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Effect of Dietary Energy Density on Performance and Lean Deposition of Growing-Finishing Pigs

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Abstract: Three experiments using a total of 1140 crossbred barrows and gilts (Yorkshire x Landrace x Duroc) were conducted to determine the effects of dietary Digestible Energy (DE) density on performance and lean deposition in growing-finishing pigs during three separate phases. A completely randomized block design within sex was used involving 480 pigs in Exp. 1 (20.8-55.9 kg), 420 pigs in Exp. 2 (57.0-76.6 kg) and 240 pigs in Exp. 3 (78.6-105.8 kg) (pigs were from three different groups). Pigs were allotted to one of five treatments containing 13.62, 13.87, 14.12, 14.37 and 14.62 MJ DE kg^{-1}. Pig body weight and feed consumption were determined every 2 weeks and carcass composition was evaluated at the start and end of the experiments. The quadratic or broken-line model was used to estimate the requirement of dietary DE concentration. In Exp. 1, there were no differences ($p>0.05$) in weight gain or feed efficiency. Meanwhile, carcass fat-free lean gain decreased (linear, $p = 0.02$; quadratic, $p = 0.02$) and fat-free lean index decreased quadratically (quadratic, $p = 0.05$) with increasing dietary energy density. The optimum dietary DE to maximize lean deposition was calculated to be 13.81 MJ DE kg^{-1}. In Exp. 2, for pigs weighing 57.0-76.6 kg both weight gain (linear, $p = 0.02$) and feed efficiency (linear, $p = 0.02$) increased linearly with increasing DE density while carcass fat-free lean gain ($p = 0.05$) and fat-free lean index decreased ($p<0.01$). The optimum dietary DE for lean deposition was 13.76 MJ DE kg^{-1}. In Exp. 3, the linearly decreased feed intake (linear $p = 0.04$) and increased weight gain (linear, $p<0.01$; quadratic, $p = 0.01$) resulted in an improvement in feed efficiency (linear, $p<0.01$; quadratic, $p = 0.01$). The quadratically decreased carcass fat-free lean gain (quadratic, $p = 0.02$) and decreased fat-free lean index ($p<0.01$) suggested that the optimum dietary DE for lean deposition was calculated to be 13.82 MJ DE kg^{-1}.

Key words: Digestible energy, growing-finishing pigs, growth performance, lean deposition, producer, China

INTRODUCTION

An evaluation of the relationship between dietary energy and performance or tissue deposition is usually based on energy intake (Campbell and Dunkin, 1983; Kyriazakis and Emmans, 1992a, b; Weis *et al*., 2004). In commercial environments, free access to feed is commonly used which dictates that researcher can modulate the energy intake of pigs only by compounding diets with different energy levels and not by altering feeding levels.

Many studies have been conducted to investigate the energy range which maximizes pig performance. Black (1995) suggested that the critical lower limit would be 13.77 MJ DE kg^{-1} for pigs weighing 20-50 kg and 9.83 MJ DE kg^{-1} for pigs >50 kg. King (1999) found that the performance of growing pigs would not be impaired at dietary DE concentrations above 14.5 MJ kg^{-1}. However, in the NRC (1998) recommendations, dietary DE requirement for all growing-finishing pigs was all 3400 kcal kg^{-1} (14.2 MJ kg^{-1}).

In economic terms, the amount of lean tissue and its distribution are of prime concern for pig producers and these are the main determinants of the amount and quality of pork that can be derived from the pig's carcass. To satisfy consumer demands for leaner pork, recent emphasis in the pork industry has been to maximize lean growth in pigs through genetic selection and nutrition (Lawrence *et al*., 1994).

Noblet *et al*. (1989) showed that the energy requirements for protein and lipid deposition were 9.7 and 15.9 kJ g^{-1}, respectively. Thus, it is possible that the energy requirement for lean deposition is different from that for the growth of the whole body. The objective of this study was to determine the effect of dietary energy

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density (ranging from 13.62-14.62 MJ DE kg^{-1}) on performance and lean deposition of growing-finishing pigs (20.8-55.9, 57.0-76.6 and 78.6-105.8 kg).

MATERIALS AND METHODS

The procedures used in these experiments followed those proposed by the China Agriculture University Animal Care and Use Committee (Beijing, China). The experiments were conducted at a commercial swine farm located in Hunan province (Yiyang city, China).

Animals and feeding: Three experiments were conducted to evaluate the effects of increasing dietary energy density on performance and lean deposition of growing-finishing pigs over three phases (20.8-55.9, 57.0-76.6 and 78.6-105.8 kg). A completely randomized block design within sex was used. Pigs (Yorkshire x Landrace x Duroc) were allotted to one of five treatments (13.62, 13.87, 14.12, 14.37 and 14.62 MJ DE kg^{-1}) with the treatments applied to six pens containing an equal number of barrows and gilts. The pigs were raised in pens with concrete floors that were half solid and half slatted. Different pigs were used for the three experiments to avoid any potential for a residual effect of treatment in one phase affecting the performance in the other phase.

The DE concentration of the treatment diets was increased by changing the ratio of low to high energy ingredients. Wheat bran was chosen as the low energy ingredient and corn and soybean oil as high energy ingredients. The range of energy between DE treatment concentrations was 0.25 MJ kg^{-1} (60 kcal kg^{-1}) this range exceeds the variability within cereal grains of 53 kcal (Fairbairn *et al*., 1999) allowing differences to be more readily attributed to treatment and not to ingredient variability. Digestible energy values for individual feed ingredients were previously determined in the laboratory and were used to calculate the DE content of the diets. The DE values were 14.06 MJ DE kg^{-1} for corn, 15.88 MJ DE kg^{-1} for soybean meal and 10.41 MJ DE kg^{-1} for wheat bran (Table 1). The DE value for soybean oil of 36.61 MJ kg^{-1} was obtained from the China Feed Bank (2006). All diets were formulated to meet or exceed the NRC (1998) recommended levels for other nutrients. Feed samples were collected in each trial and analyzed for their chemical composition (Table 2-4).

