# REVIEW OF RELATIONSHIPS BETWEEN ENERGY INTAKE AND PERFORMANCE AND BODY COMPOSITION CHANGES IN 60-108 KG PIGS WITH MODERN GENETICS USING A DXA SCANNER

## A3A-102

Final Report prepared for the
Australasian Pork Research Institute Limited
(APRIL)

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January 2021

Australasian Pork Research Institute Ltd
APRIL

# Executive Summary

Dietary energy is a main factor affecting the cost of production and carcass value in the pig industry. Quantifying energy requirements and establishing lean tissue deposition potential in finisher pigs will help nutritionists set daily energy allowances to maximise lean tissue growth without excessive fat deposition.

This experiment quantified the relationship between tissue deposition and dietary energy intake in pigs with modern genetics (Primegro™ Genetics, Corowa, NSW, Australia) in 2019. Intact male and female pigs were fed seven different amounts of digestible energy (DE) of a wheat-based diet containing 14.3 MJ DE/kg [25.8, 29.0, 32.6, 35.3, 38.5, 41.5 and 44.2 MJ DE/d (*ad libitum*) for males, and 25.8, 28.9, 32.0, 35.6, 38.3, 40.9 and 44.5 MJ DE/d (*ad libitum)* for females] between 60 kg and 108 kg live weight. The amount of feed intake in the *ad libitum group* was measured as actual voluntary feed intake. Body composition of anaesthetised pigs was measured using the Dual Energy X-ray Absorptiometry (DXA) method when individual pigs reached 108 kg, and lean, water, protein fat and ash gain rates were calculated. Pigs were slaughtered on the 2nd day post-DXA scan, and commercial carcass traits were recorded.

Overall, comparing our results with the previous studies in 2000s using the same breed of pigs and the DXA method, the current genetics featured a lowered whole-body fat composition (reduced from 18% to 16% and 21% to 18% in males and females, respectively) and backfat thickness while voluntary energy intake was not changed significantly. Our results showed every MJ increase of daily DE intake increased the rate of daily protein gain by 3.83 g (the regression coefficient) in intact male pigs (linear regression model, $P<0.001$; $R^2=0.781$) and increased the rate of daily protein gain in female pigs by 2.50 g (linear regression model, $P<0.001$; $R^2=0.643$) throughout the tested range of DE allowance. The linear relationships between DE intake and protein deposition rate agreed with the previous study (King *et al.* 2004). Carcass backfat thickness (standardised at 83.8 kg hot carcass weight; measured using Hennessey and Chong's probe) increased by 0.125 mm for every MJ increase in daily DE intake in intact male pigs (linear regression model, $P=0.004$; $R^2=0.130$). By comparison the carcass backfat increased by 0.20 mm for every MJ increase in daily DE intake in male pigs two decades ago (King et al. 2004). Carcass backfat of female pigs was not affected by daily DE intake over the tested range of DE intake in our experiment, whereas the previous study showed carcass backfat increased by 0.32 mm for every MJ increase in daily DE intake in female pigs (King *et al.* 2004). The results reflected the genetic progress in showing reduced whole-body fat composition and backfat (P2 site) measures over the last 15 to 20 years.

Our results provide some important implications for commercial pork production. Pigs from modern genetics (Primegro Genetics™) as of 2019 maintained the linear relationship between DE intake and protein deposition rate. Restricting the energy allowance for intact finisher male pigs can reduce carcass backfat thickness. *Ad libitum* feeding (i.e., 44.5 MJ DE/d in the current study) in female pigs should be practised in order to shorten the days to reach the marketable body weight, because their protein gain rate increased linearly with daily DE intake, and the carcass backfat was not likely to be affected by DE intake when the female pigs are slaughtered at a fixed live weight. Importantly, these recommendations are made based on the scenario that finisher pigs can be marketed by body weight. Future experiments should evaluate the economics of restricted and unrestricted feeding strategies in male and female pigs respectively under commercial conditions, taking the growth duration and mortality rate into account.

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# 1. Introduction

Reducing carcass backfat thickness through dietary energy restriction is of commercial importance to the Australasian pork industry. Quantifying energy requirements for maximum lean tissue deposition in finisher pigs will help nutritionists set daily energy allowances to maximise lean tissue growth without excessive fat deposition. The relationship between energy intake and protein deposition of finisher pigs was well researched in the 1980-90s (Campbell *et al.* 1985; Campbell and Taverner 1988; Menzies *et al.* 1995); e.g., Figure 1 demonstrated the relationship in earlier genetics followed a linear-plateau pattern. The most recent study in Australia was conducted almost two decades ago, and it showed the protein deposition rate increased linearly in response to elevated dietary energy intake in both male and female pigs (King *et al.* 2004). These results have served as a great reference for the pig industry to set energy allowances to avoid excessive fat deposition.

Genetic selection has markedly increased growth rate and reduced backfat thickness (e.g., unpublished data from Rivalea's sire line and analysed by Pig BLUP) in the past two decades, implying that current Australian genetics have an increased potential for lean meat deposition compared with earlier genetics. These genetic improvements are driven by traits such as reduced maintenance costs, altered rates of tissue deposition or changes in voluntary feed intake. Phenotypically, there have been improvements in technologies such as health/vaccines, housing and environmental control. Therefore, the previously established relationship between energy intake and protein/lean tissue deposition rate may not be fully applicable to modern genetics in current production systems. This experiment aimed to re-investigate the relationship between lean tissue deposition rate and dietary energy intake in intact male and female finisher pigs with a modern genetic source and provide suggestions to feed management under current conventional production systems.

Dual-energy X-ray absorptiometry (DXA) can accurately estimate lean and fat composition in anaesthetized pigs (Suster et al., 2003 and 2004). Therefore, we proposed to quantify the relationship between DXA-predicted whole-body lean tissue deposition rate and energy intake in intact male and female pigs between 60 to 108 kg body weight.

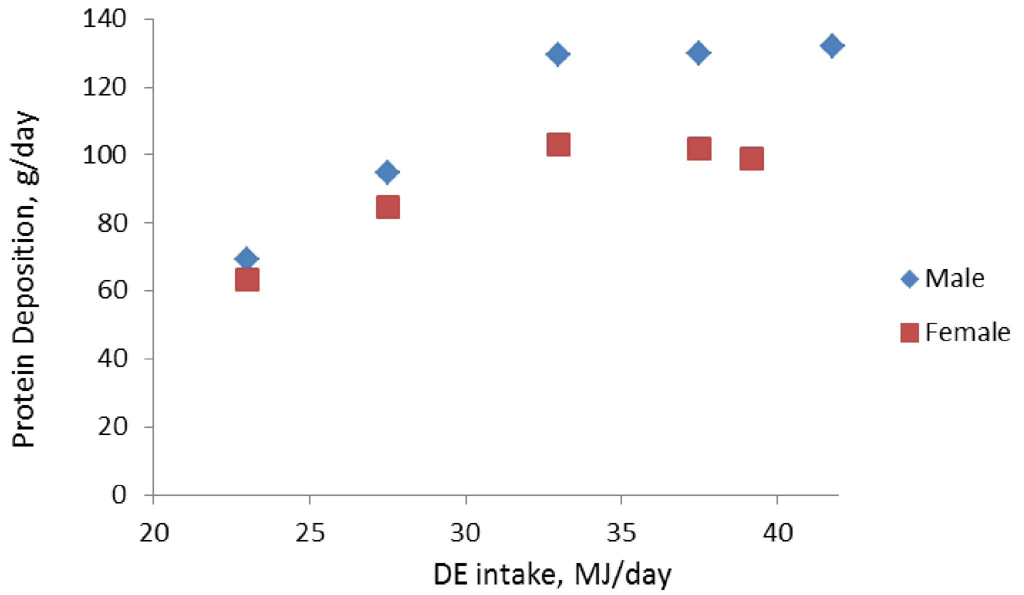


**Figure 1.** Relationship of protein deposition and energy intake (Campbell *et al*. 1985).

## 2. Methodology

### *Animals and experimental design*

All procedures that involved animals in the current study were in accordance with Australian Code for the Care and Use of Animals for Scientific Purposes (8$^{th}$ edition, 2013), and the protocol (ID:19N004C) was approved by the Animal Ethics Committee of Rivalea Australia Pty Ltd, Corowa, NSW, Australia.

Sixty-three intact male and 63 female cross-bred pigs (Large White × Landrace × Duroc; Primegro$^{TM}$ Genetics, Corowa, NSW, Australia) were selected into the experiment at 15 weeks of age [59.6 ± 2.49 kg and 59.4 ± 2.39 kg (mean ± standard deviation) for intact male and female pigs respectively]. Pigs were sourced from a batch averaged at 60 kg weight and housed at a commercial grower piggery. All the pigs were housed in the same shed and fed *ad libitum* using the same commercial diet before the selection. Seven pigs from each sex were randomly selected and their body composition was measured by Dual Energy X-ray Absorptiometry (DXA) as the initial body composition parameters, then the scanned pigs came off-trial. The remaining 56 pigs in each sex were randomly allocated into seven levels of feeding levels ranging from 58% to 100% of the *ad libitum* amount of feed intake.

