

Technical review of the energy and protein requirements of growing pigs: food intake

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Abstract

Food intake in pigs is highly variable across different production circumstances. This report concludes from a critical review of published observations that it was unrealistic to expect from the scientific literature purporting to express nutrient requirement any reasonable prediction of the particular food intake of groups of pigs. None the less, such knowledge is essential for the practical purposes of their day-to-day nutrition. The literature does however yield general principles from which may be derived: (a) the likely forms (but not the parameter values) of intake functions relating food intake to pig live weight; and (b) the likely factors involved in the modulation of food intake at any given live weight. Using these principles two methods for determining on-farm food intake from the use of simple and available records were proposed. The first requires knowledge only of start and final weight, the time elapsed, and total food intake: it involves two steps, the determination of a suitable growth curve followed by the fitting of a suitable food intake curve. The second method is appropriate in the absence of information on total food intake, and requires a minimum number of spot measurements through the growth period. Different functions were tested for the curve of best fit. As a further benefit it appeared that models could be constructed from the information presented that would speculate for diagnostic purposes upon the likely modulators of food intake. Such models could explore the constraints of gut capacity, the energetic requirements of maintenance and potential growth, the influence of excessive or inadequate environmental temperature, the quality of housing and stocking density.

Keywords: food intake, growth, nutrient requirements, pigs.

Introduction

For the satisfaction of the nutrient requirement for growth, it is prerequisite that the food intake be known. Food intake is known in the case of pigs given a prescriptive daily food allowance that is below their appetite. Where the food consumed is not known, then food intake must be estimated. In the event of pigs being given food *ad libitum* the estimation of actual intake may also be indicative of the appetite prevailing under the particular circumstances of food type, pig type, management quality, herd health and housing environment. Estimates of the outer bound of the potential for nutrient supply requires the assumption that the boundary characteristic of interest is that which is the first limiting, and constraints from other characteristics are not active.

The daily food intake is separately and together a function of: the food that is allocated to the pig by means of some prescriptive formula based on the weight of the pig or on an indicator of pig weight such as time elapsed since the last known weight; the food that the pig is able to obtain within the constraints of physical environmental elements such as feeder space and peer competition; the health and demeanor of the animal; the effective environmental temperature; the size (capacity) of the gut of the pig (usually defined, rather imperfectly, by its mass); the characteristics of the diet influence the capacity of the gut, such as food volume and weight and the rate of passage of indigestible material through the most limiting sector of the intestine; the nutrient requirement (usually expressed in terms of energy) of the pig for the day in question (conventionally the sum of the requirements of maintenance, protein

retention, lipid retention, and cold thermogenesis) the type of pig under consideration.

It is not evident to what extent the type of pig, and selection pressure upon the type, might affect voluntary food intake independently of the genetically controlled characteristics of gut capacity or nutrient requirement. Certain breeds (such as the Chinese types) may have a superior capacity for fibrous feeds, whilst halothane positive pigs eat some 15-20% less than negative types (Henry, 1985; Webb, 1989; Kalm, 1986). Schinckel (Schinckel and de Lange, 1996) observed a 30% difference between genotypes of pigs fed under similar conditions. It is also evident that whilst the nutrient requirement proposition would imply that faster growing improved pigs would have a greater appetite, it is the unimproved genotypes which may have appetites up to 30% greater than those selected for leanness (Meat and Livestock Commission, 1982; Webb, 1989; Cole and Chadd, 1989). Knap (2000), in common with many others, has collected evidence from the literature which clearly shows the appetite of pigs diminishing over recent decades simultaneously with positive genetic selection for leanness. The idea that increased potential for lean tissue deposition may be associated with diminished appetite is unhelpful to the notion that pigs will eat to their energy requirement. However, a decreased potential for fatty tissue deposition would be consistent with appetite reduction. This matter also raises the complex issue of identifying the 'nutrient requirement' for lipid accumulation in pigs which appear, when given food to appetite, to eat excessively and become obese. The requirement as perceived by the pig thus becomes at variance with the requirement as perceived by the nutritionist.

Measurements of food consumed by pigs at various body weights (or times) do not quantitatively differentiate between all the influences mentioned above (with the exception of weight). Mathematical functions describing data sets collected in the course of investigations, however complex, may therefore be accurate in their *description*, but will not necessarily illuminate the quantification of causal principles required for simulation and *prediction*. There are also unresolved ambiguities in the expectations for food intake according to the requirements for growth and maintenance, and observations in practice. The concept of causal principles (for example, Kyriazakis and Emmans, 1999) would suggest curvilinear incrementation at the very time when practical measurements (for example, Tullis, 1982) can find a plateau in response. There is a presumption that empirical descriptions of food intake determined in the course of

experimentation may, if expressed with adequate accuracy and complexity, serve to define food intake for purposes of the satisfaction of practical nutrient requirement (Agricultural Research Council (ARC), 1981; National Research Council (NRC), 1998). This presumption would be faulted if it were to be found that such empirical descriptions were irreconcilable, as would appear to be the case, with experience gathered in the field.

This analysis examines the likelihood of empirical determinations being unsafe for the practical estimation of food intake. Next, alternative methodologies for the determination of food intake from field data will be presented. It is taken as a self-evident truth that the feeding of pigs requires the most intimate knowledge as is possible to gather concerning the pig's daily food intake.

Published observations

Observers' food intake data frequently fail to differentiate between limits imposed by satisfaction of nutritional desire and those imposed by the capacity of the gut or some other constraint. In the early stages of growth, young pigs show characteristics that would be indicative of gut capacity limiting intake below that desired. These include rapid increase in food intake commensurate with rapid increase in body weight, and immediate positive growth response to increased diet nutrient density. In the later stages of growth older pigs show converse characteristics including diminishment of food intake toward a plateau even though body weight continues to increase, and no reduction in growth rate when food nutrient density is decreased; pigs are evidently 'eating to energy' (Cole and Chadd, 1989). The empirical relationships discussed below are taken as appropriate for the 20 to 120 kg live weight growth period and, being empirical, should not be applied outside the range of the data from which they were derived. Neither should it be presumed that any biological interpretation is due from an empirical relationship.

