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Effect of the form of dietary fat and the concentration of dietary neutral detergent fiber on ileal and total tract endogenous losses and apparent and true digestibility of fat by growing pigs[1]

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ABSTRACT: An experiment was conducted to determine the effect of the form of dietary fat (extracted or intact fat) and of dietary NDF on ileal and total tract endogenous losses of fat (ELF), on apparent ileal (AID) and apparent total tract digestibility (ATTD) of fat, and on true ileal (TID) and true total tract digestibility (TTTD) of fat in growing pigs. A cornstarch-based basal diet that contained 1.27% fat was prepared and 3 diets were formulated by adding 2.0, 4.0, or 6.0% extracted fat (corn oil) to the basal diet at the expense of cornstarch. Three additional diets were formulated by adding 3.1, 6.2, or 9.3% Solka-Floc (International Fiber Corp., North Tonawanda, NY) to the diet containing 4.0% corn oil at the expense of cornstarch. The remaining 4 diets were prepared by adding whole corn germ meal to the diet at the expense of defatted corn germ meal to contain 3.0, 6.0, or 9.0% intact fat. Solka-Floc was also included in this diet at the expense of cornstarch in an attempt to keep NDF constant. Eleven barrows (initial average BW of 38.1 ± 1.3 kg) were fitted with a T-cannula in the distal ileum, allotted to the 11 diets in an 11 × 11 Latin square design, and fed the diets at 3 times the energy requirement for maintenance. Increasing dietary extracted fat increased (linear and quadratic, $P < 0.001$) the AID and ATTD of fat. Increasing dietary intact fat also increased (linear and quadratic, $P < 0.05$) the AID and ATTD of fat. The average apparent digestibility of extracted fat (81.9%) was greater ($P < 0.001$) than that of intact fat (63.2%). Estimates of ELF were smaller ($P < 0.05$) for extracted fat than for intact fat at the end of the ileum and over the entire intestinal tract, but the TID (93.8%) and TTTD (94.2%) of extracted fat were greater ($P < 0.05$) than the TID (78.6%) and TTTD (84.1%) of intact fat. Increasing dietary extracted fat had no effects on the TID and TTTD of fat, but increasing dietary intact fat resulted in a quadratic reduction ($P < 0.05$) in the TTTD of fat. Increasing dietary NDF had a quadratic effect ($P < 0.05$) on the ATTD of fat but did not influence the AID, TID, and TTTD of fat. In conclusion, extracted fat induces a smaller amount of ELF and has a greater apparent and true digestibility than intact fat at the end of the ileum and over the entire intestinal tract. Purified NDF has little influence on apparent and true digestibility of fat.

Key words: apparent digestibility, endogenous loss, fat, neutral detergent fiber, pig, true digestibility

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INTRODUCTION

Estimation of endogenous losses of nutrients from the digestive tract is required for the determination of true digestibility of nutrients. Values for endogenous losses of CP and AA (Stein et al., 1999; Moter and Stein, 2004) and P (Dilger and Adeola, 2006; Petersen and Stein, 2006) in pigs have been published. Values for endogenous losses of fat (**ELF**) in pigs have also been reported, but results have been inconsistent (Freeman et al., 1968; Adams and Jensen, 1984; Jørgensen et al., 1993). Therefore, determination of fat digestibility has mostly been limited to apparent digestibility, and true digestibility is usually not calculated.

Endogenous losses of fat may be influenced by the source of fat and by dietary concentrations of fat and fiber (Freeman et al., 1968; Juste et al., 1983; Bach Knudsen and Hansen, 1991). Dietary NDF may decrease apparent digestibility of fat (Bach Knudsen and Hansen, 1991), but to our knowledge, the effect of NDF on the true digestibility of fat has not been reported.

Although fat in swine diets may originate from either intact fat in feed ingredients or supplemented extracted

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fat (Azain, 2001), the effect of the form of fat on ELF has not been investigated. In addition, ELF in pigs most often has been measured over the entire intestinal tract, and information about the ELF at the end of the ileum is limited.

The objectives of this experiment were to estimate ELF in growing pigs and to measure the influence of the form of fat (extracted or intact form) and the concentration of dietary NDF on the apparent and true digestibility of fat. An additional objective was to compare estimates for ELF and fat digestibility at the end of the ileum and over the entire intestinal tract.

