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Meat Quality, Digestibility and Deposition of Fatty Acids in Growing-finishing Pigs Fed Restricted, Iso-energetic Amounts of Diets Containing either Beef Tallow or Sunflower Oil*

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ABSTRACT : The influence of dietary beef tallow (BT) versus sunflower oil (SO) on meat quality and apparent digestibility and deposition of individual fatty acids in the whole carcass was investigated in pigs fed diets containing either BT or SO. The diets contained equal amounts of energy in the form of the variable fats and were fed on an iso-energetic, restricted basis. Crude fat in the SO diet was better digested ($p<0.001$) than in the BT diet. The dietary fat type had no effect on growth performance, physical properties of the carcass and meat quality. The pigs fed the BT diet showed lower ($p<0.001$) apparent digestibilities for palmitic and linoleic acid, but those of oleic and α-linolenic acid were not affected. The ratio of deposition in the carcass to intake of digestible fatty acids for the whole feeding period was decreased ($p<0.01$) for oleic and linoleic acid in pigs fed the SO diet. The pigs fed the SO diet instead of the BT diet had a lower ($p<0.05$) deposition:intake ratio for mono-unsaturated fatty acids. The calculated minimum *de novo* synthesis of saturated fatty acids was increased for the SO diet, but that of mono-unsaturated fatty acids was not different. In conclusion, the iso-energetic replacement of BT by SO had a marked impact on the fatty acid composition of tissues, but did not affect carcass and meat quality traits in spite of the marked difference in the deposition of linoleic acid in adipose tissues, loin muscle and the whole body. In addition, it became clear that the type of dietary fat had marked, specific effects on the synthesis and oxidation of fatty acids. (**Key Words** : Deposition, Digestibility, Fat Type, Fatty Acid, Meat Quality, Pigs)

INTRODUCTION

There is great interest in the use of vegetable oils instead of animal fat as dietary fat source for pig production. Vegetable oils are generally rich in polyunsaturated fatty acids (PUFA), which will be reflected in the pig meat (Nguyen et al., 2003), thus yielding healthy meat for human consumption (Liu et al., 2005; Kim et al., 2007), but their technical quality may be diminished due to high susceptibility to oxidation and low consistency (Rey et al., 2001; Ramirez et al., 2004; Guo et al., 2006; Morel et al., 2006). In addition, there is increasing concern among the general public on the use of animal feedstuffs, including animal fat, in pig diets. Therefore, the objective of this research was to further evaluate the effects of animal fat versus vegetable oil in pig diets.

In general, vegetable oils are better digested by pigs than animal fats (Cera et al., 1988; Cera et al., 1989). The influence of replacement of dietary animal fat by vegetable oil on meat quality of pigs has been described (Wiseman and Agunbiade, 1998; Wood et al., 2004; Mitchaothai et al., 2007). However, the various studies on meat quality can be criticized because the pigs had free access to diets containing equal inclusion percentages of either animal or vegetable fat. The unrestricted feed intake and difference in digestibility between the experimental fats interferes with

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Table 1. Composition of the diets (as-fed basis)

Item	BT[1]	SO[1]
Raw materials (g)		
Cassava chips	45.53	45.53
Soybean meal (44% CP)	34.00	34.00
Extruded soy beans	7.00	7.00
Beef tallow (BT)	5.00	-
Sunflower oil (SO)	-	4.50
Molasses	4.00	4.00
Calcium carbonate	1.00	1.00
Di-calcium phosphate	2.70	2.70
NaCl	0.35	0.35
DL-Methionine	0.17	0.17
Premix	0.25	0.25
Total	100.00	99.50
Analyzed nutrients (%)		
Dry matter	88.63	88.05
Crude protein	20.94	21.55
Crude fat	7.34	7.31
Crude fiber	6.65	6.25
Ash	8.37	8.36
Calculated ME (MJ/kg)	13.82	13.86

[1] BT = Beef tallow; SO = Sunflower oil.

Table 2. Analyzed fatty acid composition of the experimental diets

Item	BT[1]	SO[1]
Fatty acids (g methylester/100 g methylesters)		
C 10:0	0.13	0.13
C 14:0	1.34	0.26
C 15:0	0.42	0.09
C 16:0	21.69	14.21
C 17:0	1.32	0.17
C 18:0	24.72	5.85
C 20:0	0.42	0.35
C 22:0	0.42	0.82
C 24:0	0.28	0.45
C 16:1	0.62	0.14
C 17:1	0.21	0.00
C 18:1 n-9	23.24	30.45
C 18:1 n-7	3.92	1.22
C 20:1 n-9	0.58	0.51
C 22:1 n-9	0.00	0.08
C 18:2 n-6	12.37	40.47
C 18:3 n-6	0.24	0.00
C 18:3 n-3	1.50	1.35
C 20:5 n-3	0.11	0.11
Unidentified	6.48	3.35
∑SFA[2]	50.72	22.33
∑MUFA[2]	28.57	32.40
∑PUFA[2]	14.22	41.92

[1] BT = Beef tallow; SO = Sunflower oil.

[2] SFA = Saturated fatty acids; MUFA = Mono-unsaturated fatty acids; PUFA = Poly-unsaturated fatty acids; ∑SFA = C10:0+C14:0+C15:0 +C16:0+C17:0+C18:0+C20:0+C22:0+C24:0; ∑MUFA = C16:1+C17:1+ C18:1 n-7+C18:1 n-9+C20:1 n-9+C22:1 n-9; ∑PUFA = C18:2 n-6+ C18:3 n-6+C18:3 n-3+C20:5 n-3.

the interpretation of the results.

In this study we used diets containing iso-energetic amounts of either vegetable oil or animal fat, and the diets were fed on a restricted basis to growing-finishing pigs so that their energy intake was identical. Thus, sunflower oil (SO) and beef tallow (BT) were used as representatives of vegetable and animal fat sources to determine their differential effects, if any, on the quality of meat, fatty acid composition of tissues, digestibility and deposition of individual fatty acids, the ratio of deposition to digested amount of fatty acids and minimum, whole body *de novo* fatty acid synthesis.

