to house the boar. The same design may be used for a multi-suckling system where sows are moved at 7–10 days post-farrowing to suckle their litter in communal groups of four sows through to weaning at 28 or 35 days.
Fig. 17.9 Strawed yards with electronic sow feeding station, suitable for 40 sows: (a) covered kennel area; (b) strawed lying area; (c) electronic transponder sow feeder with rear entry and forward exit; (d) dunging and loafing area.

Fig. 17.10 Housing for pregnant sows: (a) with voluntary stalls and a trickle-feed system; (b) with individual feeders. System (a) is shown with slats, system (b) with a solid strawed floor. The space allocation in system (b), excluding the individual feeders, is limited to 1.8 m² per sow, which implies that the rear doors of the individual feeders should be left open between feeds to allow sows access to lie in them. Because system (a) cannot provide different levels of feed to individual sows, systems using trickle-feeding should also have individual feeder facilities (b) to deal with problem animals needing special attention.
Fig. 17.11  Solid floor arrangement for mating house allowing easy access of boars to sows, adequate mating areas and the possibility of stalled or group penning: (a) stalls; (b) boar working area or group pen; (c) boar/mating pen; (d) group pen for sows, or boar pen.

Fig. 17.12  Facilities for washing, weighing and measuring fat depth of sows: (a) working office area; (b) crate and wash area; (c) farrowing house; (d) gestation/mating house.
Fig. 17.13  Farrowing pen: (a) creep area (with heating lamp over); (b) rails for piglet protection; (c) sow lying/suckling area; (d) sow excretion/movement area; (e) trough. In Sweden sows are allowed to be placed into crates for only 7 days in any reproductive cycle. Some producers choose to place their sows in farrowing crates for 7 peri-parturient days, whilst others place sows in stalls for the week after weaning. The Swedish experience of farrowing sows in accommodation that allows free movement and sow grouping has failed, by and large, through an unacceptable level of neonatal mortality. Low levels of piglet mortality may be obtained, however, in individual farrowing pens which protect the piglets with rails, provide adequately warmed creep areas and also allow space for the sow to turn around. Bedding is an integral part of these systems.

Fig. 17.14  Farrowing crate for lactating sows, providing a separate microclimate for sucking pigs and close confinement of the sow: (a) the crate may be bedded with straw or wood shavings, solid excreta may be removed by hand and the urine run off into a drain (b), or (c) slatted area and slurry chamber may be fitted; (d) lightweight walling to confine young piglets; (e) special covered creep nest area; (f) heat source for piglets. Water and feed would be provided in the creep area for young pigs from 14 days of age.
Fig. 17.15 Intensive housing for newly weaned pigs: (a) the floor is entirely of mesh, slotted metal or slats, with a slurry pit (b) below. No bedding can be provided. *Ad libitum* feed hoppers (c) form the front of the pen and water troughs or nipple drinkers are provided at the rear. Pigs are usually housed in batches of 8–16. Pens are 1 m wide.

Fig. 17.16 Traditional straw yards suitable for young weaned pigs or growers (particularly to 50–70 kg): (a) deep-strawed kennel which may also contain the *ad libitum* hopper, set on a small plinth (b). Alternatively, or in addition, the feed hopper could be situated in the yard (c) with access from the front (d). Water is provided next to the feed troughs. Excreta is removed from the yard with the straw. Pigs are housed in groups of 15–30.

Fig. 17.17 House for growing pigs: (a) solid floor lying area which could be bedded with straw or shavings; (b) kennel roof provided over lying area with hinged panel allowing access (c) to *ad libitum* hoppers (d). Pigs excrete onto a slatted (or mesh) floor area (e) which may be outside as shown, or covered. Watering points are usually situated over the slats.

Fig. 17.18 Pens for growing pigs: (a) with a solid floor lying area and (b) with a slatted area for excretion. Animals may be floor-fed automatically from hoppers (c) held above, or troughs (d) could be provided for pipeline feeding.
Fig. 17.19 Part-slatted grower/finisher pen with automatic *ad libitum* hopper feeding system: (a) solid floor; (b) *ad libitum* hopper; (c) automatic auger feed line; (d) passage; (e) slatted floor; (f) water line; (g) nipple drinker.

Fig. 17.20 Pens for growing pigs: (a) fully slatted floor; (b) feed trough suitable for pipeline wet feeding; (c) central feeding and access passage. Each pen may contain 8–20 pigs. Slurry is pumped out from below the slats.

Fig. 17.21 Straw-based grower/finisher house with pipeline wet feeding system: (a) straw-bedded kennel; (b) movement/excretion area (with or without straw); (c) pipeline; (d) trough.

Fig. 17.22 Pregnant sows group-housed in a deep straw-bedded yard.
Fig. 17.23  Electronic sow feeder available to group-housed sows lying in straw.

Fig. 17.24  Group housing for sows. The sows are protected from the heat within but may come out into the yard to excrete, drink and eat from individual feeders. Each pen is for six sows, and the space allowance is generous.
Fig. 17.25  Fully slatted group pens for pregnant sows.
Fig. 17.26  Farrowing crate for lactating sow.
Fig. 17.27 Metering device for measuring ration allowance for a lactating sow held in a farrowing crate. The container is replenished by an auger system twice daily.
Fig. 17.28  Fully slatted plastic-coated metal suspended flooring for lactating sow and litter. Note the solid pad for piglets to lie on (with heater over) and the flat dish for early provision of supplementary creep feed.
Fig. 17.29  Newly weaned piglets on suspended wire mesh floor demonstrating that they are cold.
Fig. 17.30  Newly weaned piglets on suspended wire mesh floor and provided with a heater over.
Fig. 17.31  Growing pigs on solid floor with slatted area for excretion to the rear. The trough is positioned down the side of the pen for automatic liquid feeding.
Fig. 17.32 Growing pigs on solid flooring provided with some straw bedding, scraped/solid floor passage to the rear for excretion and four-space self-feed *ad libitum* hopper replenished by auger and downpipe.
Fig. 17.33  Young growing pigs on fully slatted floor with self-feeder trough provided with water nipples above. The feed is delivered into the trough through the central downpipe. Water is allowed to flow onto the feed, upon activation by the pigs. There are eight spaces provided around the circular feed bowl. The pen was designed to hold 16–18 pigs.

Fig. 17.34  Growing pigs on solid floor pens with access to outside runs. Feed available to appetite in simple troughs replenished twice daily through an auger and downpipe system.
Fig. 17.35  Electronic feeder for growing pigs. This system allows the recording of individual feed intake of pigs housed in groups, and it is especially appropriate for nucleus breeding herds pursuing genetic improvement objectives where it is helpful to know individual candidate boar feed intake.

Fig. 17.36  Young gilts newly introduced to an outdoor system. The simple arcs are placed in pairs in each paddock. Note also bulk feed hoppers and office area to the rear.
Fig. 17.37  Outdoor pig production: pregnant sow paddock. Note the lack of vegetation. Picture courtesy of the Cotswold Pig Development Company Ltd.

Fig. 17.38  Outdoor pig production: hut for lactating sow and litter. Picture courtesy of the Cotswold Pig Development Company Ltd.
Fig. 17.39  Naturally ventilated house for tethered pregnant sows. Sows are fed manually from a feed trolley passing down the passage. Spain.

Fig. 17.40  Natural side ventilation for pig grower house. The flexible wall is raised half-way up; it may be wound down to ground level. Within the flexible wall there are plywood boards which may also be removed at particularly high temperatures as there is a metal bar barrier within. Japan.
Fig. 17.41  Young growing pigs on a suspended metal mesh floor with *ad libitum* self-feed hoppers. Europe.

Fig. 17.42  Conventional fully slatted floor house for growing pigs with *ad libitum* self-feed hoppers (manually filled). Southern Europe.
Fig. 17.43  High-welfare straw yard and kennel housing for finishing pigs or young gilts.

Fig. 17.44  Straw yards for pregnant sows, equipped with automatically provisioned individual feeders (centre) and covered kennels with straw over (left). Picture courtesy of Martin Looker, Trevor Cook and the Cotswold Pig Development Company Ltd.
Site lay-out

Often approval by local government will be needed when a new piggery is built or major modifications are made to an existing unit. Consent may cover environmental impact, animal welfare, vehicle traffic and provision of utilities and services. Buffer zones, particularly to avoid odour nuisance, will be required to protect all parties. Local guidelines should be followed: a minimum distance of 200 m from the boundary of the piggery to a rural residence is a common requirement in some countries.

Selection of a site for a pig farm requires consideration of its proximity to other farms and dwellings, and site topography, particularly local climate, soil type and drainage. Farms should be separated by at least 2 km and preferably 5 km to minimise the risk of disease spread by wild birds, vermin or airborne transmission.

On the site, the location and orientation of each building will be affected by the following:

- Orientation. East–west alignment is preferred, especially in hot climates, to minimise solar gain and maximise shade from overhanging eaves. However, account will need to be taken of the prevailing wind direction.
- Aspect. In temperate climates in the northern hemisphere, a south-facing slope is favoured. Valley bottoms should be avoided because of frost pockets.
• Shelter belts. Airflow over buildings is affected up to 15–30 times the shelter height, potentially interfering with ventilation. The minimum separation is at least five times shelter height.

• Building layout. Layout depends on pig traffic and feeding and manure systems, with bulk bins sited close to the boundary fence for remote filling. The separation distance between buildings is governed by ventilation requirements rather than disease transmission and five times building height is the minimum.

Extensive pig production

Outdoor systems for breeding sows

Outdoor pig production is almost wholly confined to breeding sows; weaners moving to conventional intensive growing units at 21- or 28-day weaning. It is largely a characteristic of UK pig keeping within a modern context of pig production. Although traditional unimproved breeds (as, for example, the Spanish and Portuguese black pigs) may remain in outdoor systems to produce traditional dry-cured ham, modern outdoor pig production systems elsewhere than in the UK are limited to about 5% of total production. Some 20–25% of UK sow herds are presently ‘out-of-doors’. This proportion will tend to fluctuate between 5 and 25%, and the meaning of ‘outdoor’ can vary. Pregnancy housing and feeding provision may become rather sophisticated as higher standards of management are applied, and rather high specification farrowing houses may come also to be used. It appears to be an inherent characteristic of outdoor pig keeping systems that they progressively move indoors over time, with housing, management and feeding arrangements inexorably developing toward those used on intensive units as management becomes more focused. Many outdoor units are established initially on the basis of minimum capital requirement for buildings; as money becomes available from profits it is often returned to the outdoor unit in the form of progressive buildings capitalisation; such as improved farrowing accommodation, specialised mating and early pregnancy housing arrangements, individual feeding facilities and sophisticated heavily insulated kennelling arrangements for growing pigs.

Pigs kept in outdoor systems do not range freely. They are batched into groups, given shelters for minimal protection from the elements and confined to fenced paddocks. The system depends upon:

• low capital costs (about 0.3 of the equivalent of an intensive breeder herd);
• the relatively low environmental temperature requirements of the lactating sow;
• the ability of piglets (and pregnant sows) to keep warm by huddling together in groups in deep straw bedding.

The paddocks may not be assumed to yield any significant nutrient supply. Quite the reverse; feed usage by sows will be significantly greater (usually 1.4–
1.5 t/sow/year, in contrast to 1.2–1.3 t/sow/year for conventional protected environments), and this is on account of:

- feed wastage;
- use of feed for cold thermogenesis.

Lactating sows may readily eat 8–12 kg per day and pregnant sows may need 3 kg daily – especially in winter.

The pigs will root and tread the ground area, destroying all vegetation in a relatively short period of time. The paddocks will therefore tend toward becoming either dry earth (in hot dry weather) or mud (in wet weather).

Whilst there is unquestionably more freedom of movement for sows kept outdoors as compared to those kept in farrowing crates and pregnant sow stalls, it would be wrong to assume that there is always an elevation in sow welfare. Outdoor pigs require the highest levels of management and avoidance of:

- poorly draining and heavy soil types;
- sloping ground;
- cold and wet;
- heat stress and sunburn;
- bullying;
- unequal food provision;
- variability in sow condition;
- physical injury;
- excessive piglet mortality;
- loss of fertility;
- excessive food usage;
- inadequate nutrient supply;
- inadequate water supply.

Outdoor systems, in addition to using around 16% more food (an extra 0.5 kg per day), tend to need more expensive feed compounded into large (16–24 mm) cobs or rolls which are required to reduce wastage when scattered on the ground or in heaps. Sow productivity will, on average, be around 1.5–2 piglets less weaned per sow per year, and sow replacements will be about 10% higher than in a conventional system. Mortality between birth and weaning can range from 10–25%, and numbers weaned per sow per year from 16–24. Overall feed conversion efficiency for the breeding herd can be 15–20% worse for outdoor as compared to indoor production systems. This, however, need not necessarily always be the case. The sows chosen for outdoor pig breeding require to exhibit special characteristics relating to their need to rebreed readily and to withstand the rigours of outdoor life. Robust pig strains, often containing Duroc or Saddleback genes, tend to be rather slower growing and more predisposed to be fat than other strains suitable for more highly protected environments. This can result in less efficient performance in the grow-out unit and fatter carcasses.
Independent (EASICARE) statistics indicate the following comparative performance figures for indoor and outdoor pig breeding units respectively: farrowing percentage, 81.2 and 75.3; number of litters per sow per year, 2.27 and 2.14; number of pigs reared per sow per year, 21.3 and 18.8; number of lost days, 45 and 64; quantity of sow feed used per sow per year, 1.21 and 1.43; number of pigs reared per litter, 9.39 and 8.78; feed used per pig reared, 61 and 84 kg; overall feed conversion efficiency for the herd, 3.1 and 3.8–4.5. Even given a substantial saving in overhead cost, the statistics suggest that the average performance in outdoor herds needs to be improved if outdoor production is to be sustainable in the longer term. A study in Denmark compared an intensive housed system with a semi-intensive (straw-based) housed system and an outdoor system of production. Capital costs for the semi-intensive and the outdoor system were, respectively, some 85% and 50% of the intensive system. Productivity on the intensive and semi-intensive systems was similar, but there was a 10% reduction in productivity on the outdoor system. Feed costs were similar for the two housed systems, but some 10% higher on the outdoor system. Energy expenditures for the semi-intensive and the outdoor system were 70% and 20% respectively of the intensive housed system, but in the latter two cases there were expenditures on straw bedding which did not, of course, exist in the fully intensive system. Overall the profitability was highest for the semi-intensive housed system and that for the intensive and outdoor systems was similar.

Fifteen to 20 sows rearing their young to 30 kg on an outdoor system will require 1 ha of dry free-draining ground (for example, sand and gravel or chalk), in a temperate climate not prone to high rainfall, snow, severe frost, high humidity, high temperature, high radiation levels or high winds. The near presence of trees acting as shelter belts is advantageous. In some countries legislation relating to land requirements per sow may demand a lower density of stocking. In Denmark a population of 15 sows/ha is regarded as acceptable for environmental purposes when piglets are weaned at 4 weeks of age (8 kg). In the Netherlands the recommendation is for 16 sows/ha.

The whole set-up requires to be moved annually to new ground and the same ground should not be used for pigs more than once every 4 years. The system is therefore ideal as part of a 5 year arable rotation, moving on to grass established the year previously and followed by a cereal crop. The presence of arable crops will also facilitate the ample amounts of straw that will be used (around 60 tons per 100 sows).

For every 100 sows, an outdoor system may be expected to comprise the following:

- One hectare of service area with 6 boars working around 4 paddocks. Each hut (6–6.5 m²) will hold 5 sows (4–5 sows will be weaned weekly); making total provision to allow for 20 sows in the mating area. There may also be a separate 5th paddock (and huts) to receive (and mate) replacement gilts. Major problems in relation to successful mating with outdoor systems have resulted in some cases in the construction of large sheds in which the boars are kept, and to which newly
weaned sows go to be mated. Problems in early pregnancy, failure to hold service and even abortions have resulted in sows being kept in such sheds for at least 5 weeks after they conceive. Thus the weaning to conception interval and the early part of pregnancy are spent indoors in straw yards rather than ‘outdoors’. Such sophistications of the system may increase productivity by up to 2 pigs per sow per year.

- Pregnant sows will occupy an area of 4ha with 15 huts (1–1.25 m² floor space/sow) found in 3–5 paddocks; making a total provision which will allow for 75 sows.
- Farrowing and suckling sows will be accommodated in 24 farrowing huts (1 sow per hut of 3–4 m²) found in 4–6 paddocks in a total area of 1ha. As outdoor systems develop, farrowing huts are becoming of increasingly high specification (and cost) with substantive rails for the protection of the piglets, creep feeding facilities and high-tech insulation provision.
- Out of the total 6ha, the required space for equipment, services, feed hoppers, paths and so on will have to be found; these may add up to as much as 1ha in themselves, the pigs occupying 5ha. Some protagonists would consider this a minimum area requirement, and larger hectarages may be beneficial.

Young pigs are weaned at 21–28 days from the outdoor system, usually into weaner huts. As pigs are often retained within the environs of the farrowing hut by a fender until 21 days of age, the amount of actual ‘outdoor freedom’ afforded to piglets may be limited. The weaners may have well protected and highly densely stocked indoor kennel areas allowing 0.2 m² of space or less per pig. There may be an outdoor yard allowing 0.4 m² per pig, which may or may not be strawed. With an 8 week stay to grow to 30kg at 12 weeks of age, weaning 50 piglets (5 litters per week) would require eight 50-pig huts; or more realistically twenty 20-pig huts.

The principal redeeming features of outdoor pigs systems are their low capital setting-up costs and a public perception of greater sow freedom. The latter is likely to be rivalled by improved pregnant sow housing now available to replace stalls and tethers. However, by definition, the building costs of the highly protected environment of the intensive unit will always greatly exceed those of simple sheet-metal and wood huts placed upon the bare ground. The outdoor system also has the advantage of being free of all the waste management costs and problems associated with intensive production units. When properly looked after, small items of equipment will last 4–8 years, pregnant sow arcs 4–8 years and farrowing arcs 8–12 years. In general, however, unless some premium for outdoor production is available, only when the cost of borrowing money is high will outdoor production be financially superior to indoor production. Furthermore, although outdoor systems are often perceived by the general public to be of higher welfare, such a conclusion would be unsafe.

Semi-extensive loose housing systems for pregnant sows

Yards and kennels (preferably strawed) for groups of 6–12 sows, with individual feeding facilities allowing separate rationing of each sow, remain the longest-tested
effective means of looking after pregnant sows within the context of welfare regulations which disallow sow stalls. Straw yards for dry sows can be constructed to include insulated areas for lying in deep straw, dunging areas that can be cleaned with a tractor and scraper, and individual feeders filled automatically. Layouts may accommodate a number of groups of sows (with up to 30 sows per group) held within artificially or naturally ventilated wide span buildings. Each group pen requires the same number of free or restricted access stalls as there are sows in the group; thereby allowing individual feeding and a means of escape and quiet lying for individual sows between feeds. In some designs the store of straw bedding can usefully provide the roof over the kennel lying accommodation. Normally, such loose housed systems for pregnant sows should allow some 3.5 m² (or more) of total floor space for each sow. Sows can be shut in to their individual feeding stalls, both for treatment and whilst the dunging area is scraped. Free access stall systems should allow 1.6 m² per sow for lying and 1.9 m² per sow for loafing and dunging (3.5 m² overall). Recently mated sows can be checked for return to oestrus by use of a boar held in the same accommodation. If the individual feeder and the kennel areas are combined, then space can be saved with a cubicle system – where the sows effectively lie back in their individual feeders when not active in the yards.

When sows occupy common living space they compete for lying and exercise areas, for feed if offered communally and for position in the dominant hierarchy. Competition can damage the productivity of those in the bottom third of the hierarchy, and also of those fighting to improve (or maintain) their positions. Sows loose-housed in groups require:

- to move freely about (2.5–3.5 m² total area per sow);
- distance to remove themselves from aggressors (>10 m);
- barriers/partitions for protection, or free access stalls into which to retire;
- individual feeding facilities (usually 2.2–2.4 × 0.5–0.7 m);
- diversionary substrate (such as straw) to occupy time and foraging needs;
- an ample level of feeding;
- warm and sheltered lying areas of 1.3–2.0 m²/sow to encourage resting;
- dry straw bedding (usually 0.75 t but up to 1.5 t/sow/year), or equivalent;
- freedom from excreta through the provision of separate (often scraped or slatted) dunging areas (often of around 1–2 m²/sow).

**Extensive growing/finishing systems**

Extensive outdoor systems are not usually considered as suitable for weaned piglets which are taken into relatively conventional housing for rearing from 8 kg at weaning to point of sale at 30 kg. However, pigs can be fattened ‘outdoors’ through the provision of a generous paddock area (5 m² per pig) outside of a grower house. Even with a relatively high specification for this (necessarily portable) building, and ample straw, the efficiency of feed usage can be reduced for pigs grown to slaughter in outdoor systems. Growing pigs kept outdoors had, as recorded by
EASICARE, almost 25% greater costs per kilogram of live weight gain than pigs grown indoors.

The Danish study compared intensive (slatted floor), semi-intensive (increased space allowance and fully bedded pens) and outdoor huts for growing and fattening slaughter pigs. Daily gain and feed conversion efficiency were best for the fully intensive system, but the capital costs for the three systems were in the order of 100, 70 and 60%. Profitability of the semi-intensive and the outdoor finishing systems was only 70 and 80% respectively of that of the intensive finishing system. Overall it was concluded that the outdoor system was particularly susceptible to fluctuations in performance, while the housed systems were particularly sensitive to the cost of borrowing money for initial capitalisation.

Nevertheless, there is a limited ‘niche’ market for meat from pigs kept wholly outdoors for all of their life (including the growing/finishing stages), and the extra premiums paid for such extensively produced meat may cover the extra expenditures incurred through the inherent inefficiencies of the system. Genuine free-range facilities for growing pigs should ensure availability of ample natural herbage, and at least 80 m² per pig.

Where bedding materials, such as cereal straws, are available, growing pigs can be housed in deep straw yards from weaning through to slaughter. General purpose semi-intensive housing tends to be rather less expensive than intensive constructions; but with greater area and air space, environmental control is more difficult. Pens are simple, deep-bedded areas within which the pigs identify for themselves areas for lying, exercise and excretion. Pigs will use straw to investigate and play with, to forage in, to manipulate and masticate, and to build with. Kennels may be provided, while the feeding system may be rough and ready ad libitum or a more controlled wet feeding or trickle systems. Pigs are, however, usually fed to appetite, which can lead to a greater level of feed use (and wastage) and fatter pigs at the point of finishing. Two nipple drinkers or one bowl drinker is required per 20 pigs. Water should flow at the rate of approximately 1 litre/minute. Group sizes may vary from 20–200, and whilst generous space allowances of 2.0 m²/100 kg of pig live weight at 20 kg and 1.25 m²/100 kg of pig live weight at 100 kg may give welfare benefits of freedom of movement and a greater possibility of exercise, with over-large groups there can be welfare disbenefits of competition for feed, water and quality space. The provision of adequate husbandry is more difficult in these circumstances, and individual pigs who may be failing to handle life in a large competitive group may find themselves substantially disadvantaged.

Variation in pig performance in semi-intensive large-group systems is invariably higher than when the pigs are held in smaller groups. Large floor and air spaces tend to make all-in/all-out systems difficult, and disinfection procedures between batches can often be less than adequate, allowing both within-batch spread and between-batch carry-over of disease. However, with high levels of management and animal care, large-group deep-straw-bedded yard systems can achieve high levels of economically beneficial performance, and there may be other benefits of lower building costs, the availability of general-purpose housing and the ability to present to
the final consumer a product that has emanated from a non-intensive system of pig production. Conventional straw usage rates are assumed to be about 0.5 kg of straw per pig per day. Actual usages will depend greatly upon pen layout and the rate of wastage due to soiling. Where kennels are not provided, it is essential that there is an adequate depth of dry, loose straw to provide the animal, through the medium of the straw, with adequate insulation from unfavourable ambient temperatures.
Chapter 18

Production Performance Monitoring

Introduction

The objectives of records to monitor production performance are:

1. to inform as to the present status of the production unit and the individual pigs upon it;
2. to inform as to the past performance of the production unit and the individual pigs upon it;
3. to provide a basis for production management, for diagnoses and for problem-solving; and
4. to provide factual data to allow considered forward policy planning.

Amongst the particular problems of any recording scheme are those associated with individual animal identification, with the effort of taking and storing the record, and with the difficulty in retrieving the information when it is needed from the place where it was put (be it on paper or in a computer).

