Preferred components for the construction of a new simulation model of growth, feed intake and nutrient requirements of growing pigs

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Components for a simulation model are described to predict feed intake, amino acid requirements and body composition changes over time on the basis of the inherent potential protein growth rate of pigs varying in genotype. The potential protein growth rate of the animal is predicted each day based on its genotype and state, from which the potential growth rate of the other chemical components can be predicted and hence the nutrient requirements can be calculated. By considering the potential growth rate, the nutrient requirements, the nutrient supply (the composition of the feed) and the environment simultaneously, the constrained food intake can be predicted. If this is less than the desired food intake, the actual growth rate will be less than the potential growth rate. In either case, the growth rate of each of the chemical components can be predicted for that day. This final state of the animal at the end of the day becomes the initial state on the next day, and the process is repeated.

'n Simulasiemodel word beskryf wat voerinname, aminosuurbehoeftes en veranderinge in liggaamsamestelling voorspel volgens die inherente potensiaal in proteïengroeitempo van varke wat varieer in genotipe. Die potensiële proteïengroeitempo van die dier word daagliks voorspel, gebaseer op sy genotipe en status. Die potensiële groeitempo van die ander chemiese komponente kan hiervolgens voorspel word, en vervolgens kan voedingsbehoeftes bereken word. Deur die potensiële groeitempo, voedingsbehoeftes, voorsiening van voedingstowwe (samestelling van die voer) en omgewing gelyktydig in berekening te bring, kan die beperkende voerinname voorspel word. As dit laer as die verlangde voerinname is, sal werklike groeitempo minder as potensiële groeitempo wees. In beide gevalle kan groeitempo van elke chemiese komponent vir daardie dag voorspel word. Die finale status van die dier teen die einde van die dag word die aanvangstatus vir die volgende dag en die proses word herhaal.

Keywords: Growth, modelling, nutrition, pigs.

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Introduction

There are many advantages of being able to predict the growth and feed intake of an animal, such as the determination of nutrient requirements for different periods of growth, making more effective financial and management decisions, understanding the consequences of genetic selection, and identifying research needs. The model described here simulates biological growth responses in growing pigs to changes in production circumstances, such as changes in feed quality and evironmental conditions. This paper describes the concepts and their algorithms which can be used to develop a model. The model would predict body composition and its changes, voluntary feed intake and amino acid requirements. Several other pig simulation models have been developed (Whittemore & Fawcett, 1976; Phillips & MacHardy, 1982; Black et al., 1986; Moughan et al., 1987; Pomar et al., 1991). The components for a model proposed in this paper are simple in approach, yet effective in predicting growth and nutritional requirements. These components differ from those in other pig models in that they incorporate a new approach to modelling feed intake, bioenergetics and the effects of temperature by making use of the 'Effective Energy System' proposed by Emmans & Fisher (1986) and Emmans (1987).

It can be assumed that an animal has a potential rate of protein growth which it attempts to achieve, and which it may achieve given adequate nutrition and a favourable environment. Given an accurate description of the genotype, this potential growth rate can be predicted. The nutrient and environmental inputs required in order that the animal can achieve this goal can then be calculated. When the nutritional and environmental inputs are inadequate the animal will fail to achieve its potential growth, the extent to which it is constrained being predicted according to a set of rules.

An accurate simulation model requires an adequate description of the genotype, the feed and the environment in terms of the variables that are used in the model. In this paper, the descriptors required for the genotype, the feed and the environment are discussed.

Animal description

Certain genetic characteristics of the animal need to be quantified in order to know how the animal grows. In this

description the genotype is defined by four parameters, viz.:

(i)   a rate of maturity (B),

(ii)   mature body protein weight (Pm),

(iii) inherent fatness or lipid:protein ratio at maturity (LPm), and

(iv)   an allometric exponent between the weights of protein and lipid (b_l).

The theory and practice of how these parameters interact to determine the daily rate of growth have been well explained in a series of papers by Emmans (1990). By making body protein weight and the rate of protein retention central to the model, it is simplified without losing any accuracy in predicting changes in body composition. Body protein content is used to define the current state or condition of the animal, which is then used to quantify the remaining body constituents and their respective growth rates (Taylor, 1980). This is achieved by implementing the allometric relationships between protein and lipid, moisture and ash (Moughan *et al.*, 1990). The algorithm calculates all functions on a day to day basis.

