Effects of chemical hydrogenation of supplemental fat on relative apparent lipid digestibility in finishing swine[1,2]

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ABSTRACT: Four experiments were conducted to evaluate lipid digestibility in finishing swine fed chemically hydrogenated fats. Dietary chromic oxide was used as an inert marker to measure the apparent digestibility of supplemental fat (SF) that consisted of fully hydrogenated (FH), partially hydrogenated (PH), or PH products blended with other fat sources. In Exp. 1, diets containing 5% SF (as-fed basis) comprising 100, 66.7, 33.3, or 0% FH animal fat (iodine value = 2.5), with the balance contributed by soy oil, were fed to gilts (n = 24). Apparent digestibility increased linearly (−12.0, 26.0, 61.2, and 72.6%; $P < 0.001$) as the amount of FH fat in the diet decreased, suggesting the digestibility of FH to be near zero. Experiment 2 (2 × 4 factorial; n = 48) evaluated diets containing 5% (as-fed basis) blended fat (FH tallow and yellow grease) to achieve iodine values of 20, 30, 40, or 50 compared with PH tallow with identical iodine values. Digestibility of diets formulated with PH tallow was greater than those containing blended fat (73.4 vs. 67.2%; $P < 0.01$), especially at lower iodine values (interaction; $P < 0.10$). In Exp. 3, digestibility was measured in pigs (n = 96) fed 5% (as-fed basis) PH choice white grease with iodine values of 20, 40, 60, or 80. Increasing iodine value did not alter digestibility (66.2, 69.2, 68.2, and 69.7%). Experiment 4 investigated digestibility (n = 32) of diets formulated with 8% (as-fed basis) PH fat (iodine value 20 or 50) with 0.10% lysolecithin as an emulsifier. Lipid digestibility was 14.5% greater in the 8% SF diet with an iodine value of 50 compared with the diet with an iodine value of 20 (79.15 vs. 69.12%; $P < 0.001$), but lysolecithin was without effect. These experiments indicate that partial hydrogenation is superior to blending unsaturated fat with saturated fat sources and that digestibility is not greatly affected by decreasing the iodine value via partial hydrogenation.

Key Words: Digestibility, Supplemental Fat, Swine, Triglyceride

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J. Anim. Sci. 2005. 83:1890–1898

Introduction

The combination of extreme leanness in pigs and diets composed of ingredients that contain PUFA can result in soft fat composition of pork carcasses (Averette Gatlin et al., 2002). Indeed, the fatty acid profile of pork carcass fat reflects the relative contribution of each dietary fat source as well as the fatty acids from de novo lipogenesis (Seerley et al., 1978; Miller et al., 1990; Madsen et al., 1992). Therefore, supplementation of swine diets with saturated fats should decrease the PUFA content and soft fat characteristics of pork. Nonetheless, only a small volume of tallow and other saturated fats are locally available in Southeastern states; thus, substantial supplies of highly unsaturated restaurant grease are used in swine diets in this region (Hansen, 2001). We sought an alternative to the use of saturated animal fats that would be more widely available geographically.

Catalytic hydrogenation has been used for over a century to convert vegetable oils to semisolid fats by reducing the PUFA content (Emken, 1984). Because hydrogenation can modify the melting point of fats, digestibility of chemically altered fats is a concern. In addition, the process may alter fatty acids without regard to location on the glyceride backbone. This difference has the potential to affect digestibility because fatty acids are preferentially hydrolyzed by pancreatic lipase at the 1- and 3-position of triacylglycerols, with little hydrolysis of the fatty acid at the 2-position (Brindley, 1984). Thus, our objectives were to evaluate the digestibility of hydrogenated fat supplements varying in degree of saturation and to evaluate the effects of adding emulsifier to

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[1] This research was supported in part by the North Carolina Agricultural Research Service of North Carolina State Univ., the National Pork Producers Council, Murphy Farms, Kemin Industries, Carolina By-Products, and Smithfield Foods.

[2] The authors thank S. Patel, S. Gillis, L. Xi, and G. Matsey for their assistance in implementing and supporting this study.

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Received July 9, 2004.

Accepted April 18, 2005.

Table 1. Composition of diets in Experiment 1, as-fed basis

	Soy oil, %			
Item	100	66.7	33.3	0
Ingredient, %				
Corn	76.10	76.10	76.10	76.10
Soybean meal, 48% CP	16.60	16.60	16.60	16.60
Soy oil	5.00	3.33	1.67	—
Hydrogenated fat	—	1.67	3.33	5.00
Limestone	0.95	0.95	0.95	0.95
Dicalcium phosphate, 21% P	0.69	0.69	0.69	0.69
Salt	0.38	0.38	0.38	0.38
L-Lysine HCl	0.13	0.13	0.13	0.13
Chromic oxide	0.10	0.10	0.10	0.10
Trace mineral premix[a]	0.05	0.05	0.05	0.05
Vitamin premix[b]	0.05	0.05	0.05	0.05
Antibiotic[c]	0.025	0.025	0.025	0.025
Selenium premix[d]	0.025	0.025	0.025	0.025
Calculated composition				
ME, kcal/kg	3,584	3,443	3,304	3,164
Linoleic acid, %	4.11	3.26	2.41	1.56
CP, %	14.2	14.2	14.2	14.2
Lysine, %	0.82	0.82	0.82	0.82
Ca, %	0.58	0.58	0.58	0.58
P, total, %	0.46	0.46	0.46	0.46

[a] Provided the following per kilogram of complete diet: 83.35 mg of Zn as ZnO; 83.35 mg of Fe as $FeSO_4$; 14.15 mg of Mn as MnO; 10.1 mg of Cu as $CuSO_4$; 35 μg of I; and 15 μg of Se.