MATERIALS AND METHODS

Animals, diets and feeding

Thirty-nine castrated-male pigs, Landrace×Large White×Duroc crossbred, were used in the current study. Three pigs with an average BW of 31.0 kg were selected to be slaughtered for baseline measurements. Then, the remaining pigs with an average of 30.4±2.3 kg BW were allotted to one of the two dietary treatments on the basis of BW and were housed in individual cages with concrete floor that were placed in an open barn. Electric fans were used and also water dripping was applied during high environmental temperatures (>30°C). There were two experimental diets with either beef tallow (BT) or sunflower oil (SO) as shown in Table 1. The analyzed fatty composition of the diets is illustrated in Table 2.

The pigs were fed twice a day at an energy intake level of 80% of the *ad libitum* intake determined earlier (Mitchaothai et al., in press). During the course of the experiment, the amounts of feed, which were iso-energetic for the two experimental diets, were adapted on a week to week basis. There were no feed leftovers. The pigs had free access to water throughout the experiment. The pigs were weighed weekly, without prior fasting, until the end of the experiment which lasted 98 days. All pigs were slaughtered at an average body weight of 100.7±4.6 kg in a commercial slaughterhouse.

Collection and pre-treatment of samples

The three pigs for baseline measurements were killed by an intravenous overdose of sodium pentobarbital (200 mg/kg of BW) (Nembutal®, Ceva Animale, La Ballastiere, France). The pigs were scalded, blood was collected and weighed, the head was removed, and the carcass was split into halves along the median plane according to the procedure previously reported by Shields et al. (1983). Small samples (1-2 g) of adipose tissue and loin were taken and stored at -20°C until analysis. The heads and carcass halves were dried on a mesh as described (Mitchaothai et al., in press) and the dripping oil was collected. The dried

whole carcass samples derived from each pig were pooled and then weighed. The dripping oil samples were pooled and weighed in the same way as the dried whole carcass samples so that there were dried and oil samples for each pig. The dried samples were individually ground once through a 2-mm screen and twice through a 1-mm screen by a hammer mill.

In the 4th and 10th week after the commencement of the experiment, all pigs were transferred to individual metabolism cages. After the 5-days adaptation period, faeces of each pig were quantitatively collected for five consecutive days. The metabolism cages were fitted with trays that enabled the collection of faeces without contamination by urine. The faeces were put in plastic bags that were weighed and stored at -20°C pending analysis.

The 36 pigs in the feeding trial were killed in the 14th week after initiation. Carcass measurements (loin eye area at 10th rib, LEA, and back fat depth at 10th rib, FD10R) were obtained as described previously (Wagner et al., 1999). Samples of back fat of midline between 3rd and 4th rib, right inguinal subcutaneous fat, retroperitoneal fat, and loin were collected to determine fatty acid composition.

Carcass traits and meat quality

Hot carcass weight was measured after removing all internal organs including kidney. The thickness of back fat was determined according to standard methods described previously (Sripromma, 1984). Fat-lean ratio was expressed according to the LSQ (Lenden-Speck-Quotient) system of Pfeiffer and Falkenberg (1972). Briefly, the LSQ was calculated as (B1+B2)/(2×B3) where B1 = back fat thickness at the front base of gluteus muscle, B2 = back fat thickness on top of gluteus muscle (at the thinnest part of back fat) and B3 = shortest distance from the front base of gluteus muscle to the dorsal border of the spinal cord. The right *M. longissimus* was used for meat quality assessing. The color score of *M. longissimus thoracic* was measured by using the 6-point Japanese pork color scale (JPCS; Nakai et al., 1975) and by determining the CIELAB color co-ordinates (color L*, a*, b*) in triplicate with a HunterLab (Color flex®) device after a 30-min blooming time (D65 light source, 10° standard observer, 45°/0° geometry, 1 inch light surface, white standard; Hunter, Reston, VA). Duplicate 3 g diced samples were taken to determine water-holding capacity (WHC) using the expressible moisture test of Goerl et al. (1995) with modification of duration and pressure force. Samples were placed in the center of Whatmam no. 2 filter paper and pressed between glass sheets (15 cm×15 cm×8 mm) under 1 kg/90 cm^2 pressure for 20 min. The resulting meat ring and expressed juice ring were subsequently measured using a digital planimeter (Placom KP-90N, Topcon®, Topcon Instruments (Thailand), Bangkok, Thailand). The amount of expressible moisture was recorded as the ratio of the juice area to the muscle area. Intramuscular fat content was determined after Soxhlet extraction using hexane on the meat slices. The pH-value of muscle was determined using the Meat pH meter (Model HI99163, Hanna Instruments, Portugal) at 45 min (pH_1) and 24 h (pH_U) after slaughter. Drip loss was assessed as the proportionate weight loss of a slice of muscle (175 to 185 g with thickness of 2.54 cm) that had been suspended in a plastic bag for 24 h at 2°C (Honikel, 1987). Right *M. longissimus lumborum* (loin) was collected and stored at -20°C until analyzing the remaining meat quality variables. Pork chops were weighed before and after cooking to determine percentage of cooking loss. The pork chops were put in a plastic bag and then cooked for 40 min in a water bath with constant temperature of 70°C. After the chops had cooled to room temperature (25°C), five 1.27-cm-diameter cores from each chop were removed with a cylindrical core parallel to the muscle fiber orientation. Cores were sheared perpendicular to the muscle fiber orientation using a Warner-Bratzler shear V-blade attached to an Texture Analyzer (Stable Micro System Ltd., Surrey, England) fitted with a 10-g compression load cell with a crosshead speed of 900 mm/min. Peak force values of cores sheared through the center were used to determine the mechanical tenderness of the sample. Sarcomere length was assessed (in four replicate) by taking the slice from the central part of small *M. longissimus thoracic* (3 to 4 g) according to a method described previously (Monin et al., 1999). The diet and meat samples were dried at 60°C for 72 h in a forced-hot air oven and then were analyzed for crude protein, crude fat, and ash (AOAC, 1990). The dried meat samples were quantified for the percentage of moisture and fat contents according to standard chemical analyses (AOAC, 1990) and then the percentage of fat was calculated and expressed as loin intramuscular fat.

