Developments in monogastric nutrition for the 21st century

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Abstract

The changes that have taken place in broiler and pig genotypes over the past fifty years have had significant repercussions for nutritionists, as well as for the managers of these species, and this paper begins by exploring those changes as a means of predicting the nutritional and environmental requirements of broilers and pigs in the future. The proportion of the daily requirement that is attributable to maintenance has been reduced, due to the increased growth rates and the successful selection for feed efficiency. As a result, the amino acid balance in the feed required to meet these requirements has changed markedly over the years. Similarly, the amino acid requirements at an age have increased in the early growth period, and decreased towards the time when the birds and pigs are harvested. These changes have only been recognised through the use of simulation models. But in addition to changes in genotypes has been a considerable improvement in our knowledge of the nutrient and anti-nutritional contents of feed ingredients available to the monogastric industry, as well as of methods whereby more benefits may be extracted from feed ingredients by means of improved processing and the addition of feed enzymes. Because of the importance of these changes to the efficient feeding of broilers and pigs, some of these changes, and their implications for monogastric nutrition in the 21st Century, are considered in this paper.

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Introduction

In the past fifty years, the most impressive developments among monogastric animals used in commercial agriculture have been the improvements in the growth potential of broilers and pigs, brought about by genetic selection. These developments far outweigh the improvements that have occurred over the same period of time in, for example, egg production in laying hens, and prolificacy in sows, so, to avoid making this a lengthy treatise, very little will be said in this paper of the implications of these latter developments for monogastric nutrition. Because the changes brought about by selection for rapid growth rate have had such profound effects on the nutritional and environmental requirements of broilers and pigs, and because genetic improvements in their growth are likely to continue in the future, the implications of this progress in monogastric nutrition in the 21st Century are the subject of this paper.

The changes that have taken place in broiler and pig genotypes over the years have had significant repercussions for nutritionists, as well as for the managers of these birds and animals, and this paper begins by exploring those changes as a means of predicting the nutritional and environmental requirements of broilers and pigs in the future. But in addition to changes in broiler genotypes has been a considerable improvement in our knowledge of the nutrient and anti-nutritional contents of feed ingredients available to the monogastric industry, as well as of methods whereby more benefits may be extracted from feed ingredients by means of improved processing and the addition of feed enzymes. Because of the importance of these changes to the efficient feeding of broilers and pigs, some of these changes, and their implications for monogastric nutrition in the 21st Century, are considered in this paper.

It is the combination of the genotype, the feed that is offered to the animal, and the environment in which it is kept, that determines the food intake, growth rate and carcass composition of the growing animal, and it is the integration of these three factors that enables the prediction of performance in present and future genotypes available to the monogastric industry. Due to the complexity of the interactions between the three factors, such integration can only be accomplished with the use of simulation models. Much use has been made of such a model (EFG broiler simulation model, 1990, unpublished) in this paper to predict changes in potential growth rate, and in nutritional and environmental requirements of broilers in the first few years of the 21st Century. Updates to this model now make it possible to optimise feeding programmes, nutrient density, and amino acid to energy ratios in feeds for broilers (Fisher & Gous, 2000). Such models will significantly improve the scientific basis on which nutritionists in the future will determine the optimum economic feeding programmes for broilers, given different genotypes, feed ingredient and broiler prices, mixing and transport costs. These are exciting prospects for poultry and pig nutritionists for the future.

Genetic improvements in performance of broilers

Until the 1950's poultry meat production around the world was a secondary industry to the egg industry. Males of the so-called dual-purpose breeds were used for meat production when they were about 15 weeks old, whilst the females were kept for egg production. Genetic selection was directed almost entirely at the laying hen, and very little, if any, genetic selection was applied to improving the growth rates of the males because egg production was the priority, and growth rate and egg production are genetically negatively correlated. In order to make any progress at all in the meat production area it became necessary to move away from the dual-purpose breeds, and to produce a breed that was designed specifically for meat production. The major thrust in this direction was initiated in North America; the basic stocks used being the Cornish Game, which was used as a sire line, and the Plymouth Rock as the dam line. Improvements in growth rate and related traits, such as feed conversion efficiency and meat yield, were enormous, and the age at which broilers achieved the desired dressed weight plummeted during the next three to four decades. In 1952 it took 90 days and 8.8 kg of food to produce a 2 kg chicken. By 1978 performance had been improved so that only 56 days and 4.4 kg of food were needed to produce a similar chicken. It is now possible to produce a 2 kg broiler in around 35 days, using 3.2 kg of food. This represents a reduction in slaughter age of about 1.2d per year. And the progress made by geneticists in improving broiler performance over the past fifty years is predicted to continue in the future. As a consequence, the bird used for broiler production in the past will bear little resemblance to the broiler to be used in the next ten years. Similarly, the nutrient and environmental requirements of broilers in the future will be very different from those recommended and used in the past fifty years.