Table 1: Nutrient values of ingredients used in Experiments 1-3

Nutrient values	Corn	Soybean meal	Wheat bran
Dry matter (%)	88.41	89.23	89.48
Ash (%)	1.98	5.54	5.05
Crude protein (%)	8.31	45.08	17.47
Ether extract (%)	4.07	1.96	2.95
Starch (%)	70.56	11.70	28.37
Crude fiber (%)	2.22	6.10	9.98
NDF (%)	12.58	25.62	35.85
ADF (%)	1.97	7.83	9.69
Gross energy (%)	16.25	17.71	16.34
Digestible energy[x] (MJ kg^{-1})	14.06	15.88	10.41

[x] Digestible energy of ingredients was determined previously by total collection method in growing pigs in the lab

Table 2: Ingredient and nutrient composition of experimental diets for 20.8-55.9 kg phase pigs containing five energy levels (Exp. 1 as fed basis)

	DE[x] (MJ kg^{-1})				
Experimental diets	13.62	13.87	14.12	14.37	14.62
Ingredients (%)					
Corn	50.40	56.45	59.65	60.10	60.85
Soybean meal	30.80	31.10	31.00	31.70	31.80
Wheat bran	15.80	9.50	6.00	4.15	2.50
Soybean oil	0.00	0.00	0.50	1.25	2.05
Salt	0.40	0.40	0.40	0.40	0.40
Medical stone	0.20	0.15	0.05	0.00	0.00
Dicalcium phosphate	0.40	0.40	0.40	0.40	0.40
Limestone, ground	1.00	1.00	1.00	1.00	1.00
Vitamin/Mineral premix[y]	1.00	1.00	1.00	1.00	1.00
Analyzed nutrients (%)					
Crude protein	17.94	18.01	18.06	18.11	18.09
Calcium	0.71	0.70	0.66	0.69	0.66
Phosphorus	0.54	0.54	0.57	0.55	0.53
Lysine	0.98	0.97	0.95	0.94	0.95
Methionine	0.28	0.25	0.25	0.27	0.25
Tryptophan	0.19	0.17	0.17	0.17	0.18
Threonine	0.70	0.69	0.66	0.66	0.65

Table 3: Ingredient and nutrient composition of experimental diets for 57.0-76.6 kg phase pigs containing five energy levels (Exp. 2 as fed basis)

	DE[x] (MJ kg^{-1})				
Experimental diets	13.62	13.87	14.12	14.37	14.62
Ingredients (%)					
Corn	66.40	72.30	71.70	72.40	72.55
Soybean meal	20.40	21.00	21.30	21.50	21.50
Wheat bran	10.00	3.50	2.80	1.10	0.00
Soybean oil	0.00	0.00	1.00	1.80	2.75
Salt	0.40	0.40	0.40	0.40	0.40
Dicalcium phosphate	1.00	1.00	1.00	1.00	1.00
Limestone, ground	0.80	0.80	0.80	0.80	0.80
Vitamin/Mineral mix[y]	1.00	1.00	1.00	1.00	1.00
Analyzed nutrients (%)					
Crude protein	14.83	14.83	14.81	14.81	14.79
Calcium	0.59	0.58	0.59	0.57	0.58
Phosphorus	0.47	0.47	0.43	0.45	0.43
Lysine	0.78	0.78	0.76	0.77	0.75
Methionine	0.23	0.24	0.22	0.25	0.26
Tryptophan	0.17	0.15	0.18	0.17	0.16
Threonine	0.59	0.59	0.57	0.63	0.61

[x] Calculated according to digestible energy values of corn, soybean meal and wheat determined in the lab; digestible energy value of soybean oil was obtained from the China Feed Bank (2006); [y] Premix provided the following per kg of complete diet for Exp. 1 and 2: vitamin A, 5,512 IU; vitamin D3, 2,200 IU; vitamin E, 64 IU; vitamin K3, 2.2 mg; vitamin B12, 27.6 μg; riboflavin, 5.5 mg; pantothenic acid, 13.8 mg; niacin, 30.3 mg; choline chloride, 551 mg; Mn, 10 mg; Fe, 100 mg; Zn, 100 mg; Cu, 20 mg; I, 0.3 mg; Se, 0.3 mg

Table 4: Ingredient and nutrient composition of experimental diets for 78.6-105.8 kg phase pigs containing five energy levels (Exp. 3 as fed basis)

	DE[x] ($MJ\ kg^{-1}$)				
Experimental diets	13.62	13.87	14.12	14.37	14.62
Ingredient (%)					
Corn	76.00	77.90	79.90	79.00	76.00
Soybean meal	13.20	14.10	15.10	15.40	15.30
Wheat bran	8.00	4.70	1.20	0.80	2.50
Soy oil	0.00	0.50	1.00	2.00	3.40
Salt	0.30	0.30	0.30	0.30	0.30
Dicalcium phosphate	0.70	0.70	0.70	0.70	0.70
Limestone, ground	0.80	0.80	0.80	0.80	0.80
Vitamin/Mineral mix[y]	1.00	1.00	1.00	1.00	1.00
Analyzed nutrients (%)					
Crude protein	13.79	13.84	13.87	13.77	13.77
Calcium	0.53	0.51	0.52	0.50	0.51
Phosphorus	0.41	0.43	0.43	0.40	0.42
Lysine	0.61	0.60	0.59	0.58	0.58
Methionine	0.21	0.23	0.22	0.20	0.21
Tryptophan	0.14	0.13	0.13	0.12	0.11
Threonine	0.47	0.47	0.46	0.47	0.45