Estimation of carcass fat content

The total lean mass and the total fat mass in the whole body were estimated by the following equations (Schinckel et al., 2001): Fat-free, total lean mass (kg) = 5.00+(0.434× carcass weight (kg))+(0.168×LEA (cm^2))+((-3.38)×FD10R (cm)); Total fat mass (kg) = (-10.7)+(0.395×carcass weight (kg))+((-0.150)×LEA (cm^2))+(4.49×FD10R (cm)). Thus, intramuscular fat mass = fat-free, lean mass (kg)/100× (fraction IMF×(100-fraction IMF)$^{-1}$). Based on literature data (Irie and Sakimoto, 1992; Otten et al., 1993; Enser et al., 2000), it can be concluded that the fatty acid profiles of adipose tissue from different sites are similar. Thus, the average percentage of fatty acids from different sites of adipose tissue can be considered to be representative for the whole body mass of adipose tissue. The amount of fat in

Table 3. Effect of fat type on animal performance, carcass traits, and meat quality[1]

Item	BT[2]	SO[2]	p-value
Growth performance			
Initial BW (kg)	30.44±1.79	30.33±2.81	0.888
Final BW (kg)	99.74±5.52	101.81±3.32	0.198
ADFI (kg/d)	2.07±0.05	2.04±0.06	0.137
ADG (kg/d)	0.735±0.06	0.756±0.04	0.231
Feed:gain	2.79±0.25	2.66±0.14	0.082
Carcass quality			
Hot carcass (kg)	78.64±4.44	79.93±2.47	0.307
Back fat thickness (cm)	2.24±0.30	2.22±0.38	0.892
Fat-lean ratio (LSQ)	0.21±0.06	0.21±0.06	0.887
Meat quality (loin)			
Color[3]	3.21±0.47	3.57±0.46	0.036
Color L* value	35.19±2.21	34.80±1.60	0.565
Color a* value	9.82±2.87	10.26±2.88	0.660
Color b* value	11.11±1.08	11.55±1.13	0.260
pH_1	6.03±0.27	6.03±0.30	0.982
pH_U	5.76±0.38	5.71±0.40	0.707
Drip loss (%)	1.02±0.42	1.15±0.48	0.264
Cooking loss (%)	25.03±2.73	23.85±2.34	0.312
WHC[4]	3.29±0.96	2.90±0.55	0.301
Shear force (N)	64.37±12.56	60.90±9.82	0.204
Sarcomere length (μm)	1.86±0.12	1.90±0.15	0.554
IMF[5] (% wet weight)	2.39±0.72	2.41±0.59	0.928

[1] Means±SD for 18 pigs per experimental diet. [2] BT = Beef tallow; SO = Sunflower oil.
[3] Japanese color score: 1 = pale, pinkish grey, 6 = dark, purpish red. [4] WHC = Water holding capacity. [5] IMF = Intramuscular fat.

blood is negligible and therefore was not taken into account. Thus, the mass (kg) of adipose tissue equals total fat mass (kg) in whole body minus fat mass (kg) in muscle minus fat mass (kg) in liver.

Chemical analysis

The diet and faeces samples were dried at 60°C for 72 h in a forced-hot air oven and were then analyzed for crude protein, crude fat, and ash (AOAC, 1990). The dried meat, liver, and whole carcass samples were analyzed for moisture and fat (AOAC, 1990). The fat extracted from meat was defined as intramuscular fat (IMF).

Total fat in the fresh and dried samples (diets, faeces, adipose tissues, and loin) were extracted as described previously (Horwitz, 1975). Each sample with 2 ml of ethanol was added to a flask. Subsequently, 10 ml of HCl (8 mol/L) was added; the contents were gently mixed, and the flask was placed in a water-bath of 80°C for 30 to 40 min. The tubes were cooled down, 10 ml of ethanol (96%, wt/wt) and 25 ml of petroleum ether (boiling point between 40 and 60°C) were added and the tube was shaken for one min. The fat-containing upper layer was decanted into a 150-ml round-bottom flask. The extraction procedure was repeated twice with 15 ml of diethyl ether and 15 ml of petroleum ether and the lipid extract was evaporated to dryness under N_2 in a water-bath of 40°C. The round-bottom flasks with the lipids were dried overnight at 60°C and the total lipids were measured gravimetrically. Total lipids were saponified and methylated according to the procedure of Metcalfe et al. (1966) followed by gas chromatography for determination of fatty acid composition (Javadi et al., 2004).

Calculation of digestible fatty acid intake, fatty acid deposition and minimum *de novo* synthesis

Digestible fatty acid intake, fatty acid deposition and minimum *de novo* synthesis were calculated as described (Mitchaothai et al., in press). The apparent digestibility of individual fatty acids was calculated as intake minus faecal excretion and expressed as a percentage of intake. For this calculation the average fatty acid digestibility for the two faeces collection periods were used. The apparent digestibility of groups of fatty acids was calculated as the sum of the individual fatty acids within the group minus the sum of their excretion. The total digestible fatty acid intake was calculated as fatty acid intake (kg/14 weeks)×apparent fatty acid digestibility (fraction of intake). The deposition of fatty acids was calculated with the following formula: Fatty acid deposition (kg/14 weeks) = carcass content of fatty acid at the end of the study minus carcass content of fatty acid at the start of the study. Carcass content of fatty acid at the end (kg) was calculated as the sum of adipose tissue mass (kg)×fraction of adipose fatty acid, IMF mass (kg)× fraction of IMF fatty acid and fat mass in liver (kg)×fraction

Table 4. Fatty acid composition of subcutaneous and back fat[1]

