Energy value of pig feeds: Effect of pig body weight and energy evaluation system[1]

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ABSTRACT: Ad libitum energy intake and performance in pigs depends on many animal and environmental factors in which feed energy density plays an important role. In addition, feed represents an important cost in pig production, and energy represents the greatest proportion of this cost. It is therefore important to express the feed energy value on an appropriate basis, and both energy supply (a dietary characteristic) and energy requirement (an animal characteristic) should be expressed using the same system. Energy content depends first on the nutrient composition; the constituents differ markedly in GE content (23.0, 39.0, 17.4, and 18.4 kJ/g for CP, fat, starch, and dietary fiber, respectively). Due to differences in digestibility and associated endogenous energy losses, the actual contribution of nutrients to apparent DE supply in growing pigs is even more variable and ranges from 31.7 kJ/g for fat, 22.4 kJ/g for CP, 17.2 kJ/g for starch, to only 3.2 kJ/g for dietary fiber. Nutrient composition also affects the efficiency of conversion of ME to NE, which varies from 90% for fat to 82% for starch and 60% for CP. Consequently, the energy values (relative to a conventional diet containing 14.2, 13.6, and 10.3 MJ/kg of DE, ME, and NE, respectively) of corn, soybean meal, and animal fat are 100, 104, and 235 on a DE basis; 102, 99, and 244 on a ME basis; and 107, 79, and 289 on a NE basis. Energy value thus depends on the system of evaluation. The energy density of pig feeds can also be affected by feed processing. For example, pelleting markedly increases fat and energy digestibilities in corn or full-fat rapeseed. Also the animal itself can affect the energy value of nutrients; digestion of dietary fiber becomes more efficient with increasing BW, with subsequent differences in energy content of feeds according to BW. In conclusion, a satisfactory characterization of the energy value of feeds should be based on their NE content. Factors affecting nutrients digestibility (e.g., BW and feed processing) should also be taken into account.

Key Words: Digestibility, Energy System, Energy Value, Feed, Pig, Technology

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Introduction

Ad libitum energy intake in growing pigs or lactating sows depends on many animal (e.g., BW, genotype, sex, health) and environmental factors (e.g., climate, housing system, pig density, feed characteristics). Although important, these aspects will not be discussed in the present review. Among feed effects, energy concentration of the diet plays a major role in variation in feed intake. The literature suggests that regulation of feed intake depends on energy density, so that the daily energy intake remains relatively constant across diets with different energy densities. However, at low energy densities, energy intake and subsequent growth performance are reduced (Chadd and Cole, 1999; Smith et al., 1999; De la Llata et al., 2001). A major difficulty in the interpretation of these results is the way of expressing energy density. Indeed, evaluation of energy content of pig feeds is usually based on the DE or ME contents. A more accurate estimate of the actual energy value of a feed should be its NE content, which takes into account differences in metabolic utilization of ME between nutrients (Noblet and Henry, 1993). In addition, NE is the only system in which energy requirements and diet energy values are expressed on a same basis, which should theoretically be independent of the feed. The objectives of this review are to analyze the impact of energy evaluation systems on relative energy values of pig feeds. The effects of animal factors (i.e., BW) and, to a lesser extent, feed processing will also be considered as factors of variation in the energy value of pig feeds. Methodological aspects of energy evaluation of pig feeds and definitions have been considered in previous reviews (Noblet and Henry,

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Table 1. Digestibility (%) of fiber fractions and energy in high-fiber ingredients in growing pigs (G) and adult sows (S)[a]

	Wheat bran		Corn bran		Sugar beet pulp	
Item	G	S	G	S	G	S
Digestibility coefficient of:						
Nonstarch polysaccharides	46	54	38	82	89	92
Noncellulose polysaccharides	54	61	38	82	89	92
Cellulose	25	32	38	82	87	91
Dietary fiber[b]	38	46	32	74	82	86
Energy	55	62	53	77	70	76

[a]Adapted from Noblet and Bach-Knudsen (1997).
[b]Dietary fiber = nonstarch polysaccharides + lignin.

1993; Noblet, 1996). Other reviews related to the specific role of dietary fiber (Noblet and Le Goff, 2001) or to comparison of energy systems (Noblet, 2000) can be used for further references.

Energy Utilization

Digestive Utilization

For most pig diets, the digestibility coefficient of energy (**DCe** or DE:gross energy ratio) varies between 70 and 90%, but the variation is larger for feed ingredients (0 to 100%; Sauvant et al., 2002). Most of the variation of DCe is related to the presence of dietary fiber (**DF**; defined as the sum of nonstarch polysaccharides and lignin), which is less digestible than other nutrients (<50% vs. 80–100% for starch, sugars, fat, or protein; Table 1) and decreases the apparent fecal digestibility of other dietary nutrients, such as crude protein and fat (Noblet and Perez, 1993; Le Goff and Noblet, 2001). Consequently, DCe is linearly and negatively related to the DF content of the feed (Table 2). The coefficients relating DCe to NDF are such that NDF or DF essentially dilute the diet, resulting in a lower DE content. In other terms and as quantified in Table 3, even though DF is partly digested by the young growing pig, it provides very little DE to the animal. The addition of DF is thus an efficient method for decreasing the energy density of diets. In contrast, due to its high gross energy content and its high digestibility (>80%), the DE content of fat is high and fat is the most efficient solution to increase energy density in pig diets. At least on a DE basis, energy density then mainly depends on fat and DF contents, since the other nutrients have relatively similar effects on DE content.