MATERIALS AND METHODS

The animal part of this experiment was conducted at South Dakota State University (Brookings, SD). The protocol for the experiment was reviewed and approved by the Institutional Animal Care and Use Committee at South Dakota State University.

Animals, Housing, and Experimental Design

Eleven growing barrows (initial average BW of 38.1 ± 1.25 kg) were used in this experiment. Pigs were the offspring of SP-1 boars that were mated to Line 401 females (Ausgene Int. Inc., Gridley, IL). Each pig was surgically equipped with a T-cannula in the distal ileum using procedures adapted from those reported by Stein et al. (1998). Pigs were housed individually in 1.2 × 1.8 m pens that had fully slatted tri-bar floors. A feeder and a nipple drinker were installed in each pen. Room temperature was maintained at 20 to 22°C throughout the experiment. Pigs were allotted to 11 periods and 11 diets in an 11 × 11 Latin square design. Each experimental period lasted 7 d.

Diets, Feeding, and Sample Collection

Four of the 11 diets were formulated to determine the effect of the concentration of extracted fat on measured values for fat digestibility (Table 1). For this purpose, a basal diet (1.27% acid-hydrolyzed fat, DM basis) was formulated from maize-flaking grits, casein, sucrose, and cornstarch. Three diets with increasing concentrations of extracted fat were formulated by adding 2.0, 4.0, or 6.0% corn oil (as-fed basis) to the basal diet at the expense of cornstarch. The analyzed values of acid-hydrolyzed fat in these diets were 3.22, 5.14, and 6.85% (DM basis), respectively. Three additional diets were formulated to determine the effect of the concentration of NDF on measured values for fat digestibility. These diets were formulated by adding 3.10, 6.20, or 9.30% (as-fed basis) NDF from Solka-Floc (97.0% NDF; International Fiber Corp., North Tonawanda, NY) to the basal diet containing 4.0% corn oil. Solka-Floc was included in these diets at the expense of cornstarch. The basal diet was analyzed to be 2.73% NDF (DM basis), whereas concentrations of NDF in the 3 diets containing Solka-Floc were 5.78, 9.24, and 11.28% (DM basis), respectively. The remaining 4 diets were formulated to determine the effect of the concentration of intact fat on measured values for fat digestibility. These diets were prepared by adding 3.0, 6.0, or 9.0% intact fat from whole corn germ meal to a diet based on casein, maize-flaking grits, cornstarch, and defatted corn germ meal. An attempt was made to keep the concentration of NDF constant among these diets by including 2.57, 5.14, and 7.71% Solka-Floc at the expense of cornstarch in the diets containing whole corn germ meal. The concentration of defatted corn germ meal was reduced as the concentration of whole corn germ meal increased. The analyzed concentrations of acid-hydrolyzed fat were 3.03, 5.26, 7.70, and 9.74% (DM basis) in these 4 diets. Vitamins, salt, and minerals were included in all diets to meet or exceed the estimated requirements for growing pigs (NRC, 1998). Chromic oxide (0.40%) was included in all diets as an indigestible marker.

Pigs were provided a daily quantity of feed that was calculated to supply 3 times the estimated maintenance requirement for energy (i.e., 106 kcal of ME/kg$^{0.75}$; NRC, 1998) in 2 equal meals at 0800 and 1700 h. The BW of all pigs was recorded at the beginning of each experimental period, and the amount of feed supplied during the following period was calculated based on BW. The BW of all pigs was also recorded at the end of the experiment. Water was available continuously for each pig.

The initial 4 d of each period was considered a period for adaptation to the experimental diet. On d 5, fresh fecal samples were collected as often as possible throughout the day from all pigs and stored at −20°C. Ileal digesta samples were collected continuously for 9 h on d 6 and 7 into 225-mL plastic bags that were attached to the opened cannula barrel by cable ties. Bags were removed whenever they were filled with digesta, and the digesta were stored at −20°C.

Chemical Analyses

At the conclusion of the experiment, ileal and fecal samples were thawed and pooled within animal and diet and a subsample of ileal digesta was collected. These subsamples of ileal digesta and all fecal samples were dried at 60°C in a forced-air oven for 96 and 72 h, respectively. After drying, all samples were finely ground, and ground samples of diets, ileal digesta, and feces were analyzed for DM (method 4.1.06; AOAC, 2005), acid-hydrolyzed fat (Stoldt, 1952), and Cr (Fenton and Fenton, 1979). Diets were also analyzed for CP (method 4.2.08; AOAC, 2005), ADF and NDF (method 4.6.04; AOAC, 2005), and GE using bomb calorimetry (Model 1271, Parr Instruments, Moline, IL).