Tullis (1982) purposefully encouraged the maximization of food intake over a prolonged period of growth. Her analysis, using pooled data for each of the three series, divided the data into two parts, with a clearly distinguished break point occurring at 85 kg live weight. From 5 to 85 kg:

$$\text{food intake (kg/day)} = 0.046W + 0.35 \text{ (entire males)}$$

$$\text{food intake (kg/day)} = 0.043W + 0.41 \text{ (females)}$$

$$\text{food intake (kg/day)} = 0.048W + 0.42 \text{ (castrated males)}$$

where W is the live weight (kg). Food intakes from 85 to 200 kg were characterized by wide oscillations around a flat plateau with mean values of 4.0, 3.6, and 3.7 for the three sexes respectively. As all animals were given individually as much fresh food as they cared to consume, 'environmental and competitive constraints' were presumed absent. For food intake as a function of time the break point was at 140 days of age. From 21 to 140 days:

$$\text{food intake (kg/day)} = 0.033D - 0.49 \text{ (entire males)}$$

$$\text{food intake (kg/day)} = 0.029D - 0.26 \text{ (females)}$$

$$\text{food intake (kg/day)} = 0.035D - 0.40 \\ \text{(castrated males)}$$

where D is the day of age.

The linear/plateau model is not especially endearing, as it requires three separate parameters, the slope, the break point, and the plateau, all of which are independent of each other. Further, if linear/plateau be the correct biological interpretation of the phenomenon, then a population of individuals behaving in this way would necessarily produce a data set describable with a curve (Curnow, 1973; Morris, 1999). More usually a single expression is attempted. ARC (1981) and NRC (1987) use an expression that rises exponentially toward a plateau. On the premise that pigs will eat to energy (rather than weight of food), these expressions are in terms of digestible energy (DE):

$$\text{energy intake (MJ DE per day)} = 50(1 - e^{-0.0204W}) \\ \text{(ARC, fed by scale to appetite)}$$

$$\text{energy intake (MJ DE per day)} = 55(1 - e^{-0.0204W}) \\ \text{(ARC, continuous } ad \text{ libitum access)}$$

$$\text{energy intake (MJ DE per day)} = 55(1 - e^{-0.0176W}) \\ \text{(NRC).}$$

NRC(1998), however use in their model for growing pigs to the point of slaughter a third-order polynomial:

$$\text{energy intake (MJ DE per day)} = 5.23 + (0.79W) \\ -(0.0059W^2) + (0.000018W^3)$$

which can be adjusted upwards for castrated males and downwards for entire males and females. The use of this latter curve form is limited in its safe range.

The form; $y = y_0 + ax^b$, where y = food intake (kg) per day, and often without inclusion of the constant term y_0 , has been found useful to deliver a curvilinear response fitting much of the data. This form is less asymptotic than those above, and may be inadequate as a result for description of intake at higher live weights. ARC (1981) suggest:

$$\text{energy intake (MJ DE per day)} = 4.7W^{0.51},$$

while Cole *et al.* (1967) proposed:

$$\text{energy intake (MJ DE per day)} = 2.4W^{0.68}.$$

McCracken and Stockdale (1989) report:

$$\text{energy intake (MJ DE per day)} = 2.4W^{0.63},$$

an expression also found in Whittemore (1998), while for pigs given food in groups from *ad libitum* hoppers Patterson and Walker (1989) report:

$$\text{energy intake (MJ DE per day)} = 2.1W^{0.63},$$

after allowing 4.5% measured wastage. The ARC (1981) suggestion that an outer limit to food intake may be defined as 4 X maintenance, calculates to:

$$\text{energy intake (MJ DE per day)} = 3.0W^{0.63}.$$

Using the same form, but in terms of amount of food rather than energy, Whittemore (1983) suggests:

$$\text{food intake (kg/day)} = 0.12W^{0.75}$$

as descriptive of practical food intakes from *ad libitum* dry-food hoppers. There is no particular reason to choose 0.75 as the exponent, nor to exclude the constant. Urquhart (1995), working with entire males of high genetic merit, concluded that a good fit to his data was had by the expression:

$$\text{food intake (kg/day)} = 0.310W^{0.50}$$

which with a diet of 13.3 MJ DE per kg is equivalent to:

$$\text{energy intake (MJ DE per day)} = 4.1W^{0.50}$$

in keeping with the $3.9W^{0.51}$ from unpublished observations reported by Cole and Chadd(1989). Quiniou *et al.* (2000) describing data from group-fed pigs collected in a carefully conducted experiment use the expression:

$$\text{food intake (kg/day)} = 0.055W - 0.00025W^2.$$

The data of Ramaekers (1996), who used a more complex model, could probably also have been described with:

$$\text{food intake (kg/day)} = 0.12W^{0.71}$$

(In the event, Ramaekers (1996) employed (without question) the equation form of Kanis and Koops (1990) to describe his data:

$$\text{energy intake(MJ ME)} = a \cdot e^{-bW-c/W}$$

where a , b and c are the equation's parameters and ME = metabolizable energy.)

Eissen *et al.* (1999) rejected the Kanis and Koops (1990) form to describe their data for the food intake of 192 pigs growing from 28 to 108 kg, and examined instead three alternatives to express daily food intake as a function of time on test:

$$\text{food intake (kg/day)} = a + bX$$

$$\text{food intake (kg/day)} = a + b \ln(X + c)$$

$$\text{food intake (kg/day)} = a + bX + cX^2 + dX^3$$

where X is measured in terms of time (day on test), and ranges from 1 to 89. Over the weight range concerned, visual appraisal of the plotted data would suggest an early phase of accelerating food intake (which could also be interpreted as a lag phase while the animals accustomed themselves to the test regime), a linear phase, and in the later stages an asymptotic phase. The cubic polynomial described this form rather well, the best of the three, but was rejected by the authors. The grounds were not stated, but the inevitable (and erroneous) increase in food intake at higher live weights that is inherent in this form does render the third order polynomial function unsafe. Over the weight range in question, the more simple non-linear form showed little curvature, and as all three forms were of rather similar goodness of fit, the linear form was selected by Eissen *et al.* (1999) for the subsequent interpretation of their data. A subsequent report (Eissen, 2000) would indicate for entire males and females combined mean values of + 1.23 kg for a , and 0.0161 kg/day for b . The slope of this response is only half that of Tullis(1982), shown above, whose constant term was negative. Differences in the constant are unsurprising as the start weight for the Tullis data was 5 kg. The difference in slope however is a clear indicator of the dangers inherent in using equations describing data sets reported in the literature for purposes of pig food intake prediction. In this respect it is germane that the pigs of Tullis

were given food individually in experimental facilities while those of Eissen were group-fed in circumstances akin to on-farm production.