The digestive utilization of DF varies with its botanical origin (Table 1; Chabeauti et al., 1991) with subsequent variable effects of DF on dietary energy digestibility (Noblet, 2000). The DCe prediction equations presented in Table 2 represent, therefore, average equations for mixed feeds. They should not be applied to raw materials where specific relationships are to be used (Noblet and Henry, 1993; Noblet and Le Goff, 2001; Noblet et al., 2003a).

Digestibility of energy can be slightly modified by the addition of exogenous enzymes (Partridge, 2001) and more importantly by technological treatments. Pelleting, for instance, increases the energy digestibility of feeds by about 1% (Skiba et al., 2002). However, for some feeds, the improvement can be more important and depends on the chemical and physical (particle size) characteristics of feeds. The examples given in Table 4 show that the improvement in energy digestibility was mainly due to an improved digestibility of fat provided by corn or full-

Table 2. Effect of diet composition (g/kg of DM) on energy digestibility (DCe, %), ME:DE coefficient (%), and efficiency of utilization of ME for NE of mixed diets for growth (k_g, %) and for maintenance (k_m, %)[a]

Equation	RSD[b]	Source[c]
[1] DCe = 98.3 − 0.090 × NDF	2.0	1
[2] DCe = 96.7 − 0.064 × NDF	2.2	1
[3] ME/DE = 100.3 − 0.021 × CP	0.5	1
[4] k_g = 74.7 + 0.036 × EE + 0.009 × ST − 0.023 × CP − 0.026 × ADF	1.2	2
[5] k_m = 67.2 + 0.066 × EE + 0.016 × ST	1.9	3

[a]CF = crude fiber, CP = crude protein, NDF = neutral detergent fiber, EE = ether extract, ST = starch, ADF = acid detergent fiber.
[b]Residual standard deviation.
[c]1) Le Goff and Noblet (2001; n = 77 diets; Eq. [1] and [3] in 60-kg growing pigs and Eq. [2] in adult sows, respectively); 2) Noblet et al. (1994a; n = 61 diets; 45-kg pigs); 3) Noblet et al. (1993b; n=14 diets; maintenance-fed adult sows).

Table 3. Contribution of dietary nutrients to energy supply in growing pigs (kJ/g)[a]

Item	CP	Fat	Starch	Sugars	Residue	RSD, %[b]
Gross energy	22.6	38.8	17.5	16.7	18.6	0.5
Digestible energy	22.5	31.8	18.3	16.1	0.5	2.8
Metabolizable energy	19.7	32.2	18.2	15.9	0.5	2.8
Net energy	11.8	28.9	14.8	11.5	-0.9	3.4

[a]From recalculations of data of Noblet et al. (1994a); measurements were conducted on 61 diets fed to 45-kg pigs and coefficients are obtained from multiple linear regression equations (without intercept). Residue corresponds to the difference between organic matter and the sum of CP, fat, starch, and sugars.

[b]Residual standard deviation.

fat rapeseed. Consequently, the energy values of these ingredients depend greatly on the technological treatment. In the specific situation of high-oil corn (7.5% oil), pelleting increased the DE content by approximately 0.45 MJ/kg (Noblet and Champion, 2003); for coarsely ground full-fat rapeseed, the DE values were 10.0 and 23.5 MJ DE/kg DM as mash and after pelleting, respectively (Skiba et al., 2002).

Energy digestibility is affected by factors other than those related to the diet itself. In growing pigs, DCe increases with increasing BW (Noblet and Shi, 1994; Noblet et al., 2003a). The largest effect of BW is observed when adult sows and growing pigs are compared (Noblet and Shi, 1993; Le Goff and Noblet, 2001). In addition, the difference due to BW increase is most pronounced for high-fiber diets or ingredients (Eq. [1] and [2] in Table 2; Table 5). This improvement in energy digestibility with increasing BW is due to the greater digestibility of the DF fraction (Table 1) related to a greater hindgut digestive capacity in heavier pigs and, more importantly, a slower rate of passage in the digestive tract (Le Goff et al., 2002a). The attenuated negative effects of DF on protein and fat digestibility (i.e., reduced endogenous losses) also contribute to the reduced effect of DF on DCe in adult pigs. Therefore, the negative effect of dietary fiber on DCe becomes smaller for heavier pigs or adult sows (Table 2) and the contribution of DF to energy supply becomes largely positive in heavier pigs. From a large data set of measurements (77 diets), Le Goff and Noblet (2001) calculated that 1 g of NDF provided 3.4 and 6.8 kJ in 60-kg growing pigs and mature sows, respectively; the contribution of the other nutrients to DE supply did not differ between both groups of pigs. Mainly because of the slower rate of passage of digesta in the hindgut and a subsequent higher fermentation capacity, adult pigs can degrade nutrients more completely. The DE difference between adult sows and growing pigs is then proportional to the amount of indigestible organic matter as measured in the growing pig (4.2 kJ/g on average; Noblet et al., 2002, 2003a).