[x]Calculated according to digestible energy values of corn, soybean meal and wheat determined in the lab; digestible energy value of soybean oil was obtained from the China Feed Bank (2006); [y]Premix provided the following per kg of complete diet for Exp. 3: vitamin A, 2,512 IU; vitamin D3, 1,200 IU; vitamin E, 34 IU; vitamin K3, 1.5 mg; vitamin B12, 17.6 μg; riboflavin, 2.5 mg; pantothenic acid, 6.8 mg; niacin, 20.3 mg; choline chloride, 351 mg; Mn, 10 mg; Fe, 50 mg; Zn, 50 mg; Cu, 10 mg; I, 0.3 mg; Se, 0.3 mg

In Exp. 1, a total of 480 pigs with an initial body weight of 20.8±2.1 kg were used during the 20.8-55.9 kg phase. Sixteen pigs were reared in pens measuring 5.21×2.85 m. In Exp. 2, a total of 420 pigs (57.0±2.7 kg) were used during the 57.0-76.6 kg phase with 14 pigs per pen (5.62×2.53 m). In Exp. 3, a total of 240 pigs (78.6±3.2 kg) were used for the 78.6-105.8 kg phase with eight pigs per pen (4.65×2.40 m). Prior to starting the experiment, the pigs were all fed a commercially prepared grower diet and housed in a different barn to that used for the present experiment. Diets and water were provided *ad libitum* throughout these three experiments. Pigs were weighed and feed disappearance was measured every 14 days to determine weight gain, feed intake and feed efficiency.

Carcass evaluation: At the beginning of each experiment, six additional pigs obtained from the same source as those used in the experiment with an initial body weight of 20.8 (Exp. 1), 57.0 (Exp. 2) and 78.6 kg (Exp. 3) were weighed and then transported to a processing plant where carcass data were collected to obtain initial carcass composition. Pigs were killed by exsanguination immediately following electrical stunning. Hot carcass weight was measured to determine dressing percentage. Carcass measurements including longissimus muscle area, the 10th rib back fat depth and last-rib back fat depth were obtained from the left side of the hot carcass according to the method decribed by Johnson *et al.* (2004). In addition, carcass fat-free lean weight was calculated using the equations in NRC (1998). When pigs reached the target slaughter body weight, they were fasted on the morning of the day of slaughter. One randomly selected pig from each pen was slaughtered by the previously described method and the final carcass data were collected.

NRC (1998) equations were used to evaluate fat-free lean content (lb and in. was converted to g and cm, respectively in the study):

$$\begin{aligned}&\text{Carcass fat}-\text{free lean (1b)}=0.95\times[7.231+(0.437\times\\&\text{Hot carcass weight, 1b})-(18.746\times\text{10th back fat}\\&\text{depth, in})+(3.877\times\text{10th rib loin eye area, in}^2)]\end{aligned}\quad(1)$$

$$\begin{aligned}&\text{Carcass fat}-\text{free lean gain (1b day}^{-1})=\\&\frac{[(\text{Final carcass fat}-\text{free lean, 1b})\\(\text{Initial carcass fat}-\text{free lean, 1b})]}{\text{Days from initial to final}}\end{aligned}\quad(2)$$

$$\begin{aligned}&\text{Fat-free lean index}=[50.767+(0.035\times\\&\text{Hot carcass weight, 1b})\text{-}(8.979\times\text{last-}\\&\text{rib midline backfat on hot carcass, in})]\end{aligned}\quad(3)$$

Chemical analysis: All analyses were performed in duplicate. The analysis of the proximate principles was conducted according to standard procedures (AOAC, 1990). Gross energy was determined by an automatic adiabatic oxygen bomb calorimeter (Parr 1281 Automatic Energy Analyzer, Moline, IL). Phosphorus content was analyzed using a UV-visible spectrophotometer (Hitachi, U-1000, Tokyo, Japan).

The amino acid content of the diets was determined by High Performance Liquid Chromatography (Hitachi L-8800 Amino Acid Analyzer, Tokyo, Japan) after 24 h hydrolysis with 6 NHCl in closed glass vessels according to AOAC (1990). Methionine and cysteine were determined after oxidation with performic acid (Llames and Fontaine, 1994). The tryptophan concentration of the diets was determined by reversed-phase HPLC following alkaline hydrolysis according to AOAC (1990).

Statistical analysis: Data for each response criterion were analyzed by ANOVA using the GLM procedure (SAS Inst. Inc., Cary, NC) with energy density and replicate included in the model. The pen was considered to be the experimental unit. Energy density effects on performance and lean deposition were evaluated by linear and quadratic contrasts and the qudratic or broken-line regression model was used for response variables to obtain an estimate of the dietary DE requirement (Robbins *et al*., 2006). The two models could not be used to estimate requirements for growth variables either due to a lack of response to energy concentration or because there was no breakpoint in the data. Carcass fat-free lean gain and fat-free lean index were the dependent variables to determine the dietary DE requirements for lean deposition. The least square means procedure of SAS was used to calculate mean values and the pair-wise t-tests was used to determine differences between treatment means. Differences were considered significant at $p<0.05$ and highly significant at $p<0.01$.

RESULTS AND DISCUSSION

Growth performance: Weight gain ($p = 0.21$) and feed efficiency ($p = 0.47$) was not different during the 20.8-55.9 kg period (Table 5). Feed intake was affected significantly ($p = 0.02$). Dietary DE intake (DEi) increased (linear, $p<0.01$; quadratic, $p<0.01$) with increasing DE during this time period.

In Exp. 2, during the 57.0-76.6 kg period, increasing the dietary DE concentration from 13.62-14.62 MJ DE kg^{-1} resulted in an increase of >0.09 kg day^{-1} of weight gain ($p = 0.01$) and a linear decrease of 0.10 kg day^{-1} of feed intake (linear, $p = 0.02$).