The Technisch Model Varkensvoeding Werkgroep (TMV, 1994), refer to the Kanis and Koops (1990) equation, but forward for the model a more complex update:

$$\text{food intake} = y_m e^{(-\ln 2 \cdot W_n / W) \cdot ((W - W_m) / (W_n - W_m))^{**2}}$$

where W is the live weight of the pig (kg), and the three parameters are y_m the expected maximum food intake, W_m the live weight at maximum food intake, and W_n the live weight at half maximum food intake. However, the TMV working group itself appreciates the limitations of prediction of nutrient intake by use of an equation, as compared with the entering of known and given values (C. M. C. van der Peet-Schwering, personal communication).

Common as it is, expressing food intake as a function of age (Emmans (1997) presents an excellent exposition on this matter) is unhelpful in the context of commercial pig production where pigs may grow at different rates and be of widely differing weights for age. Lorenzo-Bermejo *et al.* (2000) found the logistic expression useful:

$$\text{food intake} = a / (1 + \exp(B - c \cdot x))$$

where x is day on test, a , B and c are the equations parameters, and c approximates to 0.026. The pattern of food intake found by these authors was similar to that of Tullis (1982), with a linear phase rising to a highly variable plateau. As the x axis is time, the older pigs will also have been the slower growing, with a lower food intake. Thus on a time-based test, an apparent plateau is inevitable, and transposition of time to weight on an assumption of weight-for-age would be faulted. Nevertheless, the function may prove of merit when fitting curves to food intake as a function of weight to field data.

Food intake in 'unlimiting' circumstances

Although capacity is dependent on body weight, Parks (1982) states that in the actively growing animal it is the (increasing) body weight that is dependent on feed intake, thus:

$$W = (A - W_0)(1 - \exp(-(AB)F/A)) + W_0$$

where W is live weight (accumulated gain), A is the live weight at maturity, W_0 is the initial live weight, B is the efficiency coefficient, and F is the accumulated

food intake. Thompson *et al.* (1996) obtained a good fit to their substantial data set with this equation.

Whittemore *et al.* (1995) point out that in the consideration of the prediction of food intake, body weight is reflective only of maintenance, a minor component of food usage in the growing pig. Pigs of similar weight may wish to ingest nutrients to grow at widely dissimilar rates of growth and with widely differing targets for the accumulation of fat. The work of these authors gives support for the concept that food intake is a function of nutrient need as expressed by differing pig types with different needs. From knowledge of backfat depth and live weight, the report of Whittemore *et al.* (1995) suggested that it was possible to predict rather effectively the food intake of 10 genetically different groups of Large White pigs whose voluntary food intakes ranged from 1.87 to 3.15 kg/day. First, the total lipid (Lt) and total protein (Pt) masses were estimated from:

$$Lt = 1.12 (0.19W + 0.78(P2) - 9.2)$$

$$Pt = 0.44 (0.41W - 0.52(P2) + 2.4)$$

where (P2) is the thickness of fat plus skin measured ultrasonically on the live animal 65 mm from the mid-line at the position of the last rib. From the masses, the gains (Lr and Pr) were calculated and the total energy requirements determined from the equation:

$$\text{energy intake (MJ ME per day)} = 52Pr + 53Lr + 0.44W^{0.75}$$

Average metabolic weight for the growth phase in question was determined as:

$$(W_1^{1.75} - W_0^{1.75}) / 1.75(W_1 - W_0)$$

Kyriazakis and Emmans (1999) (having considered the Parks approach), forward the logic also favoured by Black *et al.* (1986), that food intake will equal that which is desired to fulfill the metabolic requirements of the day in question. These requirements being a function of pig weight (maintenance) and tissue weight gains:

$$\text{daily food intake} = (1/\text{food energy content}) \cdot (E_M + E_{Pr}/k_{Pr} + E_{Lr}/k_{Lr})$$

where E_M is the energy for maintenance, and E_{Pr} and E_{Lr} are the daily rates of energy retention in protein and lipid together with their respective energy cost factors (k). In cold environments an energy cost for cold thermogenesis may also be added (0.016 MJ per $W^{0.75}$ for each °C of cold ($T_c - T_e$) (ARC, 1981), where

T_c is the critical or comfort temperature and T_e the effective ambient environmental temperature). The outer limits for tissue weight gains, expressed as protein and lipid retention rates, may be defined in a variety of ways, but both may be adequately described as a Gompertz function in relation to live body weight. Emmans and Kyriazakis (2001) provide a review of the propositions underlying the hypothesis that pigs will eat to meet their nutrient requirements. The authors point out that the matter is one of potential food intake, and not actual. But the observation that some pig genotypes do not appear to have increased their appetite commensurate with selection pressure for growth remains difficult to answer, as is the inherent circularity of the argument that algorithms for potential food intake are analogous with those for the nutritional satisfaction of growth potential.

The notion that food intake can be determined from the sum of the nutrient requirements depends upon the characteristics of the efficiency coefficients (k) being the same for genotypes differing in their voluntary food intake limits. There is substantial genetic variation in food intake, mediated presumably through a combination of gut capacity limits and variation in the desired rates of protein and lipid retention. Luiting (1999) indicates a heritability of around 0.4. As Luiting (1999) points out, the presumption of constancy for values for k is unsafe, as the solution of the equation leaves an error term, which may be a characteristic of a genotype, and open to selection:

$$\text{food intake} = (b_1 \cdot (Pr + Lr)) + (b_2 \cdot W^{0.75}) + e$$

where b is the efficiency coefficient for production and for maintenance respectively, and e is the error term. The term e , or 'residual food intake', appears to be heritable, responsive to selection and highly correlated to food intake. Thus, pigs may change their food intake potential but not change their rates of retention of protein or lipid. If the propositions of Luiting (1999) hold, then food intake determined as a consequence of the animal's requirements for nutrients becomes more complex in its calculation than Kyriazakis and Emmans (1999) would presume. However, reduction in the error term would follow from expansion of the model and increasing the number of variable parameters.