The DCe or the DE differences between sows and growing pigs, for a given level of dietary fiber, also depend on the origin of DF or on the physicochemical properties of DF. This is illustrated in Table 1, in which the effects of DF from wheat bran, corn bran, and sugar beet pulp are compared. Detailed information on the effect of origin of DF on DCe in both growing pigs and adult sows has been given by Noblet and Le Goff (2001). These results indicate that growing pigs have a limited ability to digest DF, with small differences between fiber sources, whereas adult sows digest DF more efficiently but the improvement depends on the chemical character-

Table 4. Effect of pelleting and particle size on digestibility coefficient (%) of fat and energy in growing pigs

Item	Mash	Pellet
Corn-soybean meal diets[a]		
Fat	61	77
Energy	88.4	90.3
Wheat–soybean meal–full-fat rapeseed diets[b]		
Fat	27	84
Energy	73.1	87.4
Wheat–soybean meal–full-fat rapeseed diets[c]		
Fat	81	86
Energy	85.5	87.6

[a]Mean of three diets containing 81% corn and 15.5% soybean meal (Noblet and Champion, 2003).

[b]One diet containing (as-fed basis) 60% wheat, 15% soybean meal, and 20% full fat rapeseed; rapeseed was coarsely ground (Skiba et al., 2002).

[c]One diet containing (as-fed basis) 60% wheat, 15% soybean meal and 20% full fat rapeseed; rapeseed was finely ground (Skiba et al., 2002).

Table 5. Digestible energy value of some ingredients for growing pigs and adult sows[a]

	DE, MJ/kg[b]		
Ingredient	Growing pig	Adult pig	a[c]
Wheat	13.85	14.10	3.0
Barley	12.85	13.18	2.5
Corn	14.18	14.77	7.0
Pea	13.89	14.39	6.0
Soybean meal	14.73	15.61	8.0
Rapeseed meal	11.55	12.43	3.5
Sunflower meal	8.95	10.25	3.5
Wheat bran	9.33	10.29	3.0
Corn gluten feed	10.80	12.59	7.0
Soybean hulls	8.37	11.46	8.0

[a]Adapted from Sauvant et al. (2002).

[b]As-fed basis.

[c]Difference (kJ) in DE between adult sows and growing pigs per gram of indigestible organic matter in the growing pig (Noblet et al., 2002, 2003a).

istics of DF (e.g., level of lignin). The examples presented in Table 5 also illustrate the effect of botanical origin, with small differences between physiological stages for Graminae (wheat, barley, wheat bran), Brassicaceae (rapeseed), or Compositae (sunflower) and more pronounced differences for Leguminosae (pea, soybean, lupin), especially for the hull fraction of these grains. Corn (and corn bran) is rather specific since its fiber fraction is poorly digested in young growing pigs and highly digested in heavier animals (Noblet and Bach-Knudsen, 1997). The consequence is that the DE difference between adult sows and growing pigs is proportional to indigestible organic matter in growing pigs, but with specific coefficients for each (botanical) family of ingredients (Table 5).

Recent results indicate that DCe in sows is little affected by feeding level (Noblet et al., 2003a), which means that values obtained in pregnant sows fed approximately 2.5 kg/d can be extrapolated to lactating sows offered feed ad libitum. An indirect comparison between lactating sows fed above 5 kg/d and pregnant sows fed 2.4 kg/d suggests the same conclusion (Noblet et al., 2003a). Little information concerning comparative digestibility in piglets and growing pigs is available. Considering that piglets are usually fed low-fiber diets for which the effect of BW is minimized, piglets can, from a practical point of view, be considered as growing pigs concerning the digestive utilization of energy.

A consequence of the changes of DCe with BW is that digestibility trials should be carried out at approximately 60 kg BW (Noblet, 1996; Noblet et al., 2003a) in order to be representative of the total growing-finishing period. A second consequence is that at least two DE values should be given to feeds: one for growing pigs and one for adult sows (Table 5). This proposal is more justified for fibrous ingredients. In addition, the technological treatment may affect energy digestibility for some ingredients. Consequently, the relative energy density of pig feeds depends first on the chemical composition, but the hierarchy can be changed according to BW and feed processing, including particle size and pelleting. In addition, an interaction between particle size and pelleting may be observed (Table 4).

