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Comparative total tract digestibility of dietary energy and nutrients in growing pigs and adult sows[1]

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ABSTRACT: Seventy-seven diets were fed to 61-kg growing pigs at a feeding level close to their ad libitum intake and to nonlactating, nonpregnant sows slightly above their maintenance energy level (2.4 kg/d). The main objectives of this study were to compare the total tract digestibility of dietary energy or nutrients of the 77 diets in growing pigs and adult sows and to analyze the effect of diet chemical composition on total tract digestibility in both groups of pigs. Diets were formulated to represent a range of chemical compositions as large as those found in most practical situations. The DE and ME values and total tract digestible nutrient contents of diets were measured for each group of animals; each diet was measured in four to five animals per group, and collection of urine and feces lasted 10 d. The results were used to establish equations for predicting DE and ME values, total tract digestible nutrient contents, and total tract digestibility coefficients of energy from chemical characteristics for each group of animals. The results show that the total tract digestibility of energy or nutrients was higher ($P < 0.01$) in adult sows than in growing pigs; the total tract digestibility coefficients of energy, crude protein, ether extract, and NDF averaged 85.2, 85.1, 37.1, and 64.4%, respectively, for sows and 82.1, 80.3, 31.6, and 56.3%, respectively, for growing pigs. The ME/DE ratio was lower ($P < 0.01$) in sows (94.8%) than in growing pigs (96.5%), as a result of higher urinary energy losses in sows. The difference in DE values (on average, 0.6 MJ/kg of DM) between adult sows and growing pigs was not constant ($P < 0.01$) but increased with dietary fiber content (3.3, 8.6, and 10.1 kJ for each gram of NDF, ADF, and crude fiber increase in the diet, respectively), which suggests that the origin of the difference between the two physiological stages is mainly due to a higher rate of degradation of dietary fiber in the hindgut of sows. The DE and ME values could be accurately predicted from total tract digestible nutrients or from chemical characteristics for each physiological stage. Equations for predicting urinary energy loss from urinary N are also proposed. From a practical point of view, it is suggested to use two energy values for pig feeds: one applicable to growing-finishing pigs and one to adult sows. Equations for predicting DE in adult sows from energy values obtained in growing pigs are proposed.

Key Words: Digestibility, Energy Value, Fiber, Pigs, Prediction, Sows

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Introduction

The total tract digestibility of dietary energy or nutrients in pigs can be influenced by the characteristics of the feed (chemical composition and processing treatment), by animal factors (BW, sex, physiological stage, and genotype), and by the experimental procedures (method of measurement and feeding level). For instance, total tract digestibility coefficients of nutrients and energy are improved with increased BW, the largest effect of BW being observed when adult sows and growing pigs are compared (Fernandez et al., 1986). But the extent of the effect of BW depends on chemical characteristics of the diet, with larger differences observed when fiber content is increased (Noblet and Shi, 1994). The improvement of energy digestibility with BW also depends on the nature or botanical origin of dietary fiber (Noblet and Bach Knudsen, 1997). Consequently, the energy value of diets or ingredients changes according to the type of animal fed, with differences depending on the amount and the origin of dietary fiber. Another concern is the energy values reported in feeding tables. It can be assumed that these have been mostly obtained in growing pigs and are therefore applicable only to that stage of pig

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production. However, in practical feed formulation, these tabulated values are applied at all stages of pig production with probable underestimation of energy values for adult sows. To overcome this bias, Noblet (1996) suggested using two energy values: one for growing-finishing pigs and one for adult sows.

The objectives of this study were 1) to compare the total tract digestibility of dietary energy or nutrients of 77 diets in growing pigs and adult sows, 2) to analyze the effect of diet chemical composition on total tract digestibility values in both groups of pigs, and 3) to calculate prediction equations of DE and ME values of mixed diets from their chemical characteristics for each group of pigs and equations for predicting DE in adult sows from DE in growing pigs.

Materials and Methods

A total of 16 digestibility trials were conducted between 1994 and 2000 using both 60- to 65-kg BW growing pigs and adult sows under similar experimental conditions. A total of 77 diets were measured in both groups of pigs. Care and use of animals were performed according to the Certificate of Authorization to Experiment on Living Animals, no. 04739 (issued by the French Ministry of Agriculture to J. Noblet, Head of Research Unit).

Diets. The inclusion levels of ingredients and the mean chemical composition of the 77 diets used in the experiment are presented in Tables 1 and 2, respectively. Most diets were prepared in order to calculate total tract digestibility coefficients of nutrients and DE and ME values of ingredients according to the difference method (Noblet and Shi, 1994). Preliminary reports on nutritional value of some feedstuffs have been presented by Noblet and Bourdon (1997), Noblet et al. (1998), and Noblet and Le Goff (2000). Sixteen diets corresponded to the basal diet of each of the 16 digestibility trials and were prepared from a cereal only or a combination of one cereal and soybean meal. Fifty-two diets contained one or two ingredients combined with the basal diet. Most ingredients are commonly used feedstuffs. However, some unconventional fibrous ingredients, such as rapeseed or sunflower hulls, lupin hulls, rice bran, or alfalfa meal, were also included (Table 1). The remaining nine diets were quite complex, with more than 10 ingredients. All diets were supplemented with salt, dicalcium phosphate, calcium carbonate, and mineral and vitamin mixtures. In order to meet amino acid requirements for growth, some diets were also supplemented with crystalline amino acids.