Kyriazakis and Emmans (1999) point out that the limiting element within the food which is active in driving the desire to eat may not always be energy; limiting protein (or amino acid) also being a likely contender:

$$\text{daily food intake} = (1/\text{food protein content})(P_m + vPr)$$

where P_m is the maintenance requirement for protein and v accounts for the sum of the inefficiencies of conversion of food protein to retained protein. Both rules may be applied sequentially. Argument in support of pigs 'eating to protein' as well as 'eating to energy' also comes from Cole and Chadd (1989). Following a review of work they state that 'There is considerable evidence that response to crude protein in the diet is such that intake is depressed at very high or very low levels and that intake is at a maximum close to the requirement'. Similar principles apply for ideal protein and for limiting amino acids (usually lysine). Further, pigs of differing type with respect to their protein retention rate will, when given the choice, select differing levels of protein intake as appropriate to their respective need (Kyriazakis *et al.*, 1993).

It is evident that the description of food intake as a function of food need will show first an accelerating increase in intake above the requirement for maintenance as would reflect accelerating growth. Using the Gompertz function to depict growth will impose a point of inflexion, and then a reduction in food intake above the needs of maintenance as growth decelerates. Ultimately food intake as a function of need will equate to the requirement for maintenance. The food intake curve will therefore rise sigmoidally, will reach an apparent asymptote, but will then fall to a lower and more constant level with the reaching of maturity. Such is demonstrated in the analysis of Emmans (1997). However, it would be improper to seek any single mathematical expression to encapsulate the response of food intake as a function of body weight. This is achieved by an effective description of growth, together with quantification of the nutritional needs of growth and maintenance. The curve generated is the outcome of this approach to food intake description.

Limit according to capacity of the gut

The capacity of the gut is a function of its size/volume and the rate of throughput of digesta. Gut size is in turn related to the extent of habituation of the intestine to diets of low nutrient density and the size of the animal, while throughput is related to diet digestibility. Gastric emptying rate appears to be related *inter alia* to time since eating, live weight of pig, amount eaten, extent of stomach stretch, diurnal rhythm, and the chemical constituents of the diet (Rayner and Gregory, 1989). There is likely to be a genetic component to gut capacity, but it remains unquantified. Black *et al.* (1986) review data showing that the ability of pigs to increase their voluntary

intake in the face of decreasing nutrient density is strongly related to pig size. Thus there is little or no accommodation possible for pigs of less than 50 kg whose capacity for growth appears in excess of their capacity for food at any nutrient density. At around 75 kg the ability to 'eat to energy' appears to extend to diets of around 10 MJ DE per kg, while pigs of 100 kg appear to express with little difficulty a pro-rata linear response in food intake to decreasing diet density. Tybirk (1989) presents curves indicating for various pig weights the proportion of their 'energy capacity' that will be satisfied when the pigs are offered diets of differing energy density. Tybirk (1989) suggests that at 20 kg live weight pigs will be able to eat to 0.70 of their energy capacity when offered a diet of 11 MJ ME per kg, 0.85 when offered a diet of 12 MJ ME per kg, and 0.95 when offered a diet of 13 MJ ME per kg. Respective values for 40-kg pigs were 0.80, 0.95 and 1.0; for 60-kg pigs 0.85, 1.0 and 1.0; and for 100-kg pigs 1.0, 1.0 and 1.0. Following a plot of the voluntary food intake of pigs of 10 to 205 kg live weight given diets of low nutrient density, Black *et al.* (1986) set a maximum (gut capacity) food intake limit of:

$$\text{food intake (kg/day)} = 0.111W^{0.803}$$

where the food is of 900 g/kg dry matter.

Whittemore (1993) explored the influence of diet digestibility, through the medium of the equation:

$$\text{food intake (kg/day)} = 0.013W / (1 - \text{digestibility coefficient}).$$

The term 0.013W emanates from an estimate of faecal organic matter dry matter (DM) output by pigs. Ferguson *et al.* (1994) proposed that food intake be constrained by:

$$\text{food intake (kg/day)} = 0.090(\text{Pt}/\text{BULKDN})$$

where Pt is the protein mass of the pig and BULKDN is the estimated indigestible organic matter content of the food and therefore rather similar to (1 - digestibility coefficient); and as Pt is usually around 0.16W, 0.09Pt is rather similar to 0.013W. Where the fibre content of the diet is estimated by the determination of neutral-detergent fibre (NDF), the following approximation for gut fill may be interpolated from the work of Jorgensen *et al.* (1996):

$$\text{gut fill (g/kg W)} = 15 + 0.24.\text{NDF}.$$

The indigestible fraction of the diet (usually defined through the medium of an analysis of fibre) may not however be viewed as solely contributing to the bulk

constraint by the filling of available space. Increasing diet fibre content will increase gut motor functionality, decrease transit time, increase water-holding capacity (WHC) and increase the proportion of digestible nutrients appearing in (and disappearing from) the large intestine (Just, 1982; Cherbut *et al.*, 1988). The relative contributions of these effects to the operational capacity of the gut, and the influences of fibre level are not however readily quantified. Tsaras *et al.* (1998) propose that WHC can adequately describe the 'bulkiness' of fibrous foods. Thus an experiment using differing levels of inclusion of food ingredients of differing fibrosity and WHC (measured by centrifugation) yielded:

$$\text{food intake (g DM per kg W daily)} = 207 (1/\text{WHC})$$

where WHC is measured in g water per g food and the foods used included sugar-beet pulp, grass meal or soya hulls, and had WHC values ranging from 5.1 to 8.5 (the control value was 3.9). Expressed in this way, the equation is of limited use as it is presumptive upon a 'base-line' food intake of around 50 g food per kg pig live weight, and it cannot be accepted that WHC is the only variable affecting intake. An expression is required which allows WHC to modify expected food intake and not control it. The experiment of Tsaras *et al.* (1998) would suggest that a unit (g/g) increase in the WHC value of a food above 4 is associated with a decrease in food intake of some 6 g food DM per kg pig live weight. An earlier experiment (Kyriazakis and Emmans, 1995) using wheat bran, grass meal and citrus pulp as the fibre sources and examining a range of values for WHC (g/g) of less than 2 to greater than 6 had indicated one unit (g/g) increase in WHC to also be associated with a decrease in food intake of some 6 g food DM per kg pig live weight.