Item	Subcutaneous fat		Significance	Back fat		Significance
	BT[2]	SO[2]		BT[2]	SO[2]	
Analyzed fatty acids (g/100 g methylesters)						
C 14:0	1.86±0.12	1.26±0.13	***	1.59±0.14	0.99±0.08	***
C 16:0	25.39±1.41	21.28±1.78	***	22.54±0.96	18.29±1.10	***
C 17:0	0.87±0.18	0.40±0.07	***	0.85±0.13	0.38±0.06	***
C 18:0	17.63±1.64	13.55±2.19	***	14.02±1.73	10.08±1.13	***
C 20:0	0.19±0.06	0.20±0.04	NS[3]	0.12±0.09	0.17±0.05	NS[3]
C 16:1	0.51±0.33	0.33±0.06	*	0.44±0.04	0.37±0.06	***
C 17:1	0.45±0.07	0.18±0.03	***	0.53±0.06	0.21±0.03	***
C 18:1 n-7	2.52±0.18	1.32±0.24	***	2.80±0.14	1.59±0.14	***
C 18:1 n-9	32.64±2.01	30.13±2.31	**	37.17±2.42	34.25±1.70	***
C 20:1 n-9	0.67±0.10	0.57±0.07	**	0.85±0.07	0.77±0.08	**
C 22:1 n-9	0.00±0.00	0.01±0.03	NS[3]	ND[3]	ND[3]	-
C 18:2 n-6	12.11±2.13	27.09±4.03	***	13.24±1.31	28.66±2.91	***
C 18:3 n-3	1.16±0.21	1.12±0.16	NS[3]	1.21±0.13	1.14±0.12	NS[3]
C 20:2 n-6	0.35±0.07	0.81±0.07	***	0.48±0.06	1.13±0.12	***
C 20:3 n-6	0.00±0.00	0.02±0.04	NS[3]	ND[3]	ND[3]	-
C 20:3 n-3	0.02±0.05	0.00±0.00	NS[3]	0.01±0.03	0.01±0.04	NS[3]
C 20:4 n-6	0.10±0.09	0.27±0.05	***	0.11±0.09	0.27±0.04	***
C 20:5 n-3	ND[3]	ND[3]	-	ND[3]	ND[3]	-
C 22:4 n-6	ND[3]	ND[3]	-	ND[3]	ND[3]	-
C 22:5 n-3	ND[3]	ND[3]	-	ND[3]	ND[3]	-
Unknown	3.35±0.46	1.45±0.37	***	3.90±0.67	1.66±0.49	***
∑SFA[4]	45.94±2.75	36.68±3.83	***	39.11±2.55	29.91±2.07	***
∑MUFA[4]	36.79±2.08	32.54±2.61	***	41.78±2.54	37.20±1.86	***
∑PUFA[4]	13.74±2.44	29.31±4.25	***	15.05±1.51	31.22±3.09	***
∑MUFA/∑SFA[4]	0.80±0.09	0.90±0.14	*	1.07±0.11	1.25±0.11	***
∑PUFA/∑SFA[4]	0.30±0.06	0.82±0.20	***	0.39±0.05	1.05±0.18	***
∑n6/∑n3	10.64±0.77	25.31±0.99	***	11.33±0.54	26.19±1.08	***
C18:2n-6/C18:3n-3	10.43±0.61	24.31±0.93	***	10.91±0.45	25.15±0.80	***

[1] Means±SD for 18 pigs per experimental diet. [2] BT = Beef tallow; SO = Sunflower oil. [3] NS = Not significant; ND = Not detectable.

[4] SFA = Saturated fatty acid; MUFA = Monounsaturated fatty acid; PUFA = Polyunsaturated fatty acid; ∑SFA = C14:0+C16:0+C17:0+C18:0+C20:0; ∑MUFA = C16:1+C17:1+C18:1 n-7+C18:1 n-9+C20:1 n-9+C22:1 n-9; ∑PUFA = C18:2 n-6+C18:3 n-3+C20:2 n-6+C20:3 n-6+C20:3 n-3+C20:4 n-6+C20:5 n-3+C22:4 n-6+C22:5 n-3.

NS: $p>0.05$; * $p<0.05$; ** $p<0.01$; *** $p<0.001$.

of liver fatty acid. The ratio of fatty acid deposition and digestible fatty acid intake was calculated for selected individual fatty acids and groups of fatty acids. Minimum *de novo* fatty acid synthesis was calculated as fatty deposition minus digestible fatty acid intake.

Statistical analysis

The effect of dietary fat type was evaluated for statistical significance ($p<0.05$) by the Student's *t* test (SPSS, 1999). Results are expressed as means±SD.

RESULTS

Dietary fatty acid composition

The fatty composition of the experimental diets is shown in Table 2. The fat component of the BT diet contained approximately 51% total SFA, whereas that of the SO diet contained approximately 42% total PUFA. The amounts of total mono-unsaturated fatty acids (MUFA) were approximately 29% and 32% for the BT and SO diets, respectively.

Growth performance, meat quality, and fatty acid composition

There was no diet effect on feed intake, growth (average daily gain), feed conversion ratio (feed:gain) and final BW (Table 3). The feed:gain ratio in pigs fed the SO diet tended ($p = 0.082$) to be lowered.

Meat quality

Carcass traits and meat quality characteristics, except for the color score, did not differ between the two dietary fat sources (Table 3). The pigs fed the SO diet had a higher ($p<0.05$) color score than those fed the BT diet. Technical measurement of the color coordinates did not show a diet effect.

Table 5. Fatty acid composition of retroperitoneal fat and loin intramuscular fat[1]