The Gompertz growth function (Gompertz, 1825) is used to describe body protein for any age and is determined as:

$$Pt = Pm \times e\{-e\ [(\log_e(-\log_e(u_o))) - B.t]\} \quad \text{(kg)}$$

where Pt = body protein weight at time t (kg),

Pm = mature body protein weight (kg),

u_o = degree of maturity at birth,

B = rate of maturing constant (/day), and

t = age (days).

As important, is the rate of potential protein growth (pPR), viz.:

$$pPR = Pm \times B \times u \times \log_e \left(\frac{1}{u}\right) \quad \text{(g/day)}$$

where u = degree of maturity (Pt/Pm)

so, $$pPR = B \times Pt \times \log_e \left(\frac{Pm}{Pt}\right)$$

These two functions allow the potential rate of protein growth of an animal to be predicted from only two inherent characteristics, viz. B and Pm, and its present body state, as defined by protein weight Pt. The equations above indicate that the rate at which an animal grows will depend almost entirely on its current state or size (Taylor, 1980). To quantify B, the rate of maturing, live weight and protein weight data can be analysed according to the method used by Whittemore *et al.* (1988) and Kyriazakis *et al.* (1990), or a modified serial slaughter experiment can be done in order to plot the logarithm of body protein against the relative protein growth rate. The mature protein weight can be extrapolated from this function. This is repeated for lipid weight so as to determine LPm. To determine these values it is essential that the animal is growing at its potential, otherwise the estimates of the parameters will be inaccurate. An important consideration to this approach is that the same B value applies to all four chemical components (protein, lipid, water and ash) (Emmans, 1988; Ferguson & Gous, 1993b). This will allow the use of allometry to predict body lipid, moisture and ash contents from body protein weight. This technique is described in detail by Ferguson & Gous (1993a) and is illustrated in Figure 1.

The characteristics B, Pm, LPm and b_l will vary between and within sexes and strains. Examples of estimated constants for different sexes and strains of pigs derived from the literature are shown in Table 1. Whittemore (1983) and Whittemore *et al.* (1988) provide additional estimates of mature protein weight.

A model using these concepts assumes that protein growth reaches a peak at a live weight approximately 0.368 of its mature weight and then declines thereafter to zero at maturity, in accordance with the Gompertz growth function. The maximum rate is dependent on both sex and strain. Table 1 shows the predicted maximum potential protein growth rates (pPR_{max}) for different combinations of sex and strain. These estimates are higher than those suggested by Whittemore

Table 1 Inherent animal growth characteristics for different sexes and strains of pigs obtained from various literature sources

	Growth characteristics [a]				
Literature source and pig type	B (/day)	Pm (kg)	LPm	pPR_{max} (g/day)	t (days)
Campbell *et al.* (1985a)					
Large White × Landrace improved male	0.0125	36.0	3.50	167	137
Campbell *et al.* (1985b)					
Large White × Landrace commercial male	0.0140	27.0	3.30	139	105
Campbell & Taverner (1988a)					
Large White × Landrace superior male	0.0130	45.0	2.80	214	128
Kyriazakis *et al.* (1990)					
Large White × Landrace superior male	0.0135	44.0	2.60	219	122
Gatel *et al.* (1992)					
Large White × Landrace superior female	0.0135	34.0	2.30	169	121
Ferguson & Gous (1993b)					
Large White × Landrace improved male	0.0107	38.7	2.60	152	144
Large White × Landrace improved female	0.0120	28.4	3.89	125	123

[a] B = rate of maturing constant; Pm = mature body protein weight; LPm = lipid:protein ratio at maturity; pPR_{max} = predicted maximum potential protein growth rate; t = age when pPR_{max} is attained.
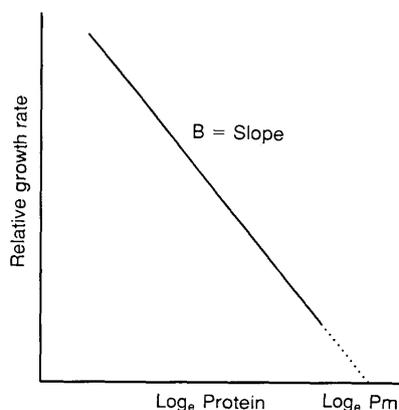
Figure 1 Relative protein growth rate as a function of the natural logarithm of protein weight.