Records – on the pig unit

Management information should be held, for as long as it may be needed, near its point of use. The expected date of parturition is essential knowledge required about a pregnant sow, so that she can be moved at the appropriate time to farrowing quarters. This may be written on a card which is associated with the pen in which the sow resides. Similarly, the prospective date of weaning is essential knowledge required about a lactating sow. After weaning, the placement of the sow in the mating pen adjacent to the boars is evidence of her empty and unproductive state. Upon mating, the next piece of relevant information is the prospective return date should she not have conceived; and, for those sows that do return to oestrus, the number of times this has happened.

Weight at weaning is useful information but for management purposes not essential for all litters. The expected and achieved dwell-time of pigs in the weaner, grower and finisher pens is essential information for smooth management and throughput control, but, equally important, this statistic indicates the growth rate that is being
achieved. Dwell-time in pens may be readily calculated from dates and weights, in and out.

Signs of ill-health, reductions in food and water intake and, of course, veterinary treatments must be noted at first sight, and recorded at the pen side. It is especially important to register all routine veterinary procedures and inoculations, such as anthelmintic administration and parvovirus, \textit{E. coli} and erysipelas vaccinations.

All such records, and indeed many more, can also be entered into paper (or data logger) recording systems and carried to the office. Office-based recording schemes can be used to deliver, on a daily basis, management information which can be taken each morning onto the production unit and acted upon. Paper and computerised records in the office, however, are always best used as an adjunct to, and never in place of, the record that can be read face-to-face with the pig it concerns.

\textbf{Simple records}

Much information can be derived from simple and readily available records:

- A description of the stock type can inform as to potential growth rate, quality of carcass and reproductive performance.
- The returns from the slaughterhouse/meat packer will inform about actual weight at finish, predisposition to fat, variability of end-weight and variability of carcass quality.
- The date of weaning together with the date of despatch will inform about growth rate. In the absence of this, the number of pigs sold per year, together with the number of pig places available on the grow-out unit, can provide the same information.
- The number of pigs marketed per year, together with the number of breeding sows on the unit, will inform about the productivity of the breeding herd as well as mortality in the grow-out unit.
- The total annual tonnage of sow feed purchased, together with breeding herd size, informs about sow feed usage.
- The total annual tonnage of grower/finisher feed purchased, together with the number of pigs sold to the slaughterhouse/meat packer, informs about feed conversion efficiency.
- A visual appraisal of the sucking pigs at weaning informs about lactation performance.
- A visual appraisal of the stocking density in pens informs about the likely performance of these pigs, and about management efficiency.
- A visual appraisal of the growing pig, at the time of movement from the weaner house to the grower pens informs about disease incidence and post-weaning growth. Visual appraisal of pig condition at this time is superior to weight gain as a method of assessment of growth rate and nutritional adequacy due to the pig’s ability to lose fat but gain water at the same time.
A visual appraisal of the condition (and the variation in condition) of the growing pig at the point of despatch informs about growth, disease status and likely carcass quality.

A visual appraisal of the condition (and the variation in condition) of the breeding sows at the points of weaning and farrowing informs about nutrition and feeding management. Visual appraisal of pig condition at this time is superior to weight change as a method of assessment because small changes in weight can be associated with large changes in body composition, and it is body composition, not body weight, that influences breeding success.

A great deal of information about a pig unit can be gained from (1) simply looking and counting, and (2) referring to gross records such as total feed deliveries and total feed despatches. The following example illuminates the possibilities:

A pig farm with both a breeding and a grow-out unit records only the feed purchased for the pigs. The unit brings in extra pigs transported from a neighbouring producer at 28 days of age, and these enter the weaner accommodation on the grow-out unit. From the meat packer’s grade returns it is apparent that (1) the average sale weight is 100 kg, (2) 80% of pigs receive top grade price, and (3) 10,500 pigs are sold for slaughter annually. Feed deliveries weekly are: sow feed deliveries 12 tonnes, starter feed deliveries 2.5 tonnes, grower feed deliveries 12.5 tonnes, finisher feed deliveries 50 tonnes. Piglets are weaned at 4 weeks of age (26–30 days) and pigs are moved from the weaner to the grower house at 20 kg and from the grower to the finisher house at 60 kg. Sows are moved from the mating pens to the pregnant sow house immediately after they are mated for the last time and are no longer in standing heat. Sows go from pregnant sow house to farrowing house 7 days before the date they are due to farrow.

The pigs found present on the farm are as follows:

- Total number of breeding sows either pregnant, lactating or awaiting mating: 500
- Sows awaiting despatch as culls: 20
- Maiden gilts: 60
- Boars: 35
- Sows in pregnant sow house: 350
- Sows in mating pens: 80
- Sows in farrowing pens: 70
- Piglets in farrowing pens: 690
- Pigs in weaner houses: 1323
- Pigs in grower houses: 1614
- Pigs in finisher houses: 1909

From this basic evidence, the performance of the breeder and the feeder herd can be calculated and compared with expected performance, as may be perceived...
from Tables 18.1 and 18.2. On the right hand side of Table 18.1 are presented the actualities pertaining to the unit in terms of those parameters that are immediately determinable on site, together with those that can be calculated. To the left of the table are given the expected statistics that might reasonably have been presumed. Expectations and actualities for the grow-out unit are similarly presented in Table 18.2.

**Records – in the office**

Paper records and computer management packages form a vital part of management control: they are the permanent record of the day-to-day activities and performances of particular pigs or groups of pigs. It is easy to gather an excess of records of the wrong sort and an insufficiency of the right sort. A wrong record is one that is never used (for example, individual sow records of litter size when only 10% of all culls occur because of low litter size). A right record is one that addresses a particular problem pertinent to the unit concerned (for example, days between weaning and conception for a herd selling less than 22 piglets per sow per year).

**Records for selection**

Breeders selecting for improved performance need information on which to base that selection. As breeding is a long-term and disciplined effort, the records need to be comprehensive. Breeding for faster growth and leaner carcasses can only be achieved if days to slaughter, weight and fat depth are carefully recorded for all candidate animals for selection within the various breeding lines. This sort of recording does not usually present any question of principle – whatever criteria are appropriate to measure are measured. Problems that arise are more often of logistics and cost. In performance tests for males an estimate of feed conversion efficiency might be thought necessary. This means recording the feed intake of each pig on each day. Recording of sow breeding performance, if comprehensively carried out to include birth weight, litter size, litter weight, weaning weight, lifetime performance, breeding regularity and so on, also consumes time and effort.

**Commercial records**

It is not sensible to mount complex recording schemes for commercial herds. Apart from the costs involved, there is a major problem of individual identification of large numbers of animals. For most producers, recording should be kept to a minimum and probably utilise a computer-based system. (See comment on page 599.)

There are two outstandingly vital statistics for the commercial herd:

1. Pigs sold annually per breeding female. This encapsulates numbers born, rebreeding regularity and mortality. It is calculated from the knowledge of
Table 18.1. The sow breeding herd. Calculations of expectations and determination of actualities.

<table>
<thead>
<tr>
<th>Expectations</th>
<th>Actualities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sows: 500</td>
<td>Sows: 500</td>
</tr>
<tr>
<td>Sows to be culled: 17 per month</td>
<td>Culls: 20</td>
</tr>
<tr>
<td>Maiden gilts: 17 per month × 2 = 35</td>
<td>Maiden gilts: 60</td>
</tr>
<tr>
<td>Sows in pregnant sow, mating and farrowing pens,</td>
<td>Piglets in farrowing pens: 690</td>
</tr>
<tr>
<td>2.25 litters/sow/year are expected: 365/2.25 = 162</td>
<td></td>
</tr>
<tr>
<td>115 − 7 = 108</td>
<td>66.7%</td>
</tr>
<tr>
<td>28 + 7 = 35</td>
<td>21.6%</td>
</tr>
<tr>
<td>19 = 19</td>
<td>11.7%</td>
</tr>
<tr>
<td>162</td>
<td>100%</td>
</tr>
<tr>
<td>Per 100 sows expect: 67 pregnant sow places</td>
<td></td>
</tr>
<tr>
<td>22 farrowing places</td>
<td></td>
</tr>
<tr>
<td>12 mating places</td>
<td></td>
</tr>
<tr>
<td>Per 500 sows expect: 335 in pregnant sow places</td>
<td>Sows in pregnant sow house</td>
</tr>
<tr>
<td>110 in farrowing pens</td>
<td>350</td>
</tr>
<tr>
<td>60 in mating pens</td>
<td>Sows in farrowing pens</td>
</tr>
<tr>
<td>70</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>Sows in mating pens</td>
</tr>
<tr>
<td>Percent of time in pregnancy pens</td>
<td>Percent of time in pregnancy pens</td>
</tr>
<tr>
<td>67%</td>
<td>350/500 = 70%</td>
</tr>
<tr>
<td>Percent of time in farrowing pens</td>
<td>Percent of time in farrowing pens</td>
</tr>
<tr>
<td>22%</td>
<td>70/500 = 14%</td>
</tr>
<tr>
<td>Percent of time in mating pens</td>
<td>Percent of time in mating pens</td>
</tr>
<tr>
<td>12%</td>
<td>80/500 = 16%</td>
</tr>
<tr>
<td>Days in pregnancy pens</td>
<td>Days in farrowing pens</td>
</tr>
<tr>
<td>0.67 × 365 = 245</td>
<td>0.70 × 365 = 256</td>
</tr>
<tr>
<td>Days in farrowing pens</td>
<td>Days in farrowing pens</td>
</tr>
<tr>
<td>0.22 × 365 = 80</td>
<td>0.14 × 365 = 51</td>
</tr>
<tr>
<td>Days in mating pens</td>
<td>Days in mating pens</td>
</tr>
<tr>
<td>0.12 × 365 = 44</td>
<td>0.16 × 365 = 58</td>
</tr>
<tr>
<td>If sows spend 28 + 7 = 35 days per litter in</td>
<td>If sows spend 28 + 7 = 35 days</td>
</tr>
<tr>
<td>farrowing pens, then 80/35 = 2.25 litters/sow/year</td>
<td>litter in farrowing pens, then</td>
</tr>
<tr>
<td>80/35 = 2.25 litters/sow/year</td>
<td>51/35 = 1.5 litters/sow/year.</td>
</tr>
<tr>
<td>If pregnant days are 256, then expected number of</td>
<td>If pregnant days are 256, then</td>
</tr>
<tr>
<td>pregnancies is 256/(115 − 7) = 2.4 per year. As</td>
<td>expected number of pregnancies</td>
</tr>
<tr>
<td>only 1.5 are achieved, then non-pregnant sows</td>
<td>is 256/(115 − 7) = 2.4 per year.</td>
</tr>
<tr>
<td>must be in the pregnant sow places</td>
<td>As only 1.5 are achieved, then</td>
</tr>
<tr>
<td>Sows should be in mating pens for 13 days or about</td>
<td>non-pregnant sows must be in the</td>
</tr>
<tr>
<td>13 × 2.3 = 30 days per year, not 58. So either</td>
<td>pregnant sow places</td>
</tr>
<tr>
<td>sows are also not being mated or they are not</td>
<td>Sows should be in mating pens for</td>
</tr>
<tr>
<td>coming on heat</td>
<td>13 days or about 13 × 2.3 = 30</td>
</tr>
<tr>
<td>Piglets per sucking litter: 10</td>
<td>days per year, not 58. So either</td>
</tr>
<tr>
<td></td>
<td>sows are also not being mated or</td>
</tr>
<tr>
<td></td>
<td>they are not coming on heat</td>
</tr>
<tr>
<td>Piglets in farrowing pens/sow in farrowing pens</td>
<td>Piglets in farrowing pens/sow in</td>
</tr>
<tr>
<td>690/70 = 9.9</td>
<td>farrowing pens = 690/70 = 9.9</td>
</tr>
<tr>
<td>Sow feed usage = 1.3t/adult/year</td>
<td>Total adult pigs on unit = 500 +</td>
</tr>
<tr>
<td></td>
<td>20 + 60 + 35 = 615</td>
</tr>
<tr>
<td></td>
<td>12 t sow feed per week × 52/615 =</td>
</tr>
<tr>
<td></td>
<td>1 t/adult/year</td>
</tr>
</tbody>
</table>

From text: 12 t sow feed weekly; 28-day weaning; sows moved to pregnant sow house after mating, and to farrowing house a week before due date.
number of pigs leaving the farm divided by the total number of breeding females in the herd.

(2) Feed used per pig sold. This is an overall feed conversion factor, and measures the efficiency of utilisation of the major raw material in the production process. It is calculated from the total tonnage of feed transferred into the unit, per month or per year, divided by the total number of pigs leaving the unit over the same period.

Compendium efficiency measures will indicate current performance levels and show changes in productivity, but cannot identify the causes of either of these. For diagnosis, closer examination needs to be made of specific aspects of performance. Pigs sold per breeding female may decrease owing to reduction in the numbers born, a lengthening of the breeding to weaning interval, an increase in mortality, a high

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### Table 18.2. The grow-out unit. Calculations of expectations and determination of actualities.

<table>
<thead>
<tr>
<th>Expectations</th>
<th>Actualities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total slaughter pigs sold annually: 10500</td>
<td>10710/4846 = 2.21 batches/year</td>
</tr>
<tr>
<td>With assumed 2% loss in grow-out unit, total pigs entering unit annually = 10710.</td>
<td></td>
</tr>
<tr>
<td>Pigs in weaner houses</td>
<td>1323</td>
</tr>
<tr>
<td>Pigs in grower houses</td>
<td>1614</td>
</tr>
<tr>
<td>Pigs in finishing houses</td>
<td>1909</td>
</tr>
<tr>
<td>Total growing pigs</td>
<td>4846</td>
</tr>
<tr>
<td>7.5–100kg: 2.6 batches/year</td>
<td></td>
</tr>
<tr>
<td>28-day weaning weight = 7.5kg</td>
<td>If weaner weight is taken as 7.5kg, then 100 – 7.5 = 92.5kg of growth is achieved on the grow-out unit</td>
</tr>
<tr>
<td>365/2.6 = 140 days per batch</td>
<td>365/2.21 = 165 days per batch</td>
</tr>
<tr>
<td>Given 140 days per batch, then:</td>
<td>Given 165 days per batch, then:</td>
</tr>
<tr>
<td>7.5–20kg at 0.43kg/day = 30 days in weaner house</td>
<td>27% of 165 = 45 days for 12.5kg gain in the weaner house (20 – 7.5) = 0.28kg daily gain</td>
</tr>
<tr>
<td>20–60kg at 0.67kg/day = 60 days in grower house</td>
<td>33% of 165 = 55 days for 40kg gain in the grower house (60 – 20) = 0.73kg daily gain</td>
</tr>
<tr>
<td>60–100kg at 0.80kg/day = 50 days in finisher house</td>
<td>39% of 165 = 65 days for 40kg gain in the finisher house (100 – 60) = 0.62kg daily gain</td>
</tr>
<tr>
<td>Age at 100kg = 140 + 28 = 168 days</td>
<td>Age at 100kg = 165 + 28 = 193 days</td>
</tr>
<tr>
<td>Feed conversion ratio dependent upon diet density, but less than 3.0</td>
<td>Feed conversion ratio 3380/971.3 = 3.48</td>
</tr>
</tbody>
</table>

From text: weight at sale 100kg; feed deliveries weekly, 25t starter, 12.5t grower, 50t finisher; pigs moved at weaning (28 day), 20kg and 60kg; 10500 pigs sold annually.
proportion of unmated herd replacements or a slowing down in growth rate. Inefficiencies of feed use might be in the growing or breeding herd, and might be caused by wastage, cold, pig quality, too high a level of feeding, too low a level of feeding or feed quality.

Modern recording schemes using electronic data collection and screen-based data management systems are readily available. These not only provide day-to-day management statistics, but also will – through benchmarking – throw up warning flags where and when deviations arise. These systems are for the most part computer-based versions of conventional recording schemes. New-generation performance monitoring awaits implementation of real-time and automatic information collection of pig performance (such as by visual imaging). Linkages may then be made directly in order to deliver requisite remedial action.

### Targets

Pig producers are helped by knowing how they are performing in comparison with their peers. In this regard, centralised computer-based recording schemes can provide seminal information of the type shown in Table 18.3, which refers to one particular scheme used in the UK. Other similar conflated statistics which may be exampled relate to reasons for culling sows (Table 18.4), or to feed ingredient usages (Table 18.5), or to the breakdown of the financial structure of the production unit (Table 18.6).

More specific data may come from particular example herds and serve to give encouragement through the medium of demonstrating that good performance is achievable (Table 18.7).

From such databases as these more generalised targets can be set. Some such average targets are listed in Table 18.8. However, even targets of this sort may be inappropriate when:

- the unit is highly sophisticated and already has performances as good as the average target, even though above-average performance is essential for the unit to be profitable;
- the target is so far in advance of the current performance of the unit that its attainment is not considered credible by the unit staff;
- the individual unit does not fit in comfortably with the average production systems or objectives, perhaps having widely different ages at weaning, feed quality, house types, breeding stocks, etc.

The best targets may often be derived internally according to each particular unit. Current performances can be identified and an achievable percentage added on. This will make for a gradual step-wise progression upwards. Individual aspects of production efficiency can be singled out one by one for special attention. Current performance levels can be compared to targets by means of histograms, graphs or...
Table 18.3. National UK average pig statistics\(^1\) for herds despatching at 90kg live weight (per 100 sows in herd).

<table>
<thead>
<tr>
<th>Stocks</th>
<th>Monthly entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sows(^2)</td>
<td>Gilts into the breeding herd</td>
</tr>
<tr>
<td>Maiden gilts(^3)</td>
<td>Boars into the breeding herd</td>
</tr>
<tr>
<td>Sucklers</td>
<td></td>
</tr>
<tr>
<td>Boars</td>
<td></td>
</tr>
<tr>
<td>Monthly exits</td>
<td></td>
</tr>
<tr>
<td>Culled boars</td>
<td></td>
</tr>
<tr>
<td>Culled sows</td>
<td></td>
</tr>
<tr>
<td>Deaths</td>
<td></td>
</tr>
<tr>
<td>CSI25</td>
<td></td>
</tr>
<tr>
<td>CSII25</td>
<td></td>
</tr>
<tr>
<td>CSIII25</td>
<td></td>
</tr>
<tr>
<td>Born alive per litter</td>
<td></td>
</tr>
<tr>
<td>Feed/gain (total breeder and feeder herd)</td>
<td></td>
</tr>
<tr>
<td>Mortality (%) birth to weaning</td>
<td></td>
</tr>
<tr>
<td>Reared per litter</td>
<td></td>
</tr>
<tr>
<td>Weaned per sow per year</td>
<td></td>
</tr>
<tr>
<td>Sold per sow per year</td>
<td></td>
</tr>
<tr>
<td>No. of sows served monthly(^5)</td>
<td></td>
</tr>
<tr>
<td>Successful services (%)</td>
<td></td>
</tr>
<tr>
<td>Litters per sow per year</td>
<td></td>
</tr>
<tr>
<td>Empty days per year(^6)</td>
<td></td>
</tr>
<tr>
<td>Weaning weight (kg)</td>
<td></td>
</tr>
<tr>
<td>Age at weaning (days)</td>
<td></td>
</tr>
<tr>
<td>Feed used per sow per year (t)</td>
<td></td>
</tr>
</tbody>
</table>

**Feeder herd performance**

- Deaths: 0.5
- Stocks (7–89kg): 707
- Batches per year (7–89kg): 3.0
- Feed/gain (feeder herd): 2.4
- Total born per litter: 11.7
- Mortality (%): 5.2
- Daily gain (kg) from birth: 0.60
- Total feed used (kg monthly): 48,660

**Annual financial performance**

- Pigs sold per productive sow in herd: 21.2
- Sales of sows and boars (£): 5,970
- Sales of finished pigs (£): 142,000
- Purchases of boars and gilts (£): 9,900
- Increase in valuation: 800
- Feed costs (£): sow and boar: 18,500
- Piglet: 440
- Growing/finishing: 68,700
- Variable costs (£): vet/med: 2,600
- Transport: 1,180
- Power and water: 3,750
- Bedding: 490
- Others: 770
- Fixed costs (£): labour: 13,500
- Contract: 570
- Repairs and maintenance: 4,250
- Rent and leasing: 1,020
- Depreciation and interest: 4,030
- Others: 4,320

---

\(^1\) Drawn from *Easicare Pig Management Year Books*.

\(^2\) Average herd size in 100 herd sample = 350.

\(^3\) Maiden gilts reside in the breeding herd for an average of 45 days between entry and service.

\(^4\) Number farrowed/number mated in equivalent period 4 months earlier.

\(^5\) Average number of ejaculations per sow served is 2.2.

\(^6\) Empty days = days between weaning and oestrus plus days lost through mated sows returning to oestrus.

\(^7\) 2120 pigs of 67kg DW and 100 p/kg.

\(^8\) 148 days to despatch, less 25 days to 7kg (365/123 = 3.0).

\(^9\) 5.840t/sow/year (of which 1.3t is used for the sow) for the production of 21.2 pigs sold at an average live weight of 89kg.
Table 18.4. Reasons for culling sows.

<table>
<thead>
<tr>
<th>Reason for culling</th>
<th>Age at culling (years)</th>
<th>Percentage of total culls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old age</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Litter size</td>
<td>2.5</td>
<td>10</td>
</tr>
<tr>
<td>Infertility: including anoestrus and failure to breed after two returns to oestrus</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td>Legs, feet and associated locomotor problems</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>Others</td>
<td>2</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 18.5. UK pig feed ingredient usage.

<table>
<thead>
<tr>
<th></th>
<th>Pregnant sow diets</th>
<th>Young and growing pig diets</th>
<th>Finishing pig and lactating sow diets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereals(^1)</td>
<td>30</td>
<td>55</td>
<td>36</td>
</tr>
<tr>
<td>Cereal by-product(^2)</td>
<td>30</td>
<td>7</td>
<td>24</td>
</tr>
<tr>
<td>Vegetable proteins(^3)</td>
<td>22</td>
<td>24</td>
<td>29</td>
</tr>
<tr>
<td>Animal proteins(^4)</td>
<td>1</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Others(^5)</td>
<td>17</td>
<td>7</td>
<td>10</td>
</tr>
</tbody>
</table>

1. About half of this as wheat, and the remaining half as barley, maize and other cereals.
2. Mostly wheat feed and other milling offals, but also including other brans, waste from flour-based human foods and maize by-products.
3. Mostly soya bean meal, but also some rapeseed and pea and bean meals.
4. Mostly fish meals.
5. Including molasses, sugar beet pulp, fats and oils, minerals, vitamins and other products.

Table 18.6. Example financial analyses (as percentage of total expenditures).

<table>
<thead>
<tr>
<th>Breeding herd: production of 30kg weaner pig</th>
<th>Grow-out unit: 30–100kg live weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total expenditures</td>
<td>100</td>
</tr>
<tr>
<td>Total income</td>
<td>110</td>
</tr>
<tr>
<td>Expenditures as percentage of total:</td>
<td></td>
</tr>
<tr>
<td>Feed for sows and boars</td>
<td>30</td>
</tr>
<tr>
<td>Feed for piglets to 30kg</td>
<td>30</td>
</tr>
<tr>
<td>Veterinary</td>
<td>4</td>
</tr>
<tr>
<td>Power</td>
<td>4</td>
</tr>
<tr>
<td>Others</td>
<td>2</td>
</tr>
<tr>
<td>(Total variable costs)</td>
<td>70</td>
</tr>
<tr>
<td>Labour</td>
<td>18</td>
</tr>
<tr>
<td>Buildings and equipment</td>
<td>10</td>
</tr>
<tr>
<td>Others</td>
<td>2</td>
</tr>
<tr>
<td>(Total fixed costs)</td>
<td>30</td>
</tr>
</tbody>
</table>

| Grow-out unit:                                |                                   |
| Total expenditures                           | 100                               |
| Total income                                 | 110                               |
| Expenditures as percentage of total:         |                                   |
| Purchase of 30kg weaners                     | 50                                |
| Feed                                         | 35                                |
| Veterinary                                   | 1                                 |
| Power                                        | 2                                 |
| Others                                       | 2                                 |
| (Total variable costs)                       | 90                                |
| Labour                                       | 4                                 |
| Buildings and equipment                      | 5                                 |
| Others                                       | 1                                 |
| (Total fixed costs)                          | 10                                |
### Table 18.7. Six-parity performance of a breeding herd.