Prior to the start of the experiment, a relationship between the live weight of pigs and the amount of *ad libitum* digestible energy (DE) intake was quantified for male and female pigs separately, based on data (*unpublished*) summarised from recent experiments conducted at the same research facility and on the same genetic line. This previously quantified relationship was temporarily used as the reference for setting up the DE allowance for the restricted-fed groups for each sex in the first 3 weeks of the experiment (when the true *ad libitum* DE intake remained unknown for this experiment). Afterwards, the relationship between the live weight of pigs and *ad libitum* DE intake was adjusted based on the experimental record of actual feed intake of pigs and body weight from the *ad libitum* group. The adjusted relationship between live weight and *ad libitum* DE intake was then used for setting up the amount of DE allowance for the restricted fed groups for each sex, which ensured the graded amount of DE allowance were studied in relative to the true *ad libitum* DE intake. The amount for each dietary energy levels was adjusted weekly and increased along with the body weight that was updated weekly.

The actual average daily feed intake (ADFI) for the seven feeding levels was 1.78 ± 0.046, 2.00 ± 0.075, 2.25 ± 0.053, 2.44 ± 0.119, 2.66 ± 0.100, 2.86 ± 0.151 and 3.05 ± 0.171 kg for intact male pigs and 1.81 ± 0.055, 2.03 ± 0.033, 2.24 ± 0.0311, 2.48 ± 0.039, 2.68 ± 0.092, 2.86 ± 0.183 and 3.11 ± 0.167 kg for female pigs (mean ± standard deviation, n=8 pigs per sex per DE treatment).

The total amount of the feed required for the whole experiment was manufactured at one blending and stored in a single silo over the duration of the experiment. The DE and standardised ileal digestible (SID) lysine contents in the major feed ingredients were analysed using NIR technology, then were used in the formulation of the compound feed (Table 1). The diet was formulated to contain 14.3 MJ digestible energy (DE) and 0.57 g SID lysine per MJ DE for both male and female pigs. The amount of SID lysine was optimised in a recent experiment for achieving the maximum growth rate of finisher pigs using the same genetics (*Unpublished data*). The amount of SID lysine in our diet was similar to the level optimised in an early study (50-85 kg range) (Giles *et al.* 2010) and the recommended level by the model developed by National Research Council (2012) (60-108 kg range), and also similar to the level (0.56 g SID lysine per MJ DE) optimised in Australian studies for pigs without ractopamine supplementation (King *et al.* 2000; Rikard-Bell *et al.* 2012; Rikard-Bell *et al.* 2013). The assumption behind the experimental design was that the effects of feeding levels on growth rate and muscle deposition rate will reflect the effects of dietary energy intake when essential amino acids are not limited. Therefore, the seven corresponding DE intake levels were treated as a fixed factor in males and females separately (25.8, 29.0, 32.6, 35.3, 38.5, 41.5 and 44.2 MJ/d for intact male pigs, and 25.8, 28.9, 32.0, 35.6, 38.3, 40.9 and 44.5 MJ/d for female pigs).

Pigs were individually housed in an enclosed and climatically controlled building (18 ± 2.7 °C for average shed temperature ± standard deviation). Pigs were injected with tulathromycin solution (0.25 mL per kg live weight; Draxxin®, Zoetis, US) at entry to the experimental facility and received water antibiotics two days per fortnight. Pigs were weighed weekly and feed allowances were adjusted to the new body weight recorded every week. Pigs were scanned using DXA when they reached 108 kg live weight and were then slaughtered as per commercial practice 48 hours post-scan. Feed delivery and refusal were recorded every week and for calculating average daily feed intake (ADFI).

**Table 1.** Composition of the experimental diet

| Ingredient | % as-fed basis |
|---|---|
| Wheat | 75.1 |
| Canola meal | 10 |
| Soybean meal | 8.9 |
| Blood meal | 1.5 |
| Tallow | 1.6 |
| Limestone | 0.96 |
| Dicalcium Phosphate | 1.4 |
| Lysine HCL | 0.15 |
| Methionine | 0.02 |
| Threonine | 0.05 |
| Salt | 0.2 |
| Copper Proteinate (24% Cu) | 0.033 |
| Vitamin Premix[1] | 0.04 |
| Mineral Premix[2] | 0.07 |
| *Calculated composition* | |
| Dry matter, % | 90.2 |
| Digestible energy, MJ/kg | 14.3 |
| Crude protein, % | 18.8 |
| Fat, % | 3.1 |
| Starch, % | 52 |
| Crude fibre, % | 3.6 |
| Ash, % | 4.9 |
| Total calcium, % | 0.8 |
| Available phosphorous, % | 0.4 |
| SID lysine, % | 0.82 |
| SID lysine:DE, g/MJ | 0.57 |

[1] Supplied per kg of diet: copper, 101 mg; cobalt, 0.5 mg; manganese, 28 mg; magnesium, 1.6 g; zinc, 50 mg; iron, 70 mg; iodine, 0.5 mg; selenium, 0.2 mg; chromium 0.2 mg.
[2] Supplied per kg of diet: vitamin A, 3000 IU; vitamin D3, 600 IU; vitamin K, 0.4 mg; vitamin B-1, 0.6 mg; vitamin B-2, 2.0 mg; vitamin B-6, 1.2 mg; vitamin B-12, 4.0 µg; Niacin, 12 mg; pantothenic acid, 6 mg, Vitamin E 19 IU.

### *Plasma urea nitrogen measurement*

A blood sample was taken from each individual pig when it was approaching 108 kg, one day before the DXA scan. Blood was collected from the jugular vein using a heparinised vacutainer. Blood samples were centrifuged for harvesting plasma. Plasma urea nitrogen (PUN) was assayed using a commercial kit (Infinity Urea Liquid Stable Reagent, Thermo Scientific, Cat No. TR12421). Briefly, the urea was firstly converted to ammonia under after the addition of urease, then the ammonia reacted with reduced nicotinamide adenine dinucleotide (NADH) and a-keto-glutamate in the presence of glutamate dehydrogenase. The rate of the above reactions, which is positively correlated with the initial concentration of plasma urea, was measured as the colorimetric change at 340 nm absorbance due to the disappearance of NADH. The assay was run in duplicate and inter-assay coefficient of variation was 5.6%.

### *Dual Energy X-ray Absorptiometry (DXA) scan*

Pigs were fasted from 15:00 h (after blood sampling for PUN measurement) until the next morning when pigs approached 108 kg. Pigs were sedated by intramuscular injection of Stresnil® (0.2 mL per kg body weight, Elanco Animal Health, NSW). Once the pig was down, a face mask was mounted and connected to an isoflurane anaesthesia machine. For rapid induction of anaesthesia, 5% isoflurane (Piramal Enterprises Limited, India) and 3.5 L/min medical oxygen was given for a short duration. Then, isoflurane was reduced to 1.5 to 2.0 % (depending on the depth of anaesthesia of the individual pig) for maintaining the anaesthesia state. Respiration rate, eyeball position, eye reflexes and conjunctiva colour were checked every 5 minutes during anaesthesia to ensure the depth of anaesthesia was appropriate. Then, the pig was placed onto the DXA scanning platform (Hologic Discovery W DXA scanner) with the belly facing down. A quantity control calibration on the scanner was performed at the beginning of every scan day. Each scan took an average of seven minutes for a 108 kg pig. Pigs were returned to a recovery area after the DXA scan and a post-anaesthesia health check was conducted every 10 minutes until the pig regained mobility. The outputs of each DXA scan were whole body mass, lean mass, fat mass and bone mineral density data, and these data were converted to chemically determined lean, water, protein, fat and ash using the algorithm validated for live pigs (Suster et al. 2003). The initial tissue composition (%) was assumed as the average values obtained from the seven male and female pigs scanned at 60 kg. The composition (%) tissue was used for calculating initial tissue mass for each trial pigs finished in the experiment. Tissue gain rates were calculated as the following equation:

$$Tissue\ gain\ rate = \frac{(Final\ tissue\ mass - initial\ tissue\ compsition\ (\%) * start\ body\ weight)}{Days\ of\ growth}$$

The gain rate of whole-body lean, water, protein and fat is expressed as grams per day; final tissue mass is the tissue weight (grams) of a whole pig estimated using DXA method (converted to chemically measured values); initial tissue composition

(%) was the average tissue composition from the seven female or male pigs scanned at 60 kg live weight; start body weight (grams) is the live weight of the individual pig at entry.

## Carcass traits' measurement

Pigs were transported to a commercial abattoir on the first day after their DXA scan and housed in a lairage until killed in the morning of the second day. The hot standard carcass weight was measured after trimming off visceral organs (Australian Trim 1 standard). Backfat thickness and loin depth were measured at the P2 site (last rib; 65 mm from the midline) using Hennessey and Chong's grading probe. Dressing percentage was calculated as the ratio between hot standard carcass weight and live weight.