Item	Retroperitoneal fat		Significance	Loin		Significance
	BT[2]	SO[2]		BT[2]	SO[2]	
Analyzed fatty acids (g/100 g methylesters)						
C 14:0	1.80±0.24	1.26±0.23	***	1.65±0.21	1.51±0.21	NS[3]
C 16:0	24.31±1.34	20.76±1.78	***	24.99±1.22	24.99±1.39	NS[3]
C 17:0	0.83±0.18	0.43±0.15	***	0.51±0.09	0.34±0.08	***
C 18:0	16.55±1.81	13.00±1.55	***	12.65±0.91	12.52±0.68	NS[3]
C 20:0	0.12±0.08	0.13±0.09	NS[3]	0.05±0.08	0.11±0.10	NS[3]
C 16:1	0.41±0.06	0.35±0.05	**	2.84±0.33	2.35±0.36	***
C 17:1	0.43±0.10	0.20±0.10	***	0.42±0.07	0.23±0.09	***
C 18:1 n-7	2.41±0.41	1.46±0.25	***	3.64±0.25	2.97±0.28	***
C 18:1 n-9	32.49±1.30	31.00±0.92	***	37.77±1.87	35.86±2.41	*
C 20:1 n-9	0.65±0.09	0.60±0.07	NS[3]	0.85±0.12	0.80±0.12	NS[3]
C 22:1 n-9	ND[3]	ND[3]	-	0.10±0.10	0.23±0.13	**
C 18:2 n-6	14.72±4.84	26.28±4.62	***	9.89±2.33	13.69±3.42	***
C 18:3 n-3	1.25±0.12	1.11±0.13	**	0.46±0.19	0.34±0.13	*
C 20:2 n-6	0.43±0.15	0.89±0.21	***	0.27±0.09	0.47±0.12	***
C 20:3 n-6	ND[3]	ND[3]	-	0.11±0.15	0.11±0.12	NS[3]
C 20:3n-3	0.01±0.03	0.00±0.00	NS[3]	ND[3]	ND[3]	-
C 20:4n-6	0.16±0.08	0.27±0.04	***	1.03±0.76	1.08±0.66	NS[3]
C 20:5n-3	ND[3]	ND[3]	-	0.01±0.05	0.00±0.00	NS[3]
C 22:4n-6	ND[3]	ND[3]	-	0.06±0.11	0.09±0.13	NS[3]
C 22:5 n-3	ND[3]	ND[3]	-	0.11±0.19	0.02±0.07	NS[3]
Unknown	3.44±0.89	2.27±2.38	NS[3]	2.51±0.65	2.26±1.03	NS[3]
∑SFA[4]	43.61±3.17	35.58±3.30	***	39.85±2.08	39.47±1.97	NS[3]
∑MUFA[4]	36.39±1.73	33.60±0.98	***	45.61±2.19	42.44±2.87	**
∑PUFA[4]	16.56±5.06	28.55±4.85	***	11.95±3.56	15.79±4.37	**
∑MUFA/∑SFA[4]	0.84±0.05	0.95±0.10	***	1.15±0.06	1.08±0.07	**
∑PUFA/∑SFA[4]	0.39±0.17	0.82±0.21	***	0.30±0.10	0.41±0.13	*
∑n6/∑n3	12.28±4.26	24.80±4.05	***	21.35±9.46	44.03±8.54	***
C18:2n-6/C18:3n-3	11.91±4.34	23.76±3.89	***	22.19±8.12	40.94±9.30	***

[1] Means±SD for 18 pigs per experimental diet. [2] BT = Beef tallow; SO = Sunflower oil. [3] NS = Not significant ND = Not detectable.

[4] SFA = Saturated fatty acid, MUFA = Monounsaturated fatty acid, PUFA = Polyunsaturated fatty acid; ∑SFA = C14:0+C16:0+C17:0+C18:0+C20:0; ∑MUFA = C16:1+C17:1+C18:1 n-7+C18:1 n-9+C20:1 n-9+C22:1 n-9; ∑PUFA = C18:2 n-6+C18:3 n-3+C20:2 n-6+C20:3 n-6+C20:3 n-3+C20:4 n-6+C20:5 n-3+C22:4 n-6+C22:5 n-3.

NS: $p>0.05$; * $p<0.05$; ** $p<0.01$; *** $p<0.001$.

Fatty acid composition of tissues

Fatty acid patterns of adipose tissues and loin are documented in Table 4 and 5. The relative concentrations of C14:0, C16:0, C17:0, and C18:0 in pigs fed with the BT diet were higher ($p<0.001$) for all three sites of adipose tissues, but in loin muscle there only was a lower ($p<0.001$) percentage of C17:0. There was no treatment difference for the levels of C16:0 and C18:0 in loin. The pigs fed the BT diet showed higher ($p<0.05$) tissue concentrations of MUFA, of which C18:1 n-9 is the major component. The concentrations of C18:2 n-6 (linoleic acid) and C20:2 n-6 (eicosadienoic acid) in adipose tissues and loin were higher ($p<0.001$) in the pigs fed the SO diet. On the other hand, there were higher ($p<0.05$) levels of C18:3 n-3 (α-linolenic acid) in the retroperitoneal fat and loin of the pigs fed the BT diet. No treatment effect was seen for the concentration of α-linolenic acid in subcutaneous and back fat. The content of SFA in adipose tissues was higher ($p<0.001$) for the pigs fed the BT diet, but the SFA content of loin was unchanged. In both adipose tissues and loin of the pigs fed BT, the levels of MUFA were higher ($p<0.01$) and those of PUFA were lower ($p<0.01$). In the pigs fed the BT diet, the ratio of MUFA/SFA was higher ($p<0.001$) in adipose tissues, but it was lower ($p<0.01$) in loin. The ratios of PUFA/SFA, n-6/n-3 and C18:2 n-6/C18:3 n-3 in both adipose tissues and loin were higher ($p<0.05$) for the pigs fed the SO diet.

Nutrient digestibility

At the 4th and 10th week of the experiment, the pigs fed the SO diet had a higher ($p<0.01$) apparent digestibility of crude fat than those fed the BT diet, but there was no significant dietary fat effect on the digestibility of DM and CP (Table 6). The digestibility of DM, CP, and crude fat tended to be increased with age, irrespective of dietary

Table 6. Effect of dietary fat type on apparent macronutrient and fatty acid digestibility[1]

Item	BT[2]	SO[2]	p-value
Apparent digestibility (% of intake in the 4th week)			
Dry matter	87.22±3.13	87.13±2.10	0.920
Crude fat	69.69±9.45	77.46±5.72	0.006
Crude protein	87.49±6.08	86.57±4.69	0.619
Apparent digestibility (% of intake in the 10th week)			
Dry matter	87.74±2.93	88.19±3.46	0.678
Crude fat	73.68±8.88	81.56±6.53	0.006
Crude protein	90.17±2.33	88.95±3.34	0.229
Apparent digestibility (% of intake in the 4th week)			
C 16:0	66.32±7.93	73.93±8.19	0.009
C 18:0	54.43±12.26	-37.86±39.35	<0.001
C 18:1 n-9	94.45±1.65	94.34±1.40	0.825
C 18:2 n-6	94.58±1.84	97.40±0.74	<0.001
C 18:3 n-3	94.60±1.86	93.97±1.57	0.292
∑SFA[3]	49.07±13.12	-20.51±20.16	<0.001
∑MUFA[3]	90.11±2.77	90.28±3.51	0.882
∑PUFA[3]	94.59±1.80	95.68±1.14	0.039
Apparent digestibility (% of intake in the 10th week)			
C 16:0	58.70±9.52	76.70±7.06	<0.001
C 18:0	42.84±12.51	-50.78±42.39	<0.001
C 18:1 n-9	94.01±1.67	94.33±2.34	0.651
C 18:2 n-6	95.65±1.28	98.06±0.86	<0.001
C 18:3 n-3	96.41±2.21	96.26±2.43	0.855
∑SFA[3]	47.12±11.09	-20.20±34.34	<0.001
∑MUFA[3]	91.68±3.17	89.37±6.71	0.270
∑PUFA[3]	96.03±1.70	97.37±1.39	0.019

[1] Means±SD for 18 pigs per experimental diet.
[2] BT = Beef tallow; SO = Sunflower oil.
[3] SFA = Saturated fatty acid, MUFA = Monounsaturated fatty acid, PUFA = Polyunsaturated fatty acid; ∑SFA = C10:0+C14:0+C15:0+C16:0+C17:0+C18:0+C20:0+C22:0+C24:0; ∑MUFA = C16:1+C18:1 n-9; ∑PUFA = C18:2 n-6+C18:3 n-3.

treatment.