[b] Provided the following per kilogram of complete diet: 1,134 IU of vitamin A; 170 IU of vitamin D_3; 4.54 IU of vitamin E; 567 μg of vitamin K; 4.1 μg of vitamin B_{12}; 0.68 mg of riboflavin; 3.18 mg of D-pantothenate; 4.54 mg of niacin; and 1.37 mg of menadione.

[c] Stafac: provided 22 mg/kg of virginiamycin.

[d] Each kilogram provided 600 mg of Se.

maximize the nutritional value of chemically modified animal fat to improve carcass fat quality.

Materials and Methods

Experiment 1

Market gilts (n = 24) from PIC 406 sires by PIC C22 dams were delivered to the North Carolina Swine Evaluation Station at 62 ± 0.8 kg. Animals were fed a diet (Table 1) containing 5% soy oil for 3 wk before allotment (average 80 kg). After adaptation, pigs were blocked by initial BW and allotted (one per pen) to one of four diets varying in PUFA content for 8 wk. All diets contained 5% added fat, composed of 100, 66.7, 33.3, or 0% soy oil (Cargill Inc., Fayetteville, NC). The balance was provided by fully hydrogenated tallow (Patrick Cudahy, Cudahy, WI), which was mixed into the diet separately from the oil (Table 2). Diets were formulated to contain 0.82% lysine and 3,584 kcal of ME/kg.

Experiment 2

Barrows and gilts (n = 48; n = 6 per treatment) were delivered to the North Carolina State Swine Educational Unit and allowed 1 wk to acclimate to the facility. Pigs (80 ± 1.1 kg) were individually housed, blocked by gender, and assigned randomly to one of eight dietary treatments according to a 2 × 4 factorial arrangement of treatments in a randomized complete block design. Dietary treatments (Table 3) varied in iodine value and hydrogenation method and were fed for 6 wk. Diets contained 5% supplemental fat with an iodine value of 20, 30, 40, or 50, which was reached by partial hydrogenation of tallow or by blending a fully hydrogenated fat (tallow; iodine value = 2.5) with an unsaturated fat (yellow grease). Fatty acid composition of supplemental fats is shown in Table 4.

Table 2. Analyzed fatty acid composition (wt %) of the fat sources used in Exp. 1

Fatty acid	Soy oil	Hydrogenated fat
C16:0	10.50	30.12
C18:0	3.20	56.61
C18:1	22.30	2.17
C18:2	54.50	0.39
C18:3	8.30	ND[a]
Other[b]	1.20	10.88
Iodine value	132.00	2.50
Saturates, %	13.90	88.83
Monounsaturates, %	22.30	2.38
Polyunsaturates, %	62.80	0.39
Unsaturate:saturate ratio	6.12	0.03

[a] ND = not detected

[b] Comprised 3% or less of each of the following fatty acids: 8:0, 10:0, 12:0, 14:0, 14:1, 16:1, 20:0, 20:1*cis*, and 20:2.

Table 3. Composition of diets in Experiment 2, as-fed basis

Item	
Ingredient, %	
Corn	72.97
Soybean meal, 48% CP	19.30
Fat blend[a]	5.00
Limestone	1.04
Dicalcium phosphate, 21%	0.76
Salt	0.40
L-Lysine HCl	0.14
Chromic oxide[b]	0.24
Trace mineral premix[c]	0.05
Vitamin premix[d]	0.05
Antibiotic[e]	0.025
Selenium premix[f]	0.025
Calculated composition	
ME, kcal/kg[g]	3,148 to 3,532
Lysine, %	0.83
Ca, %	0.62
P, total %	0.48

[a] Supplemental fats were provided by Carolina By-Product Resources (Greensboro, NC) and added (total of eight diets) from one of the following sources: partially hydrogenated tallow with an iodine value (IV) of 20, 30, 40, or 50; or fully hydrogenated tallow blended with an unsaturated fat (yellow grease) to achieve an IV of 20, 30, 40, or 50 (fatty acid composition shown in Table 4).

[b] Chromic oxide was added as an inert marker for digestibility determination.

[c] Provided the following per kilogram of complete diet: 83.35 mg of Zn as $ZnSO_4$; 83.35 mg of Fe as $FeSO_4$; 14.15 mg of Mn as MnO; 10.1 mg of Cu as $CuSO_4$; 35 μg of I as ethylenediamine dihydroiodine; and 15 μg of Se as Na_2SeO_3.

[d] Provided the following per kilogram of complete diet: 5,510 IU of vitamin A; 830 IU of vitamin D_3; 22.05 IU of vitamin E; 2.76 mg of vitamin K; 9.85 μg of vitamin B_{12}; 0.31 mg of riboflavin; 15.43 mg of D-pantothenate; and 22.05 mg of niacin.

[e] Stafac: provided 11 mg/kg of virginiamycin.

[f] Each kilogram provided 600 mg of Se as Na_2SeO_3.

[g] The range of ME values represents the calculated range in which the 5% supplemental fat diets fall. Values were computed from tabulated ingredient compositions as published by the NRC (1998).

Experiment 3

Barrows and gilts (n = 96; 76.8 ± 0.8 kg; one per pen) were fed 5% choice white grease (partially hydrogenated to an iodine value of 20, 40, 60, or 80) for 52 d according to a 4 × 2 × 2 factorial randomized complete block design involving two genders, two genotypes (PIC vs. National Pig Development), and four diets (Table 5). The study was blocked according to initial BW and location within the building. The diets were formulated to 0.79% lysine and 3,573 kcal of ME/kg. Detailed fatty acid profiles of all supplemented fats are shown in Table 6.