Calculations

The apparent ileal digestibility (**AID**) of fat was calculated for each diet (Stein et al., 2007), and the ap-

Table 1. Composition of experimental diets

	Extracted fat, %				Dietary NDF addition, %			Intact fat, %			
Item	0.00	2.00	4.00	6.00	3.00	6.00	9.00	3.00	5.25	7.50	9.75
Ingredient, % (as-fed basis)											
Casein	9.50	9.50	9.50	9.50	9.50	9.50	9.50	8.00	8.00	8.00	8.00
Maize-flaking grits	63.17	63.17	63.17	63.17	63.17	63.17	63.17	34.21	34.21	34.21	34.21
Defatted corn germ meal	—	—	—	—	—	—	—	36.60	24.40	12.20	—
Whole corn germ meal	—	—	—	—	—	—	—	—	12.20	24.40	36.60
Cornstarch	14.20	12.20	10.20	8.20	7.10	4.00	0.90	7.71	5.14	2.57	—
Corn oil	—	2.00	4.00	6.00	4.00	4.00	4.00	—	—	—	—
Sucrose	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Solka-Floc[1]	—	—	—	—	3.10	6.20	9.30	—	2.57	5.14	7.71
Limestone	0.75	0.75	0.75	0.75	0.75	0.75	0.75	1.10	1.10	1.10	1.10
Monocalcium phosphate	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Potassium carbonate	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Magnesium oxide	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin premix[2]	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Trace mineral premix[3]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Chromic oxide	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Analyzed composition, % (DM basis)											
DM	89.92	90.18	90.24	90.17	90.28	90.49	90.81	90.73	90.90	91.28	91.57
Acid-hydrolyzed fat	1.27	3.22	5.14	6.85	5.12	4.87	5.29	3.03	5.26	7.70	9.74
NDF	3.00	2.77	2.73	2.90	5.78	9.24	11.28	17.10	16.28	15.71	14.18
ADF	0.95	0.77	0.79	0.83	3.75	6.41	8.30	4.83	6.43	8.84	9.25
CP	15.4	16.0	14.1	14.8	14.9	15.3	14.6	21.6	20.3	20.2	18.0
GE	4,266	4,365	4,464	4,540	4,461	4,466	4,464	4,448	4,499	4,560	4,630
Calculated composition[4]											
ME, kcal/kg	3,378	3,467	3,555	3,643	3,431	3,308	3,184	3,268	3,523	3,779	4,035

[1]International Fiber Corp. (North Tonawanda, NY).

[2]Provided the following quantities of vitamins per kilogram of complete diet: vitamin A, 6,594 IU as vitamin A acetate; vitamin D_3, 989 IU as D-activated animal sterol; vitamin E, 33 IU as α-tocopherol acetate; vitamin K_3, 2.6 mg as menadione dimethylpyrimidinol bisulfite; thiamine, 2.0 mg as thiamine mononitrate; riboflavin, 5.9 mg; pyridoxine, 2.0 mg as pyridoxine hydrochloride; vitamin B_{12}, 0.026 mg; D-pantothenic acid, 20 mg as calcium pantothenate; niacin, 33 mg; folic acid, 0.66 mg; and biotin, 0.10 mg.

[3]Provided the following quantities of minerals per kilogram of complete diet: Cu, 16 mg as copper sulfate; Fe, 165 mg as iron sulfate; I, 0.36 mg as potassium iodate; Mn, 44 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 165 mg as zinc oxide.

[4]Calculated using the following assumptions for ME in ingredients (kcal/kg, as-fed basis): casein, 3,535; sucrose, 3,635; cornstarch, 3,985; corn oil, 8,400; whole corn germ meal, 6,131; defatted corn germ meal, 3,196; and maize-flaking grits, 3,345.