Experimental design. Each diet was measured with four to six Piétrain × (Landrace × Large White) castrated male pigs weighing about 61 kg during the collection period and with four or five nonlactating, nonpregnant adult Large White or Large White × Landrace sows (236 kg, mean BW). Each growing pig received only one diet, whereas sows received several diets successively. In fact, 52 sows were used in the entire experiment, each sow receiving successively 1 to 11 of the 77 diets. Pigs were adapted to the diet and digestibility cage for 10 d before total collection of feces

Table 1. The inclusion level of ingredients in the 77 diets

Ingredient	Number of diets[a]	Inclusion level, % Mean	Inclusion level, % Maximum
Alfalfa meal	1	20.0	20.0
Animal fat	3	5.0	7.5
Barley	14	41.8	96.8
Cane molasses	5	3.4	4.0
Cocoa hulls	1	20.0	20.0
Corn	12	51.6	96.4
Corn by-products[b]	5	25.2	30.0
Corn by-products[c]	5	30.0	30.0
Corn germ meal	2	25.0	30.0
Corn gluten feed	6	10.6	20.0
Faba beans	1	30.0	30.0
Fish meal	6	1.8	2.0
Grass meal	1	20.0	20.0
Lupin seeds	2	25.0	25.0
Oats	4	15.8	25.0
Peas	8	13.0	30.0
Rapeseed hulls	1	15.0	15.0
Rapeseed meal	2	20.0	20.0
Rice bran	2	25.0	25.0
Soybean hulls	5	11.2	20.0
Soybean meal	53	12.4	25.0
Soybean, full fat	2	25.0	25.0
Sugar beet pulp	5	17.7	26.0
Sunflower hulls	1	15.0	15.0
Sunflower meal	9	11.3	20.0
Sunflower, full fat	1	20.0	20.0
Triticale	5	74.5	96.0
Vegetable fat	6	5.3	6.0
Wheat	60	61.2	96.0
Wheat by-products	15	21.3	40.0

[a] In diets in which the ingredient was included.
[b] Corex: fiber fraction from cornstarch industry.
[c] Corex + cornstarch and(or) soluble fractions from cornstarch industry.

Table 2. Chemical composition of the 77 diets

Item	Mean	SD	Minimum	Maximum
Chemical composition, g/kg of DM				
Ash	59	9	45	84
Crude protein	167	27	101	214
Ether extract	30	23	10	108
Crude fiber	51	26	19	181
Nitrogen-free extract	692	51	553	800
NDF	179	52	112	394
ADF	60	29	24	212
ADL	12	9	3	54
Starch	519	82	221	686
Sugars	35	10	19	68
Water-insoluble cell walls	176	56	102	419
Fiber[a]	189	60	99	450
Gross energy, MJ/kg of DM	18.20	0.51	17.55	19.89

[a] Fiber = 1,000 − (ash + crude protein + ether extract + starch + sugars).

and urine over a period of 8 to 11 d. The feeding level in growing pigs was fixed at about 90% of the ad libitum intake recorded in previous trials with comparable pigs kept in the same conditions (Quiniou et al., 1996). This feeding level corresponded to about 2.3 times the ME requirement for maintenance (Noblet et al., 1999); the feeding level was progressively increased during the adaptation period. Feeding level in sows was generally 2.4 kg of feed per day. Almost all diets were given as mash feed mixed with water (1:1.5, wt/vol); eight diets were given as pellets. All the pigs received their diets twice daily (0830 and 1530) and had free access to water. Pigs were weighed at the beginning and at the end of the collection period. Feed refusals and spillage were collected daily and analyzed for DM content. For each diet, a sample of feed was collected and measured for its DM content and subsequently used for chemical analysis. Feces and urine were collected daily, stored at 4°C, weighed, and subsampled at the end of the period. The urine of sows was collected via Foley catheters (Silastic, distributed by Dow Corning, Crawley, U.K.).

Chemical analyses. For feed samples, the methods of AOAC were used for measuring moisture, ash, CP (N × 6.25), Weende crude fiber (**CF**), and ether extract (**EE**). Gross energy (**GE**) content was measured using an adiabatic bomb calorimeter (IKA, Staufen, Germany). Cell wall fractions (NDF, ADF and ADL) were determined according to the methods of Van Soest and Wine (1967) by using a sequential procedure with prior amylolytic treatment. Water-insoluble cell walls (**WICW**), which include all water-insoluble, nonstarch polysaccharides, were measured according to the method of Carré and Brillouet (1986). Starch content (**ST**) was measured using the Ewers polarimetric method (EEC, 1972), and the content of sugars (**SU**) corresponded to alcohol-soluble carbohydrates was obtained by the method of Luff-Schoorl (BIPEA, 1976). Moisture, ash, CP, and GE analyses were carried out on each sample of feces. In addition, EE after hydrochloric acid hydrolysis and cell wall fractions were measured on pooled samples of feces (one per diet and per physiological stage). Nitrogen in urine was measured on fresh material, whereas energy content was obtained after freeze-drying approximately 30 mL of urine in polyethylene bags.