Experiment 4

Thirty-two gilts (n = 8 per treatment; 113.5 ± 1.5 kg) were allotted randomly (one per pen) to one of four dietary treatments (Table 7) for a period of 19 d. Diets were formulated to contain 8% supplemental fat from partially hydrogenated choice white grease with an iodine value of 30 or 50 (fatty acid composition shown in Table 8). Emulsifier was added to two of the diets in the form of 0.10% lysolecithin (Lysoforte PC, Kemin Industries, Inc.) at the expense of corn.

Live Animal Care and Measurements

All animal procedures were approved by the Institutional Animal Care and Use Committee of North Carolina State University. Pigs and feeders were weighed at the start and end of the experiments, and feed allotments were weighed daily to determine ADG, ADFI, and G:F. Feed and water were available ad libitum for all experiments.

Digestibility Determination

Diets contained chromic oxide (ranging from 0.10 to 0.24%) as a digestibility marker, which was included

Table 4. Fatty acid composition (wt %) of supplemental fats varying in iodine value (IV) achieved by blending or partial hydrogenation (Exp. 2)

	Blend (fully hydrogenated tallow and yellow grease)				Partially hydrogenated tallow (PHT)			
Fatty acids	IV 20	IV 30	IV 40	IV 50	IV 20	IV 30	IV 40	IV 50
C14:0	2.47	2.34	1.80	1.44	3.42	3.79	6.52	2.40
C16:0	28.47	27.02	24.85	23.48	25.45	25.43	27.79	24.51
C16:1	1.12	1.64	1.69	1.98	1.21	2.46	5.07	3.68
C18:0	48.54	41.99	39.31	31.78	42.61	31.66	14.93	15.11
C18:1	11.40	17.67	21.82	29.68	18.84	27.65	30.10	43.06
C18:2	3.68	5.61	6.26	7.86	0.34	0.60	3.40	4.95
C18:3	0.21	0.34	0.34	0.38	0.00	0.00	0.00	0.00
Other[a]	4.11	3.39	3.93	3.40	8.13	8.41	12.19	6.29
Calculated IV[b]	20.60	31.90	39.70	51.00	18.90	28.00	40.00	52.00
Saturates, %	79.48	71.35	65.96	56.70	71.48	60.88	49.24	42.02
Monounsaturated, %	12.52	19.31	23.51	31.66	20.05	30.11	35.17	46.74
Polyunsaturated, %	3.89	5.95	6.60	8.24	0.34	0.60	3.40	4.95
Unsaturate:saturate ratio	0.21	0.35	0.46	0.70	0.29	0.50	0.78	1.23

[a] Comprised 3% or less of each of the following fatty acids: 8:0, 10:0, 12:0, 14:1, 20:0, 20:1*cis*, and 20:2.

[b] Calculated using the following equation: IV = C16:1 (0.95) + C18:1 (0.86) + C18:2 (1.732) + C18:3 (2.616) + C20:1 (0.785) + C22:1 (0.723); AOCS (1998).

Table 5. Composition of diets in Experiment 3, as-fed basis

Item	
Ingredient, %	
Corn	77.66
Soybean meal, 48% CP	15.35
Partially hydrogenated fat (Iodine value 80, 60, 40, or 20)	5.00
Limestone	0.51
Defluorinated phosphate, 18% P	0.92
Salt	0.27
L-Lysine HCl, 78.8% lysine	0.13
Vitamin/Trace mineral premix[a]	0.14
Antibiotic[b]	0.025
Calculated composition	
ME, kcal/kg	3,573
Lysine, %	0.79
Linoleic acid, %	2.16
Ca, %	0.55
P, total %	0.49

[a] Supplied per kilogram of complete diet: 5,535 IU of vitamin A as retinyl acetate; 1,110 IU of vitamin D_3; 22 IU of vitamin E as DL-α-tocopherol acetate; 2 mg of vitamin K as menadione dimethylpyrimidinol bisulfite; 165 mg of choline as choline chloride; 22 mg of niacin; 17.6 mg of D-pantothenic acid as DL-calcium pantothenate; 4.4 mg of riboflavin; 1.1 mg of pyridoxine as pyridoxine-HCl; 0.57 mg of thiamine as thiamine mononitrate; 22 μg of vitamin B_{12}; 0.34 mg of folic acid; 38.8 μg of D-biotin; 110 mg of Zn as $ZnSO_4$; 110 mg of Fe as $FeSO_4$; 22 mg of Cu as $CuSO_4$; 55 mg of Mn as MnO; 0.28 mg of iodine as ethylenediamine dihydriodine; and 0.30 mg of Se as Na_2SeO_3.

[b] BMD60: supplied 18.5 mg of bacitracin methylene disalicylate per kilogram of diet.

Table 7. Composition of diets in Experiment 4, as-fed basis

Item	
Ingredient, %	
Corn	74.03
Soybean meal, 48% CP	15.06
Hydrogenated fat, IV 30 or IV 50[a]	8.0
Limestone	0.92
Dicalcium phosphate, 21% P	1.02
Salt	0.35
L-Lysine HCl	0.15
Vitamin/TM premix[b]	0.25
Antibiotic[c]	0.025
Chromic oxide[d]	0.10
Emulsifier, lysolecithin	0.10
Calculated composition	
ME, kcal/kg	3,684
Lysine, %	0.79
Ca, %	0.62
P, total %	0.50

[a] Supplemental fat was added as choice white grease hydrogenated to an iodine value (IV) of 30 or 50.

[b] Provided the following per kilogram of complete diet: 352 mg of Cu as $CuSO_4$, 110 mg of Fe as $FeSO_4$, 55 mg of Mn as MnO, 110 mg of Zn as $ZnSO_4$, 3 mg of Se as Na_2SeO_3, 2.8 mg of I as ethylenediamine dihydriodine, 5.54 kIU of vitamin A, 1.11 kIU of vitamin D_3, 22.05 IU of vitamin E, 2.05 mg of menadione, 38.75 μg of biotin, 165 mg of choline, 0.34 mg of folic acid, 22 mg of niacin, 17.5 mg of pantothenic acid, 1.13 mg of pyridoxine, 4.4 mg of riboflavin, 0.57 mg of thiamine, and 21.83 μg of vitamin B12.