ME:DE Ratio

The ME content of a feed is the difference between DE and energy losses in urine and gases (i.e., as methane and hydrogen). In growing pigs, average energy loss in methane is equivalent to 0.4% of DE intake (Noblet et al., 1994a). In sows fed at maintenance level, methane production represents a much greater proportion of DE intake (1.5%; Noblet and Shi, 1993) and may reach up to 3% of DE intake in sows fed very high-fiber diets (Ramonet et al., 2000). More generally, methane production increases with BW and DF level in the diet (Noblet and Shi, 1993; Bakker, 1996; Jorgensen et al., 2001). From the compilation of literature data conducted by Le Goff et al. (2002a) and unpublished data from our laboratory, Noblet et al. (2002) suggested that methane energy is equivalent to 0.67 and 1.33 kJ per gram of fermented DF in growing pigs and adult sows, respectively. Unlike humans, hydrogen production in pigs is rather low and can be neglected.

Energy loss in urine represents a variable percentage of DE since urinary energy depends greatly on the urinary nitrogen excretion. At a given stage of production, urinary nitrogen excretion depends mainly on the (digestible) protein content of the diet. Consequently, the ME:DE ratio is linearly related to the dietary protein content (Table 2). In most situations, the ME:DE ratio of complete feeds is approximately 0.96. However, this mean value cannot be applied to single feed ingredients (Noblet et al., 1993a) and Eq. [3] in Table 2 cannot be applied beyond the range of typical CP contents of pig diets (10 to 25%) and is therefore not applicable for most ingredients. The most appropriate solution is then to estimate urinary energy (kJ/kg DM intake) from urinary nitrogen (g/kg DM intake). The following equations have been proposed:

$$\text{Urinary energy in pigs} = 192 + 31 \times \text{urinary nitrogen}$$
$$\text{Urinary energy in sows} = 217 + 31 \times \text{urinary nitrogen}$$

for growing pigs and adult sows, respectively. The residual standard deviation of both equations was 54 kJ. For implementing these equations to feed ingredients, it can be assumed that urinary nitrogen represents 50% of digestible nitrogen (Noblet et al., 2002).

Metabolic Utilization of ME

Net energy is defined as ME minus heat increment associated with the metabolic utilization of ME and with the energy cost of ingestion, digestion, and some physical activity. It is generally calculated as the sum of (estimated or measured) fasting heat production and retained energy (Noblet and Henry, 1993). The NE content, as a percentage of ME content (k) corresponds to the efficiency of utilization of ME for NE (Noblet et al., 1994a). Apart from variations due to the final utilization of ME (e.g., maintenance, protein gain vs. fat gain vs. milk production), k varies according to the chemical characteristics of the feed because nutrients are not used with the same efficiencies. Nevertheless, the ranking of nutrients for a specific function appears relatively constant; the energetic efficiency increases with the addition of dietary fat and starch and decreases with the addition of fiber and protein (Noblet et al., 1993b, 1994a,b). The variations in k are due to differences in efficiencies of ME utilization between nutrients with the highest values for fat (approximately 90%) and starch (approximately 82%) and the lowest (approximately 60%) for DF and crude protein. These values were confirmed in recent trials (van Milgen et al., 2001; J. van Milgen and J. Noblet, unpublished data). These differ-

Table 6. Energy value of starch, crude protein, and fat according to energy systems[a]

Item	Starch	Crude protein[b]	Crude fat[b]
Energy values, kJ/g[b]			
Digestible energy	17.5 (100)	20.6 (118)	35.3 (202)
Metabolizable energy	17.5 (100)	18.0 (103)	35.3 (202)
Net energy	14.4 (100)	10.2 (71)	31.5 (219)
Heat production, kJ/g	3.1	7.8	3.8

[a]Adapted from Noblet et al. (1994a; n = 61 diets).
[b]In parentheses, energy values as percentage of starch; crude protein, and crude fat are assumed to be 90% digestible; starch is 100% digestible.

ences in efficiencies between nutrients also mean that heat increment (per unit of energy) associated with metabolic utilization of energy is higher for crude protein and DF than for starch or ether extract (Noblet et al., 1994a; Table 6). Finally, NE measurements conducted in pigs that differ for their BW and the composition of BW gain suggest that the efficiency of ME for NE is little affected by the composition of BW gain, at least under most practical conditions (Noblet et al., 1994b).