There was no difference in DE intake during this period ($p = 0.72$). Feed efficiency improved (linear, $p<0.01$; quadratic, $p = 0.07$) with increasing energy levels (Table 5). Pigs in Exp. 3 (78.6-105.8 kg) fed diets containing lower energy contents grew at a lower rate than pigs fed higher energy diets (linear, $p<0.01$; quadratic, $p = 0.01$, Table 5). The linearly decreased feed intake (linear $p = 0.04$) and increased weight gain (linear, $p<0.01$; quadratic, $p = 0.01$) resulted in an improvement in feed efficiency (linear, $p<0.01$; quadratic, $p = 0.01$).

Lean deposition: During the 20.8-55.9 kg period, there was a quadratic response in longissimus muscle area (quadratic, $p<0.01$) and a decrease in carcass fat-free lean gain (linear, $p = 0.02$; quadratic, $p = 0.02$) as DE concentration increased. For fat-free lean index, a negative trend (quadratic, $p = 0.05$) was present (Table 6).

Increasing the dietary DE concentration from 13.62-14.62 MJ DE kg^{-1} resulted in an increase of >8.8 mm of back fat depth (linear, $p<0.01$; quadratic, $p<0.01$) in the 57.0-76.6 kg period. However, longissimus muscle area was decreased (linear, $p = 0.03$). Furthermore, for carcass fat-free lean gain and fat-free lean index, decreased values (linear, $p<0.01$; quadratic, $p<0.01$) were observed although, carcass fat-free lean gain at the level of 13.87 MJ kg^{-1} was numerically higher than those of the other treatments (Table 6).

Increased 10th rib back fat depth was present in the 78.6-105.8 kg period (linear, $p<0.01$; quadratic, $p<0.01$) with the highest value of 2.32 cm at the level of 14.62 MJ kg^{-1}. Longissimus muscle area was linearly decreased (linear, $p<0.01$). There was a quadratic response in fat-free lean gain (quadratic, $p = 0.02$) and a decrease (linear, $p<0.01$; quadratic, $p<0.01$) in fat-free lean index with increasing the dietary DE concentration.

The optimum energy density to maximize lean deposition is defined as the DE level which supports maximum fat-free lean gain and fat-free lean index,

Table 5: Effects of dietary energy density on growth performance of growing-finishing pigs reared in a commercial environment[x]

	DE (MJ kg^{-1})						p^y		
Effects	13.62	13.87	14.12	14.37	14.62	SEM	ANOVA	Linear	Quadratic
20.8-55.9 kg									
Initial BW (kg)	20.82	20.74	20.81	20.72	20.84	0.05	1.00	0.99	1.00
Final BW (kg)	56.67	55.28	55.00	56.26	56.41	0.74	0.93	0.92	0.73
Weight gain (kg day^{-1})	0.80	0.77	0.76	0.79	0.79	0.01	0.21	0.82	0.15
Feed intake (kg day^{-1})	1.55^{ab}	1.47^{bc}	1.45^{c}	1.57^{a}	1.56^{ab}	0.03	0.02	0.35	0.05
Feed efficiency	0.52	0.53	0.53	0.50	0.51	0.00	0.47	0.35	0.38
Digestible energy intake (MJ day^{-1})	21.15^{b}	20.33^{b}	20.43^{b}	22.51^{a}	22.76^{a}	1.14	0.02	<0.01	<0.01
57.0-76.6 kg									
Initial BW (kg)	56.11	57.58	56.43	58.25	56.42	0.92	0.99	0.92	0.96
Final BW (kg)	74.71	76.36	76.24	78.18	77.27	1.29	0.99	0.60	0.86
Weight gain (kg day^{-1})	0.78^{b}	0.78^{b}	0.83^{ab}	0.83^{ab}	0.87^{a}	0.01	0.01	0.02	0.13
Feed intake (kg day^{-1})	2.16	2.11	2.13	2.10	2.06	0.04	0.15	0.02	0.67
Feed efficiency	0.36^{b}	0.37^{b}	0.38^{ab}	0.40^{ab}	0.42^{a}	0.01	0.06	<0.01	0.07
Digestible energy intake (MJ day^{-1})	29.43	29.28	30.00	30.18	30.11	0.52	0.72	0.49	0.79
78.6-105.8 kg									
Initial BW (kg)	78.65	78.94	78.39	78.29	78.61	0.25	1.00	0.94	1.00
Final BW (kg)	104.33	105.50	105.85	106.40	107.16	1.06	0.98	0.52	0.81
Weight gain (kg day^{-1})	0.92	0.95	0.98	1.00	1.02	0.01	0.09	<0.01	0.01
Feed intake (kg day^{-1})	3.10	2.98	2.96	2.94	2.90	0.08	0.33	0.04	0.11
Feed efficiency	0.30^{b}	0.32^{ab}	0.33^{ab}	0.34^{ab}	0.35^{a}	0.30	0.05	<0.01	0.01
Digestible energy intake (MJ day^{-1})	42.26	41.31	41.77	42.18	42.40	0.45	0.93	0.70	0.76

[x] A total of 480 pigs were used in Exp. 1, 420 pigs in Exp. 2 and 240 pigs in Exp. 3; [y] p-values for treatment are based on ANOVA using all five treatments; within a row, means followed by same or no letter do not differ ($p>0.05$)

Table 6: Effects of dietary energy density on lean deposition of growing-finishing pigs reared in a commercial environment[x]