It might therefore be proposed that:

$$\text{food intake (kg/day)} = (0.111W^{0.803}) - (0.006(\text{WHC} - 4)W).$$

An idea has been forwarded that gut constraints may become plastic when (ruminant) animals are in frank nutrient deficit through being given bulky foods. This means that the influence of food bulk upon food intake can be over-ridden (Tolkamp and Ketelaars, 1992). If this proposition were to hold for pigs, then any model of food intake would require to give consideration to the Tolkamp and Ketelaars (1992) concept of eating to optimize the efficiency of the metabolic processes as expressed by the ratio of net energy consumption to oxygen utilization rate. This would be difficult as both the concept and its target

efficiency is unquantified. A recent series of carefully constructed experiments (Whittemore *et al.*, 2000) have shown that the balance of evidence is in favour of the assumption that, even when nutritionally embarrassed by being presented with a bulky diet, the pig cannot readily over-ride the constraint of gut capacity. The pigs of Whittemore *et al.* (2000) appeared limited at around 50 g daily food intake per kg W.

Influence of environmental temperature

Pigs at first eat more, and then less in a quadratic response of food intake to environmental temperature (see Close, 1989; Whittemore, 1998). Effective temperatures (the combined effects *inter alia* of ambient temperature, rate of heat transfer to contact surfaces, humidity and air movement) *below* that required for the metabolic comfort of the pig will increase energy demand for cold thermogenesis. Effective temperatures *above* comfort temperature will decrease intake at a more marked rate at higher pig weights. Thus Quiniou *et al.* (2000) found:

$$\text{food intake (kg/day)} = -1.264 + 0.073.6W - 0.00026W^2 + 1.177T_a - 0.0024T_a^2 - 0.00095T.W$$

where T_a is the environmental temperature.

The determination of effective temperature (T_e) is disputatious. The seminal text is often seen as that of Bruce and Clark (1979). This was considered by ARC (1981) but put aside in favour of less deductive coefficients accounting for insulation, draughts and bedding. Whittemore (1983 and 1998) followed the ARC lead by developing the empirical findings of Mount's Cambridge School to give:

$$T_e = T_a.V_e.V_l$$

where T_a is the ambient temperature and V_e and V_l are described with a series of coefficients ranging from 0.6 to 1.4 depending upon rate of air movement, draught and lying conditions. Examples are given in Table 1.

Black *et al.* (1986) quote Bruce and Clark (1979) extensively, but validate their model only in respect to the main effect of temperature upon food intake; that is, the influence of factors bringing about differences between T_a and T_e are not tested. There appears to be little present alternative to a choice between the deductions of Bruce and Clark (1979), and the empiricism of Whittemore (1983 and 1998) but there is little comfort in either.

Table 1 Effect of nature of housing upon effective temperature. The parameter values given are appropriate for the description of VeVI. (Interpolated from ARC (1981) and Whittemore (1983 and 1998))

VeVI	Wall/ceiling insulation present	Wall/ceiling insulation absent
Floor insulation/bedding material present	Draughts present 0.9	Draughts present 0.8
	Draughts absent 1.1	Draughts absent 1.0
Floor insulation/bedding material absent	Draughts present 0.7	Draughts present 0.6
	Draughts absent 1.0	Draughts absent 0.8

The energy cost of cold thermogenesis (MJ) when the effective temperature (T_e) is below the animal's comfort temperature (T_c) is probably between 0.011 and 0.016 per degree difference between effective (T_e) and comfort (T_c) temperatures per kg $W^{0.75}$ (Verstegen, 1971; Verstegen *et al.*, 1973). Whittemore and Fawcett (1976) give:

$$\text{energy cost of cold thermogenesis (MJ ME)} = 0.016W^{0.75}(T_c - T_e).$$

Appetite predicted as a function of nutrient (energy) requirement will therefore increase in strict proportion to this need.

Effective temperatures *above* that required for the metabolic comfort of the pig will reduce appetite as a response to an increasing embarrassment of body heat that cannot be dissipated into the environment. This has the consequence of an increasing imperative to reduce the rate of heat formation by limiting nutrient input, and/or by ingesting energy in the form of substrates that generate a lower heat output (such as highly digestible starches and fats). As environmental temperature increases, food intake at first decreases due to a reduction in energy requirement, then after a period of stability decreases once again as a result of heat stress.

Smith *et al.* (1988) analysed data relating to North American pigs grown from 26 to 108 kg and kept at temperatures of 4 to 28 °C. They found a linear rate of food intake change above and below T_c , and the slope to be 0.7 g per kg W per °C of temperature change. Rinaldo *et al.* (2000) reported food intake reduction as high as 68 g/day per degree Celsius above T_c in growing finishing pigs kept in hot climates. Whittemore (1998) suggests a 1 g food reduction per kg body weight per degree of heat above comfort level, or:

$$\text{reduction in nutrient intake (MJ DE per day)} = 0.014W(T_e - T_c)$$

where T_e is the effective ambient temperature, and T_c the comfort temperature of the pigs in question

derived by Whittemore and Fawcett (1976) in part from Verstegen (1971) as:

$$T_c = 27 - 0.6H$$

where H expresses the total heat output generated from the body of the pig. Effective temperature results from the combined effects of ventilation rate, insulation protection against radiant heat and the type of floor upon which the pig is expected to lie (Whittemore, 1983). Close (1989) gives an average value for the growing pig of 0.65 MJ ME per day change in intake for each degree change in environmental temperature. This figure is compatible with the above at $W = 50$ kg. The necessary inclusion of W into the estimate is accommodated by Close (1989) with an equation derived from a variety of sources:

$$\begin{aligned} \text{energy intake (MJ ME per day)} \\ = 9.6 + 0.075T_e + 0.52W - 0.012W.T_e \end{aligned}$$

which is consistent with each degree change in temperature resulting in a 1% change in food intake at 20 kg live weight, and in a 2.5% change at 100 kg. Black *et al.* (1986) extend their estimate of the limit to gut capacity thus:

$$\begin{aligned} \text{food intake (kg/day)} &= 0.111W^{0.803} \\ &+ (0.111W^{0.803} \cdot 0.025(T_c - T_e)). \end{aligned}$$