<table>
<thead>
<tr>
<th>Parity</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number born alive</td>
<td>10.1</td>
<td>10.3</td>
<td>11.5</td>
<td>12.2</td>
<td>11.3</td>
<td>11.4</td>
<td>11.0</td>
</tr>
<tr>
<td>Number born dead</td>
<td>0.14</td>
<td>0.28</td>
<td>0.23</td>
<td>0.79</td>
<td>1.37</td>
<td>1.90</td>
<td>0.51</td>
</tr>
<tr>
<td>Piglet birth weight (kg)</td>
<td>1.45</td>
<td>1.47</td>
<td>1.45</td>
<td>1.40</td>
<td>1.37</td>
<td>1.24</td>
<td>1.43</td>
</tr>
<tr>
<td>Number weaned</td>
<td>9.2</td>
<td>9.8</td>
<td>10.1</td>
<td>10.6</td>
<td>10.0</td>
<td>9.9</td>
<td>9.8</td>
</tr>
<tr>
<td>Average weaning weight (kg)</td>
<td>6.56</td>
<td>7.17</td>
<td>6.98</td>
<td>6.83</td>
<td>6.66</td>
<td>6.19</td>
<td>6.82</td>
</tr>
<tr>
<td>Days to weaning</td>
<td>22</td>
<td>21</td>
<td>21</td>
<td>22</td>
<td>21</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Mortality (%) (to weaning)</td>
<td>9.2</td>
<td>5.5</td>
<td>12.1</td>
<td>13.5</td>
<td>12.3</td>
<td>12.7</td>
<td>10.7</td>
</tr>
<tr>
<td>Lactation feed (kg)</td>
<td>110</td>
<td>119</td>
<td>122</td>
<td>137</td>
<td>137</td>
<td>127</td>
<td>122</td>
</tr>
<tr>
<td>Condition score (farrowing)(^1)</td>
<td>3.67</td>
<td>3.64</td>
<td>3.56</td>
<td>3.96</td>
<td>3.56</td>
<td>4.31</td>
<td>3.70</td>
</tr>
<tr>
<td>Condition score (weaning)(^1)</td>
<td>2.95</td>
<td>2.98</td>
<td>2.90</td>
<td>3.13</td>
<td>3.14</td>
<td>3.53</td>
<td>3.02</td>
</tr>
<tr>
<td>Sow weight (kg) (farrowing)</td>
<td>196</td>
<td>230</td>
<td>251</td>
<td>262</td>
<td>267</td>
<td>285</td>
<td>236</td>
</tr>
<tr>
<td>Sow weight (kg) (weaning)</td>
<td>174</td>
<td>207</td>
<td>226</td>
<td>238</td>
<td>245</td>
<td>263</td>
<td>212</td>
</tr>
<tr>
<td>Backfat (mm) (farrowing)</td>
<td>23.8</td>
<td>21.2</td>
<td>20.8</td>
<td>20.5</td>
<td>18.3</td>
<td>18.3</td>
<td>20.9</td>
</tr>
<tr>
<td>Backfat (mm) (weaning)</td>
<td>17.9</td>
<td>16.6</td>
<td>15.7</td>
<td>15.2</td>
<td>14.9</td>
<td>15.1</td>
<td>16.0</td>
</tr>
</tbody>
</table>

\(^1\) Five-point scale.

### Table 18.8. Example performance targets. Values relate to 100 breeding females (sows + mated gilts).

<table>
<thead>
<tr>
<th>Category</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maiden gilts</td>
<td>5–7</td>
</tr>
<tr>
<td>Sows served weekly</td>
<td>4–6</td>
</tr>
<tr>
<td>Boar ejaculations weekly</td>
<td>3–5</td>
</tr>
<tr>
<td>Matings per sow per oestrus</td>
<td>&gt;2</td>
</tr>
<tr>
<td>Number of boars, including young boars</td>
<td>&gt;5</td>
</tr>
<tr>
<td>Sows farrowing/sows mated</td>
<td>&gt;0.8</td>
</tr>
<tr>
<td>Sows anoestral for up to 14 days post-weaning</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Farrowings per week</td>
<td>4–5</td>
</tr>
<tr>
<td>Litters per breeding female per year</td>
<td>&gt;2.2</td>
</tr>
<tr>
<td>Pigs born alive per litter</td>
<td>&gt;10.5</td>
</tr>
<tr>
<td>Pigs weaned per litter</td>
<td>&gt;9.5</td>
</tr>
<tr>
<td>Pigs weaned per month</td>
<td>&gt;180</td>
</tr>
<tr>
<td>Birth weight of pigs (kg)</td>
<td>&gt;1.3</td>
</tr>
<tr>
<td>21-day weight (kg)</td>
<td>&gt;6</td>
</tr>
<tr>
<td>28-day weight (kg)</td>
<td>&gt;8.5</td>
</tr>
<tr>
<td>Interval from weaning to mating (days)</td>
<td>3–5</td>
</tr>
<tr>
<td>Interval from weaning to conception (days)</td>
<td>&lt;12</td>
</tr>
<tr>
<td>Number of farrowings per month</td>
<td>18–21</td>
</tr>
<tr>
<td>Pig sales yearly</td>
<td>&gt;1900</td>
</tr>
<tr>
<td>Pig sales monthly</td>
<td>&gt;170</td>
</tr>
<tr>
<td>Breeding herd replacements per quarter year</td>
<td>&lt;12</td>
</tr>
<tr>
<td>Feed used per breeding female per year (t)</td>
<td>1.1–1.4</td>
</tr>
<tr>
<td>Total feed usage by the breeding herd per month (t)</td>
<td>10–11</td>
</tr>
<tr>
<td>Feed used by growing pigs yearly (t)</td>
<td>&lt;550</td>
</tr>
<tr>
<td>Feed used by growing pigs monthly (t)</td>
<td>&lt;45</td>
</tr>
<tr>
<td>Feed used by each growing pig in one month (kg)</td>
<td>&lt;50</td>
</tr>
<tr>
<td>Age at 100kg (days)</td>
<td>&lt;160</td>
</tr>
<tr>
<td>Feed conversion efficiency to 100kg using medium nutrient density diet</td>
<td>&lt;2.8</td>
</tr>
<tr>
<td>Feed conversion efficiency to 100kg using high nutrient density diet</td>
<td>&lt;2.4</td>
</tr>
<tr>
<td>Mortality post-weaning to slaughter (%)</td>
<td>2–3</td>
</tr>
<tr>
<td>Growth rate from 5–15kg live weight (g/day)</td>
<td>&gt;350</td>
</tr>
<tr>
<td>Growth rate from 15–50kg live weight (g/day)</td>
<td>&gt;600</td>
</tr>
<tr>
<td>Growth rate from 50–100kg live weight (g/day)</td>
<td>&gt;800</td>
</tr>
</tbody>
</table>
Table 18.9. Example management points for farrowing and lactating sows, and sucking pigs.

<table>
<thead>
<tr>
<th>Observe</th>
<th>Consider</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sows</strong></td>
<td></td>
</tr>
<tr>
<td>Days to parturition</td>
<td>Move to maternity ward after 108th day of pregnancy</td>
</tr>
<tr>
<td>Cleanliness of quarters</td>
<td>Disinfect and rest for 7 days between pigs</td>
</tr>
<tr>
<td>Cleanliness of pig</td>
<td>Wash and scrub, treat with dressing against internal and external parasites and mange</td>
</tr>
<tr>
<td>Temperature of house</td>
<td>Different requirements of lactating sows and young piglets</td>
</tr>
<tr>
<td>Welfare of pig</td>
<td>Correct pen arrangements</td>
</tr>
<tr>
<td>Onset of parturition</td>
<td>Cost–benefit of attending the birth</td>
</tr>
<tr>
<td>Post-parturient problems</td>
<td>Lack of milk for young piglets, high temperature (above 40°C) fever in mother</td>
</tr>
<tr>
<td>Availability of water</td>
<td>Drinkers regularly checked</td>
</tr>
<tr>
<td>Days to weaning, reproductive performance of female</td>
<td>Record data in preparation for decisions to move, cull or remate</td>
</tr>
<tr>
<td>Disease</td>
<td>Routine injections</td>
</tr>
<tr>
<td>Sow condition</td>
<td>Adequacy of feed intake</td>
</tr>
<tr>
<td><strong>Sucking pigs</strong></td>
<td></td>
</tr>
<tr>
<td>Completion of routine tasks within 3 days of birth</td>
<td>Administration of iron compound</td>
</tr>
<tr>
<td></td>
<td>Clipping teeth</td>
</tr>
<tr>
<td></td>
<td>Ear mark (to record at least the week of birth)</td>
</tr>
<tr>
<td>Completion of routine tasks within 15 days of birth</td>
<td>Castrate if necessary</td>
</tr>
<tr>
<td></td>
<td>Provide highly palatable creep feed diet for young piglets; keep fresh by twice-daily provision and attention to cleanliness of trough</td>
</tr>
<tr>
<td></td>
<td>Water supply to young piglets</td>
</tr>
<tr>
<td>Signs of diarrhoea</td>
<td>Treatment</td>
</tr>
<tr>
<td></td>
<td>Improve standards of cleanliness</td>
</tr>
<tr>
<td>Environment</td>
<td>Bedding, temperature, draughts</td>
</tr>
<tr>
<td>Growth performance</td>
<td>Reductions in suckled milk supply can be offset by increased intake of supplementary creep feed</td>
</tr>
</tbody>
</table>

charts. These aids to management – serving to encourage the staff of the unit on to greater things – must, of course, reside in the clear view of that staff. Progression towards the target should be monitored and, when reached, rewarded. Computer-based systems readily facilitate such management aids.

**Routine control**

Management checks are best designed around the individual characteristics of the staff, buildings, problems to be solved and production processes. On large units even the vital statistics are hard to keep up with: whether or not a female is pregnant, when a litter is due for weaning, how often a male has been used, how old is a pen of growing pigs. Maintaining control is simplified if information is incorporated into the physical structure of the unit; for example, a special area of the house set aside
for females not yet pregnant, weaning always on the same day of the week, marking pens of weaners with expected moving-on date, pens of growers with expected slaughter date and so on.

Day-by-day tactical management requires both a computerised (or paper) recording system and close day-by-day observation of the current physical status of all the animals on the unit. Tables 18.9, 18.10 and 18.11 are presented as examples of some of the control points that management may feel essential to the day-to-day routine of the production unit.

Performance monitoring is now moving away from the interpretation of historical data and toward real-time management of performance. This will include prediction of outcomes, and the possibility of remedial action being taken automatically. Quality Assurance Schemes (and HACCP) have been helpful in reducing the risk of unnoticed performance failures and have focused attention on monitoring and the taking of early action when targets are being missed.

Table 18.10. Example management points for boars, sows awaiting mating and pregnant sows.

<table>
<thead>
<tr>
<th>Observe</th>
<th>Consider</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Boars</strong></td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>Feed allowance</td>
</tr>
<tr>
<td>Willingness to mate</td>
<td>Age</td>
</tr>
<tr>
<td>Health</td>
<td>Feed allowance</td>
</tr>
<tr>
<td>Frequency of use</td>
<td></td>
</tr>
<tr>
<td>Numbers born</td>
<td>Frequency of use</td>
</tr>
<tr>
<td>Use of two males on same female</td>
<td></td>
</tr>
<tr>
<td>Disposition</td>
<td>If aggressive, check staff</td>
</tr>
<tr>
<td>Check water supply</td>
<td></td>
</tr>
<tr>
<td><strong>Sows</strong></td>
<td></td>
</tr>
<tr>
<td>Days between weaning and conception</td>
<td>Feed allowance, feed specification, disease, management</td>
</tr>
<tr>
<td>Culling policy</td>
<td></td>
</tr>
<tr>
<td>Housing type</td>
<td></td>
</tr>
<tr>
<td>Body condition</td>
<td>Feed allowance in lactation</td>
</tr>
<tr>
<td>Pregnancy feed allowance</td>
<td></td>
</tr>
<tr>
<td>Confirmation of pregnancy</td>
<td>Check with males 18–25 days after previous matings</td>
</tr>
<tr>
<td>Use pregnancy diagnosis equipment</td>
<td></td>
</tr>
<tr>
<td>House temperature</td>
<td>Use max./min. thermometer</td>
</tr>
<tr>
<td>Draughts</td>
<td></td>
</tr>
<tr>
<td>Behaviour of animals</td>
<td></td>
</tr>
<tr>
<td>Welfare and restlessness</td>
<td>Environment; space allowance</td>
</tr>
<tr>
<td>Concentration of diet, provision of roughage, feed allowance</td>
<td></td>
</tr>
<tr>
<td>Cleanliness</td>
<td>Penning arrangements</td>
</tr>
<tr>
<td>Physical abrasions</td>
<td>Penning arrangements</td>
</tr>
<tr>
<td>Group antagonisms</td>
<td></td>
</tr>
<tr>
<td>Time since mating</td>
<td>Movement to maternity quarters</td>
</tr>
<tr>
<td>Feed and water supply</td>
<td>Automation</td>
</tr>
<tr>
<td>Disease</td>
<td>Routine vaccinations</td>
</tr>
<tr>
<td>Observe</td>
<td>Consider</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Adequacy of environment</td>
<td>Provision of plenty of space but not so the animals are cold</td>
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<td>Possibilities of deep, clean straw</td>
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<td>Housing quality</td>
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<td>Diarrhoea</td>
<td>Medication of feed</td>
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<tr>
<td>Feed provision</td>
<td>Supply of more feeding space and fresher, more palatable feed</td>
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<tr>
<td>Growth rate/pig condition</td>
<td>Temperature, respiratory disease levels, intestinal disease,</td>
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<td>welfare, feeding arrangements, feed supply, size of group,</td>
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<td></td>
<td>stocking density, water provision</td>
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<td>External and internal parasites</td>
<td>Dress and dose</td>
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<td>Cannibalism</td>
<td>Environment, bedding material, diet</td>
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<tr>
<td>Feeding arrangements</td>
<td>Adequate space</td>
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<td>Slow growth, variable growth rates within pens</td>
<td>Too frequent mixing and moving</td>
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<td>Ration or diet</td>
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<td>Stocking density</td>
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<td>Water</td>
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<td>Weight for slaughter</td>
<td>Weigh regularly to check pigs’ weights</td>
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Chapter 19
Simulation Modelling

Introduction

Simulation modelling is ordered and quantified thinking; it is a satisfactory scientific endeavour in its own right, involving the creation and validation of understanding through the development and testing of hypotheses. However, equally as important, once an effective simulation model has been created it becomes a highly useful part of production management.

Modelling creates a system that is similar in scope to the industrial process of pig production itself, thereby facilitating effective simulation. Simulation offers prediction; prediction offers planning and control.

Development of simulation models

The ultimate drive for response prediction modelling is – through the application of science – to increase the profitability of production. Production managers must decide upon production strategies that will give the greatest profit within the wider context of the business environment. Only if the biological and monetary outcomes of a change in production practice are known can a sensible decision be made as to what optimum production practice might be.

Broadly, responses to changes in management practice can be predicted by either one of two methods. The first is on the basis of historical precedence, previous experience leading to the conclusion that a certain action will result in a certain response. Unfortunately in pig production this is not particularly useful, as both production and financial circumstances change rapidly. The second approach requires an understanding of the causal forces of responses. If the nature of the driving mechanisms for a response is understood, then responses may be predicted. It is this approach that leads to the building of simulation models. Models can represent the individual production system, and allow themselves to be manipulated in a similar way as would occur to the system in real life. The scope of the modelled system can range from an individual nutritional requirement through to an integrated industry. If the model is good, then the simulated responses and outcomes will mirror the happenings that are likely to occur in reality. By this means managers may reject courses of action that are considered likely to be counter-productive, and may select
appropriate courses of action from amongst various suggested feasible and winning solutions.

Response prediction is most effective when the causes of the responses are relatively few and the system abides by laws that are relatively simple. Causal forces are fewest and operational activities closest to simple laws at the lower, more fundamental levels of biology. Consequently, applied experimentation, being at the higher biological levels, is not the best route to the creation of algorithms for applied response prediction. It is better to use data relating to the lower layers of the active elements of the system and to operate underneath the levels of the interactions.

Production managers who previously made decisions on the basis of a blueprint or historical approach to husbandry practice are likely to experience an inversion of their preconceptions when they move to decision-making on the basis of response prediction. What were previously assumed to be given rules (nutrient requirements, carcass quality targets and the like) are now variables open to manipulation. Success is no longer measured in terms of closeness of fit between biological production targets and biological production achievements, but rather in terms of profitability. Methods of production previously seen as ends are now placed where they should always have been – into the category of means. For example, the blueprint approach to grow-out production begins with a definition of recommended nutrient requirement. Diets are mixed to a given specification and presented to the pigs in a given amount. Such rules have been delineated to provide for pigs of predetermined quality. The production manager works on the assumption that the given feed composition is optimal, and that if the target of pig quality is successfully met, then the production system has been well-controlled and profit will automatically follow. This is not true. On the contrary, the pig production manager requires, first and last, to target profit as the criterion of success. The nutritional specifications of the feed and the feed allowance now become flexible variants open to manipulation, and their optimal definition becomes dependent not on any given recommendation but on the specific circumstances of the production unit and its entrepreneur. The concept of nutrient requirement moves from the domain of the nutritional biochemist to the domain of the nutritional economist. The task of the nutritionist is to predict the outcome of changes in nutrient specification of the diet, not to make the final specification for that diet. The actual specification used should be variable, not given.

Pig producers are well aware of the complexities caused by interrelationships between the factors impinging upon pig growth and sow reproduction, for example increased feeding levels accelerate growth rate and increase throughput, but they also reduce carcass quality. Reductions in feed usage for breeding sows have beneficial short-term effects on margins, but longer-term production may be compromised. The cost–benefit of increasing the feed allowance to growing pigs or breeding sows is a profound calculation which cannot be completed until the facets of the production process are linked interactively. Doing only one part of the calculation (such as the relationship between feed intake and fatness) can lead to erroneous
conclusions. Because of interactions, the manager must be aware simultaneously and quantitatively of all the factors impinging upon the production process. The provision of production recommendations on the basis of intermediate goals, such as growth rate, feed conversion efficiency, carcass quality and sow weight change, is inadequate from the manager’s point of view. Optimum decisions will change with changing production circumstance. Appropriate feed allowances and diet specifications, for example, are likely to vary year by year. Incidentally, it is also an unsatisfactory way of conveying the sum of scientific knowledge that is available.

By simulating the production process, models can allow the manager to make both short-term (tactical) and long-term (strategic) decisions on the basis of improved information, and with proportionately reduced risk. The financial and production consequences of alternations in management practices are deserving of equal consideration, but the bottom line of a management model will always be financial rather than biological. A model does not need to come to a single optimum solution; rather, it is better if it lays out the options that are open to a decision-maker and gives guidance as to the likely outcome of taking those options.

The main purpose of a model (a general description of a nutrient flow model is given in Figure 19.1) is to show the direction and magnitude of the response and the sensitivity of the production system to a tactical or strategic change. For example, altering from *ad libitum* to restricted feeding might be shown by a growth model to reduce growth rate from 900 to 750g per day, and to decrease backfat thickness from 15 to 14mm. What is important is not so much that the simulated growth rate should show an identical response to that in real life, but rather that the model should deliver the information that (1) both growth rate and fatness were reduced, (2) growth rate was reduced to a substantially greater degree than fatness, and (3) these effects are open to being assessed in terms of their financial consequences.
Nevertheless, if a model is to predict consequences of change from a given position, it is helpful if the model starts from a place close to the real-life position so that it can then be tuned in as closely as possible to the current production situation. The simulation should give results similar, but not identical, to those found in real life. This is because responses from any one position do change according to where that position is on the scale (Figure 19.2). For example, growth rate is more sensitive to change in feeding regimes at lower growth rates than at higher growth rates, and 1 mm of backfat depth would be more important for pigs near the upper limit of fatness.

In general, therefore, the results from a simulation model should reflect reasonably closely the real-life situation being simulated. However, exact replication should not be looked for, nor is exactitude a necessary prerequisite for the model to fulfil its purpose.

A model might be referred to by the decision-maker when:

- production is to be optimised, but it is not presently known if that is so;
- performance being achieved is different to that required;
- a change in the production system is contemplated but the consequences of the change are not clear;
- the circumstances of production change;
- the market to which the product is directed changes;
- the markets supplying input to the system change.

A model might be referred to by the pig technician or scientist when:

- experiments are to be planned;
- shortfalls in knowledge require to be identified;
- there is a need for a repository of information to collate knowledge from disparate sources;
- biological phenomena and/or their economic consequences are to be investigated;
- relationships between inputs and outputs require to be demonstrated.
**Diagnosis and target setting**

A simulation model predicts a future outcome. Given an adequate definition of inputs (especially feeding, pig type and environment) and an understanding of the relationships between inputs and outputs, a picture of the resultant response is derived. Model responses may thus serve as targets for the production process: a description of what level of performance is possible within any given set of defined circumstances. A mismatch between predicted outcome and achieved outcome may be due to: inadequacy of definition of inputs; the incursion of perturbing forces not accounted for in the model; or, indeed, errors in the model itself. However, most frequently, a difference between the predicted response and what is achieved in practice simply identifies, and measures quantitatively, a shortcoming in some aspect of management. In addition to indicating the costs of failing to optimise the production system, a model may thus also be used as a diagnostic tool to identify the most likely area of sensitivity which requires priority attention and resolution.

**Information transfer**

In addition to acting as a decision-making aid, simulation models may also be used to transfer information and identify gaps in knowledge. Computer simulation models can contain within them a full range of current scientific awareness, and bring together separated disciplines and experimental results. A model may serve as a library that does not require the books to be either read or understood, but merely used. A sophisticated methodology can by this means be made available to end-users who need not be concerned with the detail.

Short-circuiting the need to understand deep science may also open up such models to misuse. The model builder will have had to make choices and to have included information of varying degrees of validity. Because models require information in a chain of events, the modeller must sometimes interpolate in order to fill gaps, and the user may be (dangerously) unaware of such weaknesses. Nevertheless, whilst it is important that model-builders are honest with model-users about the weaknesses (and strengths) of their products, a model need not necessarily be exactly right in order to be helpful. It is sufficient merely that a new methodology is some improvement upon that which it supersedes.

There is little doubt that from now on computers will ensure that the vast proportion of information transfer between science and practitioners will be through the medium of simulation models and other similar computer packages. If the need to complete information strings is a short-coming in a simulation model, this is an advantage inasmuch as the gaps in knowledge are identified and not ignored. One of the beauties of a model is that it requires quantification of production parameters. Researchers may be pointed toward areas of ignorance where further experimentation is needed. Sensitivity analysis of model components will throw light upon which aspects of a system require to be known accurately and which only approxi-
mately. It is sometimes the case that the pursuit of science may encourage ever more precise knowledge in areas where an approximation would do. On the other hand, matters of primary importance for investigation may (wrongly) be left on one side because they are perceived as being too difficult, or worse, scientifically unfashionable. Computer models can assist in organising research resources to avoid the study of non-problems, and to prevent the refinement of measurements that do not need to be further refined.

**Production control systems**

Growing pigs for meat is, like other production processes, only efficient when there is a production control system optimising the process, and this implies some level of understanding of how the variables can be manipulated. This in turn implies effective measurement of present performance, and a model through which change in that performance may be modulated in a predictable way. Thus:

- The rate of production (daily live weight gain) relates to the rate of input of the primary raw material (daily feed supply).
- The efficiency of production of the output is a function of the total quantity of input resource used (kilograms of feed used per kilogram of pig sold).
- Inefficiencies result in waste products (such as ammonia) which have disposal costs.
- The process is limited by the availability of the first limiting resource, which will likely be one of:
  - the quality of feed and of management inputs;
  - the ability of the pig to make use of the inputs presented to it.
- Management depends upon process control:
  - production targets;
  - measurement of the status of the product at any given moment;
  - the possibility of predictable correction of deviations from required performance.
- Amongst management’s tools would be:
  - the genetic selection of the pig to grow high quality meat at the required rate and of the required ratio of lean to fat;
  - the daily amount of feed supplied;
  - the balance of energy to amino acid in the diet;
  - the choice of the moment of slaughter (target size).

Effective use of these tools, and the decisions pertaining to their use, is necessarily an on-going (day-by-day) process, not least because:

- the amount of feed the pig requires changes daily as it grows;
- the balance of energy to amino acids required in the diet changes daily as the pig grows;
• both of the above are affected by the ambient and the disease environment which fluctuates on a short time-scale;
• the inherent potential of an individual batch of pigs is not well characterised at the point of entry into the grow-out unit;
• all the interacting elements of the production process are subject to short-term biological variation.

Presently, pig production is usually managed retrospectively, and not in real time. At worst, pigs are fed according to some general rules (nutrient requirements) pertaining to general populations and measured with pigs from various points in historical time. At best, pigs are fed according to the lessons learned from previous batches reared in like circumstances. Pig production systems therefore rarely use the available management tools to control the process and maximise the efficiency of production of meat of the required quality. There are three important reasons for this:

(1) The relationships between change in input (amount and quality of feed) and change in output (amount and quality of pig carcass) are inadequately known at the level of the individual production plant (farm). Such descriptors require to be flexed to fit the conditions prevailing to any given time, place and circumstances of production. There is a need for accurate and flexible models of pig nutrition and growth.