These improvements in production characteristics have been due mainly to the efforts of the handful of primary breeders who produce the genetic basis of the great majority of the day old chicks used to produce broilers throughout the world. Their main strategy in the early years was to select those birds that were heaviest at a fixed age and to breed from them. This strategy was highly successful, as the heritability of the 'weight for age' trait was moderately high. By using very large populations the selection pressure was enormous and rapid progress could be made. As selection was successful the average birds were heavier at the age originally chosen for the selection and so the age at selection was steadily reduced. Selection in this way continues to be one of the main criteria used by geneticists to improve the broiler

The heaviest birds at an age are either those that would end up being larger at maturity, or which are showing more rapid early growth. It appears that in the early stages of past selection the main effect was to choose birds of larger mature size. But as selection proceeded, and the weight at which selection was made became a smaller proportion of maturity, so the emphasis switched to a rapid rate of maturing at low weights. It is certain that current broiler genotypes are both heavier at maturity and mature more rapidly than did the stocks from which they originally came. These changes are reflected in two of the three important parameters in the Gompertz growth curve (the mature weight, W_m, and the rate of maturing, B), which is a useful method of describing the potential growth rate of an animal, and which is central to the prediction of the nutritional and environmental requirements of a growing animal.

Whilst improving growth rate in broilers, geneticists have discovered correlated responses some of which have made life relatively easy for them. As broilers have become more fast-growing they have achieved their desired market weight earlier, and have therefore used less food for maintenance purposes, with a consequent improvement in the efficiency of utilization of their feed. FCR has therefore been improved even though this was not the primary objective for the geneticist. Of course, even more progress is possible when FCR is specifically targeted, but this has been only a recent innovation, and much progress in the improvement in FCR occurred before geneticists started selecting specifically for improvements in this trait. Breast meat yield, too, has been improved concomitantly by selecting for more rapid growth rate.

Of course, selection for rapid growth rate has brought with it a number of problems: reduced heart and lung function leading to ascites, weak legs and fragile bones, increased susceptibility to disease, lower egg production in the parents, etc. Geneticists have had to work extremely hard in their attempts to ensure that these negative traits were eliminated or at least reduced to an acceptable level as selection for the more desirable traits continued. In addition, the conventional wisdom is that by selecting for faster growth rates, geneticists have made broilers fatter. Whilst it is true that broilers are fatter now than they were two or three decades ago at an age, they could be considerably leaner at a weight than they were in the past if fed properly. That they are fatter at an age is not surprising, given that when past and present broilers are compared at an age, all components of the body are likely to be heavier now than they were thirty years ago.

It is also true that modern broilers could be leaner than they are at present, at an age or at a weight, if they were fed diets that more closely met their requirements for amino acids (Gous *et al*., 1990). In spite of the considerable gains that have been made by geneticists over the past decades, there has been virtually no change in the recommended nutrient specifications for broilers in terms of the amino acid contents of broiler starter, grower and finisher feeds. Certainly, these feeds are now fed for a shorter period than they were previously, but the amino acid specifications within each feed remain largely the same. Many nutritionists believe, incorrectly, that broilers will simply increase their intake of the feed in order to obtain sufficient of the limiting nutrients when an inadequate feed is offered. Whereas broilers may attempt to consume sufficient of the feed to meet the requirement for the first-limiting nutrient in the feed, it is seldom that they achieve the intake that is required to enable them to grow at their potential (Morris & Njuru, 1990). Certainly, this is even more unlikely in the hostile environment of a commercial broiler house, especially at high temperatures. The consequences are that many broilers do not achieve anywhere near their potential protein growth rate, becoming over-fat as a result of overconsuming energy in their attempt to obtain sufficient of the amino acid(s) that is limiting in the feed. Body weight may not be adversely affected, but the fat content of such broilers is far higher than is desirable. Geneticists have only relatively recently been made aware of the consequences of selecting for rapid growth rate whilst making use of feeds that are low in protein content. The fastest-growing birds on a low protein feed are those with the largest appetite, and by selecting these birds to be the parents of the future generation, the tendency to overconsume food in the succeeding generations is increased. It is imperative that, in order to identify the most efficient converters of feed to body protein, geneticists must feed high quality feed to the broilers under selection. There is no reason why commercial broiler producers should not do likewise.