Close (1989) further suggests that a change in air speed of 0.2 m/s is equivalent to a change in T_e of one degree. The effects of relative humidity (militating against evaporative heat loss from the body of the pig) are greater at higher temperatures. The review of Close (1989) points to a proportional increase in relative humidity of 0.15 being equivalent to an increase of one degree in T_e .

NRC (1998) first calculate optimum temperature (T_c) as a function of body weight (which is more simple than heat output (H); but less accurate):

$$T_c = 26 - 0.0614W,$$

and then calculate an adjustment:

adjustment = MJ DE intake per day $0.0165(T_c - T_e)$.

Black *et al.* (1986), invoking the support of Close (1978), also propose that allowance be made for a reduction in the coefficient for the efficiency of utilization of metabolizable energy (k) at higher temperatures of 0.8% per $^{\circ}\text{C}$, or;

$$k = k - 0.008(T_e - T_c).$$

From the foregoing there is an evident a lack of any unifying theme for the adjustment of food intake according to insufficient or excessive environmental heat. There is also a wide range of values suggested for each.

Influence of stocking density

It is recognized that pigs will grow more slowly as the stocking density increases. A substantial element of this response is a negative effect on food intake. Whittemore (1998) indicates that where:

$$\text{area occupied by the pig (m}^2\text{)} = kW^{0.67}$$

a change in k value of 0.005 below optimum can be associated with a 4% change in food intake. It may be interpolated from Edwards *et al.* (1988) that optimum space allowances in intensive housing conditions (with respect to food intake considerations) are associated with values for k of approximately 0.050 . Rather similarly, Black (1995) forwards on optimum space allowance of 0.04 m^2 per $W^{0.67}$ and suggests food intake will be depressed linearly by 20% if space allowance falls to 0.02 m^2 per $W^{0.67}$ (a 5% change in food intake with each 0.005 increment below optimum). NRC (1998) offer the following adjustments to account for space allowances below 1.1 m^2 per pig (a value which will result in the inevitable evocation of the adjustment):

$$\text{adjustment (MJ DE)} = \text{MJ DE intake per day} \cdot (0.773 + (0.429\text{SP}) - (0.203\text{SP}^2) - 1)$$

for pigs of <50 kg, and for pigs of >50 kg;

$$\text{adjustment (MJ DE)} = \text{MJ DE intake per day} \cdot (0.617 + (0.701\text{SP}) - (0.320\text{SP}^2) - 1)$$

where SP is the space allowed (m^2).

Influence of sex

Hsia and Lu (1989) report castrated males to eat proportionately 0.11 more than females, while the review of Cole and Chadd (1989) suggests a figure of 0.07 to 0.16 . In common with many others, McCracken and Stockdale (1989) found no effective difference in food intake between entire males and

females. Whilst it would appear that differences between entire and castrated males are more likely to occur than differences between entire males and females, generalized quantification across pig types may not be warranted. Nevertheless, NRC (1998), adjust their third-order polynomial model for the estimation of energy intake, upwards for castrated males and downwards for entire males and females with a complex formula differentiating the sexes after 40 kg W by about plus or minus proportionately 0.07 of the mean.

$$\text{adjustment (MJ DE)} = \text{MJ DE intake per day} \cdot ((0.00385W) - (0.0000235W^2) - 0.083).$$

Summary

In summary, it may be concluded that a characteristic quality of food intake in growing pigs is that of variability. There is variation in general level amongst pig types and production circumstance, and in specific level in terms of day by day oscillation. Certain equation forms may have some utility. Linearity appears often to be the practical outcome of testing for the relationship between food intake and live weight over the growing/finishing period. The individual linear/plateau form is implied for populations in the form:

$$\text{food intake} = b \cdot (1 - e^{-aW}).$$

A less severe statement of the curvilinear reduction in food intake with increasing live weight is achieved with:

$$\text{food intake} = a \cdot W^b.$$

More complex equations may be fitted to specific data sets, but their general usefulness may be limited. The argument that pigs will eat to satisfy their requirements for maintenance and for protein and lipid retention, although to an extent self-fulfilling, is a way toward definition of the outer limits to food intake potential. Such limits appear modulated by the physical capacity of the tract, which in turn is influenced by (amongst other things) gut size, digestibility, and bulk density. It is evident that a large number of extrinsic factors, such as disease, environmental temperature, stocking density and sex influence food intake in ways that are also rather difficult to predict in individual farm circumstance.

On-farm food intake performance

For the reasons stated above, pigs for which food is putatively continuously and freely available (*ad libitum*), will not eat to the limits of their appetite as may be defined by nutrient requirement (if that be

known). What they do eat at any given live body weight is nevertheless essential information for effective nutrition management. In general, though not invariably, food intakes realized in practice are substantially different from those reported from scientific experimentation. There are wide differences between pig genotypes, farm management practices, and individual farm environments. In the absence of reliable and effective methods for the prediction of realized food intake (which we believe the foregoing review demonstrates in some part), there is an imperative for direct on-farm measurement. The minimum of information would be: a view of the likely shape of the curve describing food intake as a function of live weight; a reliable estimate of food intake at known live weights in the course of the growth period in question; an estimate of wastage.

Schinckel and de Lange (1996), quote a number of sources in support of food intake being better estimated by observations upon subsamples than by prediction. They recommend live weight and food intake measurement on a duplicate of two pens measured over a two-week period at the beginning, middle, and end of the growth range. This will allow a fit to a non-linear function. However, most pig grow-out operations have access to total food used over a given time period. Where the time period is short and the grow-out period is divisible into a number of phases, then linearity may be assumed. Differences in slope for each phase will track the overall shape of the response from start weight to finish weight. The fewer the phases over which total food intake information is available and the longer the time period for each phase, the less secure will the linear assumption be. In practical circumstances the data relate to long phases.