(1983) but similar to those estimated by Campbell & Dunkin (1983), Campbell & Taverner (1988a), Whittemore *et al.* (1988), and by Rao & McCracken (1990). The age at which pPR_{max} is attained is, by the function which defines protein growth, proportional to the mature size of the animal and will therefore vary according to sex. Values shown in Table 1 are similar to those reported by the Standing Committee on Agriculture (SCA) (1987).

Potential protein growth (pPR) will only be realized if there is sufficient quantities of energy and the first limiting amino acid, and if the environment will allow the animal to lose the subsequent heat production. Otherwise, actual protein growth (PR) will be lower than pPR. The peak value for pPR or the maximum protein retention (pPR_{max}), can be determined from B and Pm as:

$$pPR_{max} = B \times (\frac{1}{e}Pm) \quad \text{(g/day)}$$

This value (pPR_{max}) can be used to provide an estimate of B if Pm is known.

According to Webster (1989) and Emmans (1989) an animal strives to achieve an inherent mature size and condition described by the asymptote for body protein weight. Associated with this desired condition is a desired quantity of fat. This inherent mature fatness is best described in relation to body protein in the form of a lipid:protein ratio at maturity (LPm) and, during growth, an allometric coefficient relating lipid content to protein (b_l). The desired body fatness (dLt), at a point in time, and the rate of desired lipid deposition (dLR) can be obtained using the method proposed by Emmans (1989) such that:

$$dLt = LPm \times Pm \times (\frac{Pt}{Pm})^{b_l} \quad \text{(kg)}$$

and

$$dLR = pPR \times LPm \times b_l \times (\frac{Pt}{Pm})^{b_l - 1} \quad \text{(g/day)}$$

The allometric coefficient (b_l) which describes the relative growth between protein and fat can range in value from 1.50 in entire males to approximately 1.85 in castrated male pigs (Emmans, 1988). The lipid content of an animal growing at its potential can thus be predicted at any time from the current protein weight of the animal. The actual body lipid content (Lt) and the actual rate of lipid deposition (LR) will be

dependent on the quantity and quality of the food consumed, the environmental conditions, and to what extent the animal is fatter or leaner than it would desire to be. A knowledge of the desired fatness is particularly useful in situations where the animal has deviated from the desired level of fatness (discussed later). Linked to the desired level of fatness is the extent to which the diet being fed is balanced with regard to the first limiting nutrient:*ME* ratio. A poor-quality diet will result in an animal being fatter than its desired fatness. Similarly, restricted feed intake will be associated with a leaner animal (Emmans, 1989) (Figure 2).
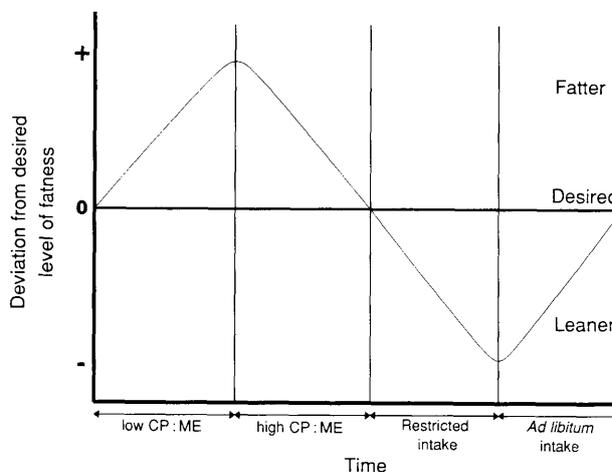
Figure 2 Animal responses to different nutritional stimuli.

As few data exist on the mature weight of lipid for different strains of pigs, it is difficult to obtain LPm values. An additional constraint is that body lipid weight is entirely dependent on the supply of resources. Therefore, the problem with determining the LPm at maturity from experimental data is the large variation in experimental conditions. Unless the pigs are given free and continual access to a non-constraining feed in a non-constraining environment, the ratio will vary considerably between experiments (Emmans, 1989; Ferguson & Gous 1993a; 1993b). In addition to this, the inherent fatness will vary between sexes and strains, so different LPm values will be required if the model is to be useful in predicting growth under different conditions. At present only Ferguson & Gous (1993b) have published estimates of LPm for pigs, although Bridges *et al.* (1986) and Whittemore *et al.* (1988) have provided realistic estimates. By making use of the experimental technique described by Ferguson & Gous (1993a) to determine the mature protein and lipid weight, this problem can be solved.