Genetic improvements in performance of pigs

The pig industry has in some respects developed along the same lines as the broiler industry, with different breeds being combined to give hybrid vigour and favourable fleshing, conformation and reproductive efficiency. However, the order in which selection has been carried out in pig production has been almost the reverse of that used in the broiler industry. Before 1980, primary selection objectives in northern Europe were for fat reduction (Whittemore, 1998), with a concomitant improvement in feed conversion efficiency. So successful were the breeders that appetite was severely reduced, to the extent that over the last decade emphasis has changed to enhancement of lean tissue growth rate through, among other avenues, increased appetite. This has resulted in an improvement in feed conversion efficiency through a reduction in the maintenance requirement, due to the more rapid growth to slaughter. Even though selection in the pig industry followed a different path to that in the broiler industry, the result of the selection programme is that commercial pigs are now very different from those used in commercial operations in the past, and the consequences of these changes on nutritional and environmental requirements are the same as with modern broiler strains.

Selection for reduced fatness and improved FCR

With the move to further processing of broilers that has occurred in the past 25 years it has become apparent that the majority of broilers produced at that time contained more fat than was desirable. Geneticists therefore shifted their attention, in the mid 1980’s, towards selecting for a leaner carcass when it became apparent that body fat content would respond favourably to selection (Leenstra, Vereijken & Pit, 1986). The difficulty with this selection criterion is that the birds have to be killed in order to measure accurately the carcass fat content, whether this be the total fat content in the carcass or just the abdominal fat weight. And this means that sib-selection is imperative, which reduces the rate of progress compared with mass selection. Although a number of non-destructive measurements of carcass fatness have been discovered, these are not as accurate as measuring the carcass fatness itself.

It then became apparent that carcass fatness would be reduced as a correlated response to the improvement in feed efficiency brought about by genetic selection (Leenstra, 1986). It had become evident before this that feed efficiency could also be improved by genetic selection, and some of the larger broiler breeding companies took the decision to select for this trait many years ago. Considerable improvements have been made in feed efficiency over the past 15 to 20 years, brought about by direct selection for this trait, and this has resulted also in a reduction in the carcass fat content of broilers.

But as selection for improved feed efficiency and/or reduced fatness continues, there is a danger that the resultant genotypes will be less capable of performing adequately in a third-world environment, where access to high quality feed ingredients is not as easy as in the first world. In order to survive under conditions in which poor quality feeds are offered, broilers and pigs must be able to consume large amounts of the relatively indigestible feed on offer. For this to be possible, the strain must be able to store the excess energy consumed in this way as fat, and it is this attribute that is being progressively eroded away by selection for leanness. It would be wise for breeding companies to continue to produce a range of products, such that the most appropriate genotype for a given environment may be chosen from the range available.

Nutritional consequences of improvements in growth rate in poultry

As genetic progress is made, so the methods used to grow the birds to their potential would be expected to change. Apart from a more rapid turn-around time in broiler houses, there are a number of less-obvious consequences of improvements in growth rate in poultry that will have to be addressed in the years to come. These relate mainly to the feeds offered to the birds, and to the feeding programmes used, as well as to the environmental conditions that will best suit the faster-growing broilers of the future.

Different amino acid ratios needed because of differences in maintenance requirements

Because the broilers will be growing faster, and spending less time in the broiler house before being harvested, the nutrient requirements for maintenance will be lower, leading to improved feed conversion efficiencies. This has been happening for the last 50 years. But one of the consequences of the lower maintenance requirements that has not been considered is that a different amino acid profile in the feed will be required compared with that recommended in the past. This is because the amount of each amino acid required for maintenance and for growth is in most cases very different. Because the rates of these processes are changing as growth rates are modified by selection, the proportion of each amino acid required for maintenance and for growth will change, resulting in a different amino acid profile of requirements as time goes by. Using the EFG broiler growth model to simulate the growth of broilers of the 1970's and those of 2005, the ideal ratios between lysine and methionine+cysteine, and between lysine and threonine, over a 56d growing period are compared in Fig. 1. It is clear that the ideal ratio has changed with time, and it is likely that this will continue to change as the growth rates are further improved by selection.