[c] Stafac: provided 11 mg/kg of virginiamycin.

[d] Chromic oxide was added as an inert marker for digestibility determination.

in the diets for a period of 5 to 7 d before fecal collection. Digestibility was calculated using the marker-ratio method in all experiments. Due to inherent limitations of the marker-ratio method using chromic oxide to determine apparent digestibility (Jagger et al., 1992), we have used this method primarily to describe relative relationships between treatments, and we do not intend for the resulting numerical values to be considered as exact digestibility values for those fat sources. Fecal grab samples were collected from one pig per pen by removing the pig from the pen for 15 to 30 min. The

Table 6. Fatty acid composition (wt %) of partially hydrogenated choice white grease in Exp. 3

	Iodine values			
Fatty acids	20	40	60	80
16:0	25.79	24.40	23.82	23.11
16:1 *cis*	0.46	0.41	0.30	0.26
18:0	51.27	30.73	13.95	8.94
18:1 *trans*	11.46	18.41	10.37	1.16
18:1 *cis*	8.59	22.62	37.54	33.15
18:2	ND	0.31	7.68	28.91
18:3	ND	0.15	ND	0.44
Other[a]	2.43	2.97	6.34	4.03
Calculated iodine value[b]	18.7	38.5	57.6	85.4
Saturated, %	79.26	57.83	43.68	35.11
Monounsaturated, %	20.74	41.71	48.64	35.54
Polyunsaturated, %	0.0	0.46	7.68	29.35
Unsaturate:saturate ratio[c]	0.26	0.73	1.29	1.85

[a] Comprised 3% or less of each of the following fatty acids: 8:0, 10:0, 12:0, 14:0, 14:1, 20:0, 20:1, and 20:2.

[b] Calculated using the following equation: C16:1 (0.95) + C18:1 (0.86) + C18:2 (1.732) + C18:3 (2.616) + C20:1 (0.785) + C22:1 (0.723); AOCS (1998).

[c] Weight ratio of unsaturated (monounsaturated fatty acids + polyunsaturated fatty acids) to saturated fatty acids.

Table 8. Fatty acid composition (wt %) of fats with iodine values (IV) of 30 or 50 (Exp. 4)

Fatty acids	IV 30	IV 50
C14:0	3.28	2.64
C16:0	25.08	22.25
C16:1	0.6	3.4
C18:0	37.11	12.35
C18:1	25.53	39.25
C18:2	0.45	6.68
C20:0	0.89	0.24
C18:3	nd	0.37
Other[a]	9.06	12.82
Calculated IV[b]	21.87	50.17
Saturates, %	68.18	39.42
Monounsaturated fatty acids, %	24.68	44.06
Polyunsaturated fatty acids, %	0.45	7.05
Unsaturate/Saturate ratio	0.37	1.30

[a] Comprised 3% or less of each of the following fatty acids: 12:0, 13:0, 14:1, 20:1*cis*, 22:0, and 22:1.

[b] Calculated using the following equation: IV = C16:1 (0.95) + C18:1 (0.86) + C18:2 (1.732) + C18:3 (2.616) + C20:1 (0.785) + C22:1 (0.723) (AOCS, 1998).

samples were collected from each pig over three consecutive days. Samples were composited by animal, dried at 55°C for 48 h, and analyzed for Cr concentration by atomic absorption spectrophotometry according to Williams et al. (1962) and for total fat by ether extraction (AOAC, 1996). Acid was added to the ether for extraction of fecal samples to solubilize mineral fatty acid soaps (Skuhija and Palmquist, 1988). Feed samples also were obtained from each feeder and analyzed for Cr and total fat by the same procedures.

Fatty Acid Analysis

Lipids from supplemental fat samples were isolated and extracted in duplicate following the method of Averette Gatlin et al. (2002). Methyl ester standards were used to identify sample FAME. Integration software (Millenium, Waters, Inc.) was used to calculate the proportion of each fatty acid present. Iodine value was calculated using the following equation (AOCS, 1998): iodine value = C16:1 (0.95) + C18:1 (0.86) + C18:2 (1.732) + C18:3 (2.616) + C20:1 (0.785) + C22:1 (0.723).

Statistical Analyses

All analyses were conducted using the GLM procedure of SAS (SAS Inst., Inc., Cary, NC). Least squares treatment means were obtained assuming fixed models that included the effects of block and treatment (with orthogonal polynomial contrasts) for Exp. 1, and the effects of block, iodine value, hydrogenation method, and iodine value × hydrogenation method interaction for Exp. 2. In Exp. 3 the model included block, diet, gender, and genotype and their interactions. Contrasts were used to test linear and quadratic effects of diets. In Exp. 4, the model included iodine value and emulsifier treatment. Unless otherwise noted, treatments were considered significantly different at $P < 0.05$.

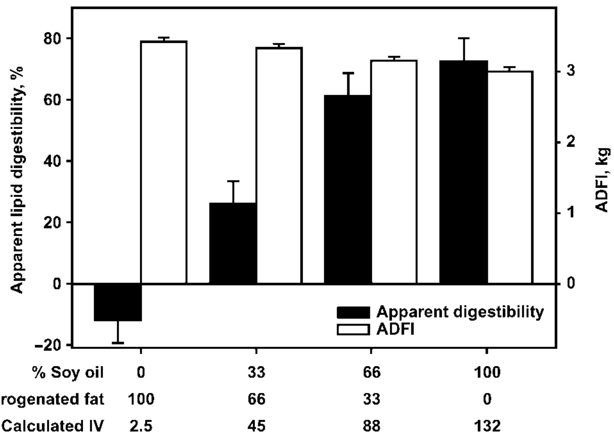

Figure 1. Apparent digestibility of dietary fat composed of fully hydrogenated animal fat combined with soy oil and ADFI (as-fed basis; Exp. 1). Linear effect for digestibility ($P < 0.001$) and for feed intake ($P < 0.05$). Values are means for six pigs per treatment. Error bars represent SEM. See Table 4 for iodine value (IV) computational formula.