The relative proportions of moisture and ash are less likely to vary between sexes and strains than are the proportions of lipid. Ash deposition (AR) proceeds at a constant ratio to protein deposition (Moughan *et al.*, 1990; Kyriazakis & Emmans, 1992a; 1992b), such that:

$$AR = 0.19 \times PR \quad \text{(kg)}$$

As the allometric coefficient which describes the relationship between body protein and body moisture content is not one, the method of determining moisture deposition (WR) is similar in approach to that of determining dLR, viz.:

$$WR = PR \times WPm \times b_w \times (\frac{Pt}{Pm})^{b_w - 1} \quad (kg)$$

where WPm = moisture:protein ratio at maturity, and

b_w = allometric coefficient of moisture on protein.

The value of b_w varies between 0.814 (Kyriazakis & Emmans, 1992a) and 0.925 (Moughan *et al.*, 1990).

Compensatory lipid growth has been demonstrated in growing pigs (Tullis *et al.*, 1986; Kyriazakis *et al.*, 1991). Lipid compensatory growth is determined by summation of the desired lipid growth (dLR) and the difference between actual body fat (Lt) and desired body fat content (dLt).

$$LR = dLR + \frac{(dLt - Lt)}{1\,000} \quad (g/day)$$

If the animal is fatter than desired then LR on the following day will be less, in order to compensate for the extra fat deposited the previous day (Kyriazakis & Emmans, 1991; Kyriazakis *et al.*, 1991). Provided it is possible the animal will deposit less lipid on the following day. Similarly, if the animal is leaner than expected, for a given protein content, then LR would be higher than the inherently desired LR.

To determine the compensatory responses of an animal based on its body state is preferable to the approach of Black *et al.* (1986) who used a compensatory gain factor to multiply the protein deposition rate, irrespective of the current physiological status of the animal.

In summary, the genotype and state of the animal at the beginning of the day will determine the potential rate of growth of protein on that day. The potential growth rate of the other chemical components of the body can be predicted, by allometry, from the protein growth rate. If this potential growth rate is added to the initial condition of the animal, the state of the animal at the end of the day can be predicted. This state becomes the initial state on the following day, and the process is repeated.

Whether the animal is able to achieve its potential growth rate each day is dependent on the feed being offered and on the environment in which it is housed. The constraining effects of the feed and the environment have to be calculated in order to predict the actual growth rate and carcass composition of the animal each day.

Food intake

The theory involved in predicting feed intake is based on that proposed in a collection of papers by Emmans (1990). In brief, the theory proposes that an animal will eat what it needs within the constraints of gut volume and environmental temperature. The concept has been used to predict realistic results for broilers (Emmans, 1987; R.M. Gous, 1992, unpublished work), turkeys (Emmans, 1989), and growing pigs (Ferguson & Gous, 1993b). Derivations of the equations given in this paper and the theory behind them are described in detail by Emmans & Fisher (1986), Emmans (1988) and Emmans & Oldham (1988).

It is assumed that the pig will attempt to consume an amount of feed that will satisfy its requirements for potential growth and maintenance. In a thermal neutral environment, the constraining factor is the first limiting nutrient. The desired feed intake will, therefore, be the quantity of the diet needed to satisfy the requirement for the most limiting nutrient, whether it be energy, an amino acid or some micro-nutrient.

To calculate the amount of energy required for growth and maintenance, use is made of the 'Effective Energy System' proposed by Emmans & Fisher (1986) and Emmans (1987). The effective energy required (EER) by the animal is described as follows:

$$EER = MHEAT + (50.3 \times PR) + (56 \times LR) \quad (kJ/day)$$

where $MHEAT$ = fasting heat production − fasting urinary energy (kJ/day)

The effective energy content (EEC) of a diet can be described as the metabolizable energy (ME) of a diet less the heat production owing to defecation and potential losses resulting from the food being eaten (Emmans, 1984). The heat increment associated with fermentation is excluded for pigs as it is assumed to be negligible. The EEC is calculated as follows:

$$EEC = ME - (3.8 \times FOM) - (4.67 \times DCP) + (k \times 12 \times DFAT)$$
$$(kJ/g)$$

where

ME = metabolizable energy of the feed (kJ/g),

FOM = faecal organic matter or undigestible carbohydrate component (g/kg),

DCP = digestible protein content of the feed (g/kg),

k = proportion of dietary fat retained as body fat, and

$DFAT$ = fat content of the feed (g/kg).