Table 2. Effect of including dietary NDF on apparent ileal digestibility (AID), apparent total tract digestibility (ATTD), true ileal digestibility (TID), and true total tract digestibility (TTTD) of fat

	Dietary NDF, g/kg of DM						*P*-value	
Item	27.3	57.8	92.4	112.8	Mean	SEM	Linear	Quadratic
AID of fat, %	87.7	86.6	87.5	87.6	87.4	0.7	0.799	0.254
ATTD of fat, %	87.9	86.3	86.0	87.0	86.9	0.7	0.186	0.043
TID of fat,[1] %	94.1	93.1	94.2	93.8	93.8	0.7	0.907	0.508
TTTD of fat,[1] %	95.3	93.8	93.7	94.1	94.3	0.7	0.145	0.130

[1]TID and TTTD of fat were calculated by correcting values for AID and ATTD for endogenous losses estimated in diets containing extracted fat.

parent total tract digestibility (**ATTD**) of fat was calculated using the same equation. True ileal digestibility (**TID**) and true total tract digestibility (**TTTD**) of fat from the 2 sources of fat (extracted and intact fat) were calculated using the regression method (Jørgensen et al., 1993). Apparently digested fat (g/kg of DMI) at the end of the ileum or over the entire intestinal tract was regressed against dietary fat intake (g/kg of DM) for each pig in each period. The Y-intercept of this regression equation was considered the ELF (g/kg of DMI), whereas the slope of the regression line represented true digestibility of fat (Jørgensen et al., 1993). The TID and TTTD of extracted fat and of intact fat were also calculated by correcting the AID and ATTD of fat for ELF (g/kg of DMI) derived from each form of fat at the end of the ileum or over the entire intestinal tract, respectively (Stein et al., 2007). The TID and TTTD of fat in diets containing added dietary NDF were calculated by correcting values for AID and ATTD for ELF (g/kg of DMI) obtained for diets containing extracted fat (Stein et al., 2007).

Statistical Analyses

Data were analyzed using the MIXED procedure (SAS Inst. Inc., Cary, NC). Homogeneity of the variance was verified using the UNIVARIATE procedure of SAS. The residual vs. the predicted plot procedure was used to identify outliers. Diet was a fixed effect and pig and period were the random effects in the model. The interaction between collection sites (ileum and total tract) and the form of fat (extracted and intact) was included in the model, but because these interactions were not significant, only main effects were included in the final model. The LSMEANS procedure was used to calculate mean values of all dietary treatments. Orthogonal polynomial contrasts were used to detect linear and quadratic responses to dietary concentrations of extracted fat, intact fat, or dietary NDF. The REG procedure of SAS was used to estimate the Y-intercept for determining ELF, and the slope was used to determine TID and TTTD for extracted fat and intact fat. Intercepts and slopes were compared between the 2 forms of fat and between sample collection sites using confidence intervals derived from the SE of the respective regression coefficients (Dilger and Adeola, 2006). The pig was the experimental unit for all analyses, and an α-value of 0.05 was used to assess differences among means.

RESULTS

All pigs remained healthy and readily consumed their diets throughout the experiment. Mean BW of pigs at the beginning and at the end of the experiment were 38.1 ± 1.3 and 97.0 ± 2.0 kg, respectively. The ADG of pigs was 0.77 kg throughout the experiment; this was considered normal because feed intake was restricted to 3 times the energy requirement for maintenance.

Because the concentration of NDF was greater for diets containing fat from corn germ than diets containing extracted fat, digestibility differences between these 2 diets are confounded with dietary concentration of NDF. Therefore, the effect of adding NDF to one of the diets supplemented with extracted fat on ileal and total tract digestibility of fat was also tested. Addition of NDF to the diet did not change the AID, TID, or TTTD of fat (Table 2), However, the ATTD of fat (87.9, 86.3, 86.0, and 87.0% for diets with 0.0, 3.0, 6.0, and 9.0% added NDF, respectively) showed a quadratic response ($P < 0.05$) to dietary NDF concentration. Although source, composition, and particle size of NDF differed between the diets supplemented with NDF and the diets containing corn germ, failure of added NDF to linearly depress AID or ATTD indicates that NDF was not directly or markedly altering the site or extent of fat digestion. Therefore, no adjustment in fat digestibility estimates for the greater concentration of NDF of the diets containing corn germ was attempted.