The comparison of our results on ME utilization with literature data and the practical consequences on energy evaluation system have been reviewed by Noblet (1996; 2000). They have also been validated in recent experiments conducted in our laboratory (Ramonet et al., 2000; Le Bellego et al., 2001; Noblet et al., 2001; van Milgen et al., 2001). They confirm that the increase of dietary crude protein results in increased heat production (**HP**; Table 7). On the other hand, the inclusion of fat contributes to reduction of HP. Diets with low crude protein and/or high fat contents can then be considered as low heat increment diets and are potentially better tolerated under conditions of heat stress (Renaudeau et al., 2001; Le Bellego et al., 2002). However, the effect of DF on HP remains unclear. In some trials, HP is significantly increased when DF is increased (Noblet et al., 1989; Noblet et al., 1993b, 1994a; Ramonet et al., 2000; Solund Olesen et al., 2001; Rijnen et al., 2003), whereas in other trials HP remains constant or even decreases (Rijnen et al., 2001; Le Goff et al., 2002b,c). From a biochemical perspective, HP should increase and most results are consistent with this. However, the addition of DF may change the behavior of animals (i.e., reduced physical activity) or the overall metabolism, thereby decreasing HP (Schrama et al., 1998). Furthermore, the effects of DF probably also depend on the nature of DF, and the specific effect of sugar beet pulp DF (Rijnen et al., 2001) cannot be generalized to other DF sources. Differences in the design of trials and limits of methodologies may also explain these discrepancies. Finally, another interesting aspect illustrated in the results of van Milgen et al. (2001) concerns the HP associated with the utilization of dietary protein either for protein deposition or for lipid deposition. The data show that the heat increment associated with both pathways is similar and efficiencies are equivalent. From a practical point of view, this means that the NE value of dietary CP is constant, irrespective of its final utilization.

Energy Systems

Digestible and Metabolizable Energy

Apart from direct measurement on pigs, the DE value of raw materials can be obtained from feeding tables

Table 7. Energy utilization of low-protein diets

Item	Trial 1[a]		Trial 2[b]	
Crude protein (as-fed basis), %	17.4	13.9	21.9–17.4	17.2–12.7
Digestible lysine, g/MJ NE	0.76	0.76	1.05–0.72	1.05–0.72
Energy balance, MJ/kg BW$^{0.60}$				
ME intake	2.46	2.46	2.57	2.57
Heat production	1.42[x]	1.37[y]	1.40[x]	1.34[y]
Energy retained	1.05[x]	1.09[y]	1.17[x]	1.23[y]
ME/DE, %	95.5[x]	96.7[y]	95.7[x]	96.7[y]
NE/ME, %	73.2[x]	75.3[y]	73.9[x]	75.9[y]

[a]From Le Bellego et al. (2001) and Noblet et al. (2001); 65-kg pigs; wheat, corn, and soybean meal-based diets; the low-protein diet was supplemented with HCl-lysine (0.43%), methionine (0.11%), threonine (0.16%), tryptophan (0.05%), isoleucine (0.04%), and valine (0.09%); indirect calorimetry method was used for measuring heat production.
[b]From Noblet et al. (2003b); in 25-, 55-, and 85-kg pigs; wheat, corn and soybean meal-based diets; indirect calorimetry method was used for measuring heat production. Values for CP and lysine levels are given for the 25- and 85-kg pigs; values at 55 kg were intermediate.
[x,y]Within trial, values with different superscripts differ ($P < 0.05$).

Table 8. Equations for prediction of DE in adult sows (DEs) from DE in 65-kg growing pigs (DEg), MJ/kg of dry matter

Item	Equation	RSD	Source[a]
Mixed feeds	DEs = 4.37 + 0.742 × DEg	0.24	1
Wheat products	DEs = 2.68 + 0.860 × DEg	0.37	2
Corn products	DEs = 17.43 − 0.892 × DEg + 0.0527 × DEg^2	0.31	2
Soybean products	DEs = 7.31 + 0.615 × DEg	0.31	3

[a]1) Le Goff and Noblet (2001); n = 77 diets; 2) Noblet and Le Goff (2000); n = 9 samples for wheat products and for corn products; 3) J. Noblet, unpublished data (n = 7 samples).

(NRC, 1998; Sauvant et al., 2002), but using these tabulated values should be restricted to ingredients having similar chemical characteristics. The effect of variations in chemical composition can be taken into account by using prediction equations of DCe or DE content of families of ingredients (Noblet et al., 2003a).

As illustrated in the previous section, DCe is affected by BW of the animals. It is therefore appropriate to use DE values adapted to each situation. However, from a practical point of view, only two DE values are suggested, one for "60-kg" pigs, which can be applied to piglets and growing-finishing pigs, and one for adult pigs applicable to both pregnant and lactating sows. Values given in feeding tables are typically obtained in the 40- to 60-kg pig. Equations can be proposed to estimate DE for adult sows from (measured) DE in growing pigs but only for a few families of ingredients (Table 8). A complete methodology based on the fact that the difference in DE between adult and growing pigs is proportional to the amount of indigestible organic matter in the growing pig has been proposed by Noblet et al. (2003a) for estimating DE values in adult pigs from DE values in growing pigs; a complete set of DE values in adult pigs for most ingredients has been proposed by Sauvant et al. (2002). Some of these are presented in Table 5.