Different dietary amino acid: energy ratios needed

Higher amino acid concentrations are needed in broiler feeds today, in relation to energy, to meet requirements for growth, compared with those needed 30 years ago. As growth rates are improved with selection so the relative growth rate at a protein weight is increased, resulting in a higher requirement for each of the essential amino acids. The bird must consume more amino acids to meet this higher requirement, but its gut capacity is the same as that of a similar-sized broiler of a few decades earlier. There is thus no possibility of the modern broiler being able to consume larger amounts of food than the same sized birds in the past, so the feed on offer needs to contain higher concentrations of amino acids than did the feeds of the past. This is not generally the case with broiler diets currently being fed, resulting in higher than desired amounts of fat in the carcasses of the broilers.

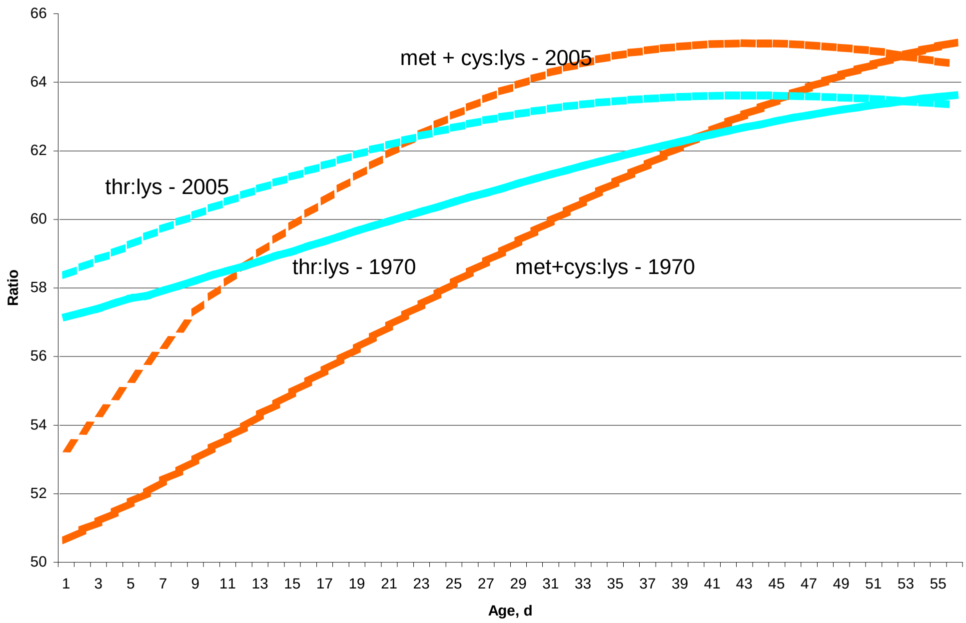

Figure 1 Amino acid to lysine ratios with age, for broilers of 1970 and 2005 predicted by means of a broiler growth model.

Of course, these high concentrations of amino acids do no need to be fed for as long as was the case in the past, as the growth rate of modern broilers is so rapid that food intake also increases at a faster rate than it did previously. As the content of amino acids in the food is a function of both the requirement of the bird for each amino acid and the rate of food intake, the amino acid requirements of modern broilers over time are vastly different from those of broilers in the past, as illustrated in Table 1 for lysine, for methionine + cysteine, and for threonine.

Table 1 A comparison of the dietary lysine (lys), methionine + cysteine (met&cys) and threonine (thr) contents required for maximum growth in broilers of 1970 and 2005, as predicted by the EFG broiler growth model

Day	lys (%diet)		met&cys (% of diet)		thr (%diet)	
	1970	2005	1970	2005	1970	2005
1	1.61	1.66	0.81	0.89	0.92	0.97
7	1.50	1.51	0.78	0.85	0.87	0.90
14	1.37	1.35	0.75	0.80	0.81	0.82
21	1.26	1.21	0.72	0.75	0.75	0.75
28	1.16	1.09	0.68	0.69	0.71	0.69
35	1.07	0.99	0.65	0.64	0.66	0.63
42	1.00	0.92	0.63	0.60	0.62	0.59
49	0.93	0.87	0.60	0.57	0.59	0.55
56	0.88	0.83	0.57	0.53	0.56	0.52