	DE (MJ kg^{-1})						P[y]		
Traits	13.62	13.87	14.12	14.37	14.62	SEM	ANOVA	Linear	Quadratic
20.8-55.9 kg									
Hot carcass weight (kg)	37.03	35.38	36.98	37.47	34.27	0.53	0.28	0.37	0.44
Dressing percentage (%)	68.39	68.75	69.30	69.09	67.56	0.48	0.82	0.70	0.50
Back fat depth[z] (cm)	1.00	0.95	1.01	1.19	1.05	0.03	0.12	0.29	0.47
Longissimus muscle area (cm^2)	22.75^{a}	22.88^{a}	22.87^{a}	21.38^{ab}	18.83^{b}	0.49	0.02	0.31	<0.01
Fat-free lean gain (g g day^{-1})	264.79	254.16	264.07	247.84	213.46	6.68	0.13	0.02	0.02
Fat-free lean index (%)	57.29^{ab}	58.61^{a}	57.30^{ab}	54.51^{b}	55.16^{b}	0.51	0.06	0.07	0.05
57.0-76.6 kg									
Hot carcass weight (kg)	57.36	57.84	56.72	57.52	59.12	0.46	0.60	0.34	0.36
Dressing percentage (%)	69.47^{bc}	72.31^{a}	68.53^{c}	70.18^{abc}	71.48^{ab}	0.45	0.04	0.59	0.73
Back fat depth[z] (cm)	2.07^{b}	1.99b	2.14^{b}	2.51^{ab}	2.87^{a}	0.11	0.03	< 0.01	<0.01
Longissimus muscle area (cm^2)	36.24	35.22	34.42	33.38	31.30	0.77	0.31	0.03	0.08
Fat-free lean gain (g g day^{-1})	304.72^{a}	311.38^{a}	271.38^{ab}	233.57^{ab}	198.43^{b}	14.40	0.05	<0.01	<0.01
Fat-free lean index (%)	51.79^{a}	51.72^{a}	50.76^{a}	48.13^{ab}	45.09^{b}	0.72	<0.01	<0.01	<0.01
78.6-105.8 kg									
Hot carcass weight (kg)	73.13	75.87	77.20	74.27	75.87	1.37	0.28	0.39	0.32
Dressing percentage (%)	65.49	68.42	68.13	67.72	68.57	1.26	0.10	0.06	0.08
Back fat depth[z] (cm)	1.95^{b}	2.00^{b}	2.00^{b}	2.04^{b}	2.32^{a}	0.10	<0.01	<0.01	<0.01
Longissimus muscle area (cm^2)	41.65	41.31	40.64	39.82	37.76	1.34	0.09	<0.01	0.20
Fat-free lean gain (g day^{-1})	330.23	343.71	352.65	299.18	272.98	11.00	0.05	0.10	0.02
Fat-free lean index (%)	52.01^{a}	51.37^{a}	50.92^{a}	50.79^{a}	48.75^{b}	0.29	<0.01	<0.01	<0.01

[x] A total of 480 pigs were used in Exp. 1, 420 pigs in Exp. 2 and 240 pigs in Exp. 3; [y] p-values for treatment are based on ANOVA using all five treatments; within a row, means followed by same or no letter do not differ ($p>0.05$); [z] Back fat depth = back fat depth at the 10th-rib

respectively. According to Baker (1986), the quadratic model indicates the requirements for maximal response of all animals in a population whereas a broken-line response predicts requirements for the average animal in the population. In the experiments, the quadratic or broken-line model was used to get the optimum dietary DE estimates under different conditions (Robbins *et al*., 2006). For pigs weighing 20.8-55.9 kg since, fat-free lean gain was higher in the three lower DE treatments than those values in the higher DE treatments there was not an increasing linear-plateau curve for a broken-line model. Under this condition, the quadratic model could give an estimate of the optimum dietary DE density for fat-free lean gain (Fig. 1a). However, for fat-free lean index during this period, the quadratic broken-line model gave a good estimate of the optimum DE concentration and the quadratic model gave a large underestimation for it as shown in Fig. 1b. Therefore, the broken-line model was used to estimate the requirement of DE density for fat-free lean index.

Conversely, the broken-line model and quadratic model were used to estimate the requirements for fat-free lean gain and fat-free lean index in the 57.0-76.7 kg period, respectively for similar reasons described (Fig. 2a, b). However, for pigs weighting 78.6-105.8 kg, the quadratic model was used to estimate the optimum DE density for fat-free lean index.

Both the broken-line model and quadratic model gave a good estimation of the optimum energy level for fat-free lean gain. Therefore, the optimum energy level was the average of the three estimates. For fat-free lean gain of pigs weighing from 20.8-55.9 kg using the quadratic model, the data were fitted to a quadratic regression equation:

$$Y = -84.16X^2 + 2333.0X - 15904.0 \ (R^2 = 0.89) \qquad (4)$$

The dietary DE concentration that maximized fat-free lean gain was calculated to be 13.86 MJ DE kg^{-1} (Fig. 1a). However, a breakpoint of 13.76 MJ DE kg^{-1} was determined for fat-free lean index using a broken-line model (Robbins *et al*., 2006) (Fig. 1b). Therefore, the optimum dietary DE density for lean deposition was 13.81 MJ DE kg^{-1}, the average of the above two estimates. For pigs weighing from 57.0-76.6 kg, the dietary DE concentration required to maximize lean deposition was 13.76 MJ DE kg^{-1}, the average of 13.78 MJ DE kg^{-1} (the breakpoint determined for fat-free lean gain using broken-line model) and 13.73 MJ DE kg^{-1} (estimated for fat-free lean index by the quadratic model:

$$Y = -8.697X^2 + 238.8X - 1587.4, \ R^2 = (0.99)$$

which are shown in Fig. 2. Finally, for pigs weighing from 78.6-105.8 kg, the dietary DE concentration required to maximize lean deposition was 13.82 MJ DE kg^{-1}, the average of 14.02 MJ DE kg^{-1} (the optimum energy density for fat-free lean gain estimated from quadratic broken-line model:

$$Y = 347.3 - 66.3\,(14.12\text{-}X)^2 - 157.2\,(X\text{-}14.12), \ R^2 = (0.97)$$

Quadratic model:

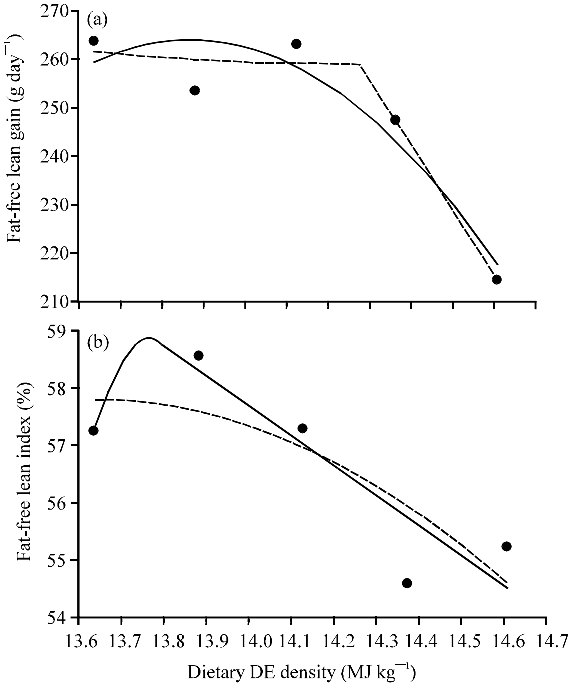

Fig. 1: Effect of DE density on fat-free lean gain (a) and fat-free lean index (b) in growing pigs weighing 20.8-55.9 kg (Exp.1) described with a broken-line and a quadratic model. a) Observed treatment mean values (●), a broken-line (---) and a quadratic (—) plot are shown. The quadratic model $Y = -84.2X^2+2333X - 15904$, $R^2 = 0.89$ gave a better estimate of the dietary DE density for fat-free lean gain. The DE density that maximized fat-free lean gain was calculated to be 13.86 MJ DE kg^{-1}. b: Observed treatment mean values (●), a broken-line (—) and a quadratic (---) plot are shown. The broken-line model was used to estimate the requirement of DE density for fat-free lean index. The equation was $Y = 58.96 - 89.57\ (13.76 - X)^2 - 5.26\ (X - 13.76)$ ($R^2 = 0.81$) ($R^2 = 0.81$) and the DE density that maximized fat-free lean index was calculated to be 13.76 MJ DE kg^{-1}. Thus, the optimum level of dietary DE to maximize lean deposition was 13.81 MJ DE kg^{-1} for pigs weighing 20.8-55.9 kg

$$Y = -161.0X^2 + 4484.0X - 30873,\ R^2 = (0.90)$$

and 13.62 MJ DE kg^{-1} (estimated for fat-free lean index by the quadratic model):

$$Y = -2.83X^2 + 77.2X - 473.8,\ R^2 = (0.91)$$

which are shown in Fig. 3.

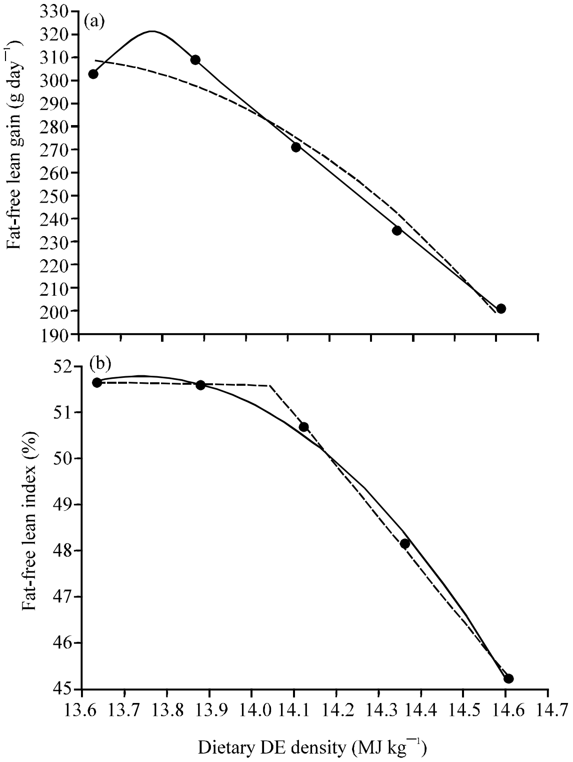

Fig. 2: Effect of DE density on fat-free lean gain (a) and fat-free lean index (b) in growing pigs weighing 57.0-76.6 kg (Exp. 2) described with a broken-line and a quadratic model. a) Observed treatment mean values (●), a broken-line (—) and a quadratic (---) plot are shown. The broken-line model was used the estimate the DE requirements for fat-free lean gain. The equation was $Y = 323.5 - 717.0\ (13.78 - X)^2 - 150.7\ (X - 13.78)$ ($R^2 = 0.99$) and the DE density that maximized fat-free lean gain was 13.78 MJ DE kg^{-1}. b) Observed treatment mean values (●), a broken-line (---) and a quadratic (—) plot are shown. The quadratic model ($Y = -8.70X^2+238.8X - 1587.0$, $R^2 = 0.99$) gave a better estimate of the DE density for fat-free lean index. The DE density that maximized fat-free lean index was 13.73 MJ DE kg^{-1}. The optimum level of DE to maximize lean deposition was 13.76 MJ DE kg^{-1}

Growth performance: Increases in weight gain of growing pigs as the dietary energy concentration increases have been reported by previous studies (Urynek and Buraczewska, 2003; Campbell and Taverner, 1988). Bikker *et al.* (1995) also showed that young pigs from 20-45 kg were energy-dependent. In contrast, in Exp. 1 of the present study, energy density had no effects