(2) The progress of the process is usually only poorly known. Short-term (and long-term) changes in growth rate are difficult to measure. There is a need for an effective way to monitor and measure the growth of pigs in real time.

(3) The most effective means of controlling the rate of pig growth and the fatness of the end-product is by altering the amount and the composition of the feed supplied. As the deviations are in the short term, so also must be the corrective actions. Feeding systems that allow daily control of both amount and composition of diets fed are presently available. However, they are rarely used to their full level because of inadequate monitoring of present positions of the pigs, and insufficient accuracy of prediction of consequences of changes to the pigs’ diets. In the event, systems that can deliver variable quantities and qualities of feed on a daily basis are usually programmed to a preset pattern over the whole of the grow-out cycle. Computer-controlled feeding systems await management tools for their effective deployment.

The position of a model in the management system is depicted in Figure 19.3. Importantly, a model should be flexible enough to learn from its errors. Crucial to its use is an ability to measure effectively change in pig state. The model requires information on nutrient inputs, pig character and farm character.

An effective model will link primary nutrients to tissue retention, determine variable efficiencies for energy and protein utilisation, and integrate nutrient cycling into a single system for maintenance and growth. These characteristics allow the model to be optimised on the basis of few parameter values. Models need to be
good not just at predicting the magnitude and direction of the growth response to nutrients, but also at quantifying that response. Given the nature and number of the variables in the system, it is unreal to expect a model to hit its targets without knowledge of the system in which it is operating (measurement), and without ability to flex to that system. Model flexing requires the manipulation of model parameters; clearly, the fewer the better. Recently at Edinburgh we have determined that manipulating only two parameters could optimise our model, and when flexed, the model was sufficiently accurate to be used in a management control context for particular (rather than general) production circumstances. The parameters concerned were lean tissue growth rate (pig genotype) and ‘maintenance requirement’ for both energy and protein, which essentially described the production management and the effects of disease upon the efficiency of nutrient use.

**Model-building approaches**

Simulation models usually exercise themselves through the medium of computing, and are made up of algorithms comprising mixtures of rules and mathematical equations. Relationships within models can range from empirical regression derived from trial data (for example, live weight gain on feed intake, litter size on parity number) to deductive sequences of mathematical descriptions relating to the fundamentals of biochemistry and physiology. Empirical regression tends to be static and inflexible, and strictly best used to find intermediate points within a given data set. There is no reason to believe that a regression relationship will necessarily throw light on the nature of the causes of the responses achieved.

Relationships linking inputs to outputs can be of three general types. The first is unacceptable in all circumstances, the second acceptable where no better methodology is available and the third is the gold-standard for simulation modelling:

1. the empirical linking of parameters of production with high statistical accuracy, but using constants and coefficients that are biologically nonsensical;
(2) the empirical linking of parameters of production through the use of constants and coefficients which are reconcilable with biological expectations;

(3) the linking of inputs and outputs through the medium of their causal forces; that is, by the employment of deduction;

For deductive methodology to be effective, a relatively complete knowledge of the system is required. Therefore, although more logical, the deductive approach is likely to contain a mixture of hard fact, soft fact, hypothesis and even inspired guesswork. Empiricism, on the other hand, is often an undeniable and exact expression of a past observation, but that expression may or may not be useful in terms of understanding or of predicting a future response.

Working models tend to be made up of mixtures of empirical and deductive relationships, but the greater the extent to which the model relies upon the deductive approach, the more likely it is to be truly informative. Deduction – building up input:output relationships from a knowledge of the causal forces – increases the flexibility of a model and allows prediction outside the circumstances within which the information was collected. Such a model can therefore account for a wide range of interactions. The same deductive approach also helps in the understanding of the system: it highlights ignorance and allows sensitivity analysis and definition of crucial components.

Deductive modellers should be judged on their ability to form hypotheses about the nature of life, because these will control the algorithms. Modelling is best pursued at the level of basic principles. Preconceived notions on the use of empirical analyses of trial data are likely to lead to less effective simulation. Deductive models employ what is known of the science of pig production, and the necessary hypotheses reflect the nature of the science that goes into them. The deductive model thus goes further than merely re-describing phenomena previously observed. It avoids simplistic recounting of history and attempts to foresee the outcome of future activities. There remain, nevertheless, many phenomena that need to be described within a model but for which causal forces are not understood. In this event, relationships can only be approached in an empirical way. It is evident from preceding chapters that it is easier to be deductive about the growth responses to nutrition than about the equivalent reproductive responses. Of necessity, therefore, sow reproduction models are much more empirical in their structure than growth models. Similarly it is easier to be deductive about how much fatty tissue will be deposited in the body than about where it may be deposited; the latter can only be simulated empirically.

The empirical and deductive approach may be contrasted with the following example. It is accepted that as pigs grow bigger they become fatter. Regression relationships can be drawn up with fatness as a function of live weight. Using this relationship, increasing fatness may be predicted as a consequence of increasing weight. This empirical relationship leads to the conclusion that slaughter at a heavier weight will invariably result in a fatter carcass. On the other hand, to obtain a deductive function between fatness and live weight, the causative forces require to be identi-
fied. One reason why animals may get fatter as they get bigger is because their appetite increases, and the extra feed consumption has gone into the production of fat. This will only happen if the potential rate for lean growth has been reached. Therefore there are interactions between pig type, feeding level and the likelihood of fattening. By considering the causal forces, fatness is seen not to be a direct function of live weight itself but manipulable according to feed intake and pig type. At the extreme, there need be no relationship between fatness and live weight, animals of high lean growth potential being able to eat to appetite and remain equally as thin at 100kg as they were at 20kg. The deductive and the empirical approaches present the production manager with quite different sets of propositions as to how pig carcasses may be made more lean, and as to what the consequences of an increase in slaughter weight might be.

It is evident that the empirical paradigm of the growth response to feed intake shown in Figure 19.4, whilst being a wholly correct construct for an experimental result, is quite inadequate for effective simulation of the type required by production managers. The deductive approach is shown in Figure 19.5 in the form of a flow...
diagram relating feed to growth. This second approach is more complete, requires a deeper understanding of the relationships and is therefore more likely to simulate real life responses under a wide range of circumstances, including those different from the original conditions under which data were collected. The flow diagram shows how information is required about the relationships in the system. So, in wishing to define growth response to feed intake, relationships between pairs of factors such as feed and maintenance, feed and cold thermogenesis, feed and lean tissue growth potential, feed and fatty tissue production must all be understood at the level of their causal forces.

A model forces its builder toward better understanding of the system being modelled; otherwise it will not work effectively. The scientist must describe a living system systematically, and ensure all the parts are interlinked in a way that properly reflects nature. Once built, however, good models may stand in the place of real life experiments. Traditional nutritional response trials are no longer required now that the causal forces of these responses may be modelled effectively. Where possible, modelling approaches discussed here are deductive (deal stepwise with causal relationships in a biologically coherent manner), dynamic (respond sensitively to changes in inputs in a way reflective of real-life pig production) and deterministic (simulate response by arrival at a single quantitative prediction of an outcome).

A simulation model to predict the performance of the growing pig

The object here is to describe a model that is able to predict dynamically the effects of genotype, and the nutritional, thermal and social environments on the voluntary feed intake, growth and body composition of pigs. The starting point is the prediction of potential growth from descriptions of the genotype and current state of the pig. The effects of the nutritional, thermal and social environments on pig performance are then represented.

Composition and growth

Initial body composition

Simulation of growth and its component parts requires characterisation of the live weight (W, kg) and composition at the start, which may be immediately after weaning or at some subsequent point. At the point of weaning, pigs will usually contain 0.16 × W of protein from which the weights of ash (At, kg), water (Yt, kg) and lipid (Lt, kg) can be calculated, assuming that the pig has its desired chemical composition:

\[ \text{Protein (Pt, kg)} = 0.16 \times W \]  \hspace{1cm} (19.1)

\[ \text{Ash (At, kg)} = 0.19 \times \text{Pt} \]  \hspace{1cm} (19.2)
where \( P_{t_{\text{max}}}, L_{t_{\text{max}}}, \) and \( Y_{t_{\text{max}}} \) are the weights of lipid, protein and water respectively at maturity (kg), \( Y_{t_{\text{max}}}/P_{t_{\text{max}}} \) is the water to protein ratio at maturity with an assumed value of 3.04 kg/kg for all genotypes. The value of \( d \) is estimated as \( 1.46 \times (L_{t_{\text{max}}}/P_{t_{\text{max}}})^{0.23} \) to reflect its strong relationship with mature fatness.

The whole empty body of the pig (without the content of the gut, \( W_{e} \)) is the sum of its parts:

\[
W_{e} (\text{kg}) = P_{t} + L_{t} + A_{t} + Y_{t} \tag{19.5}
\]

As the gut contents usually comprise about 5% of the body weight, then the live weight \( W \) is:

\[
W (\text{kg}) = 1.05 \times W_{e} \tag{19.6}
\]

Gut fill may, however, be better estimated with a knowledge of the fibre content of the diet concerned. Fibre both attracts water into the gut and increases the volume of dry matter in the intestine as a result of a reduction in the rate of digestion and of passage. There can be 1–2% difference in carcass yield due to the effects of variation in gut fill alone. So where:

\[
W (\text{kg}) = W_{e} + \text{gut fill} \tag{19.7}
\]

gut fill may be estimated as:

\[
\text{Gut fill (kg)} = 0.05 \times W_{e} \times [1 + 8 \times (\text{CF} - 0.04)] \tag{19.8}
\]

where \( \text{CF} \) indicates dietary crude fibre concentration (kg/kg).

**Potential growth**

The limits to the rate of growth, as described by the inherent maximum value for daily protein retention \( (\text{Pr}_{\text{max}}, \text{kg/day}) \) are best described by the Gompertz function:

\[
Pt (\text{kg}) = P_{t_{\text{max}}} \times e^{-e^{-B_{p}(t-t_{r})}} \tag{19.9a}
\]

\[
\text{Pr}_{\text{max}} (\text{kg/day}) = dPt/dt = B_{p} \times Pt \times \ln(P_{t_{\text{max}}}/Pt) \tag{19.9b}
\]

where \( B_{p} \) is the Gompertz rate coefficient for protein (per day), \( Pt \) is the present protein mass (kg) and \( P_{t_{\text{max}}} \) is the final (mature) protein mass (kg). Of limited use is the alternative expression of the first derivative of the Gompertz function as a function of time:

\[
\text{Pr}_{\text{max}} (\text{kg/day}) = B \times e^{-B_{p}(t-t_{r})} \times P_{t_{\text{max}}} \times e^{-e^{-B_{p}(t-t_{r})}} \tag{19.10}
\]
Here $t$ indicates time (days) relative to the point of inflection, $t^*$ (days). The absolute value of $t$ is arbitrary, and has no connection with the age of the animal. $Pr_{\text{max}}$ is more properly a function of the state of the animal ($Pt$) rather than of time, so Equation 19.9b is generally the more appropriate.

Values for $Bp$ may range from 0.0095 to 0.0135 and $Pt_{\text{max}}$ from 32.5 to 52.5, dependent upon sex and genotype. Values for $Pr_{\text{max}}$ increase rapidly in early life to reach a peak value soon after one third of the mature size has been attained. The function has a relatively flat-topped plateau over much of the 20–120 kg growth period, diminishing to zero as maturity is approached. The point of inflection, $t^*$, denotes the time of maximum growth. This maximum growth rate is given by:

$$Pr_{\text{max}}^* (\text{kg/day}) = B_p \times Pt_{\text{max}} / e$$

and occurs at the point $Pt = Pt_{\text{max}} / e$, where $e$ is the base of natural logarithms. In the knowledge of any two of $Pr_{\text{max}}^*$, $Pt_{\text{max}}$ and $B_p$, the third may be determined.

Fat growth might be perceived as also following a Gompertz growth curve, and as having its own appropriate estimates for $Lt_{\text{max}}$ and $B_L$ (mature lipid mass and the rate coefficient) from which a value for $Lr_{\text{max}}$ (the maximum daily limit to lipid retention pertaining at any given point in growth) can be derived. However, such an approach is not appropriate for total body fat, which may often fulfil the role of body energy storage and the accommodation of excess dietary energy provision over daily need. It is probably realistic to suggest that no upper limit to lipid growth need be set independent of that imposed by appetite.

It is reasonable to require in a model some view of a minimum level of lipid growth. Here it can be proposed that under normal conditions of positive growth, and when nutrient supply is insufficient to maximise protein growth ($Pr < Pr_{\text{max}}$), the pig will nevertheless wish to deposit some fatty tissue. This will set the minimum fatness for the animal. The proposition can be framed in terms of a minimum ratio of lipid to protein in the total body ($Lt:Pt)_\text{pref}$ and in the daily live weight gain ($Lr:Pr)_\text{min}$, both may range from 0.4 to 1.2, depending on sex and genotype. The ratio may depend to a small extent upon the size of the pig and its degree of maturity, thus:

$$\frac{(Lt:Pt)_\text{pref}}{(Lt:Pt)_\text{pref} + b(Pt)} = \frac{(Lr:Pr)_\text{min}}{(Lr:Pr)_\text{min} + b(Pt)}$$

where $b$ is presently an unknown small number.

Unless $(Lt:Pt)_\text{pref}$ is particularly high and pigs are reaching slaughter weight with excess levels of fat and failing to grade satisfactorily, it is to be expected that under normal circumstances $Lt$ will exceed $(Lt:Pt)_\text{pref}$ and $Lr$ will exceed $(Lr:Pr)_\text{min}$. Where $(Lr:Pr)_\text{min}$ is less than 0.9, and body composition at slaughter is such that $Lt < Pt$, it is unlikely that pigs would be considered overfat. Therefore this lower boundary to fat growth is significant to carcass quality with pigs of fatty type destined for meat markets that discriminate against fat.

In times of energy shortage, not only can pigs grow lean tissue without accumulating fatty tissue, but also lipid may actually be catabolised ($Lr$ is negative) to
support protein growth (Pr is positive). In these circumstances (of fatty tissue catabolism), it is important to present in a model some view of both Lr:Pr (the ratio of lipid to protein in the growth) and Lt:Pt (the ratio of lipid to protein in the total body mass). In the absence of better information, values for (Lt:Pt)$_{pref}$ may also be used to approximate settings for (Lr:Pr)$_{min}$. It is notable in this respect that Lt:Pt $> 1$ is considered necessary for effective reproduction in breeding sows.

Suffice it to say that an effective simulation is crucially dependent upon full and exact characterisation of the pig that is to be simulated. The correct estimation of Pr and (Lt:Pt)$_{pref}$ is essential for the modelling of growth, as these parameters describe the bounds within which the nutritional response will function.

**Nutrient yield from the diet**

**Energy**

Where the digestible energy (DE) content of a diet is not known from direct measurement of the diet itself or of the ingredients, it can be postulated that for dry matter (DM), where the nutrient proportions are given as kg/kg:

\[
\text{DE (MJ/kg)} = 16 \times \text{STARCH} + 35 \times \text{OIL} + 19 \times \text{PROTEIN} + 1 \times \text{FIBRE} \tag{19.13}
\]

which is probably a little generous in its assumption about the digestibility of the diet components. The term for starch includes simple carbohydrate. Fibre in this regard is not, of course, crude fibre (CF) but more properly the larger non-starch polysaccharide fraction, as may be represented by neutral detergent fibre (NDF). Empirical regressions have included the useful:

\[
\text{DE (MJ/kg DM)} = 17.5 - 15 \times \text{NDF} + 16 \times \text{OIL} + 8 \times \text{CP} - 33 \times \text{ASH} \tag{19.14}
\]

where CP is crude protein. If CF has been determined rather than NDF, it is possible to use the rather less efficient:

\[
\text{DE (MJ/kg DM)} = 18.3 - 32.7 \times \text{CF} - 19 \times \text{ASH} + 11 \times \text{OIL} \tag{19.15}
\]

Daily energy intake (DE$_t$) is:

\[
\text{DE$_t$ (MJ/day)} = pDM \times F \times \text{DE} \tag{19.16}
\]

where pDM is the proportion of dry matter in the air-dry feed (kg/kg) and F is the air-dry feed intake (kg/day) (pDM is omitted from those equations below where F is present). DE is an adequate descriptor of the energy value of a feedstuff but not of the ultimate yield of dietary energy to the metabolic processes of the pig. First, DE embraces the 23.6 MJ/kg of energy contained within ileal digested dietary protein moieties that are not immediately available for energy transfer, and indeed much of which will, hopefully, be used for protein growth (Pr) or milk synthesis (discussed below), and therefore not available for energy production at all. Second, there is a small element of energy ‘digested’ but not ‘captured’ (such as in gases pro-
duced from hind-gut fermentation). Metabolisable energy (ME, MJ/kg) encompasses these losses and the total available (ME$_t$, MJ/day) can be calculated for given feed intake (F) and protein retention rate (Pr):

\[
\text{ME}_t (\text{MJ/day}) = F \times (\text{DE} - 0.05 \times \text{DE}) - (7 + 5) \times (D_a \text{CP} - \text{Pr})
\]

(19.17a)

\[
D_a \text{CP (kg/day)} = F \times pD_a \text{CP} = F \times D_a \times \text{CP}
\]

(19.17b)

Here, the 0.05 $\times$ DE term indicates the gaseous losses. $pD_a$CP (kg/kg) is the proportion of air-dry feed that is ileally digestible crude protein, having digestibility $D_{il}$ (kg/kg); $D_a$CP is the daily total intake of the same. As only a part of the digested protein appears in growth as Pr, or in the milk, there will be some protein energy available from deamination; what has been digested but not retained must be deaminated and excreted. In the above equation, the mass of deaminated protein is given by the $(D_a \text{CP} - \text{Pr})$ term; it is assumed that urine carries 7 MJ/kg of protein deaminated, and the work energy needed for urea synthesis is 5 MJ/kg protein deaminated.

The available metabolisable energy (ME$_t$) has accounted for the portion (23.6 $\times$ Pr) that, although metabolisable, is nevertheless retained as body protein and not available for work. ME$_t$ may now be offered to the animal for its use to support the needs of maintenance, protein retention, lipid retention, the products of conception, lactation and cold thermogenesis.

**Protein**

The dietary content of protein may be determined from chemical analysis for nitrogen (crude protein, CP = 6.25 $\times$ N). The digestibility of the CP is variable amongst feedstuffs, and it is further apparent that determination of the ileal digestibility will avoid errors in estimating hind-gut disappearance. Ileal digestibility of CP ranges from 0.3 to 0.9.

In addition to knowing the daily dietary yield of ileal digested crude protein ($D_a$CP), a model to simulate protein use requires knowledge of the ileal digested amino acids and their relative proportions, in order to estimate $V$, the protein value. This is the ratio between the proportion of the most-limiting amino acid in the ileal digested amino acids ($pAA_{DilCP}$) and the proportion of the same amino acid in ideal protein ($pAA_{IP}$):

\[
V (\text{kg/kg}) = pAA_{DilCP} / pAA_{IP}
\]

(19.18)

The spectrum of amino acids in ideal protein is properly not a constant, and varies according to the size and metabolism of the animal. The total ideal protein available for metabolism (IP$_t$) and the support of maintenance, protein growth and reproduction may be determined as:

\[
\text{IP}_t (\text{kg/day}) = D_a \text{CP} \times F \times V \times v
\]

(19.19)

where $v$ is the efficiency of use of ileal digested ideal protein for body processes when not provided in excess (this value includes the material inefficiencies of
protein recycling). While $D_a$ may usually average around 0.75 for mixed pig diets, $V$ may range from 0.80 for young pig diets to 0.65 for sow diets, and $v$ is usually around 0.80.

**Nutritional requirements**

**Energy**

The total energy requirement ($E_{req}$, MJ/day), assuming thermoneutrality, is the sum of the energy requirements for maintenance, protein retention and lipid retention.

Maintenance energy requirement ($E_m$, MJ ME/day) is defined as that needed to maintain zero rates of retention of both protein and lipid. Energy expenditure from exposure to disease-causing organisms is assumed to be negligible and any costs of thermoregulation are calculated separately (see later). It can be quantified as:

$$E_m(\text{MJ ME/day}) = \left(1.63 \times P_t\right)/P_{t_{\text{max}}}^{0.27}$$  \hspace{1cm} (19.20)

where $P_t$ is the total protein mass at the given moment in time when the maintenance requirement is to be estimated and $P_{t_{\text{max}}}$ is the protein weight at maturity. The energy costs of maintenance are assumed to include a minimum level of pig activity. In many production systems activity is not minimal, and activity may be costed as a further addition of $0.1 - 0.2 \times E_m$.

The energy needed above maintenance to allow potential growth to be attained depends on the energy cost of protein ($E_{Pr}$) and lipid ($E_{Lr}$) retention and their respective daily rates of retention ($Pr$ and $Lr$). Taking the efficiency of conversion of energy for protein retention ($k_{Pr}$) as 0.44, and fixed rather than variable, which is an unfortunate oversimplification, then the simple equation

$$E_{Pr}(\text{MJ ME/day}) = 23.6 \times Pr + 31 \times Pr = 54.6 \times Pr$$  \hspace{1cm} (19.21)

expresses the energy cost of protein retention ($E_{Pr}$), 23.6 MJ being deposited and 31 MJ leaving as heat following the work of protein synthesis.

Taking the efficiency of conversion of diet ME to body lipid ($k_{Lr}$) as 0.75 (again a simplification), then the equation

$$E_{Lr}(\text{MJ ME/day}) = 39.3 \times Lr + 14 \times Lr = 53.3 \times Lr$$  \hspace{1cm} (19.22)

expresses the energy cost of lipid retention ($E_{Lr}$), 39.3 MJ being deposited in the fatty tissue and 14 MJ leaving as heat.

**Protein**

The requirement for dietary protein may be expressed in terms of ideal protein (Equation 19.19); however, where the digestibility and requirements for individual amino acids is known, this is an unnecessary approximation, and the requirement may be better constructed on the basis of the nine essential amino acids appearing at tissue level in a utilisable form.
In terms of ideal protein, the maintenance protein requirement \((IP_m)\) may be given as:

\[
IP_m (\text{kg/day}) = \left(0.0040 \times Pt\right)/Pt_{\text{max}}^{0.27}
\]  

(19.23)

Ideal protein required for production \((IP_{Pr})\) is that actually used, because the factors \(V\) and \(v\) have already accounted for all inefficiencies.

**Feed intake**

*Desired feed intake*

It is assumed that the pig will attempt to consume an amount of feed that will satisfy its requirements for both energy and protein. The feed intake that allows this to be achieved is the ‘desired’ feed intake \((F_d, \text{kg/day})\). If energy is first limiting, then \(F_d\) will be:

\[
F_d (\text{kg/day}) = \frac{E_{\text{req}}}{\text{Diet concentration of ME}}
\]  

(19.24)

If the feed is first limiting in ideal protein, then \(F_d\) will be:

\[
F_d (\text{kg/day}) = \frac{IP_{\text{req}}}{\text{pD}_{\text{a}} \times \text{CP}}
\]  

(19.25)

When a feed is perfectly balanced in its energy and protein content, then the above two equations will be equal.

*Constrained feed intake*

Calculation from perceived nutrient needs represents the upper limit to feed intake as controlled by the metabolism of the animal. This boundary may need to be curtailed if the bulk of the daily feed intake is beyond the physical capacity of the gut. The constrained feed intake \((F_c, \text{kg/day})\) is given by:

\[
F_c (\text{kg DM/day}) = \frac{C_{\text{WHC}}}{\text{WHC}}
\]  

(19.26)

where WHC is the water-holding capacity (kg water per kg dry feed) and is used as the scale of bulk, and \(C_{\text{WHC}}\) is the animal’s capacity for water holding (kg/day) and is calculated as:

\[
C_{\text{WHC}} (\text{kg DM/day}) = 0.230 \times W - 0.000476 \times W^2
\]  

(19.27)

\(F_c\) is converted from kilograms of DM to kilograms of feed as fed by dividing by the dry matter content of the feed. Actual feed intake \((F_a, \text{kg/day})\) before any thermal constraints (see below) is predicted as the lesser of \(F_d\) and \(F_c\), i.e. the pig will achieve its desired feed intake unless the bulkiness of the feed limits it. The effects of the thermal and social environments on feed intake are described later.
**Composition and growth from actual feed intake**

Where the environment is thermally neutral, the prediction of the actual rates of gain of the four body components (actual growth) can be calculated from $F_a$ and the feed composition:

$$Pr(\text{kg/day}) = e_p \times (F_a \times \text{DCPC} \times \nu - \text{IP}_m)$$  \hspace{1cm} (19.28)

subject to the $Pr_{max}$, and where DCPC is the digestible crude protein content of the feed (kg/kg) and $e_p$ is the efficiency of ideal protein utilisation for growth and equal to $0.0112 \times (\text{MEC/DCPC})$ up to a maximum value of 0.81. The ratio of metabolisable energy content to digestible crude protein content is effectively a measure of diet quality and density.