It is not only the daily pattern of requirements for each amino acid that has changed over the years, but also the overall quantity of each amino acid required from day-old to a given slaughter weight. Modern broilers require less of each amino acid in total than was the case previously, when the birds are killed at a similar weight. In Table 2 below, the total amounts of lysine, methionine+cysteine, and threonine, required to meet the daily maintenance and growth requirements of a broiler from day old to 1.8kg in weight are presented for a broiler in the 1970's (reaching that weight at 50 days of age), and for a broiler likely to be available to broiler producers in 2005, when the birds will reach 1.8 kg at about 32 days of age.

Table 2 A comparison of the total amounts of lysine, methionine+cysteine, and threonine, required to meet the daily maintenance and growth requirements of broilers from day old to 1.8 kg in weight in the 1970's and in 2005, as predicted by the EFG broiler growth model

Amino acid	1970	2005
Lysine, g	33.07	30.62
Methionine + cysteine, g	19.94	18.87
Threonine, g	20.33	19.00

Environmental consequences of improvements in growth rate in poultry

The rate of intake of a given food by a given type of bird in a given state will depend on the temperature of the environment in which it is kept. Emmans and Fisher (1986) have suggested that the heat loss of the bird varies in some way with the temperature of the environment, and as the ability of the bird to store heat is effectively zero, its rate of heat loss must equal its rate of heat production.

The environment clearly places an upper limit on the amount of heat that a bird can lose to the environment and this has important consequences in the design of feeds for fast growing broilers. Heat is produced in a variety of ways: as maintenance heat, activity, the direct heat increment of feeding and of excretion of waste products, the heat increments of protein and lipid retention, and, if the environment is cold, by cold thermogenesis. The amount of heat produced by a broiler at different stages of the growing period can therefore be calculated (Emmans 1989), from which the comfort temperature of the broiler can be determined. As the rate of growth of broilers has been improved, so the environmental temperature at which they would be comfortable has been reduced, although this constraint on the potential growth rate of modern fast-growing broilers has largely been ignored.

Heat production will increase as food intake increases providing that, at all intakes, the environment is thermally neutral. It follows that the temperature of the environment that is thermally neutral will decrease as the rate of food intake increases. Food intake is predicted to increase as the feed content of a limiting nutrient is decreased, so the growth rate, which defines the requirement, and the composition of the feed, which determines the desired food intake, interact to define the temperature that will be thermally neutral for the bird at that time. Feeds with a low nutrient to energy ratio will cause the thermoneutral temperature to decrease. The calculations involved in determining the consequences of these interactions are complex and therefore benefit from well-constructed simulation models.

Because modern broilers are growing and processing food at faster rates than did broilers previously, the heat output by modern broilers is considerably higher than it was previously, at the same age, and hence lower environmental temperatures are needed in poultry houses today. As an example of the higher heat output likely to be produced by modern broilers, at the age when broilers reach 1.8kg in weight, the 1970's broiler, at 50d of age, would have been producing about 100kJ of heat less each day than a broiler of similar weight in 2005, at 32d of age. Cooling of the environment will become more essential than was the case in the past as modern broilers grow older, with more birds likely to die of heat exhaustion if the environment is not modified adequately in the hotter areas of the world during the summer months. Perhaps broiler production will have to cease in the hotter parts of the world, and be moved to cooler areas where it is not as costly to modify the environment to suit the needs of the fast-growing birds. Stocking densities may have to be reviewed also, as the predicted increased heat load in the house would be reduced by using a lower stocking density. These are economic considerations, based on changes in the biological processes of the bird, that will have to be addressed as growth rates and feed efficiencies continue to be improved by genetic selection.

Housing design in the future must take these factors into account. The difference in the performance of growing animals in modern farm buildings, in which efficient use is made of air flow, evaporative cooling, and solar insulation, and that in traditional farm buildings is likely to widen in the future, as heat output by animals at an age continues to increase.