Calculations and statistical analysis. Apparent total tract digestibility coefficients (**DC**) of organic matter, nutrients and energy, and DE and ME contents were calculated using routine procedures (Noblet et al., 1989). The ME value was calculated as the difference between DE value and energy losses in urine. According to Graham et al. (1986) and Bach Knudsen and Hansen (1991), starch and sugars were assumed to be 100% digestible at the fecal level. Experimental data (n = 641 sets of data) were subjected to analysis of variance with diet (n = 77) and pig stage (n = 2) as the main effects; the interaction between pig stage and diet was also tested. Mean DC and energy values were calculated for each diet at each stage (n = 154). In order to determine the relationship between total tract digestibility coefficients of nutrients, and energy and chemical characteristics of diets according to pig stage, covariance analyses were carried out on mean dietary values (n = 154) with chemical characteristics as covariates and pig stage as a fixed effect. Linear regression equations for predicting total tract digestibility coefficients of energy and nutrients and GE, DE, and ME values of diets from chemical characteristics or total tract digestible nutrient contents were calculated at each stage (n = 77) according to the step-wise procedure. Finally, equations for predicting urinary energy from urinary nitrogen were established. SAS (SAS Inst. Inc., Cary, NC) was used for all statistical analyses.

Results

As shown in Table 2, chemical composition of diets was highly variable for all criteria and representative for most practical situations. A total of 641 total tract digestibility measurements were conducted, 312 of which were for adult sows and 329 for growing pigs. According to the experimental design, daily feed intake was higher ($P < 0.01$) in adult sows than in growing pigs (Table 3); however, when expressed relative to the metabolic body size of the pig, it averaged 2,270 kJ ME/kg$^{0.60}$ for growing pigs and 565 kJ ME/kg$^{0.75}$ for adult sows, or 2.3 and 1.3 times maintenance energy requirements, respectively.

Effect of Physiological Stage on Total Tract Digestibility of Dietary Energy and Nutrients

Data presented in Table 3 indicate an effect ($P < 0.01$) of diet, physiological stage (growing pig vs adult sow), and the interaction between diet and physiological stage on the mean DC of organic matter, crude protein, and energy. The DC of organic matter and energy were higher ($P < 0.01$) for adult sows (87.6 and 85.2%, respectively) than for growing pigs (84.8 and 82.1%, respectively). Most nutrients contributed to the greater total tract digestibility coefficients of organic matter and energy in sows. Even if it has not been statistically demonstrated, the difference between both stages was numerically the most pronounced for the fiber fractions: +14 percentage units for crude fiber and +8 percentage units for NDF. Consequently, the DE content of diets was 0.6 MJ/kg of DM greater ($P < 0.01$) in sows than in growing pigs, and the DE values in growing pigs represented 87.4 to 99.7% (96.3%, on average) of those in adult sows.

The ME/DE ratio was lesser ($P < 0.01$) in sows (94.8%) than in growing pigs (96.5%). That result is related to the lower ($P < 0.01$) nitrogen retention in sows and the subsequent higher ($P < 0.01$) urinary energy loss (Table 3). In fact, daily urinary energy loss was linearly related to the daily nitrogen excreted in

Table 3. Comparative digestive utilization of 77 diets in growing pigs and adult sows

Item	Mean		Growing pigs, relative to sows, %		Residual SD	Effect[a]
	Growing pigs	Adult sows	Mean	Range		
BW, kg	61	234			13	
DM intake, g/d	1,854	2,104			49	D**; S**; DS**
Digestibility coefficient, %						
Organic matter	84.8	87.6	96.7	89–100	1.0	D**; S**; DS**
Crude protein	80.3	84.9	94.5	85–99	2.0	D**; S**; DS**
Ether extract	31.6	37.1	80.8	—	—	—
Crude fiber	37.6	51.7	73.2	21–99	—	—
Nitrogen-free extract	90.8	92.3	98.3	90–100	—	—
NDF	56.3	64.4	87.9	61–105	—	—
ADF	37.8	48.9	79.3	54–117	—	—
Fiber[b]	50.9	59.5	86.0	63–102	—	—
Energy	82.1	85.2	96.3	87–100	1.1	D**; S**; DS**
Digestible nutrients, g/ kg of DM						
Organic matter	798	824	96.7	89–100	9	D**; S**; DS**
Crude protein	134	142	94.5	85–99	3	D**; S**; DS**
Ether extract	14	15	80.8	—	—	—
Crude fiber	19	26	73.2	21–99	—	—
Nitrogen-free extract	630	640	98.3	90–100	—	—
NDF	99	115	87.9	61–105	—	—
ADF	23	29	79.3	54–117	—	—
Fiber[b]	96	113	86.0	63–102	—	—
ME/DE, %	96.5	94.8	101.8	101–103	0.5	D**; S**; DS**
Energy values, MJ/kg of DM						
DE	14.94	15.51	96.3	87–100	0.21	D**; S**; DS**
ME	14.43	14.71	98.1	89–101	0.21	D**; S**; DS**
Nitrogen balance, g/d						
Intake	49.7	56.3	—	—	1.3	D**; S**; DS**
Excreted						
Fecal	9.7	8.5	—	—	2.8	D**; S**; DS**
Urinary	19.9	40.8	—	—	4.0	D**; S**; DS**
Total	29.6	49.3	—	—	4.6	D**; S**; DS**
Absorbed	40.0	47.7	—	—	3.0	D**; S**; DS**
Retained	20.1	7.0	—	—	4.7	D**; S**; DS**

[a] From analysis of variance on 329 and 312 sets of data for growing pigs and adult sows, respectively; D, S, and DS for the effects of diet (n = 77), physiological stage (n = 2), and the interaction between diet and physiological stage, respectively; levels of significance: *$P < 0.05$; **$P < 0.01$. Ether extract and cell wall fraction contents of feces were measured on samples pooled per diet and per physiological stage and corresponding digestibility coefficients and digestible nutrient contents could not be subjected to the analysis of variance.