We would wish to propose that the daily food intake (DFI) under circumstances of pigs being given free access to a continuous supply of food may be determined under practical on-farm conditions according to one or other of the following methods. The methods presume (as would commonly be the case) to be known: the start weight (W_0) and finish weight (W_1) over which the pigs are grown (for example, 20 to 120 kg W); the time elapsing ($T_1 - T_0$) over the same weight range (for example, 133 days).

Method 1

In addition to the above, this method will also presume known the total food intake (TFI) per pig in the course of its growth over the stated weight range (typically, the annual food usage/number of pigs fed less the estimated food wastage per pig), (for example, 250 kg).

(i). Where the food intake curve is assumed to follow the curvilinear form,

$$DFI = a.W^b$$

a value must be provided for b (for example, $b = 0.75$).

(ia). For short periods of growth, linearity in daily live-weight gain (G) is assumed.

$$W = W_0 + (G.T)$$

$$G = (W_1 - W_0)/(T_1 - T_0)$$

so

$$DFI = a.(W_0 + T.G)^b$$

Integration gives

$$\int DFI dT = a.((W_0 + T.G)^{(b+1)})/(G.(b+1))$$

and

$$a = TFI/((W_1^{(b+1)} - W_0^{(b+1)})/(G.(b+1)))$$

Using the example values, a solves to 0.079.

(ib). For longer periods of growth, as the pig may grow at different rates within the stated range, a view must be taken of the shape of the growth curve. Daily live-weight gain may not be linear. If exponential growth is assumed (the pig growing progressively faster), then

$$W = W_0.exp(G.T)$$

$$G = \ln(W_1/W_0)/(T_1 - T_0)$$

so

$$DFI = a.(W_0.exp(T.G))^b$$

Integration gives

$$\int DFI dT = a.(W_0^b).exp(b.G.T)/(b.G)$$

and

$$a = TFI/((exp(b.G.T_1) - exp(b.G.T_0)).(W_0^b)/(b.G))$$

Using the example values, a solves to 0.094.

(ic). The exponential assumption is faulted over longer growth ranges as no allowance is made for deceleration. Various workers (see Emmans, 1988)

would suggest the Gompertz function to be the preferred descriptor of growth. If this function be taken, then

$$W = A \exp(-\exp(-B.(T - T^*)))$$

and a value must be provided for A (for example, 300).

Given A

$$B = ((\ln(-\ln(W_0/A))) - (\ln(-\ln(W_1/A))))/(T_1 - T_0)$$

and

$$T^* = (\ln(-\ln(W_1/A)))/(B + T_1)$$

so

$$DFI = a.(A.\exp(-\exp(-B.(T - T^*))))^b$$

Rather than by integration, a may be given by

$$a = TFI / \sum_{t=t_0}^{t_1} (A.\exp(-\exp(-B.(T - T^*))))^b$$

Using the example values, a solves to 0.084.

(ii). Where the food intake curve is assumed to follow the linear form,

$$DFI = a + b.(W - W_0)$$

a value must be provided for a, the food intake at W_0 (for example, at 20 kg live weight, 0.80 kg or $0.084W^{0.75}$).

(iia). Linearity of daily live-weight gain (G) is assumed.

$$W = W_0 + G.(T - T_0)$$

$$G = (W_1 - W_0)/(T_1 - T_0)$$

so

$$DFI = a + b(W_0 + G.(T - T_0) - W_0)$$

Integration gives

$$\int DFI dT = (a.T) + b.G.T.((0.5.T) - T_0)$$

and

$$b = (TFI - (a.(T_1 - T_0)))/(G.(T_1.((0.5.T_1) - T_0) - (T_0.((0.5.T_0) - T_0))))$$

Using the example values, b solves to 0.0216.

(iib). Taking growth to be described by the Gompertz function,

$$W = A \exp(-\exp(-B.(T - T^*)))$$

and a value provided for A (for example, 300), then given A

$$B = ((\ln(-\ln(W_0/A))) - (\ln(-\ln(W_1/A))))/(T_1 - T_0)$$

and

$$T^* = (\ln(-\ln(W_1/A)))/(B + T_1)$$

so

$$DFI = a + b(A.\exp(-\exp(-B.(T - T^*))) - W_0)$$

Rather than by integration, b may be given by

$$b = (TFI - (a.(T_1 - T_0)))/\sum_{t=t_0}^{t_1} (A \exp(-\exp(-B.(T - T^*))) - (W_0.(T_1 - T_0)))$$

Using the example values, b solves to 0.0238.

(iii). Where the food intake curve is assumed to follow the curvilinear form of NRC (1998)

$$DFI = b.(1 - e^{-aW})$$

and the value for a is given (for example, the value ascribed by NRC is 0.0176).

The same methodologies as adumbrated above may be employed.

(iiia). Assuming linear growth,

$$b = TFI / \sum_{t=t_0}^{t_1} (1 - \exp(-a.(W_0 + G.(T - T_0))))$$

Using the example values, b solves to 2.82.

[Equation (iiia) can also be integrated

$$b = TFI / ((T_1 - T_0) + (1/a.G).(\exp(-a.(W_0 + G.(T_1 - T_0))) - \exp(-a.(W_0 + G.(T_1 - T_0))))]$$

(iiib). Assuming curvilinear (Gompertz) growth,

$$b = \frac{t_1}{t_1 - t_0} \text{TFI} / \sum_{t=t_0}^{t_1} (1 - \exp(-a(A \cdot \exp(-\exp(-B \cdot (T - T^*))))))$$

Using the example values, b solves to 2.96.

(iv). Where the food intake curve is assumed to follow the linear/plateau form,

$$\text{DFI} = a + bW, \text{ until } W = W_1$$

when $W = W_1$, $\text{DFI} = c$.

This assumption is insoluble in practice as W_1 cannot reasonably be provided.