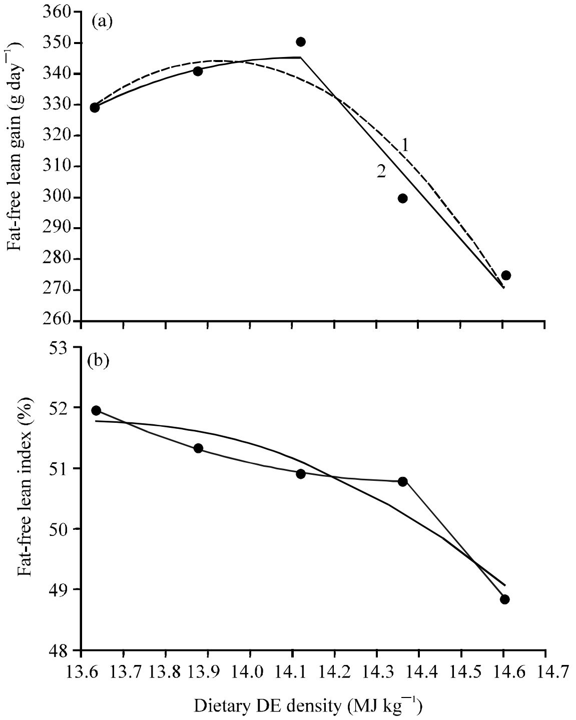

Fig. 3: Effect of DE on fat-free lean gain (a) and fat-free lean index (b) in finishing pigs weighing 78.6-105.8 kg (Exp. 3) described with a broken-line and a quadratic model. Observed treatment mean values (●), a quadratic (---, Curve 1) and a broken-line (—, black, Curve 2) plot are shown. Both the broken-line model ($Y = 347.3 - 66.3 (14.12 - X)^2 - 157.2 (X - 14.12)$, $R^2 = 0.97$) and the quadratic model ($Y = -161.0X^2+4484.0X-30873$, $R^2 = 0.90$) were used to estimate the DE requirement for fat-free lean gain. The optimal dietary level of 14.02 MJ DE kg^{-1} was the average of the two estimates. The quadratic model ($Y = -2.83X^2+77.2X-473.8$, $R^2 = 0.91$) gave a good estimate of the DE density for fat-free lean index. The DE density that maximized it was calculated to be 13.62 MJ DE kg^{-1}. Thus, the optimum level of DE to maximize lean deposition was 13.82 MJ DE kg^{-1}

on weight gain and feed efficiency in 20.8-55.9 kg pigs. This result was surprising but it was similar to that reported by Stahly *et al.* (1981) wherein increasing dietary energy level did not affect ($p>0.10$) the rate of gain and feed conversion in growing (20-60 kg) pigs. The explanation for the failure to observe a response in weight gain in the 20.8-55.9 kg period due to increasing energy concentration in the present study may be attributed to a reduction of lysine to DE ratio as the DE level increased. In the study, researchers increased dietary DE concentration but kept the lysine level constant among the five treatments which resulted the lysine to DE ratio decreased from 3.01-2.72 g lysine Mcal^{-1} DE as the dietary energy increased. Decreases in weight gain in response to a reduction in lysine to DE ratio have been reported by many previous studies (Campbell *et al.*, 1985; Fuller *et al.*, 1986). Thus, the combination of increased dietary energy concentration and decreased lysine to DE ratio might resulte in no differences in weight gain in this period (Table 5).

However, in the research of Chiba *et al.* (1991a), which was conducted in 20-50 kg pigs when the lysine level of the diet was 0.96%, similar to the level in the study, weight gain decreased linearly ($p = 0.01$) with an increase in DE concentration and feed efficiency increased linearly ($p = 0.001$) from 0.41-0.52. The differences between these two studies may be due to the DE levels used in the two studies being different. In the study of Chiba *et al.* (1991a), the four DE levels were 3.00, 3.50, 3.75, 4.00 Mcal kg^{-1} whereas in the research, they ranged from 3.25-3.50 Mcal kg^{-1} (13.62-14.62 MJ kg^{-1}). The quadratic tendency for feed intake was surprising and was not observed in previous studies evaluating energy density in pig diets (Urynek and Buraczewska, 2003; Nam and Aherne, 1994). The high feed intake observed for pigs fed 14.37 and 14.62 MJ DE kg^{-1} diets might be due to the low lysine to DE ratio for these two treatments compared with the other treatments. In these two treatments, pigs needed to consume more feed to meet their lysine requirements for growth and tissue deposition. However, for pigs fed the 13.62 MJ DE kg^{-1} diet, pigs likely consumed more feed probably to meet their energy requirement.

There were no breakpoints in the data of weight gain response to energy concentration analyzed by broken-line model in the research since weight gain was not affected by energy density in the 20.8-55.9 kg period. Thus, lower energy density should be adopted in the future to get the dietary DE requirement for growth performance of pigs in this period.

Increasing the dietary energy density of pigs from 57.0-76.6 kg and 78.6-105.8 kg (finishing period) both linearly increased weight gain and feed efficiency as well as linearly decreased feed intake. Consistent with the present study, Campbell and Taverner (1988) reported that pigs (45-90 kg) were in an energy-dependent stage of growth. Similarly, the study of Beaulieu *et al.* (2009) which was conducted at a commercial swine farm, found that weight gain and feed efficiency improved with increased energy concentration when diets providing 3.12, 3.30 or 3.43 Mcal of DE kg^{-1} were fed to pigs during the 57-79 kg period. In contrast to the present study, Smith *et al.* (1999) observed that weight gain decreased quadratically ($p<0.05$) when the dietary energy level was increased for pigs (72.6-104.3 kg). Matthews *et al.* (1998, 2003), Kerr *et al.* (2003) and Apple *et al.* (2004) also observed that increasing the energy density of finishing swine diets had no appreciable effect on weight gain. These differences might be due to energy system, dietary energy density or whether crystalline amino acid being supplemented when the dieatry energy concentration was increased.