## Statistical analyses

The responses of growth performance, tissue deposition and carcass traits to DE intake were first tested for both linear and quadratic effects using the nominal levels (25.8, 29.0, 32.6, 35.3, 38.5, 41.5 and 44.2 DE MJ/d for male and 25.8, 28.9, 32.0, 35.6, 38.3, 40.9 and 44.5 MJ DE/d for female pigs) using General Linear Model analysis in SPSS (IBM SPSS Statistics for Windows, v25, Armonk, NY). Hot standard carcass weight was used as a covariate for the measurement of carcass backfat and loin depth. A quadratic regression model was chosen for describing the relationship when adding the quadratic term increased ($P \leq 0.05$) or tended to increase ($0.05 \leq P \leq 0.10$) the coefficient of determination $R^2$ value; otherwise, a linear regression model was used.

Furthermore, where a relationship was quadratically fitted or a change of slope (known as a "breakpoint" or a "knot") was visually identified, the fit of a one-knot piecewise regression model was examined (i.e., lean gain rate, water gain rate, protein gain rate, bone gain rate and loin depth in male pigs, and whole body fat composition, fat gain rate and lean:fat gain ratio in female pigs). The following piecewise regression model was used for describing their relationship with daily DE intake:

$$Y = a + b \times DE + c \times (DE - breakpoint) \; when \; DE > breakpoint;$$
$$Y = a + b \times DE \; when \; DE \leq breakpoint$$

Here, *Y* is the outcome variable, *DE* is the nominal level of daily DE intake, *a* is the constant, *b* is the coefficient of regression, and *c* is the change of regression coefficient when *DE* is greater than the breakpoint. The piecewise regression model was estimated using the Levenberg-Marquardt method in the Non-Linear Regression function in SPSS. The best fitting piecewise regression model was identified by iteratively modifying the initial values for the parameters and breakpoint. The piecewise model with the highest $R^2$ was chosen to compare with linear or quadratic regression models.

Bayesian information criteria (BIC) is an index that reflects model residual errors as well as the model complexity. To avoid over-fitting, BIC was used for comparing the regression models when similar coefficients of determination ($R^2$) were achieved by two regression models (i.e., linear or quadratic vs the one-knot piecewise regression model). The model with a lower BIC (the difference of BIC between models ≥ 2) was selected. If both models had a similar BIC (the difference of BIC between models < 2; no superior model), then both models were chosen. The constant, regression coefficients, and their standard errors (s. e.) were computed for the chosen models. The equations for calculating BIC is referenced from (Burnham and Anderson 2002):

$$BIC = n \times \ln\left(\frac{RSS}{n}\right) + K \times \ln(n)$$

Here, RSS is the residual sum of squares; ln is the natural logarithm; n is the number of samples in the data; K is the number of parameters in the model (K=2, 3 and 4 for linear, quadratic and piecewise regression model respectively).

# 3. Outcomes

***Initial body composition at 60 kg***

The average initial lean, water, protein, lipid and ash composition was 81.3%, 63.0% 16.8%, 12.6% and 2.7% for intact males (pooled from 7 intact male pigs) and 79.8%, 61.7%, 16.6%, 14.4% and 2.8% for females (pooled from 7 female pigs) respectively.

***Growth rate***

In both sexes, increasing DE intake linearly (P<0.001 for intact males and P=0.021 for females) and quadratically (P=0.014 for both sexes) increased ADG (Figure 2). A model comparison (linear vs quadratic) showed that adding a quadratic term in the regression model improved the $R^2$ from 0.817 to 0.833 (P=0.032) in intact male pigs and improved the $R^2$ from 0.853 to 0.865 (P=0.034) in female pigs, when analysing the response of ADG. The best fit models are described as:

$$ADG\ (male) = -1.033\ (\pm\ 0.416\ s.e.) + 0.0829\ (\pm\ 0.0243\ s.e.) \times DE$$
$$- 0.00076\ (\pm\ 0.000346\ s.e.) \times DE\hat{\ }2$$
$$R^2 = 0.833, P < 0.001$$

$$ADG\ (female) = -0.680\ (\pm\ 0.300\ s.e.) + 0.0626\ (\pm\ 0.0174\ s.e.) \times DE$$
$$- 0.00054\ (\pm\ 0.000249\ s.e.) \times DE\hat{\ }2$$
$$R^2 = 0.865, P < 0.001,$$

in which ADG is average daily again (kg/day); DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients or the constant.

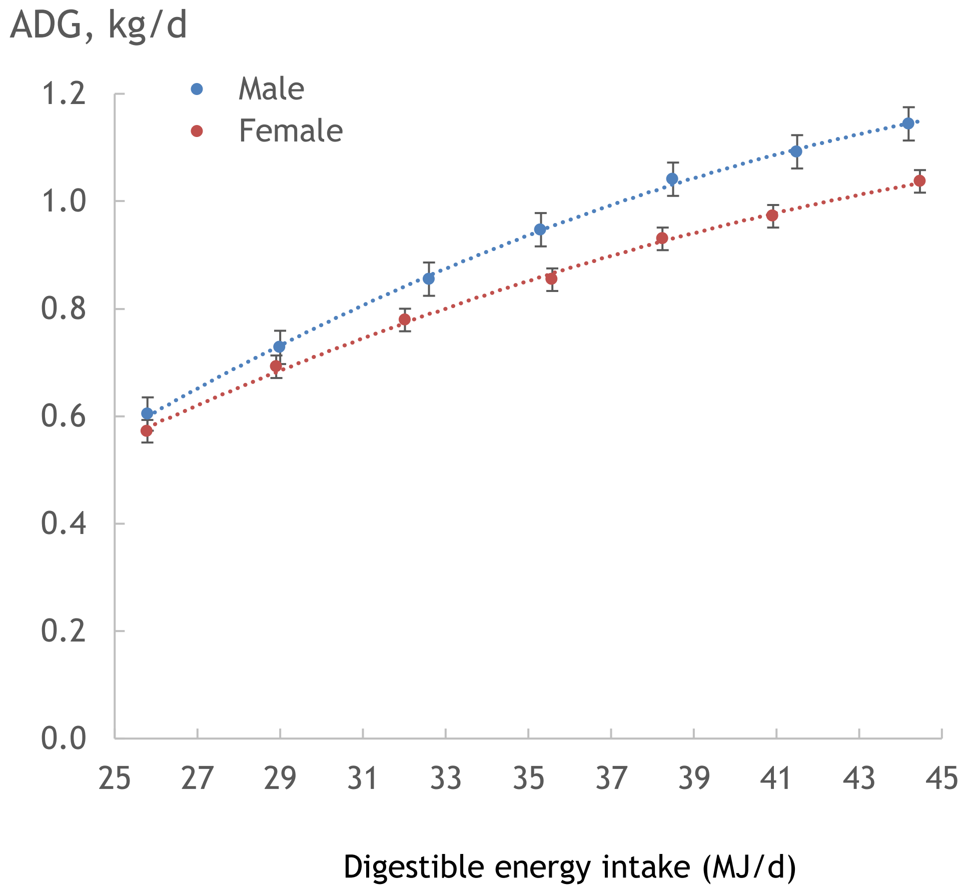


**Figure 2.** Relationship between DE intake (MJ/day) and ADG (kg/day) in intact male and female pigs.

$$\boldsymbol{ADG\ (male) = -1.033\ (\pm\ 0.416\ s.e.) +\ 0.0829\ (\pm\ 0.0243\ s.e.) \times\ DE - 0.00076\ (\pm\ 0.000346\ s.e.) \times DE^2;\ R^2 =\ 0.833, P < 0.001.}$$

$$\boldsymbol{ADG\ (female) = -0.680\ (\pm\ 0.300\ s.e.) +\ 0.0626\ (\pm\ 0.0174\ s.e.) \times\ DE - 0.00054\ (\pm\ 0.000249\ s.e.) \times DE^2;\ R^2 =\ 0.865, P < 0.001.}$$

***Days to reach 108 kg***

Increasing energy intake linearly (P<0.001 for both sexes) and quadratically (P<0.001 for both sexes) shortened the days from 60 kg to reach 108 kg live weight (Figure 3). Adding the quadratic term in the statistical model improved the adjusted $R^2$ from 0.794 to 0.856 (P<0.001) in intact male pigs and improved $R^2$ from 0.766 to 0.850 (P<0.001) in female pigs. The best fit models are described as:

$$Days\ from\ 60\ kg\ to\ 108\ kg\ (male) = $$
$$= 255.3\ (\pm\ 27.10\ s.e.) - 9.5\ (\pm\ 1.58\ s.e.) \times\ DE + 0.11\ (\pm\ 0.022\ s.e.) \times DE\text{^}2$$
$$R^2 = 0.856, P < 0.001$$

$$Days\ from\ 60\ kg\ to\ 108\ kg\ (female) = $$
$$= 274.2\ (\pm\ 26.53\ s.e.) - 10.4\ (\pm\ 1.55\ s.e.) \times\ DE + 0.12\ (\pm\ 0.022\ s.e.) \times DE\text{^}2$$
$$R^2 = 0.850, P < 0.001,$$

in which DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients or the constant.