[b] Digestible fiber is equivalent to digestible organic matter minus the sum of digestible crude protein, digestible ether extract, starch, and sugars. Starch and sugars are considered to be 100% digestible (see text).

urine (Eq. 14 and 15 in Table 4). In this case, the covariance model including data for both sows and growing pigs indicates that the intercept of the relationship was greater ($P < 0.05$) in sows than in growing pigs but the slopes were not different between pig stages ($P > 0.05$). Consequently, the difference in energy contents between the physiological stages was attenuated on a ME basis (0.3 MJ/kg of DM, on average) rather than on a DE basis. For the 77 diets, the ME value in growing pigs averaged 98.1% of the value in adult sows.

Influence of Chemical Composition of Diets on Digestive Utilization of Nutrients and Energy

Apparent digestibility coefficients of nutrients varied to a great extent (Table 3). The least digestible and the most variable was the EE fraction. The amount of total tract digestible EE (**DEE**) was linearly and positively related to the diet EE content with a negative intercept (Eq. 1 in Table 4). This equation also indicates that total tract digestibility of EE was negatively affected ($P < 0.05$) by NDF content. The coefficient attributed to EE provides an estimate of the true fecal digestibility of dietary fat (82%). According to Eq. 1 (Table 4), endogenous fat losses, calculated as DEE for zero EE intake and a NDF content of 179 g/kg of DM (mean of all diets; Table 2), averaged 10.5 g/kg of DM.

Total tract digestibility of cell wall fractions was low but numerically higher in adult sows than in growing pigs (Table 3). The NDF fraction was more digestible (56% in growing pigs) than the ADF fraction or crude fiber (38%). The total tract digestibility of fiber (calculated as organic matter minus the sum of CP, EE, starch, and sugars) was 51 and 59% in growing pigs and adult sows, respectively. Furthermore, the amount of total tract digestible NDF was linearly related to dietary NDF in growing pigs with a positive intercept (Eq. 2 in Table 4) and proportional to dietary NDF in adult sows (Eq. 3 in Table 4).

Total tract digestible CP content was positively affected by the CP content of the diet and was reduced when more ash and dietary fiber was present in the diet (Eq. 4 and 5 in Table 4). These equations also indicate that the reduction of total tract digestibility of CP was more pronounced for growing pigs than for adult sows when dietary fiber content was increased. Furthermore, the coefficients attributed to CP in Eq. 4 and 5 (Table 4) suggest that the true fecal digestibility was 100% for adult sows and 94% for growing pigs. The same equations provide an estimate of endogenous fecal crude protein losses (23 and 24 g/kg on average for growing pigs and adult sows, respectively) calculated as total tract digestible CP when NDF and ash contents are equal to the mean values measured in experimental diets (Table 1) and CP content is zero.

In agreement with changes in the total tract digestibility of nutrients, the amount of total tract digestible organic matter was negatively affected by the dietary fiber and ash contents of the diet (Eq. 6 and 7 in Table 4). Similarly, total tract digestibility of energy decreased linearly when the NDF content of the diet increased. However, the slopes were different ($P < 0.05$) for both physiological stages of pigs (Eq. 8 and 9 in Table 4). The depressive effect of dietary fiber on energy digestibility was more pronounced in growing pigs than in adult sows. In addition to cell wall predictors, the prediction of energy total tract digestibility was improved when ash content was included in the equations (Eq. 10 and 11 in Table 4). The accuracy of the equations was lower when dietary fiber estimates other than NDF were used.

In connection with the lesser depressive effect of dietary fiber on energy total tract digestibility in sows than in growing pigs, the difference in DE content of diets between physiological stages (ΔDE, kJ/kg of DM) was proportional to the fiber content of the diet. Regression equations between ΔDE and dietary fiber estimates (equations not reported) indicate that for each additional gram of NDF, ADF, crude fiber, or "fiber" in the diet, ΔDE was increased by 3.3, 8.6, 10.1, or 3.0 kJ, respectively. In connection with urinary nitrogen excretion, which is highly related to nitrogen intake, the ME/DE ratio was negatively affected by the CP content of diets in both groups of pigs, with a greater ($P < 0.05$) negative effect for sows (Eq. 12 and 13 in Table 4).