The DE content of compound feeds can be obtained by adding the DE contributions of ingredients and assuming no interaction, which is usually the case (Noblet and Shi, 1994; Noblet et al., 2003a). When the actual composition of the feed is unknown, the possibility is to use prediction equations based on chemical criteria (Noblet and Perez, 1993; Le Goff and Noblet, 2001) or estimates from near infrared or in vitro methods (Boisen and Fernandez, 1997; Jaguelin-Peyraud and Noblet, 2003). In all equations or predictions, DF has an important impact on the accuracy of the prediction. As pointed out in the above sections, the main limitation of these equations is the inability to consider the nature of DF and, to a smaller extent, the composition of fat. For these reasons, such equations cannot be used for feed ingredients.

The approaches for predicting the ME value of pig feeds are similar to those described for DE. However, since direct ME measurements are not carried out routinely, tabulated values have been calculated from DE values with either a constant ME:DE ratio or, preferably, related to the protein content of the feed (Noblet et al., 2002).

Net Energy

All published NE systems for pigs combine the utilization of ME for maintenance and for growth (Just, 1982; Noblet et al., 1994a,b) or for fattening (Schiemann et al., 1972) by assuming similar efficiencies for maintenance and energy retention. The system used in the Netherlands (CVB, 1994) has been adapted from the equations proposed by Schiemann et al. (1972). The "system" used by NRC (1998) for estimating NE values combines results from direct measurements using a questionable animal model (piglet) and estimates from prediction equations. The available NE systems have been described by Noblet (1996, 2000). More recently, Boisen and Verstegen (1998) proposed new concepts for estimating the NE value of pig feeds (so-called physiological energy) and based on the combination of in vitro digestion methods for estimating digestible nutrients and biochemical coefficients for evaluating the ATP potential production from the nutrients. Complementary and theoretical knowledge concerning endogenous secretions could also be included in this approach. Apart from difficulties for implementing the in vitro digestion methods, this approach assumes that energy is used exclusively for ATP production—which is not the case in growing pigs, for instance. Absolute values appear not consistent with standard values for energy requirements, and uncertainties concerning the (theoretical) ATP yield exist (van Milgen, 2002).

The system proposed by Noblet et al. (1994a) is based on a large set of measurements (61 diets). These results have been validated in recent trials (Le Bellego et al., 2001; Noblet et al., 2001; van Milgen et al., 2001) and its applicability for predicting performance of animals has been demonstrated (see last section). The equations used for predicting NE are given in Table 9. They are all based on information available in conventional feeding tables and are applicable to single ingredients and compound feeds and at any stage of pig production. It has also been demonstrated that these equations can determine a correct hierarchy among feeds for both growing pigs and pregnant or lactating sows. It is important to point out that different DE values or digestible nutrient contents should be used in growing-finishing pigs and adult sows with two subsequent NE values. Reliable information on the digestibility of energy or of nutrients is then necessary for the prediction of NE content of

Table 9. Equations for prediction of net energy in feeds for growing pigs (NEg; MJ/kg dry matter; composition as g/kg of dry matter)

Equation[a]	RSD, %	Source[b]
NEg2a = 0.0113 × DCP + 0.0350 × DEE + 0.0144 × ST + 0.0000 × DCF + 0.0121 × DRes	2.0	1
NEg2b = 0.0121 × DCP + 0.0350 × DEE + 0.0143 × ST + 0.0119 × SU + 0.0086 × DRes	2.4	2
NEg4 = 0.703 × DE − 0.0041 × CP + 0.0066 × EE − 0.0041 × CF + 0.0020 × ST	1.7	1
NEg7 = 0.730 × ME − 0.0028 × CP + 0.0055 × EE − 0.0041 × CF + 0.0015 × ST	1.6	1

[a]CF = crude fiber, CP = crude protein, EE = ether extract, ST = starch, DCP = digestible CP, DEE = digestible EE, DCF = digestible CF, DRes = digestible residue (i.e., difference between digestible organic matter and other digestible nutrients considered in the equation). The NEg suffix corresponds to the equation number, as given by Noblet et al. (1994a).
[b]1: Noblet et al. (1994a); 2: Noblet et al. (2002).

pig feeds. In fact, this information represents the most limiting factor for predicting energy values of pig feeds.

Comparison of Energy Systems

DE, ME, and NE systems

From the equations reported in Tables 2 and 9, it is obvious that the hierarchy between feeds obtained in the DE or ME systems will vary in the NE system according to the specific chemical composition. Since NE represents the best compromise between the feed energy value and energy requirement of the animal, the energy value of protein or fibrous feeds will be overestimated when expressed on a DE (or ME) basis. On the other hand, fat or starch sources are underestimated in a DE system. These conclusions are more clearly demonstrated in Table 10 for a series of ingredients: high fat (animal or vegetable fat, oil seeds) or high starch (tapioca, cereals) ingredients are penalized in the DE system, whereas protein rich and/or fiber rich (meals, fibrous byproducts) ingredients are favored. For mixed ingredients, the negative effect of protein or fiber (i.e., protein sources) on efficiency of DE for NE is partly counterbalanced by the positive effect of starch or fat (i.e., energy sources).