Following the calculation of protein retention, the retention of the other body components, and hence whole body growth ($BW_r$), can be calculated as follows:

$$Ar (\text{kg/day}) = 0.19 \times Pr$$  \hspace{1cm} (19.29)

$$Yr (\text{kg/day}) = Pr^a \times Y_m \times 0.855 \times (Pt/Pt_{max})^{(0.855-1)}$$  \hspace{1cm} (19.30)

$$Lr (\text{kg/day}) = [EI - E_m - (b_p \times Pr)]/b_1$$  \hspace{1cm} (19.31)

$$BW_r (\text{kg/day}) = (Pr+Lr+Ar+Yr) \times 1.05$$  \hspace{1cm} (19.32)

$EI$ is the daily energy intake (MJ, ME/day) and equal to $FI_a \times \text{MEC}$, and $b_1$ depends on whether $dL/dt$ is positive or not. In the case of a negative value for $dL/dt$, the coefficient $b_1$ is the heat of combustion of lipid which is estimated as 39.6 MJ/kg.

In this form there is no boundary to total lipid loss. However, the fact that an animal cannot lose lipid that is not present, and must have some minimum lipid content ($L_{t\min}$, kg) necessary for survival, is accounted for by assuming $(L_t \leq L_{t\min})$ to be equal to $0.1 \times Pt$. If the condition $L_t \leq L_{t\min}$ is reached then the rate of protein retention is reduced in order to maintain the minimum body lipid level.

**Influence of the thermal environment on pig performance**

When pigs are too hot the feed intake falls. When pigs are too cold they need energy to keep warm, and this must be added to the energy requirement. Whether a pig feels a temperature that is other than thermonutral is dependent not only on the ambient temperature but also how much heat the pig is generating itself. This in turn is a function of the metabolic rate (energy usage for maintenance and growth). Put simply, if heat output from the pig is high due to high feed intake and to anabolism, the pig is more likely to feel hot in a hot environment and less likely to feel cold in a cold environment. If a pig is hot it must eat less; if it is cold it will use energy to keep warm; that is, for cold thermogenesis, burning energy to increase heat generation.

Empirical measurements have estimated the energy cost of cold thermogenesis to around $0.012 \times W^{0.75}$ MJ ME/day for every degree of temperature difference.
between the temperature that the pig is seeking to be living in (thermoneutrality) and the effective temperature in which the pig actually finds itself. Effective temperature is usually presumed to be the ambient temperature modified by the rate of air movement (loss of heat to air), the extent of floor insulation (loss of heat to the floor) and the possibility of moisture falling onto the pig’s back (loss of heat by evaporation). The intricacies of quantifying these parameters have been elucidated recently by the Edinburgh group [Green, D.M. and Whittemore, C.T. (2003) Architecture of a harmonized model of the growing pig for the determination of dietary net energy and protein requirements and of excretions into the environment (IMS Pig), Animal Science, 77, 113–130].

In brief, to calculate the effect of the thermal environmental on pig performance, it is necessary to do two things. The first is to calculate the heat production (HP, MJ/day). The second is to assess the current climate in order to determine the maximum (HL_{max}, MJ/day) and minimum (HL_{min}, MJ/day) heat the pig is able to lose into the given environment. A comparison with the pig’s calculated heat production (HP, MJ/day) determines whether the pig is hot (HP > HL_{max}), cold (HP < HL_{min}) or thermoneutral (HL_{min} < HP < HL_{max}). A constraint on intake will operate in hot environments due to an inability to lose the heat produced by maintenance and growth to the surrounding environment. In cold environments, there is an extra thermal demand placed upon the pig. If conditions are thermoneutral, no further action is taken.

The pig in a cold environment

A pig may be said to be in a cold environment, below thermoneutral conditions, when the heat flow lost from its body (HL_{min}, MJ/day) exceeds that which it may suffer without increasing heat production (HP, MJ/day) in order to maintain core body temperature. Above the lower critical temperature, where HL_{min} = HP, behavioural and physiological adjustments alone are enough to maintain core temperature. Inter alia, such adjustments include, if possible:

- huddling in groups when housed in pens;
- avoiding wetting;
- decreasing heat conductivity of body surface tissues (by modifying blood flow);
- preferential contact with well-insulated surfaces.

Heat output associated with metabolism (HP) can be estimated by difference: all of the ingested energy intake that is not lost in faeces, gas or urine, or retained in bodily protein or lipid, is lost as heat. Of these losses, the faecal portion is the difference between gross and digestible energies (GE – DE), and the gaseous and urinary portions are the difference between digestible and metabolisable energies (DE – ME). Therefore the simplest statement of heat loss from the pig can be given by:

\[ HP \text{ (MJ/day)} = ME - (23.6 \times Pr + 39.3 \times Lr). \] (19.33a)
For a DE energy system, this equation becomes:

$$HP(\text{MJ/day}) = \text{DE} - [(D_a \text{CP} - \text{Pr}) \times 7.2 + G_{\text{gas}} + 23.6 \times \text{Pr} + 39.3 \times L_r] \quad (19.33b)$$

where $G_{\text{gas}}$ indicates the total loss of energy through gas (kg/day), which may be estimated as $0.05 \times \text{DE}$.

Where $HP < H_l_{\text{min}}$, the pig is cold and extra energy must be channelled into heat production. This can be achieved simply in models by adding an additional energy requirement alongside $E_m$. In models that simulate the production and use of ATP, heat production can be taken as an extra drain on the ATP pool.

The pig in a hot environment

The modelling of hot environments is similar to that of cold environments: the model algorithms are similar, with differences mainly in the parameter values. A pig is in a hot environment if the heat flow from its body ($H_{L_{\text{max}}}, \text{MJ/day}$) is less than the heat production, and thus core body temperature rises. Above the upper critical temperature, behavioural and physiological adjustments alone are insufficient to prevent this, and heat production itself must be reduced. These adjustments are largely the opposite of those mentioned for the cold environment:

- avoidance of huddling;
- wetting of the body surface;
- increasing conductivity of body surface tissues to heat flow;
- reduction of activity;
- avoidance of well-insulated surfaces.

Where $HP > H_{L_{\text{max}}}$, heat output must be reduced. This can be implemented in models through a reduction in feed intake, which causes a concomitant decrease in heat production as calculated in Equations 19.33a and b.

Live weight and fatness play a role in determining critical temperatures: larger animals have a lower surface area to volume ratio and are thus less able to lose heat readily. Therefore, there is a tendency for the lower critical temperature to be exceeded more often for smaller pigs and the upper critical temperature more often for larger pigs. Similarly, fatter animals may have more subcutaneous fat. In this case, there is more potential for the animal to reduce heat loss in cold conditions.

Parameters for heat flow models

Four routes for heat loss from the pig exist: convection, conduction to surrounding surfaces, evaporation and radiation. Additionally, the pig can receive heat radiated from external surfaces and heat sources, and through conduction. The surface of the pig can be divided into four fractions, each of which is subject to these heat losses to different degrees: area in contact with air (both wet and dry skin), with the floor and with other animals. Heat can be conducted to the floor, convected and radiated from air-exposed skin and evaporated from wet skin (and the respiratory tract).
Thus, the behaviour and posture of the animal are critical in determining the heat loss and there is flexibility in the heat loss the animal can achieve without increasing or decreasing heat production.

Table 19.1 indicates a number of environmental parameters in use by thermo-regulation models and their effects on the routes for heat loss. It should be noted that these effects are by no means additive. For example, heat loss by evaporation in conditions where the air is fully saturated will be negligible, regardless of ambient temperature. Differences in parameters would imply that different strategies are required by the pig to maximise or minimise heat loss.

### Table 19.1. The effect of environmental parameters on heat loss through the four routes. + indicate a positive effect, – a negative effect.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conduction</th>
<th>Radiation</th>
<th>Convection</th>
<th>Evaporation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature (K)</td>
<td></td>
<td>+</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Floor material (Km²/W)*</td>
<td>–</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air speed (m/s)</td>
<td></td>
<td>+</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Ambient humidity (kg/kg)</td>
<td></td>
<td></td>
<td></td>
<td>–</td>
</tr>
<tr>
<td>Wet area of pig (m²/m²)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>Group size (where cold)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

* Warmer flooring materials, such as straw bedding, have a higher value for this parameter.

Thus, the behaviour and posture of the animal are critical in determining the heat loss and there is flexibility in the heat loss the animal can achieve without increasing or decreasing heat production.

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### Influence of the social environment on pig performance

An evident and major problem in simulating and predicting pig response to nutrient intake is between-farm differences. The causes of these include inadequate feeder space provision, ill-considered self-feeder flow control, the number of pigs in the pen, the wholesomeness of the diet and a whole host of other factors under direct management control. The influence of environmental factors can make a nonsense of attempts to model feed intake and performance on the basis of pig biology.

### Representing the effects of social stressors on performance

Physical environmental stressors affect pig performance in an ordered way via known mechanisms. In contrast, the way in which social stressors act is not clear. Nonetheless, substantial advances have been made in this important subject by the Animal Health and Nutrition Group at the Scottish Agricultural College, Edinburgh. It is assumed that social stress decreases the capacity of the animal to attain its potential. This is equivalent to lowering the maximum rate of daily gain (ADGₚ, kg/day) (effectively, Pr_max), determined by B_p in the model, that the pig is able to achieve. As it is assumed that animals eat to attain their potential, a decrease in ADGₚ necessarily leads to a decrease in FIᵦ. Intake is directly affected as a result
of social stress only when feeder space allowance (FSA) is limiting. Increases in maintenance energy requirements \( (E_m, \text{MJ/day}) \) are used to represent increases in activity level due to stress.

**Space allowance**

The effective pen space allowance (SPA) per pig may be calculated as:

\[
\text{SPA (m}^2\text{)} = \frac{\text{Area}}{W^{0.67}}
\]  

Decreasin the SPA available to a group of pigs, below a critical value, SPA$_{\text{crit}}$, depresses pig performance. When \( 0.019 < \text{SPA} < 0.039 \), the relative body gain (or percentage of \( \text{Pr}_{\text{max}} \)) achieved, \( R_{\text{SPA}} \), in relation to that recorded at an \( \text{SPA} > \text{SPA}_{\text{crit}} \) is calculated as:

\[
R_{\text{SPA}} = 168 + 22 \times \ln(\text{SPA}).
\]

Above \( \text{SPA}_{\text{crit}} \) there is no effect on performance and when \( \text{SPA} < 0.019 \text{ m}^2 \ W^{0.67} \) growth is no longer able to occur: \( R_{\text{SPA}} = 0 \). To account for the greater space requirements of pigs housed on solid floors, SPA is decreased by 25%.

This paradigm replaces a previous, but similar, methodology. Where the area required for occupancy by a pig is \( k \times W^{0.67} \), and the value for \( k \) is usually around 0.05 (equivalent to 1 m$^2$ per 100 kg live weight), any change in \( k \) from 0.05 will be associated with a change in feed intake of about 8% for every 0.01 units of change in \( k \). (Thus, if a pig is eating 2 kg and \( k \) is reduced to 0.04, feed intake will fall by 0.16 kg.)

**Group size**

It is expected that as group size \( (N) \) increases, pig performance decreases. Increasing \( N \) by a fixed amount has a greater influence when \( N \) is small because the social hierarchy of small groups is disrupted to a greater degree than that of large groups which appear to lack social structure. A logarithmic form is therefore used to represent the relationship:

\[
R_N = 100 - 3.7 \times \ln(N)
\]

where \( R_N \) is the percentage of the daily gain of a singly housed counterpart that is achieved.

As \( N \) increases, the energy expenditure is increased due to increased levels of activity. This increase, \( E_{\text{group}} \text{MJ/day} \), is calculated as a proportion of \( E_m \) and can be added to the calculation of daily energy requirements. It is assumed that \( E_{\text{group}} \) will not increase indefinitely and so a proposed effective maximum is set at \( N = 20 \):

\[
E_{\text{group}} \text{(MJ/day)} = 0.0075 \times \left[ \min(N, 20) - 1 \right] \times E_m
\]
Feeder space allowance

Feed intake is reduced when the number of feeder spaces available to a group of pigs (FSA) falls below a critical value, FSA_{crit}, and continues to decrease as FSA decreases further. FSA_{crit} is reached when all of the pigs in the group can no longer satisfy their desired feed intake, F_d, due to increased competition. FSA_{crit} is dependent upon N, F_d, and maximum feeding rate (FR_{max}):

\[
FSA_{crit} = \frac{F_d \times N}{(1440 \times FR_{max})} \quad (19.38)
\]

FR_{max} depends upon aspects of mouth capacity, which increases as animals grow, and the bulk of the feed described by the water-holding capacity (WHC, kg/kg). The constant 1440 is the number of minutes in one day.

\[
FR_{max} (kg/min) = 2.85 \times W^{1.0}/(1000 \times WHC) \quad (19.39)
\]

When FSA is limiting, i.e. FSA < FSA_{crit}, then the constrained feed intake, F_c (kg/day) per pig, is calculated as:

\[
F_c (kg/day) = 1440 \times FSA \times FR_{max}/N \quad (19.40)
\]

If troughs are used, FSA is calculated as the number of pigs able to feed simultaneously, so that

\[
FSA_{crit} = \text{trough width (m)}/(0.064 \times W^{0.33}) \quad (19.41)
\]

Mixing

Mixing is a transient stressor and, given sufficient time, there are no noticeable effects of mixing on performance in the long term. There is, however, an initial decline in performance immediately after mixing, which lasts for approximately 2–3 weeks, due to the increased frequency of antagonistic encounters associated with establishing a new stable social structure. Mixing depresses performance to a greater extent in larger animals, due to the increased ferocity of their fighting, before returning to normal values. The mixing effect can be represented as:

\[
R_{Mix} = 100 - [0.6 \times W - 0.18 \times W \times \ln(t_{mix})] \quad (19.42)
\]

R_{Mix} is the percentage performance relative to that of a non-mixed pig and t_{mix} is the time in days where mixing occurs on day one. At some value of t_{mix}, R_{Mix} will be estimated to be 100%. From then on performance is normal and no longer affected by the past mixing.

Mixing also increases the energy expenditure of pigs due to increased levels of aggression, especially in the first few days after mixing. This increase in energy expenditure due to mixing, E_{mix} (MJ/day), which decreases over time as activity levels return to normal, can be added to the daily energy requirements:

\[
E_{mix} (MJ/day) = [1.15 - 0.05 \times \ln(t)] \times E_m \quad (19.43)
\]
Modified potential growth

It is assumed within the bounds of the model that the effects of multiple stressors on the stressed animal are additive and are predicted by summing the effects of the individual stressors:

$$B_s \text{ (per day)} = B_p \times \left( \frac{100 - \left( (100 - R_{SPA}) + (100 - R_N) + (100 - R_{MAX}) \right)}{100} \right)$$ (19.44)

where $B_s$ is the stressed rate parameter which is calculated on a daily basis and replaces the Gompertz rate coefficient, $B_p$, in the model.

Actual feed intake and growth

Predictions of actual feed intake, $F_a$, and gain are made taking account any effects upon energy requirements due to activity, constraints on feed intake due to limiting feeder space allowance, feed composition and the thermal environment. In cold conditions, $F_a$ is that required to satisfy $HL_{min}$, subject to intake constrains. In hot conditions, $F_a$ cannot cause heat production (HP) to exceed $HL_{max}$. The actual growth of the pig then follows as described earlier.

Carcass quality

Carcass quality may be determined (and rewarded) in terms of fat thickness (subcutaneous fat depth, usually at the P2 site or equivalents) and/or percentage of lean. The amount of subcutaneous fat is related to the total body lipid ($Lt$) and body size (expressible as $W$, the live weight):

$$P2(mm) = 73 \times Lt/W + 0.5$$ (19.45)

For any given level of body lipid, it is likely that the ‘blocky’ pig types will have slightly greater subcutaneous fat depths and, of course, greater eye muscle areas, killing-out percentages and percentages of lean meat in the carcass side. Pigs may be scored for ‘blockiness’ or, better, ‘meatiness’ according to a five-point scale, with a score of 1 being appropriate for conventional Large White/Landrace pig types, 5 for Pietrain/Belgian Landrace types, 2.5 for the first cross between these two types, and intermediate values as appropriate. Some recently bred strains of Large White/Landrace origins especially selected for meatiness should also be given a good score on a five-point scale. Where $Sm$ is the meatiness score ranging from 1 to 5,

$$P2(mm) = (73 \times Lt/W + 0.5) \times [0.98 + (Sm/50)]$$ (19.46)

The percentage of lean meat in the carcass may be predicted from $P2$ together with carcass weight or muscle depth (the latter accounting for the meaty pig types):

$$\text{Lean meat}(\%) = 65.5 - 1.15 \times P2 + 0.076 \times Wc$$ (19.47)
where \( W_c \) is the carcass weight (kg). The inclusion of muscle depth (\( Md, \text{mm} \)) (at the P2 site) allows:

\[
\text{Lean meat} (\%) = 59 - 0.90 \times P2 + 0.20 \times Md
\]

(19.48)

\( Md \) may range around 45–55 mm for a pig of 100 kg live weight, depending much on type.

The simulation of the mean value for P2 fat depth or percentage lean for a population of pigs may allow prediction of the average grade achieved by the pigs in a quality assessment scheme, but not the all-important distribution of pigs through the various grade categories. This may be undertaken by spreading the predicted mean through a distribution (skewed) on the basis of a known value for the variation. The variation is likely to be specific to particular production units, and is best obtained by on-farm measurement.

The killing-out percentage (\( ko, \% \)) – that is, the carcass yield after killing and evisceration – depends, amongst other things, on the live weight (\( W, \text{kg} \)), the fatness (P2, mm) and pig type (meatiness score, \( Sm \)):

\[
ko(\%) = 66 + 0.09 \times W + 0.12 \times P2 + Sm/2
\]

(19.49)

As this relates to a presumptive gut content, a more accurate prediction would need to include the effects of level of feeding, time from last meal and the bulk of the diet (water-holding capacity and fibre levels).

Should they be required, carcass dissected lean (\( L_d, \text{kg} \)), carcass dissected fat (\( F_d, \text{kg} \)) and carcass dissected bone (\( B_d, \text{kg} \)) might be approximated from the total body protein and lipid mass (\( P_t \) and \( L_t, \text{kg} \)):

\[
L_d(\text{kg}) = 2.3 \times P_t
\]

(19.50)

\[
F_d(\text{kg}) = 0.89 \times L_t
\]

(19.51)

\[
B_d(\text{kg}) = 0.5 \times P_t
\]

(19.52)

Other useful `rules of thumb` include:

\[
\text{Blood mass (kg)} = 0.036 \times W_e + 0.22
\]

(19.53)

\[
\text{Head mass (kg)} = 0.053 \times W_e + 1.2
\]

(19.54)

\[
\text{Daily lean tissue growth rate (kg/day)} \approx Pr \times 4.5
\]

(19.55)

**Excretion of nitrogenous waste**

As with heat output, nitrogen output from the pig (\( N_{\text{lost}}, \text{kg/day} \)) is best estimated by difference. Where the nitrogen content of the dietary crude protein (\( \text{PROTEIN, kg/kg} \)) is given by \( p\text{N}_{\text{diet}} (\text{kg/kg}) \) and the nitrogen content of retained protein is given by \( p\text{N}_{\text{pr}}, (\text{kg/kg}) \), then nitrogen output can be given by:

\[
N_{\text{lost}}(\text{kg/day}) = F \times \text{PROTEIN} \times p\text{N}_{\text{diet}} - \Delta P_t \times p\text{N}_{\text{pr}}
\]

(19.56)
It is normally sufficient to assume that both $pN_{\text{diet}}$ and $pN_{\text{Pr}}$ are equal to $1/6.25$, in which case the equation reduces to:

$$N_{\text{loss}}(\text{kg/day}) = \frac{(F \times \text{PROTEIN} - \Delta Pt)}{6.25}$$

(19.57)

In the above equation, $\Delta Pt$ indicates the change in total protein mass (kg/day). This may or may not equal $Pr$.

Some estimate can be made of the amounts of nitrogen that are lost in the faeces and in the urine. In pigs, there is little cycling of nitrogen between these two fractions, and the other fractions of nitrogen loss (mainly from the integument) are negligible. The urinary losses are the difference between protein accumulation and protein absorbed.

$$N_{\text{urine}}(\text{kg/day}) = \left[ F \times D_{il} \times \text{PROTEIN} - (\Delta Pt - Pt_{\text{endogenous}}) \right] / 6.25$$

(19.58)

where $Pt_{\text{endogenous}}$ is the amount of endogenous gut secretions of protein and $D_{il}$ is the standardised ileal digestibility of crude protein. (Where apparent digestibility values are used, the $Pt_{\text{endogenous}}$ term is omitted from the equation above, and that which follows below.) The faecal losses are:

$$N_{\text{faecal}}(\text{kg/day}) = \left[ F \times (1 - D_{il}) \times \text{PROTEIN} + Pt_{\text{endogenous}} \right] / 6.25$$

(19.59)

**A simulation model for breeding sows**

Whereas much of a simulation model to predict the growth response to nutrient supply may be deductive (as well as dynamic and deterministic), the reproductive response of breeding sows must be predicted almost entirely empirically. This is often because the causal forces of the phenomena that are to be simulated are imperfectly known. Modelling theory and practice are also far more advanced with growing pigs than with breeding sows. As the simulation of sow reproduction has not benefited from validation, through both scientific appraisal and industrial use, in the same way as has been possible for meat pigs, it might be considered ambitious to describe the precepts of sow modelling here. Nevertheless, enough is understood to put forward statements concerning relationships between one factor and another, and to draw attention to those elements of the system that can be understood as some function of other elements of the system. Qualitative descriptions alone are not most helpful, so here an attempt has been made to quantify the various relationships presented. However, such quantification is presented only as a guide to the sizes of the various forces impinging upon sow reproduction. The constants, coefficients and exponents used should be considered only as estimates of the magnitudes of the factors involved.

**Sow weight and body composition**

Modern hybrid gilts are best mated when more than 220 days of age, greater than 120kg body weight and with greater than 14mm P2 subcutaneous backfat depth.
Often the history of gilts entering into the breeding herd is not well known. Weight (W) can be determined directly, and if P2 cannot be measured directly also, it might be predicted from condition score (CS, 1–10):

\[ P2(\text{mm}) = 3 \times CS \] (19.60)

From P2 and W, Pt and Lt can be estimated:

\[ Pt(\text{kg}) = 0.19 \times W - 0.22 \times P2 - 2.3 \] (19.61)
\[ Lt(\text{kg}) = 0.21 \times W + 1.5 \times P2 - 20.4 \] (19.62)

The remainder of the body consists of gut fill, water, and ash. The ratio Pt/W will be 0.14 in very fat pigs, through to 0.17 in thin pigs.

Where Lt and Pt are known, P2 and W can be calculated by the inversion of the above simultaneous equations. The following are obtained:

\[ P2(\text{mm}) = 10.42 + 0.5828 \times Lt - 0.636 \times Pt \] (19.63)
\[ W(\text{kg}) = 12.42 + 5.3763 \times Pt + 1.161 \times P2 \] (19.64)

These equations differ from those presented for the growing pig, above. Such equations are empirically derived, and should not be extrapolated for body weights beyond those encompassed by the data on which they are based.

**Potential growth of the pregnant sow**

From the point of conception, potential protein growth (Pr\text{max}) is curtailed such that the Gompertz growth rate parameter B\text{p} is about half that found for uninhibited growth. The expression

\[ \text{Pr}_{\text{max}}(\text{kg/day}) = B_p \times \text{Pt} \times \ln(Pt_{\text{max}}/Pt) \] (19.65)

will serve, where Pt\text{max} may commonly range between 35 and 45 kg and B\text{p} is around 0.005 per day.

Sows may be considered to have become over-fat if Lt > 2 × Pt and over-thin if Lt < Pt. Recent measurements with hybrid sows have suggested that ideally the relationship between Lt and Pt should be:

\[ Lt(\text{kg}) = 1.1 \times Pt^{1.1} \] (19.66)

The actual rate of accumulation of fatty tissue in sows is highly dependent upon nutrient supply, and the body fat status is a vital component of reproductive response prediction (of which, more later). This equation is not, therefore, predictive, although it may be used for analysis and diagnosis.

**Nutrient requirements of the pregnant sow**

The energy requirements for reproduction in the sow may be divided between maintenance,
\[ E_m = 1.75 \times P_t^{0.75}, \quad (19.67) \]

retention of energy in the fetal load, growth of mammary tissue and lactation. It may be noted that the energy costs of maintenance are presumed to also account for the costs of physical activity. So they do if that activity is minimal. However, in many production systems some 10–20% more energy should be added to the calculation to cover for physical activity.