Prediction of DE and ME Contents of Diets from Their Chemical Characteristics in Growing Pigs and Adult Sows

Equations proposed in Table 5 were established to quantify the contribution of crude nutrients or total tract digestible nutrients to GE, DE, or ME of the feed

Table 4. Effect of diet composition (g/kg of DM) on digestible nutrient contents (g/kg of DM), energy digestibility (DCe, %), ME/DE ratio (%), and energy losses in urine (Eu, kJ/d) in growing pigs (G) and adult sows (S)[a]

Equation number	Physiological stage	Equation	R^2	Residual SD
1[b]	G/S	$DEE = 0.82 \times EE - 7 - 0.02 \times NDF$	0.97	3.3
2	G	$DNDF = 19 + 0.44 \times NDF$	0.70	15.0
3	S	$DNDF = 0.64 \times NDF$	0.77	17.5
4	G	$DCP = 17 + 0.94 \times CP - 0.11 \times NDF - 0.36 \times ash$	0.97	3.9
5	S	$DCP = 6 + 1.00 \times CP - 0.07 \times NDF - 0.30 \times ash$	0.98	3.4
6	G	$DOM = 1{,}035 - 0.72 \times NDF - 1.84 \times ash$	0.91	15.4
7	S	$DOM = 1{,}025 - 0.45 \times NDF - 2.03 \times ash$	0.83	17.3
8	G	$DCe = 98.3 - 0.090 \times NDF$	0.85	2.0
9	S	$DCe = 96.7 - 0.064 \times NDF$	0.70	2.2
10	G	$DCe = 102.6 - 0.106 \times ash - 0.079 \times NDF$	0.88	1.8
11	S	$DCe = 101.6 - 0.118 \times ash - 0.052 \times NDF$	0.76	2.0
12	G	$ME/DE = 99.8 - 0.019 \times CP$	0.58	0.5
13	S	$ME/DE = 99.2 - 0.029 \times CP$	0.66	0.5
14[c]	G	$Eu = 437 + 31.1 \times Nu$	0.94	110
15[c]	S	$Eu = 345 + 31.1 \times Nu$		

[a] CP, EE, and NDF = crude protein, ether extract and neutral detergent fiber, respectively; DEE, DCP, DOM, and DNDF = digestible ether extract, digestible crude protein, digestible organic matter, and digestible NDF, respectively. Nu = nitrogen excreted in urine (g/d). Equations resulted from regression analyses in which coefficients were different from zero ($P < 0.05$).

[b] The equation was the same for growing pigs and adult sows; for other equations, intercept and(or) slopes were different between sows and growing pigs ($P < 0.05$).

[c] Equations were obtained according to a covariance model including data for both sows and growing pigs, the intercept depended on the pig stage ($P < 0.01$) but the slopes were not different between sows and growing pigs ($P = 0.4$).

Table 5. Comparative contribution of nutrients or digestible nutrients (g/kg of DM) to gross energy, digestible energy, or metabolizable energy supply (MJ/kg of DM) in growing pigs (G) and adult sows (S)[a,b]

Equation number	Physiological stage	Equation	Residual SD
16	G/S	$GE = 0.0227 \times CP + 0.0388 \times EE + 0.0190 \times NDF + 0.0174 \times ST + 0.0177 \times Res$	0.12
17	G	$DE = 0.0225 \times CP + 0.0317 \times EE + 0.0032 \times NDF + 0.0172 \times ST + 0.0163 \times Res$	0.35
18	S	$DE = 0.0225 \times CP + 0.0317 \times EE + 0.0064 \times NDF + 0.0172 \times ST + 0.0163 \times Res$	
19	G	$ME = 0.0201 \times CP + 0.0318 \times EE + 0.0026 \times NDF + 0.0171 \times ST + 0.0165 \times Res$	0.34
20	S	$ME = 0.0178 \times CP + 0.0318 \times EE + 0.0064 \times NDF + 0.0171 \times ST + 0.0165 \times Res$	
21	G/S	$DE = 0.0229 \times DCP + 0.0379 \times DEE + 0.0181 \times DNDF + 0.0173 \times ST + 0.0176 \times DRes$	0.12
22	G	$ME = 0.0199 \times DCP + 0.0379 \times DEE + 0.0169 \times DNDF + 0.0173 \times ST + 0.0176 \times Dres$	0.13
23	S	$ME = 0.0183 \times DCP + 0.0379 \times DEE + 0.0169 \times DNDF + 0.0173 \times ST + 0.0176 \times DRes$	

[a] CP, EE, NDF, and ST = crude protein, ether extract, neutral detergent fiber, and starch , respectively; DCP, DEE, and DNDF for digestible crude protein, digestible ether extract, and digestible NDF, respectively; Res (for residue) is equivalent to organic matter minus the sum of other chemical constituents considered in the equation; DRes (for digestible residue) is equivalent to digestible organic matter minus the sum of other constituents considered in the equation; starch is considered to be 100% digestible.