Results

Experiment 1

As the amount of fully hydrogenated animal fat in the diet decreased, digestibility increased linearly ($P < 0.001$; Figure 1). The ADFI increased linearly (from 2.8 to 3.3 kg/d) as the proportion of saturated fat in the diet increased (from 0 to 100% of the supplemented fat), suggesting that the fully hydrogenated fat was poorly digested (Figure 1). In further support of this suggestion, G:F decreased linearly (from 0.31 to 0.26; $P < 0.05$); however, growth rates were not affected (see Averette Gatlin et al., 2002).

Experiment 2

Table 4 shows that for any given iodine value, the blended fats were higher in saturated fatty acids, but also higher in PUFA than the corresponding partially hydrogenated tallow, despite similar iodine values. In each case, the partially hydrogenated tallow had a correspondingly higher concentration of monounsaturated fatty acids. Apparent lipid digestibility of diets (Figure 2) containing partially hydrogenated tallow was 9.2% greater than the corresponding diets containing blended fats ($P < 0.01$). Furthermore, there was a tendency for digestibility to decrease with decreasing iodine value in blended fats. In contrast, over the range of iodine values studied, we were unable to detect any effect of decreasing iodine value on the fat digestibility of diets containing partially hydrogenated fat (interaction trend; $P < 0.10$). Average daily gain (0.97 kg), ADFI (2.49 kg), and G:F (0.39) did not differ among pigs receiving feed that contained partially hydrogenated fat or fat blended to iodine values ranging from 20 to 50.

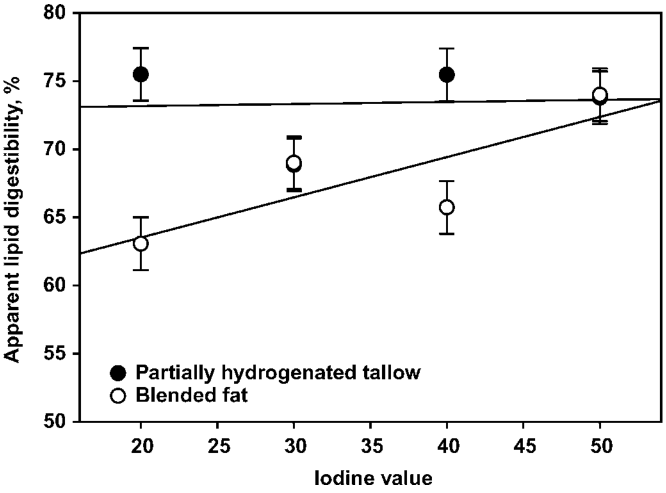

Figure 2. Apparent digestibility of partially hydrogenated tallow (PHT) or a fat blend (fully hydrogenated tallow blended with yellow grease in Exp. 2. PHT > blended fat, $P < 0.01$; interaction trend, $P < 0.10$. Blended fats were prepared by blending a mixture of fully hydrogenated tallow with yellow grease. Values are means for six pigs per treatment. Error bars represent SEM.

Experiment 3

A decrease in lipid digestibility was not detected as the iodine value of supplemental fat was decreased (Figure 3). In this experiment, increasing the saturation of the partially hydrogenated animal fat did not affect ADG (1.07 kg), ADFI (3.05 kg), or G:F (0.35). No differences due to genotype or gender were observed.

Experiment 4

Digestibility was 14.5% greater in the diet containing 8% supplemental fat with an iodine value of 50 compared with the diet supplemented with fat with an iodine value of 30 ($P < 0.001$; Table 9) and the diet saturated fatty acid content was 43% lower in the diet with an iodine value of 50. This improvement in the digestibility of the less saturated fat (iodine value 50) contrasted with the results of Exp. 3, which showed no detectable effect of iodine values within this range. The difference in fat digestibility in this study (Exp. 4) without congruent changes in growth and performance could be due to the shorter duration of the study (19 d). Moreover, the previous study evaluated performance on 240 animals (see Averette Gatlin et al., 2003), whereas this experiment evaluated only 32 pigs, which would greatly decrease the ability to detect statistical differences in growth. Furthermore, emulsifier addition did not affect ADG (1.03), ADFI (3.12 kg), G:F (0.33), or digestibility (Table 9).

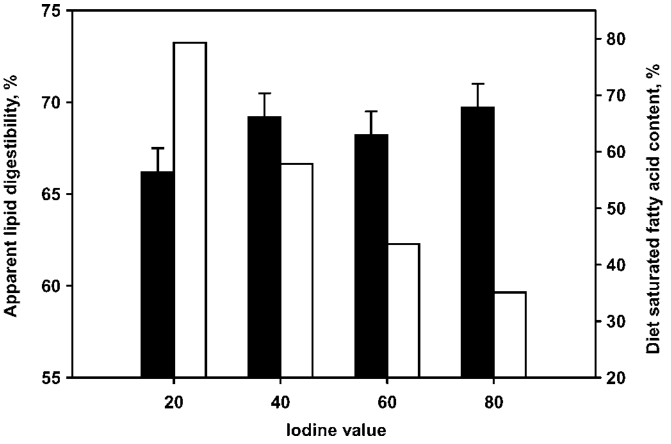

Figure 3. Apparent digestibility of partially hydrogenated animal fat and dietary saturated fatty acid content in Exp. 3. Values are means for 24 pigs per treatment. Error bars represent SEM.