Net Energy Systems

As explained above, several equations (and therefore systems) for prediction of NE of feeds are available (Schiemann et al., 1972: **NEs**; Just, 1982: **NEj**; Noblet et al., 1994a: **NEg**; CVB, 1994: **NEnl**). The proposal of NRC (1998) cannot really be considered as a system. These systems were established according to different hypotheses and under different experimental conditions. Therefore, different NE systems do not provide interchangeable estimates (Noblet, 1996), and the NE value depends on the choice of the system. For comparing these NE systems, the measured NEg values of 61 diets (Noblet et al., 1994a) have been compared to their calculated NEs, NEj; and NEnl values. Comparison with the system proposed by Boisen and Verstegen (1998) was not possible at this stage.

If we consider NEg as the 100 basis, average NEs, NEj, and NEnl are equivalent to about 94, 83, and 96.

Table 10. Relative digestible, metabolizable, and net energy values (as-fed basis) of some ingredients for growing pigs[a]

	Sauvant et al. (2002)				NRC (1998)
Item	DE	ME	NE	NE/ME (×100)	NE/ME (×100)[b]
Animal fat	243	252	300	90	64
Tapioca	101	103	110	81	NA
Corn	103	105	112	80	70
Rapeseed (full-fat)	160	162	168	78	NA
Wheat	101	102	106	78	72
Barley	94	94	96	77	80
Diet	**100**	**100**	**100**	**75**	NA
Pea	101	100	98	73	68
Soybean (full-fat)	116	113	108	72	NA
Wheat bran	68	67	63	71	61
Soybean meal	107	102	82	60	61
Rapeseed meal	84	80	64	60	61
Amino acids mixture	148	142	146	78	NA

[a]Within each system, values are expressed as percentages of the energy value of a diet containing (as-fed basis) 67.4% wheat, 16% soybean meal, 2.5% fat, 5% wheat bran, 5% peas, 4% minerals and vitamins and 0.10% of HCl-lysine; the so-called amino acids mixture contains 50% HCl-lysine, 25% threonine, and 25% methionine.
[b]NA = not available.

Table 11. Energy requirements of ad libitum fed growing-finishing pigs according to energy evaluation system)[a]

Item	Diet 1	Diet 2
Diet composition (as-fed basis), %		
Crude protein	18.8	14.5
Starch	45.9	50.9
Fat	2.5	2.6
Energy intakes, MJ/d		
DE	38.9[a]	37.3[b]
ME	37.1[a]	36.1[b]
NE	27.6	27.5
Nitrogen excretion, g/kg BW gain	50.2[a]	30.9[b]

[a]Performance was measured between 30 and 100 kg at a temperature of 22°C; energy intakes are adjusted by covariance analysis for similar BW gain (1,080 g/d) and carcass composition at slaughter; diets had the same ratio between digestible lysine and NE (0.85 and 0.70 g/MJ in the growing and finishing periods, respectively) and the ratios between essential amino acids and lysine were above recommended values; diet composition values represent the mean of the growing diet and the finishing diet. Adapted from Le Bellego et al. (2002).

As explained by Noblet (1996, 2000), these average differences are mainly due to differences in estimates of the fasting heat production. However, this ratio also depends on diet composition. It is slightly decreased for NEs and NEnl when dietary starch content is increased, which means that starch sources are underestimated according to these systems. However, both NEg and NEnl provide relatively consistent energy values. With regard to NEj, the NEj/NEg ratio is decreased when starch and fat levels are increased and increased for higher levels of crude protein or dietary fiber. It can then be considered that the NEj system is close to a ME system. For this reason, it is progressively being abandoned in Denmark. Finally, recent trials in which NE value of pig diets has been measured in growing pigs (van Milgen et al., 2001; Le Bellego et al., 2001; Noblet et al., 2001; Le Goff et al., 2002c; Noblet et al., 2003b) or in adult sows (Le Goff et al., 2002b) confirm the accuracy of the NEg system since measured NE values and predicted values according to equations presented in Table 9 were very similar. The comparison with values published by NRC (1998) cannot be as complete. However, data in Table 10 indicate that the NE/ME values provided by NRC (1998) for a limited number of ingredients are not consistent with those presented by Sauvant et al. (2002) and calculated according to the equations of Noblet et al. (1994a). The most problematic situation in NRC values concerns fat sources, which are markedly underestimated.