Feed ingredients, and improvements in digestibility

Because the world population will continue to increase in the 21st Century, and because poultry production will need to be increased to meet the resultant demand for all types of poultry products, the provision of an adequate supply of feedstuffs is essential. But more efficient use can be made of existing feedingstuffs if the compositional analyses and availability assessments are more accurately measured. The past decades have seen huge improvements in this area of research, and these are likely to continue for at least the next decade. However, of critical importance is the purpose for which feedstuffs are evaluated.

Nutritional evaluation of feedstuffs is undertaken for various purposes, but the nutritional values for feedstuffs are only useful in the context of a description of animal function and performance (Oldham and Emmans, 1990). Animal performance is therefore the essential criterion by which the relative and absolute nutritional values of feedstuffs are to be judged. The units of measurement used for feed values and animal function must therefore be the same, and this is especially true when simulation models are used to predict performance and nutrient requirements of animals. Metabolizable energy (ME), for example, is the most common unit for ascribing energy values to feedstuffs, but this system does not recognise changes in body protein and lipid as separate performance products. Rather, they are combined into a common estimate of energy retention, a simplification that is unacceptable in that it does not allow for identified variations in the relative rates of deposition of these two products.

Emmans (1994) has proposed a scheme for the conversion of ME into major animal products. The scheme, which accounts satisfactorily for heat production on the basis of unit processes, leads to an alternative and more effective means of assessing the nutritional value of feeds, based on descriptors of animal performance. He calls the system the Effective Energy system, and this has been shown to be a significant improvement over the ME system. In this system the rates of heat production from the processes of digestion, excretion of products, and growth of body protein and lipid are accounted for, making it possible to determine the amount of heat that would need to be lost from the bird or animal in order for it to eat sufficient of the given food to grow at its potential.

The principle function of feedingstuffs is to provide pig and poultry producers with cost-effective diets that meet the nutrient requirements of the stock being fed. In order to make the most efficient use of the available feedingstuffs there will be a continuing need to measure dose response relationships for the major cost-sensitive nutrients in relation to different types of output, be this meat, eggs, or progeny, on the one hand, and on the other, detailed information on the ability of the different raw materials to supply these nutrients. It is unlikely that, in the near future, it will be possible to describe raw materials in terms of available nutrients, because no appropriate methods are under development (J.M. McNab, personal communication). However, expressing these in terms of digestibility coefficients is possible, and has been shown to be considerably more accurate than making use of total nutrient concentrations. This practice has lead to increased confidence in the formulation of diets containing raw materials that are less well digested than maize, wheat, soyabean and fishmeal.

A development in feedstuff evaluation that has had a profound effect on the evaluation of feedstuffs has been the rapid assay technique originally developed by Sibbald (1976) and later refined by McNab and Fisher (1984). This technique involves the insertion, by intubation, of a small, measured amount of feed or a feedstuff directly into the crop of an adult rooster following, and followed by, a period of fasting. The excreta collected during the 48-hour collection period are dried, weighed and analysed for gross energy, in the case of ME studies, or amino acids, in the case of amino acid digestibility studies. These rapid assays have resulted in an enormous increase in the number of feedstuffs that can be assayed at low cost, without the complication of mixed diets, substitution experiments, variable feed intakes, or the uncertainties of extrapolation (Low, 1990). Because the amounts fed are small (usually 50g) corrections for endogenous energy losses and for nitrogen balance have become obligatory. The technique may be further refined in the future, although it is unlikely that any major changes will be introduced, in spite of the recognition that the gut microflora could metabolise amino acids within the gut lumen, either to amino acids in bacterial protein, or to non-amino acid compounds such as ammonia (Michel, 1966).

It has been conclusively shown that microbial activity in the large intestine of pigs does modify the amino acid composition of the digested material contained therein (Payne et al., 1968), leading to a number of techniques designed to sample the contents of the ileum, before the action of the microflora of the large intestine. The extent of microbial activity in poultry appears to be much less than in pigs, leading to the suggestion that it is not necessary to correct digestibility values for microbial activity (Fuller and Coates, 1983). This view may change with further experimentation, but the improvement in precision through surgical manipulation of the intestine of the fowl is unlikely to warrant such a procedure.