Values for AID (70.6, 81.9, 87.7, and 89.1%) and ATTD (66.6, 80.6, 87.9, and 88.7%) of fat increased (linear and quadratic, $P < 0.001$) as the dietary concentration of extracted fat increased (Table 3). Values for AID (52.7, 65.1, 71.1, and 70.0%) and ATTD (47.6, 57.4, 69.0, and 71.9%) of fat also increased (linear and quadratic, $P < 0.05$) as the dietary inclusion of intact fat increased. Total apparently digested fat increased (linear, $P < 0.001$) at the end of the ileum (9.0, 26.4, 45.1, and 61.0 g/kg of DMI) and over the entire intestinal tract (8.4, 26.1, 45.2, and 60.6 g/kg of DMI) as the dietary inclusion of extracted fat increased. Total apparently digested fat also increased (linear, $P < 0.001$)

at the end of the ileum (16.0, 34.3, 54.7, and 68.1 g/kg of DMI) and over the entire intestinal tract (14.4. 30.2, 53.1, and 70.0 g/kg of DMI) as the dietary inclusion of intact fat increased. The average apparent digestibility of fat was greater ($P < 0.001$) for diets containing extracted fat (81.9%) than for diets containing intact fat (63.2%), but the total quantity of apparently digested fat was less ($P < 0.05$) in diets containing extracted fat (35.1 g/kg of DMI) than in diets containing intact fat (42.9 g/kg of DMI; Table 4). However, the average AID of fat (73.6%) was not different from the average ATTD of fat (71.5), and the amount of apparently digested fat at the end of the ileum (39.3 g/kg of DMI) was not different from the amount of apparently digested fat over the entire intestinal tract (38.6 g/kg of DMI).

The estimates of ELF (Table 5) at the end of the ileum and over the entire intestinal tract were less ($P < 0.05$) when pigs were fed extracted fat (3.28 and 3.77 g/kg of DMI, respectively) than when they were fed intact fat (7.27 and 12.08 g/kg of DMI, respectively). The estimates for ELF at the end of the ileum and over the entire tract were not different when pigs were fed extracted fat, but ELF was greater ($P < 0.05$) for intact fat when determined for the entire intestinal tract than at the end of the ileum.

The true digestibility of fat, estimated from the slope of the regression equation, was greater ($P < 0.05$) for extracted fat than for intact fat at the end of the ileum (93.8 vs. 78.6%) and for the total digestive tract (94.2 vs. 84.1%). However, there was no difference between the TID and TTTD of fat within each source of fat.

The TID and TTTD at the end of the ileum and over the entire intestinal tract also were calculated for each source of fat by adjusting the AID and ATTD of extracted and intact fat for the ELF that was estimated for each source of fat (Table 6). In contrast to the effects of dietary fat concentration on AID and ATTD, increasing dietary fat had no effect on the TID or TTTD of extracted fat (96.3, 92.1, 94.1, and 93.9% and 96.2, 92.3, 95.3, and 94.2% for diets containing 1.27, 3.22, 5.14, and 6.85% extracted fat, respectively). Likewise, the effects of increasing dietary fat on TID of intact fat (76.7, 78.9, 80.5, and 77.4% for diets containing 3.03, 5.26, 7.70, and 9.74% intact fat, respectively) were not significant, but the TTTD was reduced (quadratic, $P < 0.05$) from 87.5 to 80.3, 84.7, and 84.3% as the concentration of intact fat in the diet increased.

DISCUSSION

Apparent Digestibility of Fat

Both AID and ATTD of fat increased curvilinearly as dietary fat concentration increased, regardless of the form of fat. This response agrees with previous data obtained in pigs (Just et al., 1980; Jørgensen et al., 1993) and poultry (San Juan and Villamide, 2000). The increase in AID and ATTD to a plateau as dietary fat concentration increased reflects the fact that ELF con-

Table 3. Apparent ileal digestibility (AID) and apparent total tract digestibility (ATTD) of fat and total apparently digested fat at the end of the ileum ($TADF_i$) and over the entire intestinal tract ($TADF_t$) in diets containing extracted or intact fat

Item	Extracted fat, g/kg of DM				SEM	*P*-value		Intact fat, g/kg of DM				SEM	*P*-value	
	12.7	32.2	51.4	68.5		Linear	Quadratic	30.3	52.6	77.0	97.4		Linear	Quadratic
AID of fat, %	70.6	81.9	87.7	89.1	1.1	<0.001	<0.001	52.7	65.1	71.1	70.0	1.5	<0.001	<0.001
$TADF_i$, g/kg of DMI	9.0	26.4	45.1	61.0	0.5	<0.001	0.387	16.0	34.3	54.7	68.1	0.9	<0.001	0.054
ATTD of fat, %	66.6	80.6	87.9	88.7	1.2	<0.001	<0.001	47.6	57.4	69.0	71.9	1.2	<0.001	0.020
$TADF_t$, g/kg of DMI	8.4	26.1	45.2	60.6	0.5	<0.001	0.908	14.4	30.2	53.1	70.0	0.7	<0.001	0.056