There were no breakpoints in the data of the weight gain response to energy concentration analyzed by broken-line model in the research since weight gain was not affected by energy density in the 20.8-55.9 kg period and it increased with increasing dietary DE level in the 57.0-76.6 and 78.6-105.8 kg periods. A larger energy concentration range should be adopted in the future research conducted to determine the effects of dietary energy density on growth performance of growing-finishing pigs.

Lean deposition: Lean growth is measured as lean gain per day of age (Fowler *et al.*, 1976) and considered to be the most appropriate expression of industry's objective for market pigs (Chen *et al.*, 2002). Fat-free lean predicted from carcass weight and measures of backfat depth and longissimus muscle surface area determines the value of pork carcasses in most markets. In the study, researchers used the carcass fat-free lean gain and fat-free lean index as published in NRC (1998) to describe lean deposition. Several factors such as genetic type, hormone level, dietary nutrient level and dietary supplement have driven research investigating the control of lean deposition in pigs. The findings in which pork carcasses tended to be fatter in response to elevating the dietary energy level were in agreement with the results of others (Apple *et al.*, 2004; Myer *et al.*, 1992; Bee *et al.*, 2002). In the research of Myer *et al.* (1992) a group of growing-finishing pigs (from 33-102 kg) were given different ME level diets (3330, 3650 and 3710 kcal ME kg^{-1}) by adding peanuts and canola oil and average back fat was observed to increase from 3.5-3.8 cm and there was no difference about longissimus muscle area among the treatments. Bee *et al.* (2002) also found that 13th-rib back fat depth of pigs (27-105 kg) decreased and lean growth rate increased when dietary DE level decreased from 14.1-8.8 MJ kg^{-1}. Apple *et al.* (2004) reported that elevating energy levels from 3.30-3.48 Mcal ME kg^{-1} (13.81-14.56 MJ ME kg^{-1}) for pigs weighing 84.3 kg resulted in an increase of back fat and a decrease of fat-free lean gain but had no effect on longissimus muscle area. Different results were also observed in other reports. Knowles *et al.* (1998) reported few effects of dietary energy levels on carcass traits of pigs (74-110 kg) and pigs fed the lowest level of dietary energy had greater 10th rib back fat depth whereas estimated lean percentage did not differ.

Several researchers have also demonstrated no differences in carcass traits when pigs were fed diets containing different energy densities (Smith *et al.*, 1999; De La Llata *et al.*, 2001a, b). The diverse results from the studies might be due to different dietary energy range.

In the research, the trend of decreased carcass lean and increased back fat depth with the increasing DE concentration of diets indicates that at low energy levels, pigs have a preference for protein deposition whereas the proportion of fat to gain increases at higher energy levels. This is in agreement with Apple *et al.* (2004) who reported that pigs fed high energy level diets deposited proportionately more fat and less muscle relative to pigs fed a low energy level diet. Similar results were also observed in the study of Chiba *et al.* (1991b) when dietary lysine level was 0.96% (similar to the dietary level in Exp. 1), protein deposition decreased from 112.2-102.2 g day^{-1} while the DE level increased from 3.00-3.50 Mcal kg^{-1}. In addition to energy level, lysine to DE ratio can also affect the composition of pigs. Szabo *et al.* (2001) reported that lowering the lysine to DE ratio increased ($p<0.05$) crude fat and fatty tissue content and decreased ($p<0.05$) protein and muscle content in the body of pigs during 60-105 kg. The reduction of fat-free lean gain in the study may also be attributed to the decreasing lysine to DE ratio as the energy level increased.

According to the quadratic and broken-line model analysis about the requirement of dietary DE concentration for lean deposition, the maximum fat-free lean gain was 265, 323 and 348 g day^{-1} for the 20.8-55.9, 57.0-76.6 and 78.6-105.8 kg periods, respectively. Since, 100 g of body protein deposition is equivalent to 255 g of fat-free lean tissue gain (NRC, 1998), the maximum of Protein deposition (Pd max) for these three periods was 104.18, 126.7 and 136.5 g day^{-1}, respectively. The values for Pd max determined in the current study fell within the higher region of the range of published values for Pd max of 90 to in excess of 200 g day^{-1} (Whittemore, 1983; Whittemore *et al.*, 2001). According to the latter finding, rate of Pd max increased with increasing body weight and the results of the present study were in consistent with it. Whereas in the study of Moughan *et al.* (2006) over the body weight range of 25-85 kg, Pd max was constant for entire male and female pigs at 170 and 147 g day^{-1}, respectively. The discrepancy may be due to the fact that different response models were applied in these studies that led to different interpretations concerning Pd max and the choice of statistical models has an important effect upon the conclusions drawn concerning the relationship between Pd max and body weight. An increasing rate of Pd max with increasing body weight for entire males and a decreasing rate of Pd max with increasing body weight for females was concluded when the quadratic model was used in researchers of Moughan *et al.* (2006) whereas a constant response conclusion was obtained with the linear model.

CONCLUSION

The results of the present study demonstrate that larger energy range should be adopted to get the DE requirement for growth performance. The optimal dietary DE to maximize lean deposition was different for the three growing-finishing phases. Pigs require different dietary energy levels for lean deposition compared with performance. Therefore, diets may be formulated with different energy levels depending on the overall goal of a swine producer.

IMPLICATIONS

A larger energy density range should be adopted in the future research about optimum dietary energy concentration for performance. The optimum energy density for lean deposition was 13.81, 13.76 and 13.82 MJ kg^{-1} for 20.8-55.9, 57.0-76.6 and 78.6-105.8 kg pigs, respectively. Different dietary energy levels are required to optimize lean deposition compared with growth performance for growing-finishing pigs which suggests that different energy requirements for different emphasis should be included in the NRC recommendations, instead of the current constant energy level of 3400 kcal DE kg^{-1} for all stages of pig growth. Also, the required differences in energy density indicated an optimal feeding strategy about dietary energy level can only be designed after appropriate definition of the desired product and market situations.

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