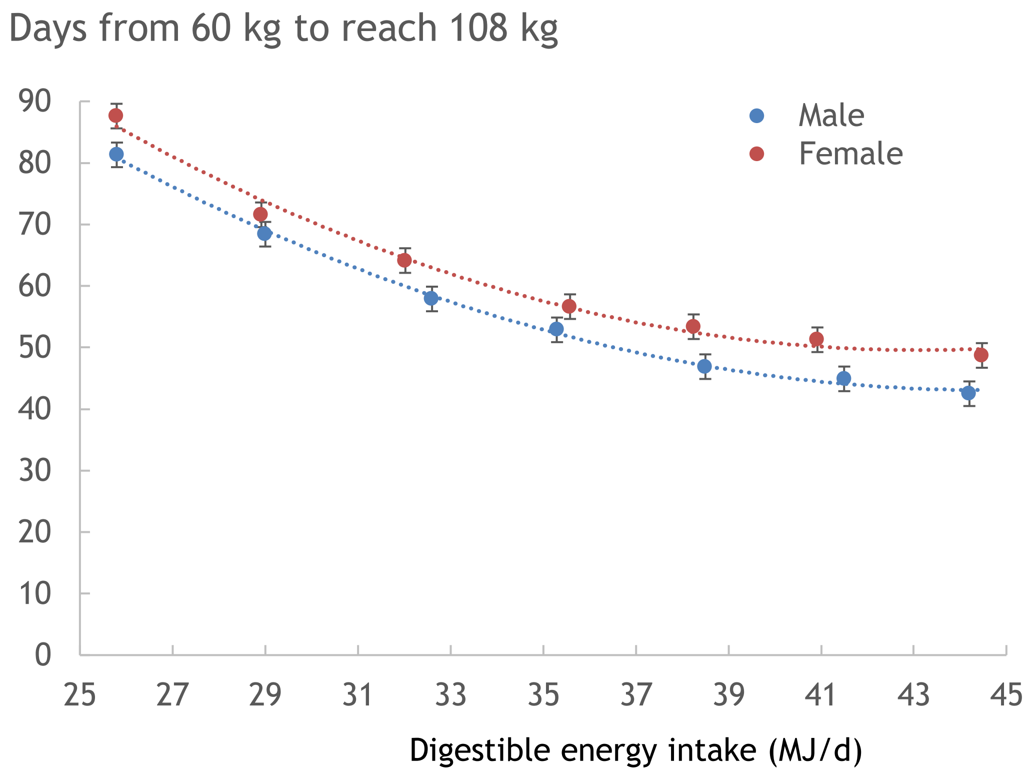


**Figure 3.** Relationship between DE intake (MJ/day) and days from 60 kg to reach 108 kg live weight in intact male and female pigs.

$$\boldsymbol{Days\ from\ 60\ kg\ to\ 108\ kg\ (male) = 255.3\ (\pm\ 27.10\ s.e.) - 9.5\ (\pm\ 1.58\ s.e.) \times DE + 0.11\ (\pm\ 0.022\ s.e.) \times DE^2;\ R^2 = 0.856, P < 0.001.}$$

$$\boldsymbol{Days\ from\ 60\ kg\ to\ 108\ kg\ (female) = 274.2\ (\pm\ 26.53\ s.e.) - 10.4\ (\pm\ 1.55\ s.e.) \times DE + 0.12\ (\pm\ 0.022\ s.e.) \times DE^2;\ R^2 = 0.850, P < 0.001.}$$

***Feed conversion ratio***

Feed conversion ratio responded to the increased daily DE intake in both a linear (P=0.004) and quadratic (P=0.003) manner in intact male pigs (adding the quadratic term improved the $R^2$ from 0.145 to 0.287 (P=0.002)). In female pigs, the response of FCR to the increased DE intake was quadratic (Linear, P=0.13, Quadratic, P<0.001) (Figure 4). The best fit models are described as:

$$FCR\ (male) = 6.453\ (\pm\ 1.010\ s.e.) - 0.206\ (\pm\ 0.0589\ s.e.) \times\ DE$$
$$+\ 0.00273\ (\pm\ 0.00084\ s.e.) \times DE\hat{}2$$
$$R^2 =\ 0.287, P < 0.001$$

$$FCR\ (female) = 6.146\ (\pm\ 0.943\ s.e.) - 0.179\ (\pm\ 0.0550\ s.e.) \times\ DE$$
$$+\ 0.00245\ (\pm\ 0.00078\ s.e.) \times DE\hat{}2$$
$$R^2 =\ 0.194, P = 0.003,$$

in which FCR is feed conversion ratio; DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients or the constant.

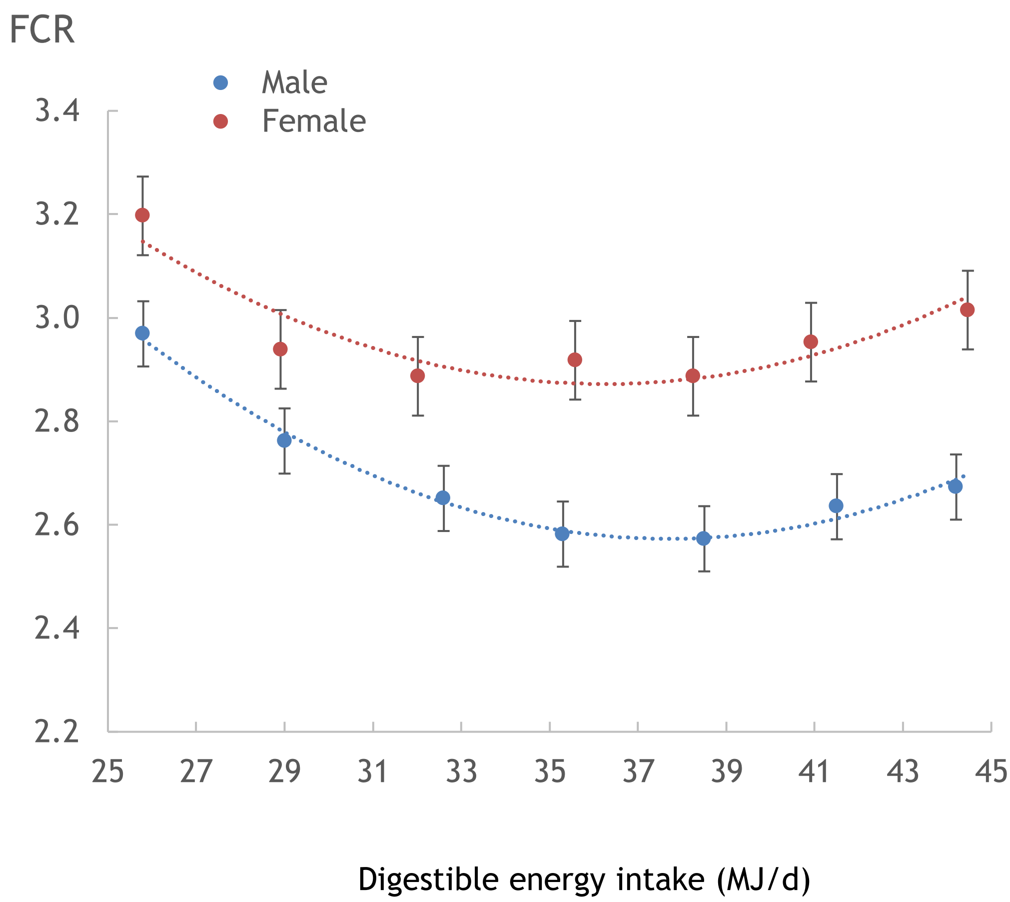


**Figure 4.** Relationship DE intake (MJ/day) and FCR in intact male and female pigs.

$$\boldsymbol{FCR\ (male) = 6.453\ (\pm 1.010\ s.e.) - 0.206\ (\pm 0.0589\ s.e.) \times DE + 0.00273\ (\pm 0.00084\ s.e.) \times DE^2;\ R^2 = 0.287, P < 0.001.}$$

$$\boldsymbol{FCR\ (female) = 6.146\ (\pm 0.943\ s.e.) - 0.179\ (\pm 0.0550\ s.e.) \times DE + 0.00245\ (\pm 0.00078\ s.e.) \times DE^2;\ R^2 = 0.194, P = 0.003.}$$

***Whole-body lean composition***

The whole-body lean percentage reduced linearly (P=0.028) but not quadratically (P=0.49) in response to the increased daily DE intake in male pigs, thus the linear regression model was used ($R^2$=0.090, P=0.024) (Figure 5). Similarly, the whole-body lean percentage reduced linearly (P=0.003) but not quadratically (P=0.17) in response to the increased daily DE intake in female pigs, thus the linear regression model was used ($R^2$=0.101, P=0.017). Every MJ increase in daily DE intake reduced lean % by 0.070 and 0.083 respectively in male and female pigs. The best fit models are described as:

$$Whole\ body\ lean\ \%\ (male) = 72.2\ (\pm\ 1.08\ s.e.) - 0.070\ (\pm\ 0.0302\ s.e.) \times DE$$
$$R^2 = 0.090, P = 0.024$$

$$Whole\ body\ lean\ \%\ (female) = 69.4\ (\pm\ 1.20\ s.e.) - 0.083\ (\pm\ 0.0337\ s.e.) \times DE$$
$$R^2 = 0.101, P = 0.017,$$

in which DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients or the constant.