The equation:

\[ E_u(MJ/day) = 0.107 \times e^{0.027\times t_p} \quad (19.68) \]

describes the rate of energy deposition in the mammary gland (\(E_{\text{mamm}}\)) (where \(t_p\) is the day of pregnancy). As both the efficiencies of energy conversion to uterus contents, \(k_u\), and mammary gland, \(k_{\text{mamm}}\) (both MJ/MJ), are around 0.5, the total energy cost of pregnancy (\(E_p\)) is:

\[ E_p(MJ/day) = (E_u + E_{\text{mamm}})/0.5 \quad (19.69) \]

Values for \(E_p\) are trivial in early pregnancy, but at day 110, \(E_p\) totals 5.5 MJ/day of ME.

Protein deposition in the products of conception (\(P_{ru}\)) proceeds at an exponential rate consequent upon the day of pregnancy:

\[ P_{ru}(kg/day) = 0.0036 \times e^{0.026\times t_p} \quad (19.70) \]

and therefore ideal protein supply required to achieve this is

\[ IP_{ru}(kg/day) = P_{ru} \quad (19.71) \]

Likewise for deposition in the mammary tissue (\(P_{r_{\text{mamm}}}\)):

\[ P_{r_{\text{mamm}}}(kg/day) = 3.8 \times 10^{-5} \times e^{0.059\times t_p} \quad (19.72) \]

and the ideal protein supply required:

\[ IP_{r_{\text{mamm}}}(kg/day) = P_{r_{\text{mamm}}} \quad (19.73) \]

Both \(P_{ru}\) and \(P_{r_{\text{mamm}}}\) are ultimately lost from the body, \(P_{ru}\) at parturition and \(P_{r_{\text{mamm}}}\) (in the urine) after weaning.

**The piglet**

**Litter size (number of piglets) at birth**

The number of piglets born per litter is highly dependent upon breed type and the extent of heterotic effects. Breeds of low prolificacy may produce around eight live piglets per litter, while those of high prolificacy may produce 13 (or occasionally more). Base litter size must therefore be obtained from objectively measured performance data.

The size of the primiparous litter, \(n_{\text{litter1}}\) (where \(n_{\text{litter}}\) is the number of live born piglets), can be predicted as a function of the number of the pubertal oestrus at which conception occurs, \(n_{\text{conception1}}\):
As parity number \((n_{\text{parity}})\) increases, so do the number of ova released \((n_{\text{ova}})\):

\[
 n_{\text{ova}} = 14.5 + 1.5 \times n_{\text{parity}} \tag{19.75}
\]

The expected proportion of ova released that reach term, to be delivered as live-born piglets, is about 0.55:

\[
 n_{\text{litter}} = n_{\text{ova}} \times 0.55 \tag{19.76}
\]

However, the incidence of fetal and perinatal deaths also increases. Earlier litters average around 0.5 piglets born dead; the number then rises gradually from parity 3 until parity 8 when it is quite usual to find 1.0 piglets born dead in each litter. The overall influence of parity number on the litter size of live-born piglets is approximately according to the following correction, \(\Delta n_{\text{litter}}\) to be added to \(n_{\text{litter}}\):

\[
 \Delta n_{\text{litter}} = 0.75 - 0.5 \times |4.5 - n_{\text{parity}}| \tag{19.77}
\]

Litter size is also diminished by early weaning and enhanced by later weaning. A similar correction factor to live-born litter size may be made for the days between parturition and conception \((t_{\text{pc}},\) a number between 15 and 45):

\[
 \Delta n_{\text{litter}} = 0.09 \times t_{\text{pc}} - 3.0 \tag{19.78}
\]

There is also evidence of effects of nutrition on litter size, although this is much weaker than nutritional effects on, for example, birth weight or weaning to oestrus interval. Nutrition during lactation and between weaning and conception can influence ovulation rate, embryo survival and final litter size. Thus where \(\Delta W\) is the total lactation weight change of the sow, it may be suggested that:

\[
 n_{\text{ova}} = 23.5 + 0.7 \times \Delta W \tag{19.79}
\]

Evidence is accumulating for a direct and substantive positive effect of pregnancy feeding on final litter size (numbers born).

Sow fatness may be used as a common measure of the variable consequences of absolute feeding levels. An estimated correction factor to live-born litter size of \(-0.5\) can be applied to sows with extreme P2 fat depth at conception of \(<10\) or \(>26\) mm, and of \(+0.5\) for medium fatness sows of 14–18 mm.

**Birth weight**

Piglet birth weight has a positive influence on individual piglet survivability and on individual piglet weaning weight, while one (substantial) data set points to a sustained positive influence upon growth throughout life to slaughter weight \((W_r,\) kg/day):

\[
 W_r = 0.42 + 0.12 \times W_b \tag{19.80}
\]

where \(W_b\) is piglet birth weight (kg).
Birth weights usually range between 0.8 and 1.6 kg. There is a suggestion that recently improved nutrition, together with the use of larger sow genotypes, has tended to raise expected average birth weight and a target of 1.3 kg is now realistic. Although conditions for the whole litter may appear identical in utero, differential fetal nutrition and uterine environmental effects (including disease) will create a normal distribution of the birth weight of pigs within a litter. Where this variation is required to be modelled (rather than simply the mean), the mean value can be spread through an appropriate distribution curve whose variation is likely to be farm-specific, and may best be judged by on-farm measurements. Meanwhile the average piglet birth weight for the litter ($W_b$) can be estimated from an equation that has been derived from data collected from hybrid sows of $W$ around 180 kg:

$$W_b (\text{kg}) = 0.89 + 0.013 \times \text{DE}$$  \hspace{1cm} (19.81)

where DE is the daily intake of digestible energy by the sow (MJ/day); this indicates a positive relationship between birth weight and maternal pregnancy feed intake.

It is known that late pregnancy feeding has a greater effect on piglet birth weight than early pregnancy feeding and, given proper feeding in the first two-thirds of pregnancy, a suitable correction factor, $\Delta W_b$, to add to $W_b$ for the effects of feeding level in late pregnancy might be speculated to be:

$$\Delta W_b (\text{kg}) = 0.008 \times (\text{DE} - 28)$$  \hspace{1cm} (19.82)

Average piglet birth weight is markedly influenced by litter size, larger litters tending to have in them piglets of smaller than average size:

$$\Delta W_b (\text{kg}) = 0.04 \times n_{\text{litter}} - 0.004 \times n_{\text{litter}}^2$$  \hspace{1cm} (19.83)

It would also appear sensible to allow expected piglet birth weight to relate in some way to maternal body size, as it is well-appreciated that the birth weight of piglets from large breeds of pig is greater than that from small breeds. Quantitative information on this point is not, however, especially reliable. It has been suggested that:

$$W_b (\text{kg}) = 0.43 + 0.0053 \times W_{\text{parturition}}$$  \hspace{1cm} (19.84)

where $W_{\text{parturition}}$ is the maternal body weight at parturition. This suggestion pertains to sows of around 180 kg and is almost certainly optimistic when used for sows with live weights above 220 kg.

Carry-over effects from lactation feeding (or pre-conception feeding in the case of first litter gilts) will also have some positive effects on $W_b$, but they are not possible to quantify.

**Survivability**

Not all live-born piglets will survive through to weaning. Minimum achievable losses appear to be around 5%, with 8–12% common in well-managed herds and 15–25%
in poorly managed herds where facilities for protection from crushing are not provided, where the standard of care is low and where disease levels are high. It is largely futile to determine with accuracy piglet survivability in particular circumstances, but the major issue should at least be raised. Lighter piglets at birth are much more likely to fail to survive than those that are heavier. Probability of survival, \( p_{\text{survival}} (0–1) \) is given by:

\[
p_{\text{survival}} = 0.55 \times W_b^{1.3}
\]

(19.85)

**Nutrient requirements of the lactating sow**

**Milk yield and supply**

Limits to the growth of sucking piglets (Wr, kg/day) may be best considered apart from post-weaning growth because it appears that if a Gompertz function is to be used, B values are somewhat higher:

\[
W_r(kg/day) = B_w \times e^{-B_w \times (t - t^*)} \times W_{\text{max}} \times e^{-e^{-B_w \times (t - t^*)}}
\]

(19.86)

where \( t^* \) can be calculated by:

\[
t^*(\text{days}) = \ln [-\ln (W_b/A)]/B_w
\]

(19.87)

In the above equation, \( W_{\text{max}} \) is the mature live body weight, \( t \) is the day of piglet age, \( W_b \) is the weight at birth and \( B_w \) is the growth coefficient, which is likely to range from 0.014 to 0.019, according to the inherent potential of the piglet to grow.

Milk yield (My) in the lactating sow will be a function of the needs of the litter according to the equation:

\[
My(kg/day) = W_r \times n_{\text{litter}} \times 4.1
\]

(19.88)

A limit to milk yield must be set according to the potential of the sow. The boundary to the lactation curve of a sow may be described by a Gompertz equation of the form:

\[
My_{\text{max}}(kg/day) = a \times e^{-0.025t_i} \times e^{-e^{0.5 \times 0.1t_i}}
\]

(19.89)

where \( t_i \) is the day of lactation and \( a \) may range between 18 and 30 kg/day.

Achieved daily milk yield will be a result of either piglet demand or the boundary limit, whichever is the lesser, provided that there is no nutritional limitation upon lactation yield.

**Nutrient requirements for milk production**

The energy value of milk is 5.4 MJ/kg and the conversion of efficiency of energy to milk, \( k_e \), is 0.7 MJ/MJ; thus the energy cost of milk production (\( E_{My} \)) is:

\[
E_{My} (MJ ME/day) = 7.7 \times My
\]

(19.90)
In the absence of an adequate energy supply from the diet, maternal body lipid may be made available with a higher efficiency of 0.85, which is to say that 1 kg of maternal body lipid may be used to create \((39.36 \times 0.85)/5.4 = 6.2\) kg milk. *In extremis*, maternal body protein may be used to provide energy for milk synthesis; the efficiency in this case is probably no greater than 0.5.

Protein secreted in milk may be determined as:

\[
I_P = M_y \times 0.055 = P_r
\]  
(19.91)

there being 0.055 kg/kg protein in milk. In the absence of adequate protein supply from the diet, maternal body protein may be made available with an efficiency that may be expected to be approximately 0.85.

The lactation feed intake of sows is often, if not usually, inadequate to supply ME\(_t\) in sufficient quantity to supply the needs of My as calculated either from sucking piglet need or from sow yield potential. This does not mean, however, that feed intake is the invariable controller of My, because the sow will readily use body stores of lipid (and protein) to supply the short-fall between the needs of milk biosynthesis and the provision of energy and protein from the diet.

Body lipid and body protein may thus be used in support of ME\(_t\) and IP\(_t\) from dietary sources in order to meet My as calculated according to piglet need within sow potential. Such support can only take place, however, if body lipid and protein stores are available to so provide; and further, the level of support from the sow by using her own body tissue to grow that of her piglets will be in proportion to the extent of the body stores that she has present. Sows in good body condition may lose up to 1 kg of lipid and 0.25 kg protein daily. The ratio of lipid:protein losses appears to range from 2.5:1 to 10:1, depending on the dietary nutrient balance and the status of sow body nutrient stores.

Broadly, when \(L_t < P_t\), sows may be judged as thin, whilst when \(L_t > 2 \times P_t\), sows may be judged as fat. It may be proposed if \(L_t / P_t < 0.7\), then no fat will be made available to resource My; however, for sows with fatness levels above this, the rate of daily lipid loss (\(L_r\)) available to support My, should the need arise, might be:

\[
L_r (\text{kg/day}) = 0.5 - 0.7 \times L_t / P_t
\]  
(19.92)

subject to an upper limit on loss of 1.0 kg/day.

Losses of protein may be put at a maximum of 0.25 kg daily and probably at a minimum value of 0.1 of the lipid losses, because it appears normal for there to be some loss of protein when fatty tissue is being catabolised, even when the shortfall is only in energy.

**Weaning weight**

The weight of the litter at the point of weaning is a function of the litter size, the birth weight of the piglets and their subsequent growth. The relationship of growth rate from birth weight to weaning, \(W_r\), to birth weight may be as in Equation 19.86 or as:
\[ \text{Wr}(\text{kg/day}) = 0.150 + 0.08 \times \text{W}_b \quad (19.93) \]

However, both the constant and the coefficient would be highly farm specific and dependent upon many other impinging factors. Early growth, however, is primarily a function of (1) potential growth rate and (2) milk yield, these being related. Equally as sound would be an empirical relationship with maternal lactation feed intake:

\[ \text{Wr}(\text{kg/day}) = 0.150 + 0.012 \times \text{F}_l \quad (19.94) \]

where \( \text{F}_l \) is the daily feed intake during lactation. The shortfalls of such equations have been discussed earlier in this section.

Estimation of piglet growth rate, approached empirically from the aspect of likely milk supply, leads to an estimation, determined with white cross-bred pigs, such as:

\[ \text{Wr}(\text{kg/day}) = 0.191 - 0.18 \times \Delta \text{P}_2 - 0.05 \times \Delta \text{W} \quad (19.95) \]

where \( \Delta \text{P}_2 \) is the change in \( \text{P}_2 \) (mm/day) that takes place during lactation, and \( \Delta \text{W} \) is the change in maternal sow body weight (kg/day) that takes place during lactation. The constant is crucial to effective prediction, and is likely to vary amongst breed types, litter size and, indeed, farms. Additionally, it is not helpful always to imply that sows losing no weight or fat will cause their piglets to grow slowly. This will be the case where the sow is eating less than is needed to satisfy the nutrient demands of milk production, but it would not be the case where ingested nutrients supplied all requirements for milk production. The equation is often a useful guide, however, as most sows do not eat enough feed to supply the needs of lactation, and so milk yield (and piglet growth) is often dependent upon the rate of catabolism of body mass in general, and body lipid in particular.

**Weaning to conception interval**

The length of pregnancy is a fairly invariable biological constant of 114–116 days. The length of lactation is at the command of man. Prediction of the number of litters that a breeding sow may have in a year is therefore dependent upon simulating the weaning to conception interval.

The major factors extending the weaning to conception interval beyond the minimum value of 4 days are maternal body condition, as indicated by the extent of maternal body fat, and protein depletion. The relationship between the weaning to oestrus interval \( (t_{wo}, \text{days}) \) and the depth of subcutaneous fat on the sow at weaning \( (\text{P}_2, \text{mm}) \) may be expressed as:

\[ t_{wo}(\text{days}) = 31.3 - 2.03 \times \text{P}_2 + 0.043 \times \text{P}_2^2 \quad (19.96) \]

for primiparous sows and as:

\[ t_{wo}(\text{days}) = 19.3 - 1.27 \times \text{P}_2 + 0.030 \times \text{P}_2^2 \quad (19.97) \]

for multiparous sows.
Australian work [King, R.H. (1987) *Pig News and Information*, 8, 15] points to the amount of tissue lost during lactation, as well as the absolute levels of protein and lipid in the body of the sow at the time of weaning, as being important factors in determining the weaning to conception interval:

\[
t_{wo}(\text{days}) = 7.3 - 0.39 \times \Delta W \\
(19.98)
\]

\[
t_{wo}(\text{days}) = 9.4 - 0.59 \times \Delta Lt \\
(19.99)
\]

\[
t_{wo}(\text{days}) = 9.6 - 3.44 \times \Delta Pt \\
(19.100)
\]

where $\Delta W$ is the total live weight change (kg) in lactation, $\Delta Lt$ is the total fat change (kg) in lactation and $\Delta Pt$ is the total protein change (kg) in lactation. If protein losses during lactation are seen as an additional factor influencing the weaning to oestrus interval already established, then the following correction factor ($\delta t_{wo}$) could be added to $t_{wo}$:

\[
\delta t_{wo}(\text{days}) = -3.44 \times \Delta Pt \\
(19.101)
\]

or, for every kilogram of protein lost from the body of the sow during the course of lactation, 3.4 more days require to be added to the weaning to oestrus interval.

Loss of maternal body weight in lactation has a lesser effect on weaning to oestrus interval for sows that are fat than for sows that are thin. The strength of the above relationships will therefore be dependent upon sow body condition; the lower the level of internal body stores, the greater the negative effects of weight loss in lactation upon rebreeding.

A beneficial effect of feeding level post-weaning on the interval may be accounted for by a further correction:

\[
\delta t_{wo}(\text{days}) = 40 \times F_{wo}^{-3.0} \\
(19.102)
\]

where $F_{wo}$ (kg/day) is the daily feed intake between weaning and oestrus.

Some workers have shown a relationship between previous litter size and subsequent weaning to oestrus interval, which is reasonable, but it is difficult to think that this effect could be independent of effects accounted for elsewhere, such as maternal tissue losses.

Whilst most trial data relate to the more easily monitored weaning to oestrus interval, the key parameter is in fact the weaning to conception interval. Conception rate ($p_c$, 0–1) is highly variable between farms, and greatly influenced by mating management and the presence of both chronic and acute reproductive disease. Better documented than the effect of management and disease upon conception rate is the lesser effect of lactation length ($t_{lact}$, days):

\[
p_c = 0.54 + 0.013 \times t_{lact} \\
(19.103)
\]

which may well be independent of body condition loss and a function, at least in part, of the strength of circulating lactation hormones if the sow is weaned before the natural peak of lactation is reached at 3–4 weeks. Similarly the effect of number of matings ($n_{mating}$ 1–3) that occur at oestrus can be described by:
Normally the proportion of sows mated that farrow is around 0.80. It is possible for farm data to yield a value for conception rate, or it could be approximated. As for weaning to oestrus interval, there is an important positive effect of sow body condition at weaning (lactation feeding level) upon conception rate. Similarly there is a positive effect of early pregnancy feeding. Quantification of the positive modification to conception rate as a function of lactation and pregnancy feeding, independent of effects already accounted elsewhere, remains difficult, however.

The additional days that are required to be added to the weaning to oestrus interval in order to estimate the weaning to conception interval \( \left( t_{\text{wc}} \right) \) can be calculated as:

\[
t_{\text{wc}} = t_{\text{wo}} + t_{\text{oc}}
\]

Alternatively, the oestrus to conception interval might be estimated from the two factors that appear to influence it most after the major – and unmodellable – effects of management and disease: the rate of body condition loss in lactation and the length of the lactation:

\[
t_{\text{oc}} = 37 \times (1 - p_c)
\]

Maternal weight and fatness

The importance of absolute maternal body weight and fatness, and of the change in maternal body weight and fatness, to the reproductive performance of the sow has been well described in the foregoing sections. These may be deduced from knowledge of nutrient inputs and product outputs, as has been shown. However, the relative fragility of the deductive approach gives ample reason for the use of empirical equations where these may be helpful.

Let it be assumed that sow live weight at first conception is 125 kg, the backfat depth \( (P2) \) is 15 mm and the DE content of the feed is 13.2 MJ DE/kg; let it be further assumed that the sow growth expectations (which may or may not be achieved) are as given in the earlier section on sow weight and body condition. Then, the total change in P2 backfat in pregnancy \( (\Delta P2, \text{mm}) \) may be estimated as:

\[
\Delta P2 = 4.60 \times F - 6.90
\]
\[ \Delta P2(\text{mm}) = 4.14 \times F - 9.3 \]  
(19.108)

Change in total body lipid (\( \Delta Lt \), kg) has been estimated as:
\[ \Delta Lt(\text{kg}) = 15 \times F - 30 \]  
(19.109)

The total maternal live weight change in pregnancy (\( \Delta W \), kg) may be estimated as:
\[ \Delta W(\text{kg}) = 25 \times F - 27 \]  
(19.110)

During lactation, the daily change in P2 backfat depth (\( \Delta P2 \), mm/day) may be estimated as:
\[ \Delta P2(\text{mm/day}) = 0.049 \times F - 0.396 \]  
(19.111)

where \( F \) is the daily lactation feed intake. The daily change in maternal live weight (\( \Delta W \)) during lactation may be estimated as:
\[ \Delta W(\text{mm/day}) = 0.343 \times F - 1.74. \]  
(19.112)

Better simulations may be forthcoming from more complex but more complete prediction equations:
\[ \Delta P2(\text{mm/day}) = -0.0101 - 0.0095 \times P2_{\text{parturition}} + 0.037 \times F - 0.0178 \times n_{\text{litter}} \]  
(19.113)

and:
\[ \Delta W(\text{kg/day}) = -0.1360 - 0.00535 \times W_{\text{parturition}} + 0.362 \times F - 0.119 \times n_{\text{litter}} \]  
(19.114)

Again, the variation in the response – the extent to which an individual sow’s description should be spread around the mean – is crucial to the use of models in the practical environment, but information on this aspect of simulation is as yet both highly farm-specific and largely undocumented.

**Physical and financial peripherals**

Previous sections have dealt with the concepts and the deductive and empirical relationships that can be used in the creation of ‘biological cores’ for models that simulate the production response of growing pigs and breeding sows. Thus far the ‘biological core’ has discussed the simulation of:

- protein and lean growth;
- fatty tissue growth;
- uterine deposition;
- lactation yield;
- energy yield from the diet;
- protein yield from the diet;
- energy use by growing pigs;
- energy use by breeding sows;
- protein (amino acid) use by growing pigs;
- protein (amino acid) use by breeding sows;
- feed intake (including the influence of environmental factors);
- the composition of growth;
- carcass quality;
- the body composition of breeding sows;
- piglet birth weight;
- piglet survivability;
- litter size;
- piglet growth and weaning weight;
- weaning to oestrus and weaning to conception intervals;
- sow maternal body weight changes;
- sow maternal fat changes.

Before a model can predict the consequences of changing production circumstance within the context of a business or production unit, however, further information is needed about the system, such as:

- gearing factors for the general production environment;
- gearing factors for the quality of management;
- gearing factors for the level of disease;
- fixed costs for the production unit;
- variable costs for each pig produced;
- numbers of pigs available;
- cost of pigs available;
- management factors, such as castration policy, split-sex feeding, refinement of feed allowance control, feed wastage, etc.;
- breed type and genetic quality of growing pigs and breeding sows;
- quality of housing;
- climate, weather and microclimate of buildings (temperature, relative humidity, air movement, air quality);
- numbers of pigs per pen, pen size, density of pigs in pens, space allocation, availability of pens for pigs of different classes, utilisation rates for pens;
- minimum and maximum dead weight limits for carcass pigs;
- method of carcass quality assessment;
- method of carcass quality payment;
- value of culled breeding sows.

Given this type of information with which to surround the biological core, a model may be constructed which can simulate growth, carcass quality and reproductive performance, and which can place the resulting predictions into the orbit of the management of the business. This is what is required for the science and the practice of pig production to be brought effectively together.
Future developments

Infectious environment

It was assumed in the example model described above that all animals were in good health and free from exposure to infectious stressors throughout. Any response to infectious stressors, such as an increase in resource requirements to acquire and express an immune response, a change in the efficiency of energy utilisation or a voluntary reduction in feed intake (anorexia), all of which would result in a decrease in performance, were ignored. In reality of course, pigs are exposed to many different kinds and intensities of infectious stressors. These include pathogens and other harmful environmental components which may trigger tissue injury or further infection, such as other individuals in the same pen, i.e. bites and scratches.

The incorporation of infectious stressors into simulation models is an important next step in the attempt to accurately predict commercial pig performance. To include the effects of infectious stressors in a model in a systematic way, a number of preliminary steps are required. The metabolic load imposed by infectious stressors, i.e. increased nutrient requirements, and the extent to which performance is decreased need quantifying. How animals allocate resources when exposed to infectious stressors, e.g. how they cope with a pathogen challenge, needs investigating and the biological mechanism responsible for the decrease in performance needs elucidating. Two possible mechanisms may lead to the decrease in pig performance observed when pigs are exposed to disease. These are either a decrease in the pigs’ ability to attain their potential, as was assumed for social stressors in the model developed here, or a direct decrease in appetite. There is also likely to be between-animal variation in immune response and resilience, i.e. differences in the ability of individual pigs to cope and perform during exposure to pathogens. This should be accounted for in any modelling attempt along with any interactions between stress and disease susceptibility.

Modelling the effects of the infectious environment with an understanding of the physiological mechanisms responsible for the observed effects on the animal would allow the important interactions between disease and the pig to be estimated; the ‘pig’ in this regard including genotype, nutrition and the climatic and social environment.

An early (and pragmatic) attempt to deal with the problem of incorporating disease into models has been made by the UK MLC in their 2004 booklet Feed Formulations for Pigs (MLC, Milton Keynes). Here, the point is made that nutrient requirement standards refer to healthy pigs, but practical feeding guidance must accept the need to also feed pigs that are in environments which demand an effective response to immune challenge. The booklet takes a four-level approach

(1) a 10% reduction in presumptive feed intake;
(2) a 20% increase in the requirement of energy for maintenance;
(3) a reduction in the presumed efficiency of use of ileal digested lysine from 0.82 to 0.73;
(4) a 10% reduction in the potential rate of protein retention.