If energy is the most limiting nutrient then the desired feed intake (dFI_e) in a thermoneutral environment will be:

$$dFI_e = \frac{EER}{EEC} \quad (g/day)$$

If, on the other hand, an amino acid is the first limiting nutrient then the desired feed intake will be based on the amino acid requirement and the concentration of dietary available amino acid. The required amino acid intake is defined in terms of a response function relating intake to the potential level of production and maintenance of the animal (Fuller *et al.*, 1989). However, the requirement is not described in terms of live weight but rather in terms of protein growth rate and maintenance protein.

The desired feed intake to satisfy potential protein growth (pPR) from the most limiting amino acid (dFI_{aa}) is:

$$dFI_{aa} = \frac{(\frac{pPR}{a} + \frac{MPROT}{b})}{dCP \times BV} \quad (g/day)$$

where

a = efficiency of protein utilization for growth,

b = efficiency of protein utilization for maintenance,

$MPROT$ = maintenance protein (g/day),

dCP = digestible crude protein (g/kg), and

BV = biological value of diet.

An important assumption is that the coefficients of utilization of the essential amino acids for growth (a) and maintenance (b) are constant across sexes, strains and breeds of pigs. From these assumptions the ideal amino acid balance for growth will be similar to that found in the protein tissue. As the digestibility of the dietary protein depends on the source, the model allows the user to enter a digestibility

coefficient for the feeds used. A certain amount of inefficiency does exist when dietary available amino acids are converted into body tissue, with the result that ideal protein requirements need to be adjusted before being stated as actual requirements. Whittemore (1983) suggests a coefficient for net utilization for growth of between 0.85 and 0.95, whilst Batterham *et al.* (1990) predict a lower value of 0.75. In the model it is possible to adjust the digestibility and efficiency of utilization for all the important amino acids for both growth and maintenance. The preferred value for efficiency of utilization of amino acids for growth is taken as 0.75, whilst for maintenance it is 1.00.

The anticipated daily food intake (aFl) of the pig in a thermal neutral environment would be the larger of dFl_e and dFl_{aa}.

if $dFl_e > dFl_{aa}$ then $aFl = dFl_e$ (g/day)

or

if $dFl_{aa} > dFl_e$ then $aFl = dFl_{aa}$ (g/day)

For a perfectly balanced feed dFl_e would equal dFl_{aa}.

The pig would fail to eat aFl only if the density or bulkiness of the diet was such that gut capacity became a limiting factor or when the environment imposed certain constraints (Emmans, 1981; Cole & Chadd, 1989). The latter factor will be discussed later. The concept of a bulk constraint is a more rational approach to determining dietary constraints than that of imposing fixed maximum feed intakes (Whittemore, 1983) irrespective of the actual dietary constituents. At present the nutrient density of a diet has not been properly quantified because the data are insufficient. A model can attempt to implement a bulk constraint by using the function proposed by Emmans (1981), viz.:

$$BULKDN = 0.1 \times digOM + (1 - water - ash - digOM) \times (5 + fform)$$

where

$digOM$ = digestible organic matter of the diet,

ash = ash content as a proportion of the diet,

$water$ = moisture content as a proportion of the diet,

$fform$ = physical form of feed   where

with pellets: $fform = 0.0$,

with crumbles: $fform = 0.2$,

with mash: $fform = 0.5$.

The constrained food intake determined by the bulk density (cFl) would be as follows:

$$cFl = \frac{90.0 \times Pt}{BULKDN} \quad (g/day)$$

Although the functional coefficients may not be absolutely correct because of inadequate data and research, the concept is preferable to any proposed to date.

To predict the voluntary feed intake of growing pigs is difficult because of the constantly changing environmental and nutritional conditions and animal requirements with time. An effective model requires food intake to be predicted as a function of sex, strain, physiological age of te animal and the quality of the diet. The latter factor needs to be expounded as it contributes significantly to the rates and composition of growth and to the daily requirements for energy and protein.