Table 6 shows the apparent digestibility for selected individual fatty acids and groups of fatty acids. The palmitic acid (C16:0) digestibility for the SO diet was greater ($p<0.01$) than that for the BT diet. The digestibilty of C18:0 for the SO diet was calculated to be negative which may be explained by a combination of low intake and faecal excretion due to bacterial synthesis. The apparent digestibility of oleic acid (C18:1 n-9) was not affected by diet. The pigs fed the SO diet displayed a greater ($p<0.001$) digestibility of linoleic acid (C18:2 n-6), but the digestibility of α-linolenic acid (C18:3 n-3) did not differ between both diets. The digestibility of PUFA was higher for the pigs fed the SO diet, but that of MUFA did not differ between the experimental diets.

Digestible fatty acid intake and deposition

The intake of digestible palmitic, stearic, and α-linolenic acid of the pigs fed the BT diet was greater ($p<0.001$) than that of the pigs fed the SO diet, whereas the pigs fed the SO diet had higher ($p<0.001$) intakes of digestible oleic and linoleic acid (Table 7). The pigs fed the SO diet had a greater ($p<0.05$) intake of total digestible fatty acids (FA), MUFA and PUFA, but had a lower ($p<0.001$) intake of digestible SFA. When the fatty acids were pooled according to their structural similarities, the SO diet was found to provide more digestible n-9 MUFA

Table 7. Effect of dietary fat type on digestible fatty acid intake, fatty acid deposition and the deposition:intake ratio during the whole feeding period[1]

Fatty acids	BT[2]	SO[2]	p-value
Digestible fatty acid intake (kg/14 weeks)			
C 16:0	1.89±0.23	1.44±0.12	<0.001
C 18:0	1.68±0.39	-0.37±0.29	<0.001
C 18:1 n-9	3.06±0.16	3.89±0.35	<0.001
C 18:2 n-6	1.64±0.09	5.36±0.49	<0.001
C 18:3 n-3	0.20±0.01	0.17±0.02	<0.001
∑FA[3]	10.03±0.89	10.69±0.83	0.031
∑SFA[3]	3.88±0.67	1.11±0.37	<0.001
∑MUFA[3]	3.63±0.19	3.93±0.36	0.006
∑PUFA[3]	1.87±0.10	5.54±0.51	<0.001
∑n-9	3.13±0.16	3.95±0.35	<0.001
∑n-6	1.66±0.09	5.36±0.49	<0.001
∑n-3	0.21±0.01	0.18±0.02	<0.001
Fatty acid deposition (kg/14 weeks)			
C 16:0	3.57±0.62	3.29±0.39	0.186
C 18:0	2.49±0.44	2.11±0.34	0.022
C 18:1 n-9	4.81±0.91	4.81±0.51	0.999
C 18:2 n-6	1.70±0.18	4.27±0.65	<0.001
C 18:3 n-3	0.14±0.03	0.14±0.02	0.768
∑FA[3]	14.36±2.22	15.77±1.42	0.072
∑SFA[3]	6.49±1.07	5.67±0.75	0.036
∑MUFA[3]	5.40±1.00	5.19±0.56	0.516
∑PUFA[3]	1.94±0.23	4.63±0.70	<0.001
∑n-9	4.92±0.93	4.92±0.53	0.432
∑n-6	1.79±0.20	4.49±0.68	<0.001
∑n-3	0.14±0.03	0.14±0.03	0.735
Deposition:intake ratio			
C 16:0	1.99±0.49	2.29±0.27	0.076
C 18:0	1.70±0.67	-7.43±5.20	<0.001
C 18:1 n-9	1.56±0.30	1.23±0.10	0.004
C 18:2 n-6	1.03±0.13	0.80±0.14	<0.001
C 18:3 n-3	0.72±0.15	0.81±0.17	0.154
∑FA[3]	1.43±0.28	1.97±1.34	0.184
∑SFA[3]	1.60±0.47	4.04±2.59	0.016
∑MUFA[3]	1.50±0.26	1.22±0.37	0.035
∑PUFA[3]	0.88±0.13	0.80±0.15	0.203
∑n-9	1.12±0.16	1.44±0.23	<0.001
∑n-6	1.04±0.13	0.80±0.14	<0.001
∑n-3	0.72±0.15	0.81±0.17	0.154

[1] Means±SD for 18 pigs per experimental diet.
[2] BT =Beef tallow; SO = Sunflower oil.
[3] SFA = Saturated fatty acid, MUFA = Monounsaturated fatty acid, PUFA = Polyunsaturated fatty acid; ∑SFA = C14:0+C16:0+C17:0+C18:0+C20:0; ∑MUFA = C16:1+C17:1+C18:1 n-9+C20:1 n-9; ∑PUFA = C18:2 n-6+C18:3 n-3.

Table 8. Effect of dietary fat type on minimum *de novo* synthesis of fatty acids during the whole feeding period[1]

Fatty acids	BT[2]	SO[2]	p-value
Minimum synthesis (kg/14 weeks)			
SFA[3]	2.75±1.57	4.64±0.79	0.002
MUFA[3]	1.76±1.02	1.26±0.45	0.141
SFA/(SFA+MUFA)[3]	0.60±0.12	0.79±0.05	<0.001

[1] Means±SD for 18 pigs per experimental diet.
[2] BT = Beef tallow; SO = Sunflower oil.
[3] SFA = Saturated fatty acid, MUFA = Monounsaturated fatty acid, PUFA = Polyunsaturated fatty acid; ΣSFA = C14:0+C16:0+C17:0+C18:0+C20:0; ΣMUFA = C16:1+C17:1+C18:1 n-9+C20:1 n-9.

and n-6 PUFA ($p<0.001$), whereas the amount of digestible n-3 PUFA was lower ($p<0.001$) than that provided by the BT diet.