Table 4. Apparent digestibility (AD) of fat and total apparently digested fat (TADF) in diets containing extracted or intact fat

	Form of fat		Collection site			P-value[1]	
Item	Extracted fat	Intact fat	End of the ileum	Entire intestinal tract	SEM	Form of fat	Collection site
AD of fat, %	81.9	63.2	73.6	71.5	1.0	<0.001	0.160
TADF, g/kg of DMI	35.1	42.9	39.3	38.6	2.3	0.017	0.829

[1]Interaction between form of fat and collection site was not significant ($P > 0.10$).

tributes more to the total output of fat, and therefore has a greater effect on apparent digestibility of fat at smaller amounts of dietary fat than at greater amounts (Jørgensen et al., 1993). Similar effects of dietary AA on the apparent digestibility of AA and responses to ELF on total excretion of AA have been reported (Fan and Sauer, 1997).

The mean values for the apparent digestibility of extracted fat (81.9%) and of intact fat (63.2%) measured in this experiment agree with values previously reported for the digestibility of fat in corn oil (80%; Carlson and Bayley, 1968) and in corn grain (59.6%; Adeola and Bajjalieh, 1997). Greater apparent digestibility of extracted fat than of intact fat also has been reported for soybean oil (Agunbiade et al., 1992), palm kernel oil (Agunbiade et al., 1999), and sunflower oil (San Juan and Villamide, 2000).

Endogenous Losses of Fat

Apparently digested fat was linearly related to dietary fat intake at the end of the ileum and over the entire intestinal tract for extracted fat and for intact fat. The linear regression procedure is therefore appropriate to calculate ELF, TID, and TTTD for both sources of fat because linearity of the response is a prerequisite for using the regression procedure to estimate ELF and TID and TTTD of nutrients (Jørgensen et al., 1993; Fan and Sauer, 1997).

The ELF for extracted fat at the end of the ileum that was estimated in this experiment (3.28 g/kg of DMI) is close to the ELF of 4.74 g/kg of DMI reported by Jørgensen et al. (1993). Estimates of ELF for extracted fat over the entire intestinal tract have ranged from 4.4 to 22.4 g/kg of DMI for diets containing corn oil (Adams and Jensen, 1984) or soybean oil (Jørgensen et al., 1993; Jørgensen and Fernández, 2000); our value (3.77 g/kg of DMI) is close to the least value of this range. When intact fat was fed, the ELF (7.27 g/kg of DMI) at the end of the ileum was greater than the value of 2.0 g/kg of DMI that has been reported previously (Shi and Noblet, 1993). The ELF estimates for the entire intestinal tract were between 6.1 and 8.7 g/kg of DMI when high-oil corn (Adams and Jensen, 1984) or sunflower seeds (Adams and Jensen, 1985) were included in the diets. Those values are less than the estimate from this experiment (12.08 g/kg of DMI). Differences between estimates of ELF in our experiment and those reported previously may reflect the fact that the least concentration of dietary fat fed and the range in fat concentrations differed among experiments. A broad range is critical for estimating regression coefficients precisely (Dilger and Adeola, 2006). Fat sources (Freeman et al., 1968; López Bote et al., 2001), nonfat dietary components (Jørgensen et al., 1992b), and effects of the animal (Jørgensen et al., 1992a) also may influence the estimates of ELF.

The estimate of ELF at the end of the ileum and over the entire tract was greater for intact fat than for extracted fat. This likely is a result of the greater concentration of fiber in diets containing intact fat compared with diets containing extracted fat. Greater intakes of fiber can depress absorption of dietary fat and resorption of endogenous fat (e.g., bile acids) before the end of the ileum, leading to increased concentrations of ELF at the end of the ileum and over the entire intestinal

Table 5. Regression of total apparently digested fat (g/kg of DMI) at the end of the ileum and over the entire intestinal tract on dietary fat intake (g/kg of DM)[1]

Item	Regression equation	SE of the slope	SE of the intercept	r^2	Estimated ELF,[2] g/kg of DMI	Estimated true digestibility of fat, %
End of the ileum						
Extracted fat	$y = 0.938x - 3.28$	0.0117	0.531	0.99	3.28[x]	93.8[y]
Intact fat	$y = 0.786x - 7.27$	0.0179	1.245	0.98	7.27[y]	78.6[x]
Entire intestinal tract						
Extracted fat	$y = 0.942x - 3.77$	0.0140	0.637	0.99	3.77[x]	94.2[y]
Intact fat	$y = 0.841x - 12.08$	0.0156	1.083	0.99	12.08[z]	84.1[x]

[x–z]Within a column, values lacking a common superscript are different ($P < 0.05$).
[1]n = 44.
[2]ELF = endogenous losses of fat.