The adequacy of a diet is also linked to the desire of the animal to deposit fat according to its physiological state (Kyriazakis & Emmans, 1991). The current state of the animal would reflect the response of the animal to its thermal environment as well as its nutritional history. An important corollary to the concept of maintaining a desired level of fatness is that at all times the animal can utilize body fat reserves, to a greater or lesser extent, to supplement dietary *ME*, when the need arises. The use of body fat reserves is limited to periods when dLR is less than or equal to zero. It is therefore possible to obtain significant protein growth rates at the expense of fat gains growth, which would not be possible if a minimum lipid:protein ratio was used, as proposed by many other models (Whittemore & Fawcett, 1976; Moughan *et al.*, 1987; Pomar *et al.*, 1991).

If it is assumed that the environment is not a constraining factor, there are three possible paths that could be followed by the animal:

(i)   where $aFl = dFl_e$

This is the simplest case where the animal consumes enough protein to satisfy potential protein growth, and energy to provide for a certain amount of lipid growth that is associated with 'normal' growth. Any excess protein is deaminated which incurs an energy cost, thereby reducing the amount of *ME* available for growth. The net result will be that feed intake will have to be increased to overcome the lower *EEC* and to provide sufficient energy for growth and maintenance.

(ii) $aFl = dFl_{aa}$

In this situation there is sufficient energy, but protein, or more specifically an amino acid is limiting. The energy above that used for maximum protein retention and maintenance will be deposited as fat (Campbell *et al.*, 1985a; 1985b). The additional fat deposited will result in the pig being fatter than its inherent fatness. On the following day the animal would attempt to deposit less fat in order to return to its desired state. It could only achieve this if the constraining factor, which had caused it to deposit more fat, was removed. In this case, it would mean increasing the concentration of the limiting amino acid.

Associated with the increase in fat deposition is the amount of heat produced by the animal. If the heat produced is greater than that which could be lost to the environment then additional constraints are placed on growth rate and feed intake. This will be discussed in more detail in the environmental section below.

(iii) $aFl = cFl$

When the bulkiness of the food prevents the animal from meeting its potential growth rate, then a further factor has to be considered, viz. what is the next most-limiting nutrient in the feed. This is an important consideration as it determines whether the animal can reach its potential protein growth rate or not. It may be possible for the animal to consume sufficient protein to enable it to reach its potential but be restricted in energy intake. This would be the case if energy was the next most-limiting factor after bulk. The model can be designed first to allocate energy for maintenance. Secondly, energy will be allocated to maintain potential protein growth (pPR). If there

is insufficient energy for *pPR* then *PR* will be lower than *pPR*. In addition to this, the efficiency with which protein is deposited will be adversely affected. The change in efficiency is dependent on energy intake or more specifically the energy:protein ratio, as demonstrated by Campbell & Taverner (1988a; 1988b) and Kyriazakis & Emmans (1992b).

Finally, any remaining energy will be deposited as fat. This amount will be less than desired resulting in a reduction from the animal's desired level of body fatness (Figure 2), such that:

$$LR = \frac{(aFI \times EEC) - (50.3 \times PR)}{56.3} \quad (g/day)$$

The other alternative to energy being limiting, as a result of a bulk constraint, is if protein is limiting. The limited amount of amino acid is used firstly to satisfy maintenance and the remainder is used for growth. The limited amount available for growth will mean that *PR* is less than *pPR* and the energy that would have been used for potential protein growth (*pPR* - *PR*) is deposited as fat, which will increase above that desired. The consequence of this will be that the following day the pig will attempt to use the excess fat that has been deposited to return to its desired fat level or, if possible, it will deposit less fat. If this is not possible then further accumulation of fat will occur.

Recent work by Kyriazakis & Emmans (1991), Kyriazakis *et al.* (1991) and De Greef (1992) provide substantial experimental support for the above-mentioned theories. Kyriazakis & Emmans (1991) found that young pigs that were made fat by eating a poor-quality diet (low CP:ME ratio) deposited fat at a much slower rate than pigs that were leaner when both groups were placed on a high protein diet. Similar results were observed by De Greef (1992) in older animals. This implies that the pig will attempt to return to a level of fatness associated with its current protein weight by restoring its inherent lipid:protein ratio (Figure 2).