[b] Equation 16 resulted from a regression analysis in which coefficients were different from zero ($P < 0.05$). Equations 17 and 18 resulted from a covariance analysis in which CP, EE, NDF, ST, and Res were covariates and physiological stage (adult sows vs growing pigs) was a fixed effect; only the coefficient for NDF was different ($P < 0.01$) between growing pigs (Eq. 17) and adult sows (Eq. 18). Equations 19 and 20 resulted from a covariance analysis in which CP, EE, NDF, ST, and Res were covariates and physiological stage (adult sows vs growing pigs) was a fixed effect; coefficients for CP and NDF were different ($P < 0.01$) between growing pigs (Eq. 19) and adult sows (Eq. 20). Equations 21, 22, and 23 resulted from covariance analyses in which DCP, DEE, DNDF, ST, and DRes were covariates and physiological stage (adult sows vs growing pigs) was a fixed effect; DE values of total tract digestible nutrients were the same ($P > 0.05$) in growing pigs and adult sows (Eq. 21), and ME values of total tract digestible CP were different ($P < 0.05$) between growing pigs (Eq. 22) and adult sows (Eq. 23).

for growing pigs and adult sows. Coefficients for sugars were not significant ($P > 0.05$) in the model, probably because the sugar content of diets was low and without sufficient variation. Therefore, sugars were included in the so-called residue, which corresponds to the sum of sugars and water-soluble fractions of nonstarch polysaccharides. Equation 16 (Table 5) provides estimates of the GE content of the chemical fractions that were analyzed. The corresponding covariance model for DE (Eq. 17 and 18) suggests that the contributions of CP, starch, EE, and residue to DE are equivalent in growing pigs and adult sows. The comparison of Eq. 16 with Eq. 17 or 18 (Table 5) also indicates that the DE contents of CP, starch, and residue are equivalent to their GE contents or that the total tract digestibility coefficients of CP (i.e., ratio 0.0225/0.0227), starch (i.e., ratio 0.0172/0.0174), and residue (i.e., ratio 0.0163/0.0177) are approximately 100%. In agreement with the true digestibility coefficient of EE estimated in Eq. 1 (Table 4), the total tract digestibility coefficient of dietary EE, which corresponds to the ratio between coefficients attributed to EE in Eq. 16 and 17 in Table 5 (i.e., ratio 0.0317/0.0388), was equivalent to 82%. In fact, as indicated by the covariance model, the difference between both physiological stages originates exclusively from the fiber fraction of the diet with a higher ($P < 0.01$) contribution to DE in adult sows (Eq. 17 and 18 in Table 5). The contribution of crude protein to ME (Eq. 19 and 20 in Table 5) differs from that to DE equation for the coefficient attributed to CP (Eq. 17 and 18 in Table 5). Coefficients for EE, starch, and residue are similar in DE and ME equations. Moreover, the covariance analysis shows that DE values of total tract digestible nutrients are the same ($P > 0.05$) in growing pigs and adult sows (Eq. 21 in Table 5). Finally, the covariance analysis shows that the ME value of total tract digestible CP differs ($P < 0.05$) between growing pigs (Eq. 22) and adult sows (Eq. 23).

Prediction equations of DE content of compound feeds from chemical characteristics are presented in Table 6. The first predictor included in the stepwise regression equation was systematically an estimate of the dietary fiber level at both physiological stages. Among the different dietary fiber estimates, the predictions with the lowest residual standard deviations were obtained with NDF. Equations for estimating ME content from chemical characteristics were derived similarly; the best equations were obtained with the same predictors as DE. The residual standard deviation of the equations was then equivalent to about 0.3 MJ/kg of DM (2% of the mean value of DE) for both physiological stages. The equations show that DE content or ME content is negatively affected by ash and fiber content and positively affected by CP and EE content at both stages. In agreement with coefficients of NDF in Eq. 17 to 20 in Table 5, the effect of fiber is less negative ($P < 0.05$) in adult sows than in growing pigs in equations for estimating DE or ME values (Table 6).

As shown in Table 7, the DE values for sows can be directly predicted from DE values obtained in growing pigs. However, the accuracy of that equation was dependent on the presence of diets that had a high EE content and subsequent high DE values. In those diets, DE variation was not related to dietary fiber level, which is the major factor of variation of DE difference between sows and growing pigs, but rather to the content of dietary fat, which is digested similarly at both physiological stages. Therefore, we excluded these diets for establishment of Eq. 28. Other prediction equations that consider DE content and one dietary fiber estimate are also proposed (Eq. 29 to 32 in Table

Table 6. Prediction of DE or ME contents (MJ/kg of DM) of compound feeds from chemical composition (g/kg of DM) in growing pigs (G) or in adult sows (S)[a]

Equation number	Physiological stage	Equation	R^2	Residual SD
24	G	DE = 17.69 − 0.0341 × ash + 0.0071 × CP + 0.0146 × EE − 0.0132 × NDF	0.90	0.31
25	S	DE = 17.26 − 0.0401 × ash + 0.0093 × CP + 0.0162 × EE − 0.0080 × NDF	0.85	0.32
26	G	ME = 17.64 − 0.0323 × ash + 0.0039 × CP + 0.0151 × EE − 0.0135 × NDF	0.91	0.30
27	S	ME = 17.17 − 0.0381 × ash + 0.0049 × CP + 0.0159 × EE − 0.0085 × NDF	0.85	0.32

[a]CP, EE, and NDF = crude protein, ether extract, and neutral detergent fiber, respectively. Equations resulted from regression analyses in which coefficients were different from zero ($P < 0.05$).

7). Even if diets that had a high EE were excluded for establishment of Eq. 29 to 32, the accuracy of the latter equations is not dependent on dietary EE level.