Discussion

Because the fatty acid content of pork carcasses is reflective of the relative contribution of each fatty acid source, increasing the saturated fatty acid content of the diet can increase the saturated fatty acid content of the carcass (Averette Gatlin et al., 2002), which in turn may have favorable effects on pork processing characteristics. Nonetheless, saturated fats are known to be less well digested (Stahly, 1984; Wiseman et al., 1991; Azain, 2001). Therefore, this series of experiments was designed to evaluate the digestibility of an alternative fat source: chemically hydrogenated animal fat.

The hydrogenation process has been used for many years to convert liquid oils to semisolid fats (Emken, 1984). Basic steps in the hydrogenation process include pumping of source fat or oil into the heated reaction vessel, addition and mixing of the catalyst material (typically nickel) with the oil, pumping in hydrogen, and lastly hydrogen removal, catalyst filtration, and clean-up of the final product (Bockisch, 1998). The reaction temperature, time, catalyst type and specificity, and hydrogen pressure are several of the factors that may be altered to lead to different types of products or product properties. The resulting fat products have an altered fatty acid composition due to saturation of double bonds and isomerization that can occur during the process. One crude method used to describe the saturation level of fat products is iodine value, defined as grams of iodine bound per 100 g of fat. A fat with a low iodine value is more saturated than a fat with a high iodine value. Because the iodine value does not distinguish between the location of the double bonds or degree of isomerization, it is possible to have two fats with the same iodine value that are structurally different because of the intramolecular distribution and location of the double bonds. For example, one triacylglycerol can have two saturated fatty acids and one highly unsaturated fatty acid, whereas another triacylglycerol could have three monounsaturated fatty acids, yet both

Table 9. Effect of emulsifier (lysolecithin) addition on apparent lipid digestibility of diets containing 8% partially hydrogenated fat with iodine values (IV) of 30 or 50[a]

	IV 30		IV 50		
Item	− Emulsifier	+ Emulsifier	− Emulsifier	+ Emulsifier	Pooled SEM
Apparent lipid digestibility, %[b]	69.51	68.73	79.01	79.28	2.74

[a] Values are means for eight pigs per treatment.
[b] Iodine value main effect, $P < 0.001$.

could have identical iodine values. Thus, two fats with similar iodine values could vary considerably in digestibility. We examined this possibility in Exp. 2 by comparing the digestibility of fats that were partially hydrogenated to a desired iodine value or created by blending an unsaturated source of triglycerides with a fully hydrogenated triglyceride source to achieve the same endpoint iodine value. This difference has the potential to affect digestibility because fatty acids are preferentially hydrolyzed by pancreatic lipase at the 1 and 3 position of triacylglycerols, with little hydrolysis of the fatty acid at the 2 position (Brindley, 1984). Despite this, however, Emken (1984) discussed several studies on absorption in animals and humans and concluded that consumption of hydrogenated oils with altered melting points, double-bond positions, configurations, and *cis*/*trans* positional isomers did not affect absorption.

In contrast to previous reports, our studies revealed that complete saturation of animal fat by chemical hydrogenation clearly produced an indigestible fat supplement (Exp. 1). This fat source was hydrogenated almost completely, unlike the partially hydrogenated fats used in the subsequent experiments. The fatty acid composition (Table 2) would indicate that this fat product had a melting point greater than body temperature, which was supported by evidence of visible fat flakes found in the fecal material of pigs from Exp. 1. Tullis and Whittemore (1980) evaluated the digestibility of fully hydrogenated tallow in growing pigs. The tallow supplemented in that study was provided in flake form, which can be handled easily compared with liquid fats when mixing diets. Pigs were fed diets containing 5% fully hydrogenated tallow for a 10-d period compared with pigs receiving diets that did not contain the tallow. Fecal ether extracts from pigs consuming the fat flakes were significantly higher, and these authors also observed undigested flakes in the fecal material. Tullis and Whittemore (1980) concluded that the high proportion of C18:0 fatty acid in the hydrogenated tallow was likely responsible for the poor digestibility. Bailey and Lewis (1965) measured fat digestibilities of 30 to 40% when feeding a completely hydrogated fat (containing long-chain fatty acids). However, detailed examination of the fatty acid content of the supplemented fats indicates that the fats that were supposed to be saturated (tristearin) also contained unsaturated fatty acids. Bailey and Lewis (1965) recognized this and cited the work of Renner and Hill (1961), indicating that the digestibility of free palmitic and stearic acids are −1 and −2%, respectively. The difference between their results and the −12% digestibility for the fully hydrogenated fat diet in our study is likely due to inherent limitations of the marker ratio method using chromic oxide to determine apparent digestibility (Jagger et al., 1992). The method is reasonable for measuring relative differences among treatments, especially because we also were interested in performance data that would be applicable to the commercial industry. As noted by de Souza et al. (1995), other methods such as total collection and apparent ileal digestibility do not allow for accurate measures of performance.

To examine further the implications of an apparent negative digestibility, we considered situations that might result in a greater fecal fat content than the dietary fat content. Several possibilities exist that would lead to such an endogenous fat loss including decreased reabsorption of bile fatty acids and normal sloughing of intestinal endothelium. Another possibility described by Jorgenson et al. (2000) is that fat digestibilities change with the level of dietary fat due to changes in the ratio of dietary intake to endogenous loss; however, the actual intake for the fully hydrogenated diet in Exp. 1 was 3.42 kg/d, whereas that of the second diet was 3.33 kg/d. This was a difference of 0.9 percentage points (and statistically insignificant), whereas the difference in digestibility was 38 percentage points. The slight increase in intake was likely caused by the pigs responding to a lower digestibility of the fat rather than the higher intake causing an increase in endogenous fat losses. It also should be noted that pigs in this study were acclimated to a soy oil diet for 3 wk before treatments were applied, and it is unknown how the fat saturation level during this time might influence subsequent digestibility of saturated fat.