Table 6. True ileal digestibility (TID) and true total tract digestibility (TTTD) of fat in diets containing extracted or intact fat

Item	Extracted fat, g/kg of DM					*P*-value		Intact fat, g/kg of DM					*P*-value	
	12.7	32.2	51.4	68.5	SEM	Linear	Quadratic	30.3	52.6	77.0	97.4	SEM	Linear	Quadratic
TID of fat,[1] %	96.3	92.1	94.1	93.9	1.2	0.309	0.076	76.7	78.9	80.5	77.4	1.5	0.474	0.062
TTTD of fat,[2] %	96.2	92.3	95.3	94.2	1.2	0.554	0.190	87.5	80.3	84.7	84.3	1.2	0.371	0.008

[1]TID was calculated by correcting values for apparent ileal digestibility of fat for endogenous losses of fat at the end of the ileum (3.28 g/kg of DMI for extracted fat and 7.27 g/kg of DMI for intact fat).

[2]TTTD was calculated by correcting values for apparent total tract digestibility of fat for endogenous losses of fat over the entire intestinal tract (3.77 g/kg of DMI for extracted fat and 12.08 g/kg of DMI for intact fat).

tract (Bach Knudsen and Hansen, 1991; Smits and Annison, 1996). The greater concentration of dietary fiber may also facilitate microbial growth in the hindgut of pigs, which may increase the amount of ELF in the hindgut (Eyssen, 1973; Bach Knudsen et al., 1991). These differences may explain why ELF for intact fat was greater over the entire intestinal tract than at the end of the ileum, whereas the ELF for extracted fat was not different between collection sites.

True Digestibility of Extracted Fat and Intact Fat

The TTTD of extracted fat (94.2%) estimated in this experiment, although greater than the value for corn oil (84.7%) reported by Adams and Jensen (1984), falls within the range of values (91.2 to 97.7%) reported for the TTTD of soybean oil (Adams and Jensen, 1984; Jørgensen et al., 1993; Jørgensen and Fernández, 2000). The TID (78.6%) of intact fat that was measured in this experiment agrees with the value of 77.0% that was reported for diets containing a combination of feed ingredients (Shi and Noblet, 1993). However, the TTTD (84.1%) for intact fat in our experiment was greater than the TTTD values for fat from corn (77.6%), soybeans (72.1%), and sunflower seeds (75.0%) reported by Adams and Jensen (1984). Variation in TID and TTTD for fat among experiments may be due to differences in dietary fat intake, diet composition, diet processing, and fat sources.

The procedure used to analyze fat may also influence the calculated values for fat digestibility. If samples are analyzed using a solvent extraction procedure, some of the Ca soaps and the phospholipids may not be extracted, whereas the acid hydrolysis procedure is believed to result in a more complete fat extraction. Solvent extraction of fat without acid hydrolysis will therefore result in smaller analyzed values for fat in all samples. Because the concentration of Ca soaps likely is greater in ileal and fecal samples than in diets and feed ingredients, the underestimation of the concentration of fat in the ileal and fecal samples by the solvent extraction procedure is greater than for diet samples, which results in greater calculated digestibility values. In the present experiment, the acid hydrolysis procedure was used, which may therefore have resulted in smaller digestibility values compared with experiments in which samples were analyzed without using acid hydrolysis.

The greater true digestibility of extracted fat compared with intact fat at both collection sites implies that the greater apparent digestibility of extracted fat was not due simply to the smaller amount of ELF for extracted fat. Instead, the greater true digestibility of extracted fat indicates that extracted fat has physiochemical properties that make it easier for pigs to digest and absorb extracted fat than intact fat. Intact fat is encased with fat cell membranes and thus is more resistant to the formation of emulsions and enzymatic digestion than extracted fat (Adams and Jensen, 1984;

Bach Knudsen et al., 1993); these physical restrictions may explain why TID and TTTD were smaller for intact fat than for extracted fat.