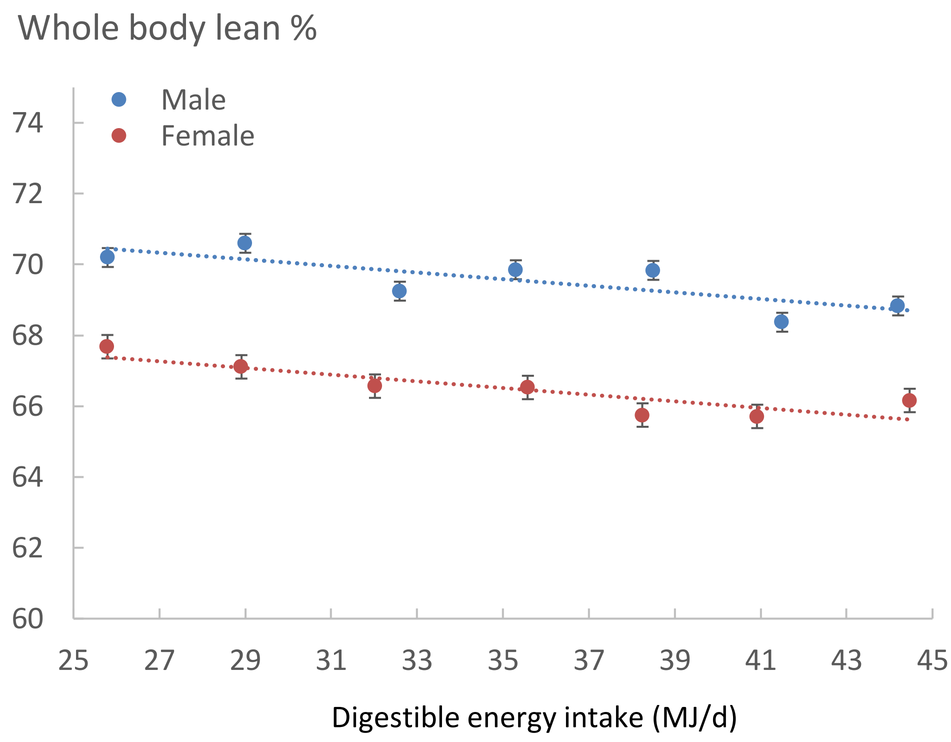


**Figure 5.** Relationship between DE intake (MJ/day) and whole-body lean composition (%) in intact male and female pigs.

$$\boldsymbol{Whole\ body\ lean}\ \%\ (\boldsymbol{male}) = \mathbf{72.2}\ (\pm\ \mathbf{1.08}\ \boldsymbol{s.e.}) - \mathbf{0.070}\ (\pm\ \mathbf{0.0302}\ \boldsymbol{s.e.}) \times \boldsymbol{DE};\ \boldsymbol{R}^2 = \mathbf{0.090}, \boldsymbol{P} = \mathbf{0.024}$$

$$\boldsymbol{Whole\ body\ lean}\ \%\ (\boldsymbol{female}) = \mathbf{69.4}\ (\pm\ \mathbf{1.20}\ \boldsymbol{s.e.}) - \mathbf{0.083}\ (\pm\ \mathbf{0.0337}\ \boldsymbol{s.e.}) \times \boldsymbol{DE};\ \boldsymbol{R}^2 = \mathbf{0.101}, \boldsymbol{P} = \mathbf{0.017}$$

***Whole-body protein composition***

The whole-body protein percentage reduced linearly (P=0.013) but not quadratically (P=0.82) in response to the increased daily DE intake in male pigs, thus a linear regression model was used ($R^2$=0.092, P=0.023) (Figure 6). The whole-body protein percentage in female pigs reduced linearly (P=0.002) but not quadratically (P=0.15) in response to the increased daily DE intake, thus the linearly regression model was used ($R^2$=0.106, P=0.014). Every MJ increase in daily DE intake reduced whole body protein % by 0.012 and 0.015 in male and female pigs, respectively. The best fit models are described as:

$$Whole\ body\ protein\ \%\ \ (male) = 15.4\ (\pm\ 0.183\ s.e.) - 0.012\ (\pm\ 0.0051\ s.e.) \times DE$$
$$R^2 = 0.092, P = 0.023$$

$$Whole\ body\ protein\ \%\ \ (female) = 15.0\ (\pm\ 0.210\ s.e.) - 0.015\ (\pm\ 0.0058\ s.e.) \times DE$$
$$R^2 = 0.106, P = 0.014,$$

in which DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients or the constant.

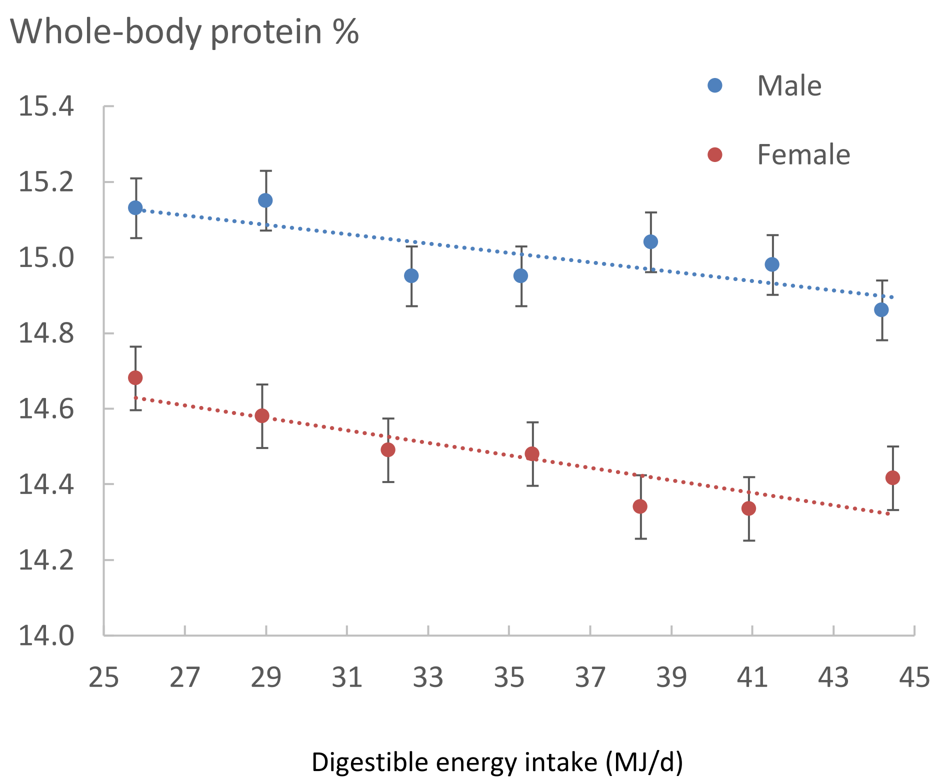


**Figure 6.** Relationship between DE intake (MJ/day) and whole-body lean composition (%) in intact male and female pigs.

$$\boldsymbol{Whole\ body\ protein\ \%\ (male) = 15.4\ (\pm\ 0.183\ s.e.) - 0.012\ (\pm\ 0.005\ s.e.) \times DE;\ R^2 = 0.092, P = 0.023}$$

$$\boldsymbol{Whole\ body\ protein\ \%\ (female) = 15.0\ (\pm\ 0.21\ s.e.) - 0.015\ (\pm\ 0.006\ s.e.) \times DE;\ R^2 = 0.106, P = 0.014}$$

***Whole-body water composition***

The whole-body water % reduced linearly but not quadratically in response to the increased daily DE intake in male pigs (Linear, P=0.026; Quadratic, P=0.78), thus a linear regression model was used ($R^2$=0.093, P=0.022) (Figure 7). The whole-body water % reduced linearly but not quadratically in response to the increased DE intake in female pigs (Linear, P=0.002; Quadratic, P=0.15) in response to the increased daily DE intake, thus the linearly regression model is used ($R^2$=0.105, P=0.015). Every MJ increase in daily DE intake reduced whole-body water % by 0.060 and 0.071 in male and female pigs respectively. The best fit model is described as:

$$Whole\ body\ water\ \%\ \ (male) = \ 55.8\ (\pm\ 0.91\ s.e.) - 0.060\ (\pm\ 0.0253\ s.e.) \times DE$$
$$R^2 = \ 0.093, P = 0.022$$

$$Whole\ body\ water\ \%\ \ (female) = \ 53.5\ (\pm\ 1.01\ s.e.) - 0.071\ (\pm\ 0.028\ s.e.) \times DE$$
$$R^2 = \ 0.105, P = 0.015,$$

in which DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients or the constant.