Ileal digestibility techniques do, nevertheless, have a place in assays for digestibility of feedstuffs for poultry. Of particular interest for the future are assays for the digestibility of phosphorus in feedstuffs, and for the evaluation of feed enzyme activity on substrates in feedstuffs. Feed enzymes have become almost an essential additive to poultry and pig diets, especially in the UK, where almost all broiler diets and many of those for laying hens and turkeys now contain feed enzymes. The addition of β-glucanase has allowed barley to be used again with confidence as a major ingredient in broiler diets, and xylanase/pentosanase is now almost a standard component of wheat-based diets in many parts of the world. The efficacy of these feed enzymes is more accurately assessed with ileal digestibility measurements than with intubation assays, because it is suggested that these feed enzymes alter the gut microflora thereby improving digestibility (M. Bedford, personal communication).

The enzyme phytase, which liberates phosphorus from phytic acid, thereby making the phosphorus that was previously unavailable to the animal both absorbable and metabolizable, has had an enormous impact on the composition of diets for both poultry and pigs in Belgium and the Netherlands. The activity of phytase enzymes can also best be measured through the ileal digestibility technique. This enzyme will play a more important role in poultry and pig nutrition around the world when farmers are penalised for adding phosphorus to the soil, as has happened in the Netherlands, when the price is more competitive compared with the cost of dietary phosphorus sources, or if the enzyme is shown to improve the digestibility of more of the essential nutrients in the feed than phosphorus alone.

It is likely that enzymes capable of degrading tannins, lignins, lectins, alkaloids and saponins may become commercially available in the future, thereby enabling poultry and pig producers to make use of previously dangerous feedstuffs, through the degradation of the anti-nutritional properties of these ingredients. In this way, more feedstuffs will become available for use in the pig and poultry industries, thereby assisting in alleviating the problem of finding sufficient raw materials to provide food for these monogastric species.

Because the supply of many nutrients in the feed has not been particularly cost-sensitive, there has been a tendency in the past to formulate diets with excessive margins of safety, particularly if doubts existed on nutrient availability, or if the requirement was uncertain. McNab (unpublished) suggests that this policy has stifled research initiatives in certain areas, and is coming under increasing criticism on environmental grounds, because nutrients for which the birds have no need are inevitably excreted and ultimately may become a source of pollution. This is particularly relevant with phosphorus and protein (nitrogen). Excretion of nutrients in excess of what is required by the birds to ensure optimum performance, or from feeds which have been badly digested, can also result in husbandry and welfare problems. For example, the incidence of carcass defects, such as breast blisters and hock burn, are often attributed to poorly digested fats or to high excretions of uric acid, arising from excesses of dietary protein, or from dietary protein which has an imbalanced, hence poorly available, amino acid profile. There is need therefore for continued research directed at understanding the barriers to complete digestion, particularly of protein and fat, as well as to a more accurate definition of the requirements of all of the essential amino acids, not simply those that are the most costly. Simulation models, again, will assist nutritionists greatly in this endeavour.

Conclusions

Prospects appear good for further impressive improvements in the genetic performance of broilers and pigs in the next decade. Such changes require nutritionists and producers to be aware of the consequences, particularly with regard to feeding programmes and environmental conditions, since the nutritional and environmental requirements of these improved genotypes are very different from those in the past. Nutritional research had not kept pace with these genetic improvements until recently, with the advent of simulation models which now accurately predict the food intake, growth rate, and chemical composition of these species. It is possible to make progress once more in many aspects of the production process: optimising the feeding programme both biologically and economically, determining the optimum environmental conditions in which to raise these fast-growing genotypes, and being able to determine more accurately the nutritional and environmental requirements for males and females separately, thereby making it more worthwhile to raise the sexes separately.

Together with a better knowledge of the requirements of broilers and pigs for essential nutrients, has come an improved definition of the nutrients that are required by these species. Hence, feed nutrient contents are better defined in terms of digestibilities than as totals to meet the nutrient requirements of the species, and the effective energy system more accurately defines the dietary energy available to pigs and poultry (and to ruminants) than does the ME system. Concomitantly, a range of feed enzymes has become available to feed manufacturers, and these enzymes are capable of improving the digestibility of specific nutrients in feedstuffs, making it possible to use ingredients that were hitherto avoided because of the adverse effects that they had on performance. It is likely that, in the future, feed enzymes will become available for eliminating the anti-nutritional factors present in many of the feedstuffs that could otherwise be used in balanced feeds for monogastrics. In so doing, a wider range of feedstuffs will be available to meet the ever-increasing demand for poultry and pig products as the world's population expands in the 21st Century.

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