Discussion

Total Tract Digestibility of Dietary Energy and Nutrients in Growing Pigs and Adult Sows

Literature results indicate that total tract digestibility of dietary energy and nutrients in growing pigs increases with BW (Cunningham et al., 1962). Literature data also suggest slight increases of energy digestibility with reduced feeding levels in growing pigs (Roth and Kirchgessner, 1984). Decreasing the level of feeding may improve the efficiency of digestion because it decreases the rate of passage. When sows and growing pigs are fed at a similar level (× maintenance), no significant difference in digestibility coefficients is observed (Everts et al., 1986). In the present experiment, effects of BW and feeding level were confounded, and it is not surprising to obtain higher total tract digestibility coefficients for energy and most nutrients in sows fed at 1.3 times maintenance requirements than in growing pigs fed at 2.3 times maintenance. This is consistent with literature results of Fernandez et al. (1986), Noblet and Shi (1993), and Noblet and Bach Knudsen (1997). However, the extent of the difference in energy total tract digestibility between adult sows and growing pigs is quite variable between experiments. On average, the difference was 3 percentage units in the present experiment and 6 and 9 percentage units in the experiments of Fernandez et al. (1986), and Noblet and Shi (1993). The results of Noblet and Shi (1993) were obtained in 45-kg pigs and nonlactating, nonpregnant sows fed at their maintenance requirements; the difference in energy total tract digestibility between the two physiological stages corresponded, then, to the maximum potential difference between growing and adult pigs. Furthermore, as discussed below, the extent of the difference also depends on diet composition.

Table 7. Prediction of energy value (MJ/kg of DM) of diets for adult sows from energy values in growing pigs[a]

Equation number	Equation[b]	R^2	Residual SD
28	DEs = 4.37 + 0.742 × DEg	0.89	0.24
29	DEs = 0.984 × DEg + 0.0045 × NDF	0.90	0.24
30	DEs = 1.012 × DEg + 0.0060 × ADF	0.85	0.29
31	DEs = 1.014 × DEg + 0.0066 × CF	0.82	0.30
32	DEs = 0.991 × DEg + 0.0036 × fiber	0.87	0.25

[a]DEs and DEg = digestible energy for sows and digestible energy for growing pigs, respectively; NDF, ADF, and CF = neutral detergent fiber, acid detergent fiber, and Weende crude fiber, respectively; chemical composition expressed as g per kg of DM.

[b]Equations resulted from regression analyses in which coefficients were different from zero ($P < 0.05$). Equations were obtained on 67 diets; diets with an ether extract content > 60 g/kg DM were not considered (see text).

Metabolizable Energy of Diets in Growing Pigs and Adult Sows

Our study shows that the ME/DE ratio was lower in adult sows than in growing pigs (Table 3); this difference was related to higher energy losses in urine in adult sows. In fact, the nonpregnant, adult sows in the present study were fed diets with a high protein content, relative to their requirements. According to Noblet and Shi (1993), each gram of total tract digestible crude protein in excess of the requirement is deaminated and increases urinary energy loss by about 3 kJ. Therefore, the energy losses in urine as measured in the present experiment are much higher compared to those in the study of Everts and Dekker (1994), in which pregnant sows were fed lower dietary CP levels. Consequently, the equations proposed in the present study for predicting ME of diets in adult sows can be applied only when N balance is close to zero; otherwise, the use of these equations would be inappropriate. For practical application, the ME content of diets in adult sows could be calculated as the difference between the DE content and the energy content of urine (Eq. 14 and 15 in Table 4). In these circumstances, ME values can be predicted irrespective of the physiological stage of the pig. However, the calculation of ME is still incomplete, because energy losses as methane are not taken into account. Methane production in pigs can vary with BW and type of diet. It increases with BW in growing pig (Noblet and Shi, 1993) or with the fiber content of the diet in adult sows (Ramonet et al., 2000). Differences in methane production are most important when adult sows and growing pigs are compared (Noblet and Shi, 1993). The variation in methane production is more or less proportional to the change in fiber total tract digestibility. Therefore, increased digestibility of dietary fiber in adult sows is also associated with higher methane energy losses, which will attenuate the difference between growing pigs and adult sows when measured on a ME basis. Further studies are necessary to predict more accurately methane losses in pigs. In conclusion, the prediction of ME content and the applicability of ME values obtained in the present study for sows are limited. For growing pigs, the accuracy and the coefficients of the equations presented in Table 5 or in Table 6 are close to those proposed by Noblet and Perez (1993).

Interaction Between Diet Chemical Composition and the Physiological Stage of the Pigs on Total Tract Digestibility of Energy and Nutrients

Our results show that the total tract digestibility of EE is not affected by the physiological stage of the pig (Table 4). In fact, starch and EE are digested in the small intestine (Lin et al., 1987) with few differences between physiological stages. The reduction of EE apparent fecal digestibility with the increase of dietary fiber can be explained by endogenous secretions and(or) a greater bacterial fat synthesis (i.e., fatty acids incorporated into bacteria) in the hindgut (Eq. 1 in Table 4). This phenomenon was also observed by other authors (Graham et al., 1986; Dierick et al., 1990). The presence of fiber in the diet also reduces the apparent fecal digestibility of CP and has a higher negative effect in growing pigs (Eq. 4 and 5 in Table 4). In this case, the depressive effect of fiber can result from an increase in bacterial nitrogen, as measured by Sauer et al. (1991) in growing pigs and by Kirchgessner et al. (1994) in sows, and can be related to a higher microbial activity in the hindgut (Dierick et al., 1990). The results are consistent with the negative correlations between fecal or ileal digestibility of CP and dietary fiber level (Yin et al., 2000). In summary, the decrease of CP total tract digestibility with increasing dietary fiber content is mainly due to higher endogenous losses in growing pigs and adult sows. The difference between the two physiological stages could result from a higher excretion of cell wall-bound proteins in growing pigs in relation to the lower degradation rate of dietary fiber at this physiological stage.