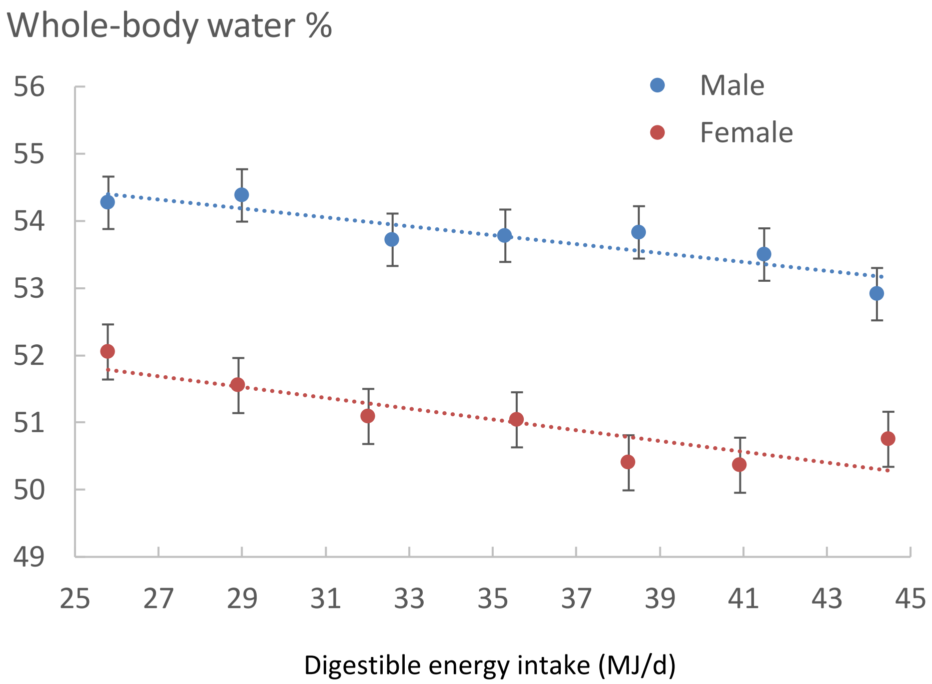


**Figure 7.** Relationship between DE intake (MJ/day) and whole-body lean composition (%) in intact male and female pigs.

$$\boldsymbol{Whole\ body\ water\ \%\ (male) = 55.8\ (\pm\ 0.91\ s.e.) - 0.060\ (\pm\ 0.0253\ s.e.) \times DE;\ R^2 = 0.093, P = 0.022}$$

$$\boldsymbol{Whole\ body\ water\ \%\ (female) = 53.5\ (\pm\ 1.01\ s.e.) - 0.071\ (\pm\ 0.028\ s.e.) \times DE;\ R^2 = 0.105, P = 0.015}$$

### *Whole-body fat composition*

The whole-body fat percentage increased linearly but not quadratically in response to daily DE intake in male pigs (Linear, P=0.001; Quadratic, P=0.99), thus the linear model was chosen for describing the relationship between DE intake and whole-body fat composition in male pigs (Figure 8).

The whole-body fat percentage increased linearly (P<0.001) and quadratically (P=0.031) in female pigs in response to the increased daily DE intake. Adding the quadratic term increased $R^2$ from 0.164 to 0.224 (P=0.048) without changing BIC (48.1 vs 48.0 for linear vs quadratic regression model). A piecewise regression model achieved a higher $R^2$ (0.268) but a similar BIC (48.0 vs 48.7 for quadratic vs piecewise regression model) than the quadratic model. The piecewise regression model identified the breakpoint (40.9 MJ DE) such that the regression coefficient of daily DE intake reduced from 0.17 to -0.52 for body fat % per MJ daily DE intake when DE intake increased above 40.9 MJ per day. The best fit models are described as:

$$Whole\ body\ lipid\ \%\ \ (male) = \ 12.1\ (\pm\ 0.96\ s.e.) + 0.083\ (\pm\ 0.027\ s.e.) \times DE$$
$$R^2 = \ 0.152, P = 0.003$$

$$Whole\ body\ lipid\ \%\ \ (female)$$
$$= \ 16.7\ (\pm\ s.e.) + 0.90\ (\pm\ 0.396\ s.e.) \times DE - 0.011\ (\pm\ 0.006\ s.e.) \times DE\text{^}2$$
$$R^2 = \ 0.224, P = 0.001, \text{BIC=48.0}$$

$$Whole\ body\ lipid\ \%\ \ (female) = 12.4\ (\pm\ 0.1.301\ s.e.) - 0.17\ (\pm\ 0.038\ s.e.) \times\ DE$$
$$when\ DE\ \leq 40.9\ MJ;$$
$$or$$
$$= 12.4\ (\pm\ 0.1301\ s.e.) - 0.17\ (\pm\ 0.038\ s.e.) \times\ DE$$
$$- 0.52\ (\pm\ 7.4239e14\ s.e.) \times\ \left(DE -\ 40.5\ (\pm\ 5.0963e15\ s.e.)\right)$$
$$when\ DE > 40.9\ MJ;$$
$$R^2 = \ 0.276, P < 0.001, \text{BIC=48.7,}$$

in which DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients or the constant.

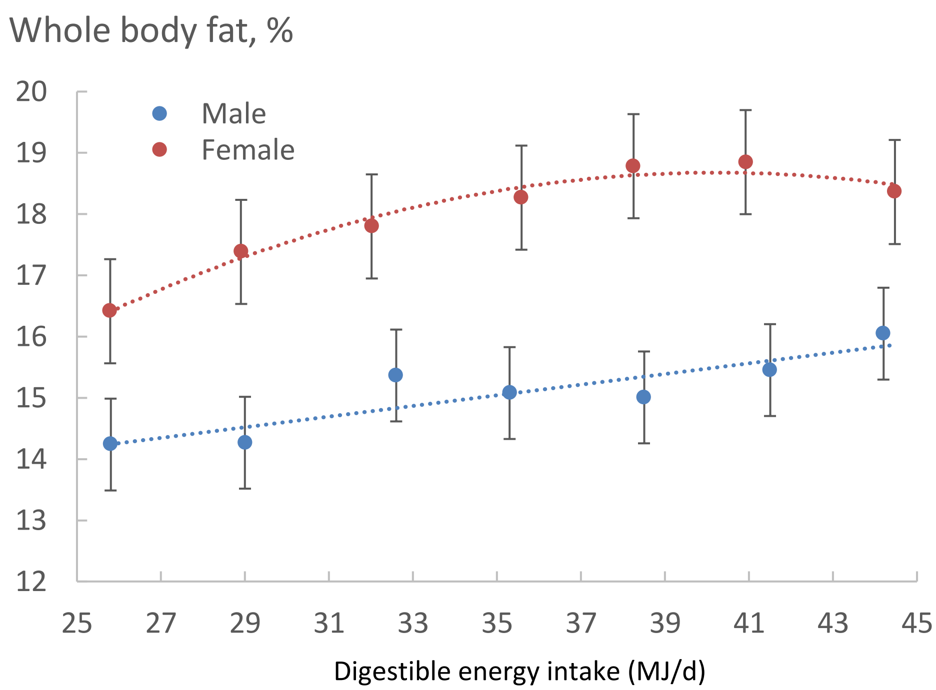


**Figure 8.** Relationship between DE intake (MJ/day) and whole-body fat composition (%) in intact male and female pigs.

$$\boldsymbol{Whole\ body\ fat\ \%\ (male) =\ 12.1\ (\pm\ 0.96\ s.e.) + 0.083\ (\pm\ 0.027\ s.e.) \times DE}$$
$$\boldsymbol{R^2 =\ 0.152, P = 0.003}$$

$$\boldsymbol{Whole\ body\ fat\ \%\ (female) =\ 16.7\ (\pm\ s.e.) + 0.90\ (\pm\ 0.396\ s.e.) \times DE - 0.011\ (\pm\ 0.006\ s.e.) \times DE^2;\ \ R^2 =\ 0.224, P = 0.001, \text{BIC=48.0}}$$

$$\boldsymbol{Whole\ body\ fat\ \%\ (female) = 12.4\ (\pm\ 0.1.301\ s.e.) - 0.17\ (\pm\ 0.038\ s.e.) \times DE\ when\ DE \leq 40.9\ MJ;\ or\ = 12.4\ (\pm\ 0.1301\ s.e.) - 0.17\ (\pm\ 0.038\ s.e.) \times DE - 0.52\ (\pm\ 7.4239E14\ s.e.) \times \left(DE -\ 40.5\ (\pm\ 5.0963E15\ s.e.)\right)\ when\ DE > 40.9\ MJ;\ R^2 =\ 0.276, P < 0.001, \text{BIC=48.7}}$$

***Whole-body ash composition***

The whole-body ash percentage declined linearly (P=0.002) but not quadratically (P=0.091) in response to the increased DE intake in male pigs, thus the linear regression model was used ($R^2$=0.168, P=0.002) (Figure 9). Every MJ increase of DE intake reduced the whole-body ash composition by 0.0059%. Whole-body ash percentage did not respond (Linear, P=0.58; Quadratic, P=0.86) to DE intake in female pigs. The best fit model is described as:

$$Whole\ body\ ash\ composition\ \%\ \ (male)$$
$$=\ 2.72\ (\pm\ 0.064\ s.e.) - 0.0059(\pm\ 0.00179\ s.e.) \times DE$$
$$R^2 = \ 0.168, P = 0.002,$$

in which DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients or the constant.