If the pig is fatter than its inherent fatness then it will deposit less fat as soon as the constraint causing it to deviate from its desired fatness is removed. Similarly, if it is very lean and it is given the chance to fatten, the pig will deposit fat at a faster rate than a pig that is at its desired degree of fatness (Stamataris *et al.* 1991). Therefore, the efficiency with which the energy is utilized will vary according to the state of the animal and its inherent level of fatness (Kyriazakis *et al.*, 1991). Fatter animals will utilize a high-quality diet more efficiently than will leaner animals because they will make available more energy, from excess fat reserves, for potential growth. This will result in less dietary energy being required. In this way the pig can achieve its potential protein growth whilst reducing its excess body fat. The effect will be to reduce feed intake, provided an amino acid or some other nutrient does not become limiting, until such time as the animal reaches its desired fatness. This has clearly been demonstrated by Kyriazakis and Emmans (1991) and De Greef (1992).

Environmental considerations

Climatic environment has a considerable effect on voluntary food intake (Bruce & Clarke, 1979; Mount, 1975; Verstegen, 1987). It is necessary to establish the extent of the interaction

of the environment with the animal and with the diet before the voluntary food intake of the animal, and hence its actual growth rate, can be assessed.

Many approaches to modelling heat production have been attempted, ranging from a simple approach of calculating the difference between *ME* intake and the amount retained (Whittemore, 1983), to the sophisticated physical type model (Bruce & Clarke, 1979). The method proposed in this paper is an intermediate approach. Heat storage is assumed to be zero such that heat production is determined as the sum of the components of evaporative and non-evaporative (sensible) heat loss.

Sensible heat loss (*SHL*) is dominant under cold conditions and diminishes at a constant rate with increasing temperature. The rate at which *SHL* decreases (*SL*$_{slope}$) depends on factors such as the wind speed, the type of floor material, the insulation of the house, the stocking density, and the thickness of the subcutaneous fat layer, with a range of between 30.0 and 50.0. *SHL* is predicted as follows:

$$SHL = SL_{slope} \times (38 - T) \times EBWT^{0.67} \quad (kJ/day)$$

SL_{slope} = rate of heat loss (kJ/°C),
$EBWT$ = empty body weight (kg), and
T = temperature (°C).

The *SHL* component contributes very little towards heat production at high temperatures, because sensible heat loss depends on the difference in temperature between the environment and the surface of the pig (Mount, 1975). At a temperature of 38 °C, *SHL* will be zero.

Evaporative heat loss is minimal (*EHL*$_{min}$) and is constant for a particular live weight at low temperatures (Verstegen *et al.*, 1973; Black *et al.*, 1986; Emmans, 1989). The minimum evaporative rate is estimated to be 20% of the total heat loss under thermoneutral conditions, while the maximum *EHL* is constant across all temperatures and is several times greater than *EHL*$_{min}$ (Figure 3) (Emmans, 1989).
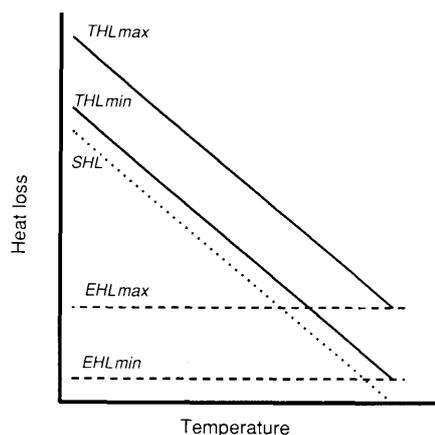
The maximum total heat loss (*THL*$_{max}$) can be defined as:

$$THL_{max} = SHL + EHL_{max} \quad (kJ/day)$$

The minimum amount of heat that is lost (*THL*$_{min}$) is:

$$THL_{min} = SHL + EHL_{min} \quad (kJ/day)$$

Figure 3 demonstrates how heat loss is affected by ambient temperature and how, for a given temperature, there is a range

Figure 3 Components of total heat loss (*THL*) over time (after Emmans, 1989). *THL* (———); *EHL* (----); *SHL* (· · ·) .

of heat losses within which the animal can remain comfortable. The range of heat outputs is bounded by a THL_{min} and a THL_{max} within which the animal must remain.

Having reviewed the factors which define the environment, the problem is to define the response of the animal to environments which inhibit maximum expression of growth. The environment will become inhibiting if (a) temperatures are excessively low or high, or (b) if a diet is very imbalanced or of a poor quality.