Figure 1 shows solutions to the three equations assuming the Gompertz description of growth. It will be observed that the linear and the power functions give similar solutions, although this would be dependant upon the severity of the power used. The NRC exponential form is quite different from the others in giving higher intakes in the middle phase and then tending towards a plateau.

Method 2

The average amount of total food consumed per pig in the course of its growth is not known. Information on daily food intakes of pig groups of varying live weights may however be obtained from the farm in

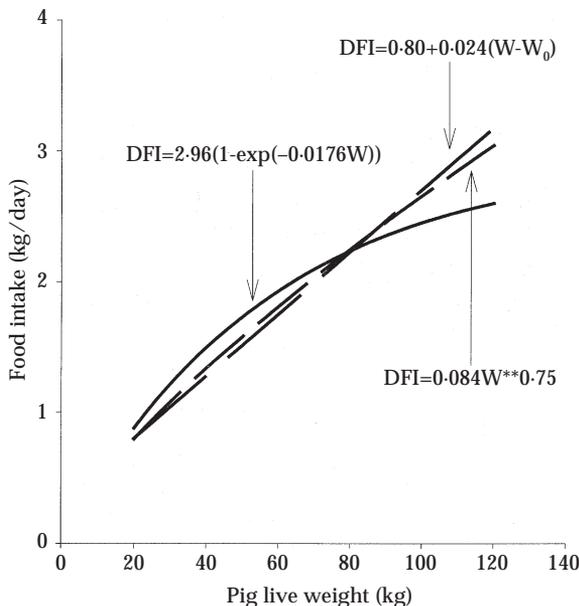


Figure 1 Patterns of food intake predicted from the equations described at (i) c) ---, (ii) b) — and (iii) b) —, and using the values given as examples.

question using subsamples of pigs as indicated in the recommendation of Schinckel and de Lange (1996). De Lange *et al.* (1999), and Porkmaster (1997) further propose a minimum of five data points to facilitate curve fitting and that daily food intake should be determined over a period of 14 days or so to reduce variation error. It is self-evident that the greater the number of measurements and the longer the period of time over which the measurements are taken, the more accurate the estimate of food intake over the growth period will be. A compromise must be struck between the ideal and what is realistic in practice. For the purposes of this report and the presentation of appropriate examples, we suggest that measurements are taken at three points (near, but not at, the beginning, near the middle, and near the end) during the growth of the pig. Three groups of pigs are required to be weighed at each point and their subsequent food consumption measured. Equally, the nine measurements could all be taken at the same calendar time; the farm being sampled from three pens at each of the three points during the growth period. For present purposes (taking 20 to 120 kg growing pigs as the example) the data of Tullis (1982), pertaining to pigs with especially high voluntary food intakes, have been used. Randomly chosen pigs of 25, 30, 35, 65, 70, 75, 105, 110, and 115 kg live weight, were recorded by her as having eaten 1.2, 1.5, 1.9, 2.9, 3.2, 3.7, 3.9, 4.0, and 4.1 kg food. For on-farm purposes curves may be fitted with readily available spreadsheet software. In the present case, curves of the forms used above in method 1 were fitted to the data using SIGMAPLOT® 5, a product of SPSS® Science. The SigmaPlot curve fitter uses the Marquardt-Levenberg algorithm (Marquardt, 1963; Press *et al.*, 1986) to find the coefficients (parameters) of the independent variable(s) that give the 'best fit' between the equation and the data. This algorithm seeks, by iteration until the differences between the residual sum of squares no longer decreases significantly, the values of the parameters that minimize the sum of the squared differences between the values of the observed and predicted values of the dependent variable (convergence). Results were as shown in Table 2.

Table 2 Estimated parameters for various equations to describe the voluntary daily food intake (DFI) of pigs (utilizing the data of Tullis (1982))

Equation	a	b	r ²	s.e. of estimate
DFI = a.W ^b	0.159	0.693	0.95	0.262
DFI = a + b(W - W ₀)	1.37	0.0312	0.93	0.319
DFI = b.(1 - exp(-a.W))	0.0113	5.72	0.97	0.198

In the case of this data set, with its high levels of recorded food intake, the estimates for parameters a and b are (naturally) markedly and informatively different to those shown in method 1. In this case, the data appear well described by the form

$$\text{DFI} = b(1 - e^{-aW})$$

forwarded by NRC. In other cases the data are likely to be best described by other functions. For example, data derived from the report of Cole and Chadd (1989) for the food intake of boars from 30 to 90 kg is fitted least well with the NRC form ($a = 0.0185$, $b = 3.49$, s.e. of estimate = 0.082), and most well with the linear form ($a = 1.60$, $b = 0.0218$, s.e. of estimate = 0.026).

Method 2 appears to be a satisfactory means of yielding on-farm food intake estimates, although the collection of the necessary data is a less trivial task than for method 1. Method 2 makes less presumptions than method 1 as both parameters are estimated from the available data, whereas for method 1 at least one of the variables must be provided externally to the data in question.

Construct for models to predict the food intake of growing pigs (20 to 120 kg W)

On-farm estimates of voluntary food intake are not appropriate where a general view of potential, rather than a specific view of actual, food consumption is needed. For this purpose deductive models that explore the outer envelopes to food intake at specific pig weights may be constructed from selection of appropriate algorithms considered in the various sections of this paper. Such models will also be useful: (i) in the estimation of food intake in the absence of any on-farm measurements of total food intake or food intake at particular pig weights, as have been employed in the previous sections, (ii) in the interpretation of on-farm food intake determinations and the identification of likely limiting constraints and (iii) predict pig response to interventions. The pig would be assumed to eat to the full potential of its metabolic requirements, subject to an upper limit imposed on food intake as a result of the limited capacity of the alimentary canal. This upper limit due to gut size would be described first, followed by a description of the metabolic requirements of the pig. The effects of stocking density, environmental conditions and sex can be incorporated into the model as modulators for intake predicted by the two primary controllers.

Conclusion

This analysis suggests that predictions of food intake either from general empirical formulae or from

requirement models may be unsafe for the practical estimation of food intake in particular circumstances. However, the forms of the responses to various factors can be usefully expressed. Such information may be incorporated into alternative methodologies for the practical estimation of food intake from data.

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