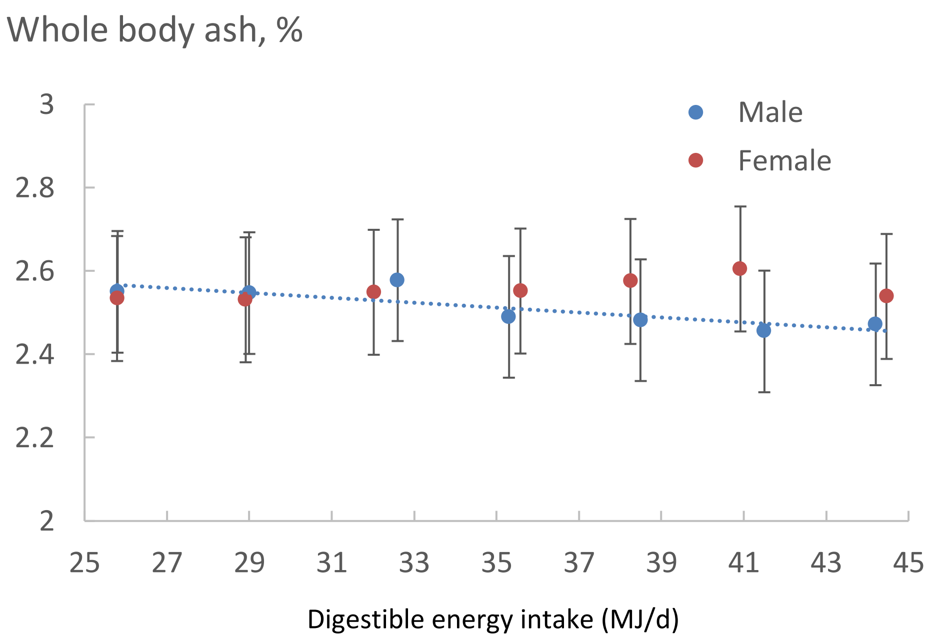


**Figure 9.** Relationship between DE intake (MJ/day) and whole-body ash composition (%) in intact male and female pigs.

$$\textbf{Whole body ash composition}\%\ (\textbf{male}) = \mathbf{2.72}\ (\pm\ \mathbf{0.064}\ \textbf{s.e.}) - \mathbf{0.0059}(\pm\ \mathbf{0.00179}\ \textbf{s.e.}) \times \textbf{DE};\ \boldsymbol{R^2} = \mathbf{0.168}, \boldsymbol{P} = \mathbf{0.002}$$

The relationship is not significant in female pigs, therefore no equation is presented.

***Whole-body lean gain rate***

Increasing daily DE intake increased lean tissue gain rate linearly (P<0.001) but not quadratically (P=0.103) in intact male pigs (Figure 10). A piecewise regression model (a breakpoint identified as DE = 38.5 MJ/d)) achieved a slightly greater $R^2$ (0.711) than the linear model, but its BIC value was higher than the linear model (478.0 vs 482.9 for linear vs piecewise regression model), hence the linear regression model was chosen for describing the relationship between DE intake and lean gain rate in male pigs. The linear regression model suggests that every MJ increase of daily DE intake increased the lean gain rate by 16.2 g per day.

Increasing DE intake linearly (P<0.001) but not quadratically (P=0.88) increased the lean gain rate in female pigs, thus a linear regression model was used ($R^2$=0.561, P<0.001). Every MJ increase of daily DE intake increased lean gain rate by 10.1 g. The best fit models are described as:

$$Lean\ gain\ rate\ (male) = -18.9\ (\pm\ 52.58\ s.e.) + 16.2\ (\pm\ 0.994\ s.e.) \times\ DE$$
$$R^2 = 0.694, P < 0.001$$

$$Lean\ gain\ rate\ (female) = 106.9\ (\pm\ 43.59\ s.e.) + 10.1\ (\pm\ 1.222\ s.e.) \times\ DE;$$
$$R^2 = 0.561, P < 0.001,$$

in which lean gain rate is expressed as grams per day; DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients, the constant or the breakpoint.

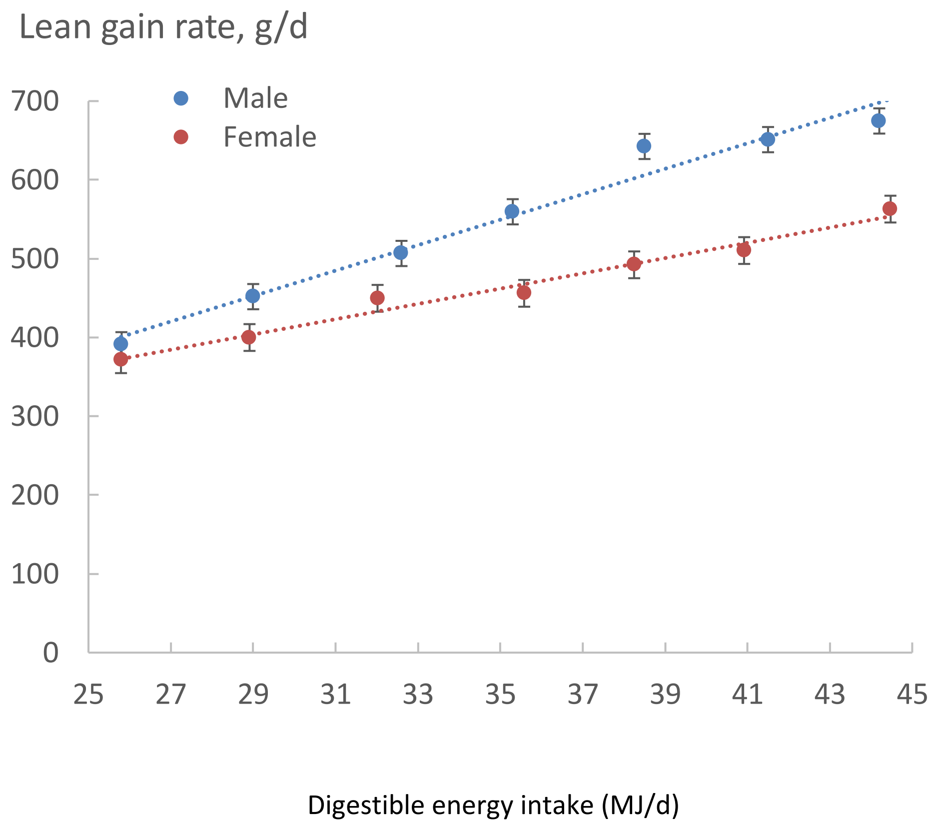


**Figure 10.** Relationship between DE intake (MJ/day) and lean gain rate (g/day) in intact male and female pigs.

$$\boldsymbol{Lean\ gain\ rate\ (male) = -18.9\ (\pm\ 52.58\ s.e.) + 16.2\ (\pm\ 0.994\ s.e.) \times\ DE;}$$
$$\boldsymbol{R^2 = 0.694, P < 0.001}$$

$$\boldsymbol{Lean\ gain\ rate\ (female) = 106.9\ (\pm\ 43.59\ s.e.) + 10.1\ (\pm\ 1.222\ s.e.) \times\ DE;}$$
$$\boldsymbol{R^2 = 0.561, P < 0.001}$$

***Whole-body protein gain rate***

Increasing daily DE intake increased protein gain rate linearly (P<0.001) and quadratically (P=0.083) in male pigs. Adding the quadratic term to the linear regression model did not improve $R^2$ (P=0.17) but yielded a higher BIC (305.1 vs 307.1 for linear vs quadratic regression model). A piecewise regression model (breakpoint at DE=38.5 MJ/d) achieved a slightly greater $R^2$ (0.749) but higher BIC (305.1 vs 310.1 for linear vs piecewise regression model), thus the linear regression model ($R^2$=0.735, P<0.001) was chosen for describing the relationship between DE intake and lean gain rate in male pigs (Figure 11). The regression coefficient in the linear regression model suggests that every MJ increase in daily DE intake increased the protein gain rate by 3.83 g per day.