**Population modelling**

Models intended to simulate animal performance, such as the one outlined above, typically represent a single animal. The assumption necessarily made is that the mean response of the population, which is an average of all individuals, will be the same as that of the deterministically simulated response of the ‘average’ individual. This will be the case only if all animals in the population have an equal growth potential, all are at the same stage of growth and all react in the same way to encountered stressors. This of course is highly unlikely.

Proper allowance for population variation is important when models are used to predict nutrient requirements, optimise pig production systems and devise animal breeding strategies. Knowledge of between-animal variation is important in commercial situations, especially for all-in/all-out systems, as variation in carcass weight and composition, i.e. the homogeneity of a group, will partly determine enterprise profitability.

However, due to between-animal variation there may be differences between the response of the average individual and the mean response of the population, which is an average of all individuals. In order to attempt to predict adequately the response of a population in a given environment it is necessary to take account of between-animal variation. Simulation models that predict the effect of the social, physical and nutritional environments on pig food intake and performance could be extended to deal with individual variation in order to investigate the impact of between-animal variation on the performance of a population of growing pigs. Such a study is presently on-going with the group at the Scottish Agricultural College in Edinburgh.
Knowledge about the biology and economics of meat production from pigs is worthwhile, not only because the industry is helped to be more economic and because more people can be fed, but also on account of the absolute benefit that comes from scientific advance. It is hoped that all three of these objectives may have touched the reader in the foregoing chapters.

If the science is found good and the production practices found effective, it will not be through the implementation of rules but through the understanding of the forces – economic and biological – which impinge upon pig production; especially through the understanding of the causes of the animals’ responses to various aspects of their nutritional, genetic, physiological and production environments.

Presentation of a blue-print instruction manual would, of course, have been easier for both the authors and reader; but less useful. This is because pig production worldwide is rapidly changing, and not necessarily in the one direction. For example, while the move toward intensification is strong in many countries where the pig industry is young and the demand for meat is high, elsewhere a move toward extensification may be found, and a perception of quality in pig products which relates as much to systems of animal care as to the nutritional value of the resultant meat.

While the production characteristics of the industry may diverge with geographic location, many aspects of science, and of scientific goals, are common:

- the importance of creating pig-meat products that the market-place demands, rather than merely producing that which is most convenient for the farmer;
- the need to put eating quality above carcass leaness;
- the possibility for improving the reproductive performance of sows, not so much to raise their potential as to achieve the potential that already exists;
- the need to optimise growth by attending realistically to the ratios between costs of input and values of output, and not just the seeking of high biological performance;
- the need to enhance feed intake of pigs, especially that of highly productive young growers and lactating sows;
- creating through genetic improvement a diversity of pig types which may be used best to exploit the prevailing wide range of production circumstances (there are substantial genetic goals yet to be reached in reproductive performance, growth
rate and carcass quality, and there may be more novel goals in the form of disease resistance and behavioural traits);
• understanding better the relationships between nutrient input and growth and reproductive response (a briefly stated goal but a discipline requiring immense scientific effort and investment);
• being able to determine effectively the real nutritional value of feedstuffs, through net energy and net amino acid systems;
• attacking the problems of diseases, both chronic and acute, not only through the development of protective or curative drugs, but also by the determination of means of avoiding disease, and of means of giving to the pig ways of bettering its own defence mechanisms against disease.

Interest in animal welfare is not only a matter of humankind’s responsibility toward the rights of animals that are used for food; it is also a matter of good and practical husbandry. Regrettably, the issues of pig behaviour and welfare may sometimes be subjugated in the quest for ever more efficient production systems. If so, there is benefit for pig producers in heeding the voice of the caring customer.

It is evident that housing systems are not yet optimal. The micro-climate is not understood, while the relations between stocking density, health and performance are fraught with complexity. Even if there were full understanding of the pig’s environmental needs (which there is not), there remains a lack of proper understanding of the housing systems that would be needed to provide for them.

Above all, regardless of the nature of any individual system, the production of pigs must be cost-effective, or it cannot take place. Optimisation requires knowledge and manipulation of the market and a readiness to be flexible because of the continually changing nature of that market. Here the simulation model represents a novel resource that science can offer to the pig industry to aid decision-making. World-wide there is a strongly developing interest in the use of simulation models to predict the response of both the breeding herd and the growing pig to changes in production circumstances – especially nutritional and genetic. Models can incorporate the body of scientific knowledge, and this strengthens further their potency in aiding good production practice. The science of computer modelling will come, covertly and overtly, to be the major force influencing the practice of feeding, breeding and management of pigs.

This book has been written mostly while in Edinburgh but also in North America, the Far East and many countries on the European Continent. The pig serves mankind best when we understand most clearly how to use its supreme adaptability and diversity, and how to exploit compassionately its innate facility for domestication.

The reader may be interested to learn where the major changes have taken place over more than fifteen years between writing the bulk of the first edition and finishing all the new material in the third edition. The structure of the industry has moved dramatically away from the family farm and toward the large integrated business; but this has not resulted in any reduction in caring attitude as the latter is
now – in its various forms – a part of quality assurance, without which the human food industry will no longer make the primary purchase from the producer. Advances in biotechnology and in health have outstripped advances in nutrition; but nutrition will take on a new dimension in pig production with the inception of computer-based integrated management control systems.
Appendix 1

Nutritional Guide Values of Some Feed Ingredients for Pigs

This guide presents especially net energy (NE), standardised ileal digestibility and digestible phosphorus (Dig P) values.

<table>
<thead>
<tr>
<th>Feedstuff</th>
<th>NE for growing pigs and lactating sows (MJ/kg)</th>
<th>NE for pregnant sows (MJ/kg)</th>
<th>DE for growing pigs and lactating sows (MJ/kg)</th>
<th>DE for pregnant sows (MJ/kg)</th>
<th>CP (g/kg)</th>
<th>NDF (g/kg)</th>
<th>Dig P (g/kg)</th>
<th>Standardised ileal digestible amino acids (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DM (g/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CP</td>
</tr>
<tr>
<td>Barley</td>
<td>870</td>
<td>9.6</td>
<td>9.8</td>
<td>13.0</td>
<td>13.3</td>
<td>100</td>
<td>175</td>
<td>1.1</td>
</tr>
<tr>
<td>Wheat</td>
<td>870</td>
<td>10.5</td>
<td>10.7</td>
<td>14.2</td>
<td>14.5</td>
<td>105</td>
<td>115</td>
<td>1.2</td>
</tr>
<tr>
<td>Maize</td>
<td>870</td>
<td>11.1</td>
<td>11.3</td>
<td>14.6</td>
<td>15.1</td>
<td>78</td>
<td>95</td>
<td>0.7</td>
</tr>
<tr>
<td>Oats</td>
<td>870</td>
<td>8.0</td>
<td>8.4</td>
<td>11.4</td>
<td>12.1</td>
<td>98</td>
<td>300</td>
<td>1.3</td>
</tr>
<tr>
<td>Cassava (67% starch)</td>
<td>880</td>
<td>10.0</td>
<td>10.2</td>
<td>12.5</td>
<td>12.7</td>
<td>25</td>
<td>85</td>
<td>0.1</td>
</tr>
<tr>
<td>Triticale</td>
<td>870</td>
<td>10.2</td>
<td>10.5</td>
<td>13.5</td>
<td>13.7</td>
<td>100</td>
<td>115</td>
<td>1.2</td>
</tr>
<tr>
<td>Wheat bran</td>
<td>870</td>
<td>6.2</td>
<td>6.8</td>
<td>9.4</td>
<td>10.3</td>
<td>150</td>
<td>440</td>
<td>3.0</td>
</tr>
<tr>
<td>Wheat meal</td>
<td>880</td>
<td>7.7</td>
<td>8.1</td>
<td>11.4</td>
<td>12.2</td>
<td>156</td>
<td>330</td>
<td>2.6</td>
</tr>
<tr>
<td>Maize gluten meal</td>
<td>880</td>
<td>7.0</td>
<td>7.7</td>
<td>11.3</td>
<td>13.0</td>
<td>200</td>
<td>350</td>
<td>1.8</td>
</tr>
<tr>
<td>Maize gluten feed</td>
<td>880</td>
<td>10.5</td>
<td>10.7</td>
<td>18.0</td>
<td>18.1</td>
<td>610</td>
<td>35</td>
<td>0.8</td>
</tr>
<tr>
<td>Sugar-beet pulp</td>
<td>890</td>
<td>6.6</td>
<td>7.1</td>
<td>10.8</td>
<td>12.2</td>
<td>85</td>
<td>385</td>
<td>0.4</td>
</tr>
<tr>
<td>Peas</td>
<td>860</td>
<td>9.7</td>
<td>9.9</td>
<td>14.0</td>
<td>14.5</td>
<td>205</td>
<td>120</td>
<td>1.8</td>
</tr>
<tr>
<td>Field beans</td>
<td>860</td>
<td>8.6</td>
<td>8.8</td>
<td>13.4</td>
<td>13.8</td>
<td>255</td>
<td>137</td>
<td>1.8</td>
</tr>
<tr>
<td>Lupin (white)</td>
<td>875</td>
<td>8.8</td>
<td>9.2</td>
<td>14.5</td>
<td>15.4</td>
<td>330</td>
<td>210</td>
<td>1.9</td>
</tr>
<tr>
<td>Sunflower (extracted)</td>
<td>890</td>
<td>5.4</td>
<td>6.0</td>
<td>9.5</td>
<td>10.6</td>
<td>330</td>
<td>340</td>
<td>1.8</td>
</tr>
<tr>
<td>Rapeseed meal</td>
<td>900</td>
<td>6.5</td>
<td>6.9</td>
<td>11.9</td>
<td>12.8</td>
<td>340</td>
<td>260</td>
<td>3.5</td>
</tr>
<tr>
<td>Soya (44)</td>
<td>875</td>
<td>8.1</td>
<td>8.6</td>
<td>14.8</td>
<td>15.8</td>
<td>435</td>
<td>115</td>
<td>2.1</td>
</tr>
<tr>
<td>Soya (48)</td>
<td>875</td>
<td>8.4</td>
<td>8.8</td>
<td>15.3</td>
<td>16.1</td>
<td>475</td>
<td>80</td>
<td>2.1</td>
</tr>
<tr>
<td>Soya (full fat)</td>
<td>880</td>
<td>11.4</td>
<td>11.8</td>
<td>16.8</td>
<td>18.2</td>
<td>350</td>
<td>110</td>
<td>1.9</td>
</tr>
<tr>
<td>Fish meal (70)</td>
<td>920</td>
<td>10.0</td>
<td>10.0</td>
<td>17.0</td>
<td>17.0</td>
<td>698</td>
<td>150</td>
<td>1.5</td>
</tr>
<tr>
<td>Vegetable oil (soya)</td>
<td>990</td>
<td>31.0</td>
<td>31.0</td>
<td>36.0</td>
<td>36.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dried skimmed milk</td>
<td>950</td>
<td>11.1</td>
<td>11.1</td>
<td>16.5</td>
<td>16.5</td>
<td>340</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whey</td>
<td>950</td>
<td>11.5</td>
<td>11.5</td>
<td>15.5</td>
<td>15.5</td>
<td>125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monocalcium phosphate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>195</td>
</tr>
<tr>
<td>Dicalcium phosphate (18)</td>
<td>990</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>120</td>
</tr>
</tbody>
</table>

Supplemental free L-lysine, DL-methionine, L-threonine, L-tryptophan and DL-tryptophan contain standardised ileal digestible amino acids of 790, 980, 980, 980 and 800 g/kg, respectively.

\(^1\) The nutritive value of feedstuffs is variable, and the compositions given above are for guidance only.
## Table A1.2. Nutritional guide values of some feed ingredients for pigs: cereals

<table>
<thead>
<tr>
<th>Barley</th>
<th>Wheat</th>
<th>Maize</th>
<th>Oats</th>
<th>Rice</th>
<th>Rye</th>
<th>Sorghum</th>
<th>Cassava/Manioc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry matter (g/kg)</td>
<td>860</td>
<td>860</td>
<td>880</td>
<td>860</td>
<td>870</td>
<td>860</td>
<td>860</td>
</tr>
<tr>
<td>Crude protein (g/kg)</td>
<td>105</td>
<td>110</td>
<td>90</td>
<td>103</td>
<td>66</td>
<td>110</td>
<td>95</td>
</tr>
<tr>
<td>Faecal digestibility of protein</td>
<td>0.76</td>
<td>0.82</td>
<td>0.78</td>
<td>0.75</td>
<td>0.70</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Ileal digestibility of protein</td>
<td>0.72</td>
<td>0.75</td>
<td>0.73</td>
<td>0.70</td>
<td>0.65</td>
<td>0.65</td>
<td>0.70</td>
</tr>
<tr>
<td>Crude fibre (g/kg)</td>
<td>45</td>
<td>30</td>
<td>23</td>
<td>115</td>
<td>15</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Neutral detergent fibre (g/kg)</td>
<td>175</td>
<td>120</td>
<td>90</td>
<td>270</td>
<td>170</td>
<td>140</td>
<td>35</td>
</tr>
<tr>
<td>Oil (g/kg)</td>
<td>15</td>
<td>16</td>
<td>36</td>
<td>42</td>
<td>4</td>
<td>16</td>
<td>35</td>
</tr>
<tr>
<td>Ash (g/kg)</td>
<td>24</td>
<td>18</td>
<td>15</td>
<td>30</td>
<td>8</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Lysine (g/kg)</td>
<td>3.5 (0.70)</td>
<td>3.0 (0.73)</td>
<td>2.6 (0.70)</td>
<td>3.8 (0.67)</td>
<td>2.4 (0.70)</td>
<td>3.8 (0.67)</td>
<td>2.0 (0.75)</td>
</tr>
<tr>
<td>Methionine + cysteine (g/kg)</td>
<td>3.8 (0.75)</td>
<td>4.0 (0.82)</td>
<td>3.7 (0.82)</td>
<td>3.8 (0.78)</td>
<td>2.3 (0.72)</td>
<td>3.5 (0.78)</td>
<td>3.4 (0.85)</td>
</tr>
<tr>
<td>Threonine (g/kg)</td>
<td>3.4 (0.63)</td>
<td>3.0 (0.65)</td>
<td>3.3 (0.70)</td>
<td>3.4 (0.58)</td>
<td>2.5 (0.70)</td>
<td>3.5 (0.60)</td>
<td>4.0 (0.75)</td>
</tr>
<tr>
<td>Tryptophan (g/kg)</td>
<td>1.5 (0.73)</td>
<td>1.3 (0.75)</td>
<td>0.8 (0.70)</td>
<td>1.5 (0.65)</td>
<td>0.6 (0.70)</td>
<td>1.4 (0.66)</td>
<td>1.1 (0.75)</td>
</tr>
<tr>
<td>Isoleucine (g/kg)</td>
<td>5.1 (0.73)</td>
<td>5.0 (0.80)</td>
<td>3.4 (0.78)</td>
<td>5.0 (0.72)</td>
<td>3.0 (0.72)</td>
<td>3.3 (0.70)</td>
<td>3.6 (0.85)</td>
</tr>
<tr>
<td>Linoleic acid (g/kg)</td>
<td>9</td>
<td>8</td>
<td>21</td>
<td>18</td>
<td>7</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>Calcium (g/kg)</td>
<td>0.5</td>
<td>0.3</td>
<td>0.2</td>
<td>1.0</td>
<td>0.7</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Phosphorus (g/kg)</td>
<td>3.5</td>
<td>3.4</td>
<td>2.4</td>
<td>3.2</td>
<td>1.0</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Digestible energy (MJ/kg)</td>
<td>12.9</td>
<td>14.0</td>
<td>14.5</td>
<td>11.4</td>
<td>15.0</td>
<td>13.3</td>
<td>13.0</td>
</tr>
<tr>
<td>Inclusion in starter diets</td>
<td>&lt;0.4</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.4</td>
<td>&lt;0.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Inclusion in grower diets</td>
<td>&lt;0.6</td>
<td>&lt;0.6</td>
<td>&lt;0.6</td>
<td>&lt;0.5</td>
<td>&lt;0.3</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Inclusion in finisher diets</td>
<td>&lt;0.7</td>
<td>&lt;0.6</td>
<td>&lt;0.6</td>
<td>&lt;0.6</td>
<td>&lt;0.4</td>
<td>&lt;0.3</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>Inclusion in sow diets</td>
<td>&lt;0.7</td>
<td>&lt;0.6</td>
<td>&lt;0.6</td>
<td>&lt;0.6</td>
<td>&lt;0.4</td>
<td>&lt;0.2</td>
<td>&lt;0.3</td>
</tr>
</tbody>
</table>

1 Individual cereals may be included at a minimum of 250 g/kg to maintain continuity in diet mixtures. Cooked cereals are more palatable and should be used in starter diets; cooking avoids DE depression with young pigs, while for other pigs DE is increased by 5% and protein digestibility decreased by 5%.
2 Dehulled oats have digestibility and inclusion characteristics similar to wheat.
3 May be contaminated with ergot.
4 Low tannin varieties. High tannin varieties will have lower digestibility, especially for ileal digestibility of amino acids. DE may range from 12 to 14 (yellow varieties).
5 Ileal digestibility is given in parentheses (all measurements of ileal digestibility require verification).
6 The phosphorus in cereal grains and by-products is usually only 50% (or less) available.
Table A1.3. Nutritional guide values of some feed ingredients for pigs: by-products.

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Dry Matter (g/kg)</th>
<th>Crude Protein (g/kg)</th>
<th>Faecal Digestibility of Protein</th>
<th>Ileal Digestibility of Amino Acids</th>
<th>Neutral Detergent Fibre (g/kg)</th>
<th>Oil (g/kg)</th>
<th>Ash (g/kg)</th>
<th>Lysine (g/kg)</th>
<th>Methionine + Cysteine (g/kg)</th>
<th>Threonine (g/kg)</th>
<th>Tryptophan (g/kg)</th>
<th>Isoleucine (g/kg)</th>
<th>Linoleic Acid (g/kg)</th>
<th>Calcium (g/kg)</th>
<th>Phosphorus (g/kg)</th>
<th>Digestible Energy (MJ/kg)</th>
<th>Inclusion in Starter Diets</th>
<th>Inclusion in Grower Diets</th>
<th>Inclusion in Finisher Diets</th>
<th>Inclusion in Sow Diets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distiller's Wheat</td>
<td>900</td>
<td>290</td>
<td>0.60 (0.70)</td>
<td>0.55 (0.60)</td>
<td>100</td>
<td>275</td>
<td>40</td>
<td>7 (0.50)</td>
<td>8 (0.65)</td>
<td>10 (0.55)</td>
<td>1.5 (0.50)</td>
<td>12 (0.64)</td>
<td>45</td>
<td>0.5</td>
<td>8.0</td>
<td>12.5</td>
<td>&lt;0.03</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Wheat bran meal</td>
<td>870</td>
<td>155</td>
<td>0.70 (0.70)</td>
<td>0.60 (0.60)</td>
<td>120</td>
<td>300</td>
<td>40</td>
<td>5.2 (0.68)</td>
<td>5.6 (0.70)</td>
<td>5.5 (0.65)</td>
<td>2.1 (0.70)</td>
<td>6.0 (0.85)</td>
<td>30</td>
<td>2.9</td>
<td>7.0</td>
<td>8.0</td>
<td>0</td>
<td>0</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Maize germ meal</td>
<td>880</td>
<td>150</td>
<td>0.70 (0.70)</td>
<td>0.60 (0.60)</td>
<td>120</td>
<td>450</td>
<td>42</td>
<td>4.0 (0.65)</td>
<td>4.5 (0.75)</td>
<td>4.2 (0.60)</td>
<td>2.0 (0.70)</td>
<td>5.3 (0.74)</td>
<td>20</td>
<td>1.4</td>
<td>7.5</td>
<td>11.3</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Maize gluten meal</td>
<td>880</td>
<td>100</td>
<td>0.70 (0.70)</td>
<td>0.60 (0.60)</td>
<td>120</td>
<td>450</td>
<td>100</td>
<td>4.8 (—)</td>
<td>4.2 (0.70)</td>
<td>4.0 (0.60)</td>
<td>1.2 (0.70)</td>
<td>4.3 (0.74)</td>
<td>10</td>
<td>1.3</td>
<td>11.0</td>
<td>11.0</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.4</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Maize gluten feed</td>
<td>900</td>
<td>600</td>
<td>0.70 (0.70)</td>
<td>0.60 (0.60)</td>
<td>120</td>
<td>350</td>
<td>25</td>
<td>11 (0.72)</td>
<td>25 (0.80)</td>
<td>21 (0.80)</td>
<td>3.0 (0.70)</td>
<td>6.3 (0.70)</td>
<td>17</td>
<td>0.2</td>
<td>6.6</td>
<td>6.6</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Cooked oats</td>
<td>900</td>
<td>210</td>
<td>0.70 (0.70)</td>
<td>0.60 (0.60)</td>
<td>120</td>
<td>300</td>
<td>25</td>
<td>5.5 (0.50)</td>
<td>8.0 (0.50)</td>
<td>7.0 (0.50)</td>
<td>1.3 (0.33)</td>
<td>5.2 (0.84)</td>
<td>18</td>
<td>0.6</td>
<td>8.0</td>
<td>8.0</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Cooked oat hulls</td>
<td>870</td>
<td>125</td>
<td>0.70 (0.70)</td>
<td>0.60 (0.60)</td>
<td>120</td>
<td>350</td>
<td>25</td>
<td>5.5 (0.50)</td>
<td>8.0 (0.50)</td>
<td>7.0 (0.50)</td>
<td>1.3 (0.33)</td>
<td>5.2 (0.84)</td>
<td>18</td>
<td>1.4</td>
<td>8.0</td>
<td>8.0</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Cooked oat pulp</td>
<td>900</td>
<td>35</td>
<td>0.70 (0.70)</td>
<td>0.60 (0.60)</td>
<td>120</td>
<td>350</td>
<td>25</td>
<td>4.5 (0.80)</td>
<td>4.2 (0.70)</td>
<td>4.0 (0.60)</td>
<td>1.0 (—)</td>
<td>4.5 (—)</td>
<td>18</td>
<td>0.6</td>
<td>8.0</td>
<td>8.0</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Sugar-beet pulp</td>
<td>870</td>
<td>145</td>
<td>0.70 (0.70)</td>
<td>0.60 (0.60)</td>
<td>120</td>
<td>350</td>
<td>25</td>
<td>0.8 (—)</td>
<td>0.8 (—)</td>
<td>0.8 (—)</td>
<td>0.4 (—)</td>
<td>4.5 (—)</td>
<td>18</td>
<td>1.4</td>
<td>8.0</td>
<td>8.0</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Rice bran</td>
<td>900</td>
<td>145</td>
<td>0.70 (0.70)</td>
<td>0.60 (0.60)</td>
<td>120</td>
<td>350</td>
<td>25</td>
<td>0.8 (—)</td>
<td>0.8 (—)</td>
<td>0.8 (—)</td>
<td>0.4 (—)</td>
<td>4.5 (—)</td>
<td>18</td>
<td>1.4</td>
<td>8.0</td>
<td>8.0</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Cooked potatoes</td>
<td>900</td>
<td>145</td>
<td>0.70 (0.70)</td>
<td>0.60 (0.60)</td>
<td>120</td>
<td>350</td>
<td>25</td>
<td>0.8 (—)</td>
<td>0.8 (—)</td>
<td>0.8 (—)</td>
<td>0.4 (—)</td>
<td>4.5 (—)</td>
<td>18</td>
<td>1.4</td>
<td>8.0</td>
<td>8.0</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Grass meal</td>
<td>900</td>
<td>145</td>
<td>0.70 (0.70)</td>
<td>0.60 (0.60)</td>
<td>120</td>
<td>350</td>
<td>25</td>
<td>0.8 (—)</td>
<td>0.8 (—)</td>
<td>0.8 (—)</td>
<td>0.4 (—)</td>
<td>4.5 (—)</td>
<td>18</td>
<td>1.4</td>
<td>8.0</td>
<td>8.0</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

1 Some samples may have a high copper content (100 mg/kg).
2 Ileal digestibility is given in parentheses (all measurements of ileal digestibility require verification).
3 The phosphorus in cereal grains and by-products is usually only 50% (or less) available.
4 Can cause soft and/or yellow carcass fat.
## Table A1.4. Nutritional guide values of some feed ingredients for pigs: fats, minerals, molasses and animal proteins