The amount of heat the animal produces is defined as:

$$HEAT = (aFI \times ME) - (23.8 \times PR) - (39.6 \times LR) \ (kJ/day)$$

The response of the pig to a cold environment is to increase heat production, or cold thermogenesis, by increasing feed consumption (Verstegen, 1987). The extra food required (xFI) will depend on the energy content of the diet and the additional environmental heat demand.

$$xFI = \frac{(THL_{min} - HEAT)}{ME} \quad (g/day)$$

The only constraint on the amount of food required in cold conditions is the bulk constraint, cFI.

It is difficult to determine whether the environment for immature pigs is effectively cold or hot, as growth rate, body composition and feed intake are constantly changing with time (Campbell & Taverner, 1988b; Rinaldo & Le Dividich, 1991). Nevertheless, an environment can be defined as cold if the amount of heat produced by the pig in a thermoneutral environment is insufficient to meet the heat demand from the environment (Steinbach, 1987). A hot environment is one in which the animal is prevented from consuming its desired feed intake because the amount of heat produced would be greater than what could be lost. Consequently it is unlikely that potentially fast-growing animals would be able to reach their potential when kept at temperatures above 20 °C, especially when feeds of high nutrient density are offered. The initial response of the animal will be.to attempt to alleviate the heat stress by consuming less food, move away from the heat source, and/or reduce activity to a minimum (Steinbach, 1987).

The reduced feed intake will have specific effects on the composition of body growth. Less of the most limiting nutrient will be consumed and, if this is an amino acid, then PR will decline. Fat deposition may increase or decrease depending on the severity of the heat stress. It is more likely to decline than to increase (Close, 1989). The amount by which LR will increase or decrease depends on the amount of extra energy made available from a reduced PR. If energy is first limiting then more energy will be transferred directly from the food into fat without causing a reduction in feed intake and thereby reducing the heat stress. This option is limited by the extent to which the animal can deposit fat in a hot environment (Close, 1989). If this response fails to reduce the heat stress then both aFI and LR will decline. If the reduced aFI does not satisfy the requirement for the first limiting amino acid then PR will also be reduced.

Conclusions

The problem of predicting the growth rate, body composition and feed intake of an animal is that it involves many interactive causal forces which combine to produce a response to

specific conditions. A modelling approach is the only defensible means of quantifying these forces.

The major advances of the model components forwarded in this paper are:

(i)   the prediction of the voluntary food intake. This would be a unique part of a new model as all other models require intake to be known.

(ii) In order to predict voluntary food intake, use is made of the theory proposed by Emmans (1989) of how the animal interacts with its food and environment. This interaction requires nutritional constants to convert animal requirements into feed requirements, using common units. The effective energy system is an advance over other sytems of predicting heat increment, and leads to increased accuracy in predicting food intake. In addition to this, the theory considers the response of the animal to the first limiting nutrient – a concept that is not commonly recognized.

(iii) With a knowledge of the interaction of an animal with its food and environment it is possible to calculate changes in body composition in a dynamic way.

Changes in body composition are based on nutrient and environmental interactions as well as the current physiological state of the animal, as measured by the protein content. The logical conclusion of trying to maintain a desired body state is that the animal will always attempt to return to this inherent state, if it is deviated away from it. The constraining factors will be the environment and the first limiting nutrient. A consequence of the above conclusion is that feed efficiency is automatically taken into account by the changing rates of lipid and protein deposition, as the body composition returns to its desired physiological state.

Protein growth is simulated using the Gompertz function of time as opposed to measuring biochemical protein turnover rates.

The interaction with the environment is a particularly difficult area to quantify. The effects on changes in body composition are a consequence of the pig attempting to satisfy the environmental heat demand as well as trying to grow at its maximum rate. Many unanswered questions still remain and need to be addressed for a more complete understanding of the interaction between an animal and its environment. The causes of changes in body composition in hot climates, in particular, need to be identified and quantified. One of the uses of simulation models is to highlight areas of research where such current information is lacking.

The propositions discussed here have been transcribed into a computer program, using TurboPascal, that can be used on a personal computer. The model is simple to use and requires the user to have a minimum amount of computer knowledge. The model therefore disseminates current scientific knowledge to the pig industry simply and effectively.

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