Although the apparent digestibility of fat increased as the concentration of dietary extracted or intact fat increased, the true digestibility of fat was not changed by the dietary concentration of fat over the range of fat additions that were used in this experiment. The reason for this observation is that ELF affects apparent digestibility, but not the true digestibility of fat. These results therefore support the hypothesis that the TTTD of a fat source remains constant across various amounts of dietary fat intake (Freeman et al., 1968; Adams and Jensen, 1984).

The different digestibility values for extracted and intact fat that were observed in the present experiment will likely result in different ME and NE values to pigs for extracted and intact fat. One of the implications of this observation is that TID or TTTD values for fat in a diet likely are more accurate in predicting the ME or NE of that diet than values for total fat.

Ileal vs. Total Tract Digestibility of Fat

Apparent digestibility of fat was not different between the end of the ileum (73.6%) and the total digestive tract (71.5%). This observation contrasts with results showing that the ATTD of fat is less than the AID of fat because of a net synthesis of fat in the hindgut of pigs (Shi and Noblet, 1993; Bakker, 1996). This difference may be a result of different concentrations and sources of dietary NDF in the previous experiments compared with the present experiment. Dietary fiber may increase the synthesis of endogenous fat by microbes in the hindgut of pigs, which in turn will increase ELF in the hindgut and reduce the ATTD of fat. In the present experiment, an attempt to quantify this effect was made, but because no effect on fat digestibility of the purified NDF from Solka-Floc was obtained, it was not possible to quantify the effects of fiber on endogenous fat synthesis. Possible reasons for this response may be that purified fiber does not stimulate microbial fat synthesis to the same degree as natural fiber does because unlike Solka-Floc, natural feed ingredients contain several forms of fiber. In addition, diets used in the present experiment were semipurified, so the supply of energy and nutrients reaching the hindgut for microbial digestion was likely less than if nonpurified diets had been used. Nevertheless, results of this experiment indicate that dietary fat is digested and absorbed before the end of the ileum, and differences between AID and ATTD of fat were caused mainly by microbial synthesis of endogenous fat in the hindgut of pigs. This observation agrees with conclusions from Low (1980) and Drackley (2000). Hence, dietary components that increase microbial activity and microbial synthesis of fat in the hindgut will increase ELF and reduce the ATTD relative to AID. Values for AID therefore more accurately reflect the digestibility of dietary fat and the availability of fatty acids than values for ATTD. Ileal ELF estimates also provide a more reliable estimate of the inevitable fat losses in the digestive tract of pigs than estimates for total tract ELF. However, because fecal fat produced by intestinal microbes represents a loss of energy that is derived from the feed or from endogenous secretions, total tract energy balance should be based on the total fecal loss of fat and not on the ileal loss.

Effect of Purified Dietary NDF on Apparent and True Digestibility of Fat

Addition of increasing amounts of purified NDF did not change values for AID, TID, and TTTD of fat, but a small quadratic response in the ATTD of fat was observed. These results differ from previous reports showing that an increased supply of dietary NDF decreases the apparent digestibility of fat (Just et al., 1980; Bakker, 1996; Hansen et al., 2006). The depression in fat digestibility often reported as the dietary concentration of fiber is increased may be associated more closely with characteristics of the fiber (e.g., viscosity) than with its dietary concentration (Fahey et al., 1990; Smits and Annison, 1996). The purified NDF (isolated cellulose) used in this experiment may interact less with microbes in the intestinal tract than would natural NDF (Schulze et al., 1995), possibly because of the simplified physicochemical structure of purified NDF and its composition being largely cellulose, rather than more readily fermentable hemicellulose. Therefore, purified NDF may have a less stimulatory effect on microbial growth in the hindgut and production of ELF and may have a less depressive effect on apparent and true digestibility of fat than natural NDF (Sambrook, 1979).

Conclusions

Results from this experiment indicate that extracted fat induces a smaller ELF and has a greater apparent and true digestibility than intact fat at the end of the ileum and over the entire intestinal tract. The amount of ELF induced by intact fat is less at the end of the ileum than over the entire intestinal tract, possibly because dietary fiber results in extra microbial activity and synthesis of endogenous fat in the hindgut. Apparent digestibility of fat and true digestibility of fat at the end of the ileum and over the entire intestinal tract were similar, which indicates that there was no net absorption of fat in the hindgut of pigs. Purified dietary NDF had little influence on apparent and true digestibility of fat.

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