<table>
<thead>
<tr>
<th></th>
<th>Soya oil</th>
<th>Tallow</th>
<th>Molasses</th>
<th>Fish meal</th>
<th>Herring meal</th>
<th>Meat- and bone meal</th>
<th>Separated milk (skim)</th>
<th>Whey</th>
<th>Limestone</th>
<th>Dicalcium phosphate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry matter (g/kg)</td>
<td>990</td>
<td>990</td>
<td>640</td>
<td>900</td>
<td>900</td>
<td>900</td>
<td>950</td>
<td>930</td>
<td>980</td>
<td>975</td>
</tr>
<tr>
<td>Crude protein (g/kg)</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>650</td>
<td>680</td>
<td>480</td>
<td>340</td>
<td>125</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Faecal digestibility of protein</td>
<td>0</td>
<td>0</td>
<td>0.30</td>
<td>0.92</td>
<td>0.92</td>
<td>0.65</td>
<td>0.95</td>
<td>0.90</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Ileal digestibility of amino acids</td>
<td>0</td>
<td>0</td>
<td>0.25</td>
<td>0.80</td>
<td>0.80</td>
<td>0.58</td>
<td>0.90</td>
<td>0.85</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Crude fibre (g/kg)</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Neutral detergent fibre (g/kg)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Oil (g/kg)</td>
<td>990</td>
<td>990</td>
<td>0</td>
<td>60</td>
<td>85</td>
<td>110</td>
<td>10</td>
<td>42</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ash (g/kg)</td>
<td>0</td>
<td>80</td>
<td>0</td>
<td>80</td>
<td>300</td>
<td>80</td>
<td>85</td>
<td>980</td>
<td>950</td>
<td>950</td>
</tr>
<tr>
<td>Lysine (g/kg)^4</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>47 (0.82)</td>
<td>52 (0.88)</td>
<td>25 (0.65)</td>
<td>25 (0.95)</td>
<td>8.9</td>
<td>0.93</td>
<td>0</td>
</tr>
<tr>
<td>Methionine + cysteine (g/kg)^4</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>24 (0.85)</td>
<td>26 (0.85)</td>
<td>12 (0.73)</td>
<td>12 (0.95)</td>
<td>5.0</td>
<td>0.93</td>
<td>0</td>
</tr>
<tr>
<td>Threonine (g/kg)^4</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>26 (0.82)</td>
<td>30 (0.80)</td>
<td>16 (0.58)</td>
<td>15 (0.90)</td>
<td>7.3</td>
<td>0.90</td>
<td>0</td>
</tr>
<tr>
<td>Tryptophan (g/kg)^4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7 (0.75)</td>
<td>6 (0.80)</td>
<td>3 (0.50)</td>
<td>5 (0.85)</td>
<td>2.1</td>
<td>0.85</td>
<td>0</td>
</tr>
<tr>
<td>Isoleucine (g/kg)^4</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>32 (0.85)</td>
<td>34 (0.85)</td>
<td>16 (0.67)</td>
<td>24 (0.85)</td>
<td>8.5</td>
<td>0.85</td>
<td>0</td>
</tr>
<tr>
<td>Linoleic acid (g/kg)</td>
<td>600</td>
<td>25</td>
<td>0</td>
<td>1.8</td>
<td>1.5</td>
<td>2.5</td>
<td>0.14</td>
<td>0.42</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Calcium (g/kg)</td>
<td>0</td>
<td>0</td>
<td>6.0</td>
<td>65</td>
<td>29</td>
<td>100</td>
<td>10</td>
<td>8.5</td>
<td>360</td>
<td>230</td>
</tr>
<tr>
<td>Phosphorus (g/kg)</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>32</td>
<td>20</td>
<td>50</td>
<td>8</td>
<td>7.0</td>
<td>0</td>
<td>180</td>
</tr>
<tr>
<td>Digestible energy (MJ/kg)</td>
<td>36</td>
<td>29</td>
<td>10.0</td>
<td>15.0</td>
<td>17.5</td>
<td>10.0</td>
<td>16.0</td>
<td>15.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Inclusion in starter diets</td>
<td>&lt;0.1</td>
<td>0</td>
<td>&lt;0.05</td>
<td>&gt;0.08</td>
<td>&gt;0.08</td>
<td>0</td>
<td>&gt;0.1</td>
<td>&gt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Inclusion in grower diets</td>
<td>&lt;0.1</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&gt;0.05</td>
<td>&gt;0.05</td>
<td>0</td>
<td>0</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Inclusion in finisher diets</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.08</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.1</td>
<td>0</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Inclusion in sow diets</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.08</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.05</td>
<td>0</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

High levels of fats and oils, or products containing them, may predispose to soft carcass fats.

1 Artificial amino acids may be assumed to have faecal and ileal digestibilities of 100%. L-lysine HCl contains 780 g lysine/kg, L-threonine contains 980 g threonine/kg, DL-methionine contains 980 g methionine/kg and DL-tryptophan contains 800 g tryptophan/kg.

2 Highly variable in both composition and the utilisability of the ileal digested amino acids (40–90%), according to source and treatment.

3 Especially variable in protein content according to source, and when provided in the liquid form variable in dry matter content.

4 Ileal digestibility is given in parentheses (all measurements of ileal digestibility require verification).
Table A1.5. Nutritional guide values of some feed ingredients for pigs: vegetable proteins

<table>
<thead>
<tr>
<th></th>
<th>Soya bean meal (extracted)</th>
<th>Full fat soya meal (extruded)</th>
<th>Rapeseed meal (extracted)</th>
<th>Sunflower meal (extracted)</th>
<th>Field beans</th>
<th>Field peas</th>
<th>Full fat sunflower meal</th>
<th>Lupin meal (extracted)</th>
<th>Cottonseed meal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry matter (g/kg)</td>
<td>890</td>
<td>900</td>
<td>880</td>
<td>900</td>
<td>860</td>
<td>860</td>
<td>900</td>
<td>900</td>
<td>920</td>
</tr>
<tr>
<td>Crude protein (g/kg)</td>
<td>440</td>
<td>430</td>
<td>360</td>
<td>360</td>
<td>260</td>
<td>260</td>
<td>190</td>
<td>190</td>
<td>150</td>
</tr>
<tr>
<td>Faecal digestibility of protein</td>
<td>0.87</td>
<td>0.85</td>
<td>0.70</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.70</td>
</tr>
<tr>
<td>Ileal digestibility of amino acids</td>
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<td>0.85</td>
<td>0.60</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.70</td>
</tr>
<tr>
<td>Crude fibre (g/kg)</td>
<td>67</td>
<td>50</td>
<td>120</td>
<td>200</td>
<td>80</td>
<td>80</td>
<td>54</td>
<td>54</td>
<td>150</td>
</tr>
<tr>
<td>Neutral detergent fibre (g/kg)</td>
<td>140</td>
<td>105</td>
<td>250</td>
<td>370</td>
<td>150</td>
<td>120</td>
<td>—</td>
<td>—</td>
<td>300</td>
</tr>
<tr>
<td>Oil (g/kg)</td>
<td>15</td>
<td>175</td>
<td>20</td>
<td>20</td>
<td>13</td>
<td>14</td>
<td>300</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Ash (g/kg)</td>
<td>55</td>
<td>50</td>
<td>77</td>
<td>70</td>
<td>34</td>
<td>30</td>
<td>—</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>Lysine (g/kg)</td>
<td>29 (0.85)</td>
<td>24 (0.80)</td>
<td>20 (0.72)</td>
<td>12 (0.68)</td>
<td>14 (0.78)</td>
<td>15 (0.80)</td>
<td>5.1 (—)</td>
<td>12 (0.70)</td>
<td>18 (0.70)</td>
</tr>
<tr>
<td>Methionine + cysteine (g/kg)</td>
<td>13 (0.85)</td>
<td>11 (0.75)</td>
<td>12 (0.80)</td>
<td>12 (0.85)</td>
<td>5.0 (0.75)</td>
<td>5.0 (0.70)</td>
<td>6.0 (—)</td>
<td>5 (0.65)</td>
<td>12 (0.70)</td>
</tr>
<tr>
<td>Threonine (g/kg)</td>
<td>17 (0.78)</td>
<td>15 (0.70)</td>
<td>16 (0.68)</td>
<td>12 (0.70)</td>
<td>10 (0.70)</td>
<td>9 (0.75)</td>
<td>5.5 (—)</td>
<td>9 (0.75)</td>
<td>14 (0.75)</td>
</tr>
<tr>
<td>Tryptophan (g/kg)</td>
<td>6.4 (0.75)</td>
<td>4.9 (0.70)</td>
<td>4.5 (0.70)</td>
<td>4 (0.77)</td>
<td>2.3 (0.70)</td>
<td>2.0 (0.70)</td>
<td>2.0 (—)</td>
<td>2 (—)</td>
<td>5 (0.70)</td>
</tr>
<tr>
<td>Isoleucine (g/kg)</td>
<td>22 (0.80)</td>
<td>19 (0.70)</td>
<td>13 (0.75)</td>
<td>14 (0.77)</td>
<td>10 (—)</td>
<td>9.0 (0.74)</td>
<td>6.4 (—)</td>
<td>11 (0.75)</td>
<td>14 (0.68)</td>
</tr>
<tr>
<td>Linoleic acid (g/kg)</td>
<td>5</td>
<td>80</td>
<td>3</td>
<td>12</td>
<td>7</td>
<td>12</td>
<td>280</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>Calcium (g/kg)</td>
<td>2.7</td>
<td>2.5</td>
<td>6.6</td>
<td>3.8</td>
<td>1.4</td>
<td>0.7</td>
<td>2.0</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Phosphorus (g/kg)</td>
<td>6.0</td>
<td>5.5</td>
<td>13</td>
<td>10.3</td>
<td>4.9</td>
<td>3.9</td>
<td>5.0</td>
<td>3.5</td>
<td>13.0</td>
</tr>
<tr>
<td>Digestible energy (MJ/kg)</td>
<td>14.5</td>
<td>17.0</td>
<td>11.8</td>
<td>9.0</td>
<td>13.0</td>
<td>13.6</td>
<td>17.0</td>
<td>13.0</td>
<td>13.2</td>
</tr>
<tr>
<td>Inclusion in starter diets</td>
<td>&lt;0.25</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Inclusion in grower diets</td>
<td>&lt;0.25</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>Inclusion in finisher diets</td>
<td>&gt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>Inclusion in sow diets</td>
<td>&gt;0.1</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.05</td>
</tr>
</tbody>
</table>

1 Crude protein content varies with degree of dehulling; fully dehulled, 400; partially dehulled, 350; with hulls, 280.
2 Ileal digestibility is given in parentheses (all measurements of ileal digestibility require verification).
3 The phosphorus in cereal grains and by-products is usually only 50% (or less) available.
4 Causing soft and/or yellow carcass fat.
5 Rapeseed meal may contain various anti-nutritional factors including glucosinolates, tannins, complexed fibres, complexed carbohydrates and erucic acid. These have toxic and appetite depressant effects. Varieties are available with low and double-low toxin levels and it is these that should be used. Some 'low' glucosinolate rapeseeds may contain up to 20 μmol; levels that have been found to cause performance reduction. Treatment processes show promise in further detoxifying the material and removing its appetite depressant effects; these sources can be included at higher levels (add 0.05 to limits in table).
6 Of which only 80% is actually available (total available about 60%).
7 Of which only 60–70% is actually available (total available about 40% for cottonseed meals and 50% for lupin meals).
8 Higher levels of angustifolius.
Appendix 2

Guide Nutrient Specifications for Pig Diets
Table A2.1. Guideline nutrient specifications. Chemical analysis of macro nutrients (g/kg of final feed)

<table>
<thead>
<tr>
<th>Component</th>
<th>Up to 15kg(^1)</th>
<th>Up to 30kg(^2)</th>
<th>Up to 100kg(^1) (diet A)</th>
<th>Up to 160kg(^1) (diet B)</th>
<th>Breeding sows(^1)</th>
<th>Pregnant sows(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude fat</td>
<td>50–100</td>
<td>50–80</td>
<td>30–60</td>
<td>20–50</td>
<td>30–70</td>
<td>20–40</td>
</tr>
<tr>
<td>Crude fibre</td>
<td>15–40</td>
<td>20–40</td>
<td>20–60</td>
<td>20–80</td>
<td>30–50</td>
<td>40–100</td>
</tr>
<tr>
<td>NE (MJ/kg)</td>
<td>10–12</td>
<td>10–11</td>
<td>8–10</td>
<td>8–10</td>
<td>9–11</td>
<td>8–10</td>
</tr>
<tr>
<td>Total lysine(^2)</td>
<td>11–14</td>
<td>9–14</td>
<td>6–12</td>
<td>5–10</td>
<td>8–10</td>
<td>4–7</td>
</tr>
<tr>
<td>Standardised ileal digestible lysine(^2)</td>
<td>8–12</td>
<td>8–12</td>
<td>5–10</td>
<td>4–8</td>
<td>7–9</td>
<td>3–6</td>
</tr>
<tr>
<td>Ca</td>
<td>5–10</td>
<td>5–10</td>
<td>5–9</td>
<td>5–9</td>
<td>5–10</td>
<td>6–10</td>
</tr>
<tr>
<td>Digestible P</td>
<td>3–5</td>
<td>2–4</td>
<td>2–4</td>
<td>2–3</td>
<td>3–4</td>
<td>2–3</td>
</tr>
<tr>
<td>Na</td>
<td>1.5–2.0</td>
<td>1.5–2.0</td>
<td>1.5–2.0</td>
<td>1.5–2.0</td>
<td>1.5–2.0</td>
<td>1.5–2.0</td>
</tr>
<tr>
<td>Total lysine (g/MJ DE) (approx.)</td>
<td>0.85</td>
<td>0.80</td>
<td>0.75</td>
<td>0.60</td>
<td>0.75</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Vitamins and trace elements [to add, per tonne (1000 kg) of final feed\(^4\)(approx.)]

- Vitamins A 5–15 million i.u. (1 million i.u. = 0.3 g retinol), D3 0.5–1.5 million i.u. (1 million i.u. = 0.025 g cholecalciferol), E 0.03–0.10 million i.u. (1 million i.u. = 1000 g l-tocopherol acetate)
- K\(_3\) (menadione) 1–3 g, thiamin (B\(_1\)) 1–3 g, riboflavin (B\(_2\)) 3–6 g, nicotinic acid 15–30 g, pantothenic acid 10–20 g, pyridoxine (B\(_6\)) 2–4 g, B\(_12\) 20–40 mg, biotin (H) 0.03–0.10 million i.u., folic acid 0–3 g, choline 50–500 g, zinc 75–125 g, magnesium 30 g, manganese 20–40 g, iron 75–125 g, cobalt 0.2–0.5 g, iodine 0.2–0.5 g, selenium 0.2–0.3 g, copper 5–160 g, butylated hydroxy-toluene 125 g.

\(^1\) Individual diets will vary according to the circumstances of the unit, the genetic type of the pig, the number of different diets acceptable and the economic cost–benefit. Diets for pigs up to 30 kg and for lactating sows should be fed to appetite. Diets for pigs up to 100 kg may be fed to appetite or restricted during the later stages of growth; diet A is of higher specification than B and is appropriate for improved genotypes. To achieve the required intake of nutrients, a greater quantity of diet of lower nutrient density is needed.

\(^2\) The required provision of other essential amino acids (and of total protein) may be achieved by attaining the following minima which are expressed in relative terms as proportions of the lysine requirement (1.00): histidine 0.36; isoleucine 0.60; leucine 1.10; methionine + cysteine 0.60 (at least 50% as methionine); tyrosine + phenylalanine 1.00; threonine 0.68; tryptophan 0.19; valine 0.75; minimum of total protein 2.5 times the sum of the eleven above named [which approximates to a minimum level of standardised ileal digestible protein (g/kg) of about 160, 150, 120, 100, 120 and 90 for the classes of pigs given in the table, respectively].

\(^3\) Levels vary widely according to the risk of loss of potency and local knowledge. In-feed growth promoters, medicines, diet acidifiers and probiotics may be included according to local regulations and need.

\(^4\) Higher levels if significant quantities of fat in the diet (especially if unsaturated; a rule of 30 g for every percentage unit of linoleic acid has been suggested); up to 200 g may be justified in diets offered to young pigs challenged by disease or offered unusual feedstuffs.

\(^5\) 500 mg has been suggested to help resolve reproductive problems, and up to 1000 mg to help resolve hoof problems.

\(^6\) Up to 5 g for breeding sows.

\(^7\) Widely ranging between 0 and 1000 g. A quarter to a half of the requirement is often added; total requirement is about 1500 g.

\(^8\) The higher levels for diets with added copper, the lower levels for adults.

\(^9\) Widely ranging between 0 and 500 g; adequate provision (of 400 g total Mg per tonne of feed) is likely from the main ingredients.

\(^10\) Higher levels (0.5–2.0 g) if goitrogens appear in the diet ingredients.

\(^11\) The higher level for growth promotion (local regulations apply). Background copper levels are 10–20 g and the limit for breeding sows is 30–40 g. Often 160 g is added for pigs up to 12 weeks of age, and 15 g thereafter.
### Appendix 3

**Guide Feedstuff Ingredient Compositions of Pig Diets**

**Table A3.1.** Example ingredient composition (kg/tonne) (ingredients may differ according to national availability and price)

<table>
<thead>
<tr>
<th></th>
<th>Up to 15kg&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Up to 30kg&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Up to 100kg&lt;sup&gt;1&lt;/sup&gt; (diet A)</th>
<th>Up to 100kg&lt;sup&gt;1&lt;/sup&gt; (diet B)</th>
<th>Breeding gilts/lactating sows&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Pregnant sows&lt;sup&gt;1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0–200</td>
<td>20–300</td>
<td>0–500</td>
<td>0–500</td>
<td>0–500</td>
<td>0–500</td>
</tr>
<tr>
<td>Wheat&lt;sup&gt;2&lt;/sup&gt; or other cereals</td>
<td>50–300&lt;sup&gt;3&lt;/sup&gt;</td>
<td>20–300&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0–500</td>
<td>0–500</td>
<td>0–500</td>
<td>0–500</td>
</tr>
<tr>
<td>Maize&lt;sup&gt;2&lt;/sup&gt;</td>
<td>10–500</td>
<td>10–500</td>
<td>0–400</td>
<td>0–500</td>
<td>0–500</td>
<td>0–500</td>
</tr>
<tr>
<td>Full fat soya</td>
<td>0–50</td>
<td>0–150</td>
<td>0–100</td>
<td>0–100</td>
<td>0–100</td>
<td>0–100</td>
</tr>
<tr>
<td>Extracted soya bean meal</td>
<td>0–50</td>
<td>0–100</td>
<td>0–250</td>
<td>50–200</td>
<td>50–200</td>
<td>50–200</td>
</tr>
<tr>
<td>Fish meal&lt;sup&gt;4&lt;/sup&gt;</td>
<td>50–150</td>
<td>50–200</td>
<td>0–100</td>
<td>0–100</td>
<td>0–100</td>
<td>0–100</td>
</tr>
<tr>
<td>Dried whey powder&lt;sup&gt;5&lt;/sup&gt;</td>
<td>50–200</td>
<td>50–200</td>
<td>0–100</td>
<td>0–100</td>
<td>0–100</td>
<td>0–100</td>
</tr>
<tr>
<td>Dried skim milk&lt;sup&gt;5&lt;/sup&gt;</td>
<td>100–200</td>
<td>0–150</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed oils and fats&lt;sup&gt;5&lt;/sup&gt;</td>
<td>20–80</td>
<td>10–50</td>
<td>0–30</td>
<td>0–30</td>
<td>0–50</td>
<td>0–30</td>
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<tr>
<td>Millers’ by-products</td>
<td>0–10</td>
<td>0–150</td>
<td>0–200</td>
<td>0–250</td>
<td>0–250</td>
<td>0–300</td>
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<tr>
<td>Grass/alfalfa products</td>
<td>0–100</td>
<td>0–100</td>
<td>0–100</td>
<td>0–100</td>
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<td>0–100</td>
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<tr>
<td>Limestone</td>
<td>0–10</td>
<td>0–15</td>
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<td>0–15</td>
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<tr>
<td>Dicalcium phosphate</td>
<td>0–10</td>
<td>0–15</td>
<td>0–15</td>
<td>0–15</td>
<td>0–15</td>
<td>0–15</td>
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<tr>
<td>Salt&lt;sup&gt;6&lt;/sup&gt;</td>
<td>0–5</td>
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<td>0–5</td>
<td>0–5</td>
<td>0–5</td>
<td>0–5</td>
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<tr>
<td>Lysine HCl</td>
<td>1–2</td>
<td>1–2</td>
<td>1–2</td>
<td>0–2</td>
<td>0–2</td>
<td>0–1</td>
</tr>
<tr>
<td>Vitamins and minerals</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

<sup>1</sup> Individual diets will vary according to the circumstances of the unit, the genetic type of the pig, the number of different diets acceptable and the economic cost–benefit. Diets for pigs up to 30 kg and for lactating sows should be fed to appetite. Diets for pigs up to 100 kg may be fed to appetite or restricted during the later stages of growth; diet A is of higher specification than B and is appropriate for improved genotypes. To achieve the required intake of nutrients, a greater quantity of diet of lower nutrient density is needed.

<sup>2</sup> A good proportion to be cooked up to 15 kg, a small proportion to be cooked up to 30 kg.

<sup>3</sup> Dehulled oats are a useful cereal in diets up to 30 kg. Whole oats may be used subsequently.

<sup>4</sup> Or other sources of animal protein. In some cases a minimum of 25 kg/t may be advisable.

<sup>5</sup> Or a fat-filled milk replacer. The higher levels are justified in starter diets for pigs from 14 days of age to 10 kg live weight.

<sup>6</sup> Sodium and chloride requirements will be met by inclusions of 2.5 kg/t or less depending on other ingredients present. Additional salt is used as an appetiser. Levels of 10 kg/t or above risk toxicity.
## Appendix 4

### Description Files for Raw Materials

<table>
<thead>
<tr>
<th>Name: Barley (1)</th>
<th>Name: Soya 44 (6)</th>
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<td>Currency cost</td>
<td>Currency cost</td>
</tr>
<tr>
<td>110</td>
<td>148</td>
</tr>
<tr>
<td>Minimum weight (kg)</td>
<td>Minimum weight (kg)</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Rounding (kg)</td>
<td>Rounding (kg)</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
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<tr>
<td>Analysis</td>
<td>Analysis</td>
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<tr>
<td>(Volume)</td>
<td>(Volume)</td>
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<td>100.00</td>
</tr>
<tr>
<td>DE</td>
<td>DE</td>
</tr>
<tr>
<td>12.90</td>
<td>15.00</td>
</tr>
<tr>
<td>CP</td>
<td>CP</td>
</tr>
<tr>
<td>107.00</td>
<td>435.00</td>
</tr>
<tr>
<td>DCP</td>
<td>DCP</td>
</tr>
<tr>
<td>77.00</td>
<td>410.00</td>
</tr>
<tr>
<td>Lysine</td>
<td>Lysine</td>
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<tr>
<td>3.50</td>
<td>28.90</td>
</tr>
<tr>
<td>Methionine + cysteine</td>
<td>Methionine + cysteine</td>
</tr>
<tr>
<td>3.70</td>
<td>13.20</td>
</tr>
<tr>
<td>Methionine</td>
<td>Methionine</td>
</tr>
<tr>
<td>1.7</td>
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<td>Threonine</td>
<td>Threonine</td>
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<tr>
<td>3.30</td>
<td>17.10</td>
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<td>Tryptophan</td>
<td>Tryptophan</td>
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<tr>
<td>1.50</td>
<td>6.40</td>
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<tr>
<td>Linoleic acid</td>
<td>Linoleic acid</td>
</tr>
<tr>
<td>9.00</td>
<td>4.00</td>
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<tr>
<td>Starch + sugar</td>
<td>Starch + sugar</td>
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<td>482.00</td>
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<tr>
<td>Copper</td>
<td>Copper</td>
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<td>4.10</td>
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<tr>
<td>Phosphorus</td>
<td>Phosphorus</td>
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<tr>
<td>3.40</td>
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<tr>
<td>Available phosphorus</td>
<td>Average phosphorus</td>
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<tr>
<td>Oil</td>
<td>Oil</td>
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<tr>
<td>15.00</td>
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<tr>
<td>Crude fibre</td>
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</tr>
<tr>
<td>45.00</td>
<td>67.00</td>
</tr>
<tr>
<td>Ash</td>
<td>Ash</td>
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<tr>
<td>24.00</td>
<td>60.00</td>
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<tr>
<td>Neutral detergent fibre</td>
<td>Neutral detergent fibre</td>
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<td>202.00</td>
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<td>Selenium</td>
<td>Selenium</td>
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<td>0.03</td>
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<td>Dry matter</td>
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<tr>
<td>875.00</td>
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<td>Pelleting quality factor</td>
<td>Pelleting quality factor</td>
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<tr>
<td>5.00</td>
<td>4.00</td>
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