The whole body of the pigs at baseline contained an average total fat mass of 4.1±0.8 kg. The calculated total fat mass in the carcass at the end of the experiment was 19.0± 3.0 and 19.2±1.6, n = 18 ($p = 0.819$) for the pigs fed the BT and SO diet, respectively. The pigs fed BT diet had deposited more stearic acid ($p<0.05$), but less ($p<0.001$) linoleic acid when compared with the pigs fed the SO diet (Table 7). There was no difference between both diets in the deposition of palmitic acid, oleic acid and α-linolenic acid. The pigs fed the SO diet showed a trend towards higher ($p = 0.072$) deposition of total fatty acids with unaltered deposition of MUFA. Deposition of SFA in the pigs fed the SO diet was less ($p<0.05$) than that in those fed the BT diet, whereas PUFA deposition was higher ($p<0.001$). There was more deposition ($p<0.001$) of n-6 PUFA in the pigs fed the SO diet, but deposition of the n-9 MUFA and n-3 PUFA was similar to that in the pigs fed the BT diet.

The deposition:intake ratios for palmitic acid tended ($p = 0.076$) to be higher in the pigs fed the SO diet when compared with the pigs fed the BT diet. The calculated deposition:intake ratio for stearic acid in pigs fed the SO diet was negative because of the negative apparent digestibility and thus negative digestible intake of stearic acid. This would imply that the stearic acid deposited in body of the pigs fed the SO diet originated from *de novo* synthesis. The deposition: intake ratios for oleic and linoleic acid in the pigs fed the SO diet were lower ($p<0.01$) than those in the pigs fed the BT diet. There was no diet effect on the deposition:intake ratio for α-linolenic acid, the ratio for the two groups of pigs being less than one. Dietary treatment did not influence the deposition:intake ratios for total FA, PUFA and n-3 PUFA, but the ratio for SFA and n-9 was higher in pigs fed the SO diet, whereas the ratios for MUFA and n-6 PUFA were lower ($p<0.05$).

Minimum *de novo* synthesis

The pigs fed the diet containing SO had a greater ($p<0.01$) synthesis of SFA, but no difference was observed for the synthesis of MUFA when compared to their counterparts fed the diet with BT. The synthesis ratio of SFA:(SFA+MUFA) was greater ($p<0.001$) in the pigs fed the diet containing SO (Table 8).

DISCUSSION

As far as we know, this is the first study in which growing-finishing pigs were fed on a restricted basis diets containing iso-energetic amounts of either BT or SO to determine the effect of vegetable fat on meat quality. The influence of replacement of dietary animal fat by vegetable oil on meat quality of pigs has been described by various investigations (Miller et al., 1990; Wiseman and Agunbiade, 1998; Wood et al., 2004; Mitchaothai et al., 2007). However, the various studies on meat quality can be criticized because the pigs had free access to diets containing equal inclusion percentages of either animal or vegetable fat. The well-known difference in digestibility between animal fat and vegetable oil (Cera et al., 1989) interferes with the interpretation of the results. Under those conditions, the dietary content of metabolizable energy from vegetable fat is greater than that from animal fat. As a consequence, the pigs fed the diet with vegetable fat would consume a diet containing less protein and carbohydrates, when expressed as a percentage of dietary metabolizable energy. This in turn affects *de novo* fatty acid synthesis and thus the fatty acid composition of tissues and meat quality (Liu et al., 2007). A similar reasoning would hold for a difference in feed intake. The diets and feeding regimen used in this study should allow a proper comparison of feeding either SO or BT as fat source.

The main fatty acids in the BT diet were stearic, palmitic, and oleic acid, whereas the SO diet was very rich in linoleic acid. The difference in oleic acid content between the two diets was relatively small. Thus, the BT diet can be considered representative for diets rich in SFA, whereas the SO diet may represent diets rich in n-6 PUFA. The diets were identical in terms of percentages of metabolizable energy provided by the macronutrients. The two experimental diets were fed on an iso-energetic basis. Indeed, the pigs fed the BT or SO diet showed no difference in growth performance. It may thus be concluded that in the present experiment the only dietary variable was the amount of dietary energy in the form of either BT or SO.

Carcass quality traits did not differ for the two dietary fat sources. This outcome agrees with reports published previously (Miller et al., 1990; Bee et al., 2002; Nuernberg et al., 2005; Mitchaothai et al., 2007). Meat quality characteristics, except for the Japanese color score, were not statistically different between the BT and SO treatments.

These results agree with those of Scheeder et al. (2000) who found that feeding pork fat, olive oil or soybean oil to growing-finishing pigs did not affect pH, cooking losses, texture, or color of pork. The higher Japanese color score of the pork in the current SO treatment may relate to the somewhat higher redness (color a* value). It might imply that meat color assessment by eye is more sensitive than that done technically. In keeping with the present results, Miller et al. (1990) also found no difference in drip losses, cooking losses, shear force, and marbling between pigs fed either animal fat or sunflower oil. The sarcomere length of pork of both dietary treatments (1.86 to 1.90 μm) was in the normal range (1.50 to 2.0 μm) for longissimus muscle (Wheeler et al., 2000). The intramuscular fat or marbling of loin was not statistically different between both treatments which are in accordance with the results of Nuernberg et al. (2005) when the effect of olive and linseed oil were compared. On the basis of the results for carcass and meat quality, it may be concluded that supplementation of SO instead of BT to the diet did not alter the quality of pig meat. In contrast, other types of treatment can alter the carcass quality of pigs (Yang et al., 2005; Hur et al., 2007; Li et al., 2007).