Energy Systems and Performance

In diet formulation, chemical and ingredient composition of diets for growing-finishing pigs and reproductive sows is manipulated in order to achieve: 1) a minimum level of recommended dietary energy, 2) minimum ratios between lysine and energy, and 3) minimum ratios between essential amino acids and lysine (i.e., ideal protein). These criteria are more relevant to the characteristics of the animal (i.e., BW, genotype, physiological stage) or, in other terms, the nutritional requirements. The expression of nutritional values of feeds should be as consistent as possible with the expression of nutrient requirements. From that point of view, the most consistent expression of energy value and energy requirements is theoretically based on NE. In addition, apart from minimizing the cost of diets, an objective such as minimizing heat dissipation (in heat stressed animals, for instance) can be met when formulating on a NE basis. More generally, the quality of a nutritional evaluation system is given by its ability to predict the performance of the animals and independently of the diet composition (or specific effects of nutrients). The data presented in Tables 11 and 12 illustrate the relationship between energy system and performance and confirm that NE as calculated according to Noblet et al. (1994a, 2002) is a better predictor of performance than DE or ME. In other words, the NE value is a satisfactory estimate of the energy value of feeds. On the other hand, DE or ME systems overestimate the energy value of high-CP diets and underestimate the energy value of fat-rich diets.

Table 12. Performance of ad libitum fed growing-finishing pigs according to dietary fat supplementation: Comparison of energy systems[a]

	Performance	Relative performance			
Fat supplementation, %	0	0	2	4	6
Feed intake (as-fed basis), g/d	2200	100	97.3	97.7	94.1
ME intake, MJ/d	29.7	100	100.0	103.3	102.1
NE intake, MJ/d	22.5	100	100.6	104.3	103.6
BW gain, g/d	737	100	100.5	105.7	106.1
Feed to BW gain					
kg/kg	2.98	100	96.6	92.3	88.9
MJ ME/kg	40.2	100	99.6	97.8	96.5
MJ NE/kg	30.4	100	100.1	98.8	97.9

[a]Between 36 and 120 kg BW; in three successive periods; at each period, the protein:energy ratio (digestible lysine to NE) was the same for all diets; the protein:energy ratio decreased over successive periods. Protein and energy values of diets (corn/soybean meal/choice white grease) were calculated according to Sauvant et al. (2002). Adapted from De la Llata et al. (2001).

In the specific case of low-protein diets, which are more and more recommended in order to reduce the impact of pig production on the environment (Le Bellego et al., 2002; Table 7), it is clear that their energy value is underestimated when formulated on a DE or ME basis. This may explain the tendency of fatter carcasses when low-protein diets are formulated on a DE basis: animals are in fact getting more energy than expected from DE supply (Table 11). This also illustrates the importance of formulation criteria for interpreting performance results and the risks of manipulating the composition of diets according to inaccurate or inappropriate nutritional criteria. The use of ileal digestible (or available) amino acids and NE are then highly recommended.

Conclusions

In this review, we have demonstrated that energy density can be measured according to different criteria (DE, ME, or NE) and different systems for each criterion. The most advanced and practically applicable energy evaluation system appears the NE system proposed by Noblet et al. (1994a), for which energy values of most ingredients used in pig diets are available (Sauvant et al., 2002). In addition, these authors have proposed energy values that are different for growing and adult pigs. Technological treatment can also affect the energy value. Unfortunately, current information is insufficient to take this systematically into consideration. This review also indicates that the relative energy density or the hierarchy between ingredients depends first on the energy system (DE vs. ME vs. NE) with considerable variation between ingredients or compound feeds when either fat or crude protein content deviates from values in standard diets. The relative energy density when expressed on a NE basis also depends on the system with a relatively satisfactory agreement between NEnl and NEg. The hierarchy obtained in the first proposals of Boisen and Verstegen (1998) appears also relatively close to the hierarchy in the NEnl and NEg systems, but the absolute values are totally different and not expressed according to recommendations for requirements known to most nutritionists. Refinement of the latter system is necessary.

Significant improvements in prediction of energy value of pig feeds will come from the improved knowledge of energy and nutrients digestibility, which depend on chemical characteristics of the feed, (bio)technological treatments, animal factors (body weight), and interactions between these factors. Because DF is the main factor of variation of digestive utilization of the diet, more emphasis should be given to routine techniques that identify the nutritional and physiological “quality” and the role of DF. Improving feed evaluation systems will eventually consist in using more mechanistic approaches based on a nutrient supply (i.e., glucose, amino acids, etc.), which are used for meeting requirements for ATP, protein synthesis, and fat synthesis by the animal. Modeling approaches are then essential for describing both digestion of nutrients and metabolic utilization of nutrients. Energy value (expressed as a caloric value) will then become an auxiliary variable of the model.

Implications

This review shows that a satisfactory characterization of the energy value of feeds for pigs should be based on NE content. It provides a hierarchy between feeds that differs markedly from the hierarchy obtained in DE or ME systems. As different NE systems exist, it is important that feed values and animal requirements are obtained from the same NE system. Criteria for an appropriate NE system are discussed. It is also proposed to use energy values that differ according to pig body weight; the most important consequence concerns adult sows that digest the dietary fiber fraction of the feed more efficiently than growing pigs. Finally, feed processing (e.g., grinding and pelleting) affects markedly the digestibility of energy and fat. These effects should be considered when attributing energy values to diets or making technical or economical decisions for technological treatments.

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