Freeman et al. (1968) determined that saturated fatty acids alone are less efficiently digested and they have a lower potential for micellar formation. When unsaturated fatty acids or monoglycerides are present, the potential for micellar formation of saturated fatty acids increases, thereby increasing absorption (Bailey and Lewis, 1965; Freeman et al., 1968). The fully hydrogenated fat in Exp. 1 was mixed in the diet separately from the soy oil. In Exp. 2, we melted the fully hydrogenated fat from its flake form and blended it with tallow before mixing into the complete diet and compared that to partial hydrogenation of yellow grease at the same iodine values. These preparation methods resulted in a different outcome for digestibility, thereby supporting the fact that iodine value alone cannot predict the digestibility of a modified fat supplement.

Powles et al. (1993) compared the digestibility of several fat sources comprising a wide range of unsaturated fatty acids to saturated fatty acids ratios, as well as fats of intermediary unsaturated to saturated fatty acids ratios formed by blending. When saturated and unsaturated fatty acids are mixed together, an interaction between them may allow for improved digestibility of the saturated fatty acid and result in an increase greater than either fat source alone. However, Powles et al. (1993) found that the digestibility depends more on the degree of fatty acid saturation, and that the digestibility of fat blends is not different from that predicted by the individual fat sources. Data from Exp. 2 support this observation and suggest that partial hydrogenation is superior to blending as a method of producing a more saturated dietary fat for swine diets.

To examine further the digestibility of partially hydrogenated animal fat, Exp. 3 expanded the range of iodine values evaluated (from iodine value 20 to 80). No differences in digestibility were detected in this study, even though dietary saturated fatty acid content increased greatly as iodine value decreased. The hydrogenation process may affect the fatty acid composition of each triglyceride by saturating double bonds and/or altering positional isomers. Davis and Lewis (1969) also studied the effects of different triglyceride structures on digestibility using natural lard, interesterified lard, and tallow. They found that the differences in digestibility were due to differences in the digestibility of saturated fatty acids, which resulted in natural lard having the highest value, with interesterified lard and then tallow following. Palmitic acid is esterified in the α position in tallow, in the β position in natural lard, and a decreased proportion of palmitic acid is found in the β position of interesterified lard (Renner and Hill, 1961). Because we did not detect differences in digestibility over the range of fats examined in our experiment, it is possible that chemical hydrogenation produces a variety of fatty acids in the β position that are absorbed as monoglycerides, and that the saturated free fatty acids produced by lipolysis are solubilized in micelles for absorption to a sufficient degree.

Despite the improved digestibility of the partially hydrogenated fat compared with blended fat seen in Exp. 2, we examined the possibility of increasing digestibility further by addition of an emulsifier in Exp. 4; however, we did not detect increases in digestibility due to the addition of lysolecithin. The product was mixed in the dry diet, and it is possible that mixing directly with the supplemental fat as reported by others (Jones et al., 1992; de Souza et al., 1995) and then subsequent addition to the dry diet may have proved more effective. Overland et al. (1993) also investigated the effects of lecithin addition as an emulsifier for growing-finishing pigs. Soy oil was used as the supplemental fat source and did not affect ADG. Lecithin increased G:F and ADG:ME intake during the experiment, but these authors did not determine the digestibility of the soy oil. Overland et al. (1993) hypothesized that different sources of lecithin may have different emulsifying properties that could affect the results of the study, as well as explain the inconsistency of responses in other literature. Most other studies have been conducted with young pigs immediately after weaning. Jones et al. (1992) studied both lecithin and lysolecithin in 17- to 21-d-old pigs in diets containing soy oil, coconut oil, tallow, or lard. Differences were observed in the type of emulsifier added, as well as with fat source. Emulsifier addition resulted in improvements in tallow digestibility but a decrease in lard digestibility. de Souza et al. (1995) examined the effect of lecithin addition to tallow diets fed to 3-wk-old weanling pigs using both the marker (apparent fecal digestibility), apparent ileal digestibility, and total collection methods. In the first experiment, lecithin combined with tallow resulted in an improvement in apparent fecal fat digestibility compared with tallow alone (73.2 vs. 68 ± 5.4%), but ADG and ADFI did not differ. de Souza et al. (1995) found that lecithin addition did not result in an increase in apparent fecal or ileal digestibility in the second experiment. More recently, Xing et al. (2004) noted that lysolecithin supplemented to 21-d-old pigs for 35 d did not affect fat digestibility, although performance was improved when added to diets containing 5% added fat. The improvement in ADG due to lysolecithin did not seem to be related to the digestibility of other nutrients, such as DM, gross energy, CP, and P, because lysolecithin addition resulted in decreased digestibilities of these nutrients (Xing et al., 2004).

Implications

Iodine value of supplemental fats alone does not predict digestibility. We suggest that partial chemical hydrogenation alters the intermolecular distribution of fatty acids among triacylglycerols compared with blending fats with divergent iodine values, thereby favorably affecting digestibility. Partial hydrogenation of animal fat provides an alternative source of digestible saturated fat that does not negatively affect growth performance; however, caution should be taken when decreasing the iodine value of partially hydrogenated fats because digestibility may decrease at extremely low iodine values.

Literature Cited

AOAC. 1996. Official Methods of Analysis. 16th ed. Assoc. Off. Anal. Chem., Washington, DC.

AOCS. 1998. Official Methods and Recommended Practices of the AOCS. 5th ed. Recommended practice Cd 1c-85. Am. Oil. Chem. Soc., Champaign, IL.