The relative concentrations of myristic (C14:0), palmitic (C16:0), margaric (C17:0), and stearic (C18:0) in adipose tissues were higher after feeding the BT diet. This is explained by the larger fractions of these fatty acids in the BT diet. However, in loin of the pigs fed the BT diet the incorporation of palmitic and stearic acid was not increased. Apparently, there are differences in the efficiency of deposition in different tissue types for the various fatty acids. Both adipose tissues and loin of the pigs fed the BT diet instead of the SO diet contained a higher oleic fraction, even though the amount of this fatty acid in the BT diet was smaller than in the SO diet. This could relate to diet-induced differences in hydrogenation of oleic acid and preferential utilization for energy generation. The relative concentration of linoleic acid in adipose tissues and loin of the pigs fed the SO diet was greater than that of the pigs fed the BT diet, but the concentration of α-linolenic acid was lower. The higher and lower incorporation of linoleic acid and α-linolenic acid in pigs fed the SO diet can be explained by the higher and lower intakes of these essential fatty acids.

The crude fat component of the SO diet had a higher apparent digestibility than that of the BT diet, but there were no differences in the apparent digestibilities of DM and CP between both diets. In a previous study (Mitchaothai et al., in press) we found higher apparent digestibilities of DM, CP, and crude fiber (CF) when growing-finishing pigs were fed a diet containing SO instead of BT. In that study, the pigs had *ad libitum* access to the experimental diets. It is difficult to see why *ad libitum* feeding instead of restricted feeding would increase the digestibility of DM and CP in a diet containing SO. The superior digestibility of oils rich in linoleic acid, as opposed to fats rich in SFA, is well known (Cera et al., 1989; Li et al., 1990) and probably relates to a more efficient incorporation of PUFA into micelles (Garrett and Young, 1975). As mentioned above, the higher fat digestibility of the SO was taken into account when formulating the diets. Furthermore, the BT and SO diets were fed on an iso-energetic basis. This explains why growth performance of the pigs fed either the SO or BT diet was similar.

Feeding the two fat sources was associated with marked differences in the apparent digestibility of individual fatty acids. Palmitic and linoleic acid in the SO diet were digested more efficiently than when these fatty acids were present in the BT diet. On the other hand, stearic acid in the SO diet was less well digested than that in the BT diet. There were no diet effects on the digestibilities of oleic and α-linolenic acid. A combination of different factors may be responsible for the observed diet-induced differences in apparent digestibility of identical fatty acids. As mentioned above, the total fat digestibility of SO was greater than that of BT, which may be associated with enhanced micelle formation after feeding the SO diet. An improved micelle formation may favorably influence the digestion of all fatty acids in the diet. The position of a given fatty acid in the triacylglycerol molecule also plays a role. Fatty acids at the 2 position of glycerol in triacylglycerol molecules are better digested than those at the 1,3 position (Bracco, 1994; Innis and Dyer, 1997; Nelson and Innis, 1999; Scheeder et al., 2000; Scheeder et al., 2003). During digestion, the pancreatic lipase action specifically removes fatty acids at the 1,3 position while the resulting monoacylglycerol molecule is efficiently incorporated into micelles (Lien, 1994), leading to preferential absorption of fatty acids at the 2 position of the glycerol backbone of triacylglycerols. The intake level of a given individual fatty acid and its faecal excretion of endogenous origin will also affect the calculated apparent digestibility. A low intake level in combination with a high endogenous excretion will by itself lead to a low apparent digestibility. When comparing the digestibilities of palmitic and stearic acid for the SO and BT diet, the values for the SO diet may be biased towards lower values because the intake levels were lower. This may hold especially for stearic acid, which yielded a negative apparent digestibility for the SO treatment. On the other hand, the apparent digestibility of linoleic acid for the SO diet may have been biased towards a higher value.

The calculated intake of digestible fatty acids reflects the amount in the diet and feed intake, combined with the measured apparent digestibility. The deposition in the body

of fatty acids was calculated as based on the fatty acid composition of the total body fat that was gained during the entire feeding period. As would be expected, the pigs fed the SO diet deposited more linoleic acid, whereas those fed BT deposited more stearic acid in their whole body. Similar data have been shown for mice (Javadi et al., 2004) and goats (Yeom et al., 2005). To obtain clues as to preferential deposition of fatty acids, the ratio of deposition of a given fatty acid or group of fatty acids to the intake of digestible fatty acid or group of fatty acids was calculated. The deposition:intake ratio for fatty acid reflects the net amount synthesized and/or the proportion of the digested fatty acid not oxidized. A deposition:intake ratio>1 would point at net *de novo* synthesis, whereas a ratio<1 would indicate net oxidation. The low deposition:intake ratio for linoleic acid in the pigs fed SO is consistent with the well-known preferential oxidation of linoleic acid (Jones et al., 1985; Cunnane and Anderson, 1997; Yeom et al., 2005) and the fact that linoleic acid cannot be synthesized by pigs (Azain, 2000; Nguyen et al., 2005). The deposition:intake ratio for the essential PUFA, linoleic and α-linolenic acid, cannot be higher than 1. Indeed, the ratio for α-linolenic acid was below 1 and so was the ratio for linoleic acid in the pigs fed the SO diet. The pigs fed BT had a group mean deposition:intake ratio for linoleic acid that was just above 1, but was not significantly higher than 1. The negative deposition:intake ratio for stearic acid in pigs fed the SO is a consequence of the negative apparent digestibility that was calculated.

The pigs fed SO instead of BT had a higher deposition:intake ratio for SFA, but lower ratio for MUFA and no difference for the ratio of PUFA. The diet effect on the ratios for SFA and MUFA can be explained by the calculated minimum synthesis of these groups of fatty acids. Feeding the diet containing SO stimulated the synthesis of SFA, but tended to depress that of MUFA. The higher synthesis ratio for SFA:(SFA+MUFA) in pigs fed the SO diet indicates that there was selective synthesis of SFA in the pigs fed the SO diet. This might point at *de novo* fatty acid synthesis being regulated to balance the amount of saturated and unsaturated fatty acids in the body because the intake of linoleic acid was very high in the pigs fed the diet with SO.

In conclusion, the iso-energetic replacement of BT by SO had a marked impact of the fatty acid composition of tissues, but did not affect carcass and meat quality traits. Feeding the diet with SO produced a markedly increased deposition of linoleic acid in the adipose tissues, loin muscle, and whole body. After calculating the deposition:digestible intake ratio for individual fatty acids, it became clear that the type of dietary fat had marked, specific effects on the synthesis and oxidation of fatty acids.

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