In agreement with studies of Noblet and Perez (1993) and Noblet and Shi (1993), the present experiment indicates that energy digestibility in growing pigs was reduced by approximately 1 percentage point for each 1% additional NDF in the diet (Eq. 8 in Table 4). Consequently, dietary fiber can be considered as a diluting factor in diets for growing pigs, even if about half of it is degraded in the digestive tract (Noblet and Le Goff, 2000). In both the study of Noblet and Shi (1993) and the present study, this depressive effect of NDF was less pronounced in adult sows (0.6 unit) than in growing pigs (Eq. 9 in Table 4). Consequently, the difference in DE content of diets between the two physiological stages is related to the fiber content of the diet. This suggests that the origin of the difference in total tract digestibility of energy between growing pigs and sows is due to a higher degradation rate of dietary fiber in the hindgut of sows. The higher production of methane in sows (Noblet and Shi, 1993) is consistent with this hypothesis. The reasons for the higher degradation rate of dietary fiber in adult pigs are unclear. The larger size of the hindgut (Pekas, 1991) and the subsequent lower rate of passage (G. Le Goff and J. Noblet, unpublished data) are the most probable explanations. Changes in the hindgut flora may also be implicated.

Prediction of Energy Value for Growing Pigs and Adult Sows

The results of the present study show that the energy value of a diet varies with the physiological stage of the pig. It is therefore important to consider this effect when estimating the energy value of a given feed. Energy values can be predicted from the total tract digestible nutrient contents with specific values for each physiological stage (Table 5). However, total tract digestible nutrient coefficients are not always available in feeding tables. Therefore, an equation for predicting energy values from chemical composition of the diet was proposed for each physiological stage (Table 6). From a practical point of view, results obtained in the 60-kg pigs are representative of the growing-finishing period (Roth and Kirchgessner, 1984). Moreover, the DE values of feeds obtained in adult sows can be applied to both pregnant and lactating sows, because energy digestibility is constant when DM intake increases in pregnant animals (J. Noblet, unpublished data), and energy digestibility in lactating sows is close to that in pregnant sows despite differences in feeding levels (Etienne et al., 1997). Consequently, these two “model” situations (60- to 65-kg growing pig and adult sow) provide feed energy values applicable to almost all stages of pig production. Nevertheless, the closest estimate of the true energy value of a feed is given by its NE content. Equations for predicting NE from DE and chemical characteristics or from digestible nutrient contents were previously established for growing pigs (Noblet et al., 1994). Two NE values could then be calculated by using the equations of Noblet et al. (1994) but with predictors (DE or total tract digestible nutrient contents) specific to each physiological stage; the predictors can be determined according to the equations proposed in Tables 6 and 7.

Energy values of feeds are extensively available in feeding tables and almost all values have been obtained in growing pigs. Previous results (Noblet and Bourdon, 1997; Noblet et al., 1998; Noblet and Le Goff,

2000) and unpublished data from our laboratory confirm that tabulated values underestimate the energy value of feeds when they are fed to adult sows. For practical reasons, it is almost impossible to measure all ingredients available for pig feeds in both growing pigs and adult sows. The solution proposed here was to establish equations for estimating energy values for adult sows from data obtained in growing pigs (Table 7). However, in the case of fat-rich feeds, only the equations based on DE for growing pigs and NDF can be used. Equations for predicting energy values in adult sows from data obtained in growing pigs were also proposed by Noblet and Shi (1993) using a smaller data set. Conclusions of both studies are similar. However, according to the experimental conditions of Noblet and Shi (1993), the difference between the two stages was more important than in the present study. Therefore, the slope of the relationship between DE for sows and DE for growing pigs was smaller (0.65 vs 0.74 in the present study) and the intercept was higher (6.50 vs 4.37). The difference between DE for sows and DE for growing pigs was more pronounced according to the equation proposed by Noblet and Shi (1993). As previously explained, the experimental conditions used by Noblet and Shi (1993) were different from practical conditions and the difference between the two stages were probably overestimated. Equations obtained in the present study should be preferable for practical application.

Implications

Results of the present study demonstrate that ingredients for pigs' diets should be assigned at least two different DE values. The DE content measured at about 60 to 65 kg BW is representative for the entire growing-finishing period, and the DE measured in adult nonlactating, nonpregnant sows is applicable to both pregnant and lactating sows. The DE value in sows is always higher than that in growing pigs, with differences positively related to the dietary fiber level. Equations for predicting DE values for sows from DE measured in growing pigs are proposed. The NE value can then be estimated according to the NE equations for growing pigs but with values for DE or total tract digestible nutrient contents specific to each physiological stage.

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