Averette, L. A., M. T. See, and J. Odle. 1999. Effects of chemical hydrogenation of dietary fat on apparent lipid digestibility by finishing swine. J. Anim. Sci. 77(Suppl. 1):183. (Abstr.)

Averette Gatlin, L., M. T. See, J. A. Hansen, and J. Odle. 2003. Hydrogenated dietary fat improves pork quality of pigs from two lean genotypes. J. Anim. Sci. 81:1989–1997.

Averette Gatlin, L., M. T. See, J. A. Hansen, D. Sutton, and J. Odle. 2002. The effects of dietary fat sources, levels, and feeding intervals on pork fatty acid composition. J. Anim. Sci. 80:1606–1615.

Azain, M. J. 2001. Fat in swine nutrition. Page 95 in Swine Nutrition. A. J. Lewis and L. L. Southern, ed. CRC Press, New York, NY.

Bailey, H. S., and D. Lewis. 1965. The use of fats in pig feeding. II. The digestibility of various fats and fatty acids. J. Agric. Sci. (Camb.) 64:373–378.

Bockisch, M. 1998. Modification of fats and oils. Pages 591–604 in Fats and Oils Handbook. M. Bockisch, ed. AOCS Press, Champaign, IL.

Brindley, D. N. 1984. Digestion, absorption and transport of fats: General principles. Page 85 in Fats in Animal Nutrition. J. Wiseman, ed. Butterworths, Boston, MA.

Davis, R. H., and D. Lewis. 1969. The digestibility of fats differing in glyceride structure and their effects on growth performance and carcass composition of bacon pigs. J. Agric. Sci. (Camb.) 72:217–222.

de Souza, T. R., J. Peiniau, A. Mounier, and A. Aumaitre. 1995. Effect of addition of tallow and lecithin in the diet of weanling piglets on the apparent total tract and ileal digestibility of fat and fatty acids. Anim. Feed Sci. Technol. 52:77–91.

Emken, E. A. 1984. Nutrition and biochemistry of *trans* and positional fatty acid isomers in hydrogenated oils. Annu. Rev. Nutr. 4:339–376.

Freeman, C. P., D. W. Holme, and E. F. Annison. 1968. The determination of the true digestibilities of interesterified fats in young pigs. Br. J. Nutr. 22:651–660.

Hansen, J. 2001. Dietary influencers of pork quality and practical solutions to quality problems. Pages 21–31 in Proc. 17th Annu. Carolina Swine Nutr. Conf. Raleigh, NC.

Jagger, S., J. Wiseman, D. J. Cole, and J. Craigon. 1992. Evaluation of inert markers for the determination of ileal and faecal apparent digestibility values in the pig. Br. J. Nutr. 68:729–739.

Jones, D. B., J. D. Hancock, D. L. Harmon, and C. E. Walker. 1992. Effects of exogenous emulsifiers and fat sources on nutrient digestibility, serum lipids, and growth performance in weanling pigs. J. Anim. Sci. 70:3473–3482.

Jorgensen, H., and J. A. Fernandez. 2000. Chemical composition and energy value of different fat sources for growing pigs. Acta Agric. Scand., Sect. A. Anim. Sci. 50:129–136.

Madsen, A., K. Jakobsen, and H. Mortensen. 1992. Influence of dietary fat on carcass fat quality in pigs. A review. Acta Agric. Scand. 42:220–225.

Miller, M. F., S. D. Shackelford, K. D. Hayden, and J. O. Reagan. 1990. Determination of the alteration in fatty acid profiles, sensory characteristics and carcass traits of swine fed elevated levels of monounsaturated fats in the diet. J. Anim. Sci. 68:1624–1631.

NRC. 1998. Nutrient Requirements of Swine. 10th ed. Natl. Acad. Press, Washington, DC.

Overland, M., M. D. Tokach, S. G. Cornelius, J. E. Pettigrew, and M. E. Wilson. 1993. Lecithin in swine diets: II. Growing-finishing pigs. J. Anim. Sci. 71:1194–1197.

Powles, J., J. Wiseman, D. J. A. Cole, and B. Hardy. 1993. Effect of chemical structure of fats upon their apparent digestible energy value when given to growing/finishing pigs. Anim. Prod. 57:137–146.

Renner, R., and F. W. Hill. 1961. Factors affecting the absorbability of saturated fatty acids in the chick. J. Nutr. 74:254–258.

Seerley, R. W., J. P. Briscoe, and H. C. McCampbell. 1978. A comparison of poultry and animal fat on performance, body composition, and tissue lipids of swine. J. Anim. Sci. 46:1018–1023.

Skuhija, P. S., and D. L. Palmquist. 1988. Rapid method for determination of total fatty acid content and composition of feedstuffs and feces. J. Agric. Food Chem. 36:1202–1206.

Stahly, T. 1984. Use of fats in diets for growing pigs. Page 313 in Fats in Animal Nutrition. J. Wiseman, ed. Butterworths, Boston, MA.

Tullis, J. B., and C. T. Whittemore. 1980. Digestibility of a fully hydrogenated tallow for growing pigs. Anim. Feed Sci. Technol. 5:87–91.

Williams, C. H., D. J. David, and O. Iismaa. 1962. The determination of chromic oxide in faeces samples by atomic absorption spectrophotometry. J. Agric. Sci. (Camb.) 59:381–385.

Wiseman, J., F. Salvador, and J. Craigon. 1991. Prediction of the apparent metabolizable energy content of fats fed to broiler chickens. Poult. Sci. 70:1527–1533.

Xing, J. J., E. van Heugten, D. F. Li, K. J. Touchette, J. A. Coalson, R. L. Odgaard, and J. Odle. 2004. Effects of emulsification, fat encapsulation, and pelleting on weanling pig performance and nutrient digestibility. J. Anim. Sci. 82:2601–2609.