Protein gain rate in female pigs increased linearly (P<0.001) but not quadratically (P=0.87) in response to the increased daily DE intake, thus a linear regression model was used ($R^2$=0.643, P<0.001). Every MJ increase in daily DE intake increased protein gain rate by 2.50 g per day. The best fit models are described as:

$$Protein\ gain\, rate\ (male) = -7.65\ (\pm\ 11.230\ s.e.) + 3.83\ (\pm\ 0.314\ s.e.) \times\ DE$$
$$R^2 = 0.735, P < 0.001$$

$$Protein\ gain\, rate\ (female) = 20.94\ (\pm\ 9.96\ s.e.) + 2.50\ (\pm\ 0.254\ s.e.) \times\ DE$$
$$R^2 = 0.643, P < 0.001,$$

in which protein gain rate is expressed as grams per day; DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients, the constant or the breakpoint.

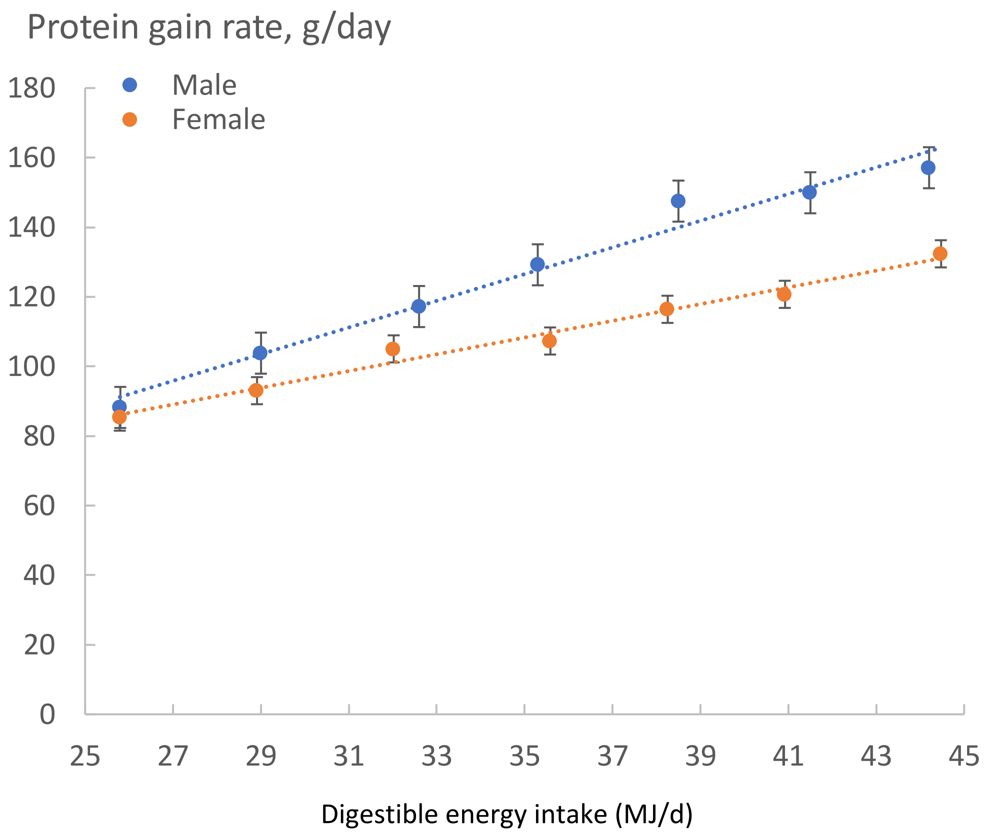


**Figure 11.** Relationship between DE intake (MJ/day) and protein gain rate (g/day) in intact male and female pigs.

$\boldsymbol{Protein\ gain\ rate\ (male) = -7.65\ (\pm\ 11.230\ s.e.) + 3.83\ (\pm\ 0.314\ s.e.) \times\ DE}$
$\boldsymbol{R2 = 0.735, P < 0.001}$
$\boldsymbol{Protein\ gain\ rate\ (female) = 20.94\ (\pm\ 9.96\ s.e.) + 2.50\ (\pm\ 0.254\ s.e.) \times}$
$\boldsymbol{DE; R^2 = 0.643, P < 0.001}$

***Whole-body water gain rate***

Water gain rate increased linearly (P<0.001) but not quadratically (P=0.107) with increased daily DE intake in male pigs. A piecewise regression model (with a breakpoint identified at DE = 38.5 MJ/d) achieved a slightly greater $R^2$ (0.696) but a higher BIC (450.8 vs 455.6 for linear vs piecewise regression model) than the linear regression model, thus the linear regression model was used ($R^2$=0.678, P<0.001) for describing the relationship between DE intake and whole-body water gain rate in male pigs (Figure 12). The regression coefficient of the linear regression model suggests that every MJ increase of daily DE intake increased water gain rate by 12.3 g per day.

Water gain rate increased linearly (P<0.001) but not quadratically (P=0.62) in response to the increased daily DE intake in female pigs, hence the linear regression model ($R^2$=0.528, P<0.001) was chosen for describing the relationship between DE intake and whole-body water gain rate in female pigs. Every MJ increase in daily DE intake increased water gain rate by 7.5 g per day. The best fit models are described as:

$$Water\ gain\ rate\ (male) = -9.9\ (\pm\ 41.23\ s.e.) + 12.3\ (\pm\ 1.15\ s.e.) \times DE$$
$$R^2 = 0.678, P < 0.001$$

$$Water\ gain\ rate\ (female) = 86.5\ (\pm\ 34.53\ s.e.) + 7.5\ (\pm\ 0.97\ s.e.) \times DE$$
$$R^2 = 0.528, P < 0.001,$$

in which water gain rate is expressed as grams per day; DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients or the constant.

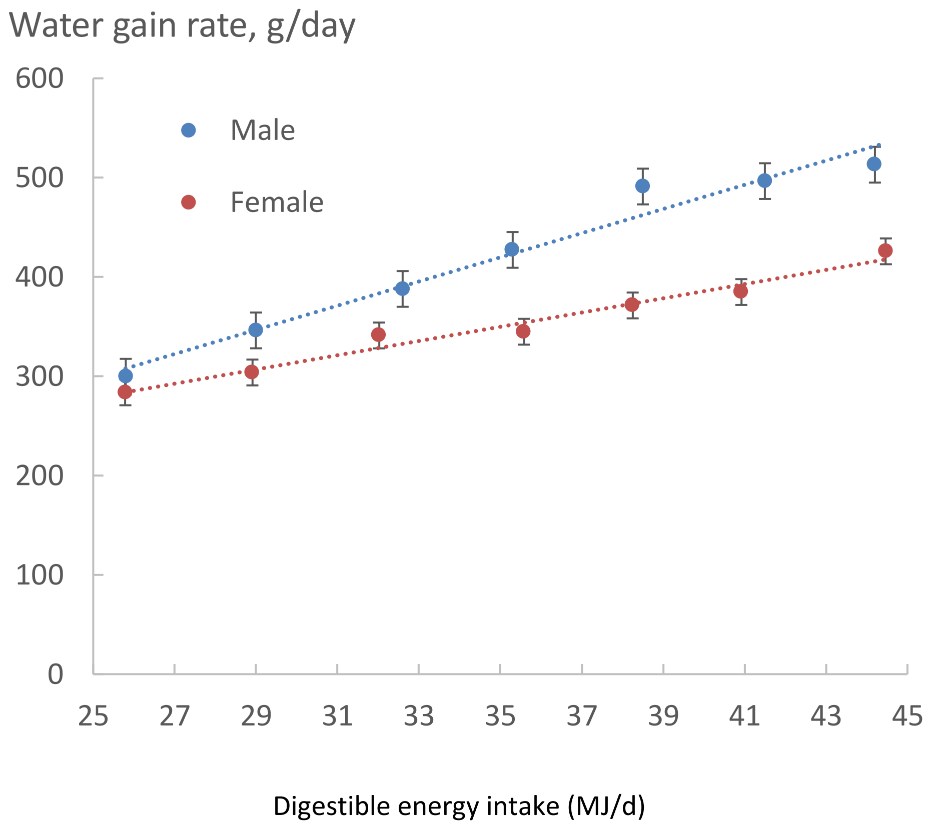


**Figure 12.** Relationship between DE intake (MJ/day) and water gain rate (g/day) in intact male and female pigs.

$$Water\ gain\ rate\ (male) = -9.9\ (\pm\ 41.23\ s.e.) + 12.3\ (\pm\ 1.15\ s.e.) \times DE;\ R^2 = 0.678, P < 0.001$$

$$Water\ gain\ rate\ (female) = 86.5\ (\pm\ 34.53\ s.e.) + 7.5\ (\pm\ 0.97\ s.e.) \times DE;\ R^2 = 0.528, P < 0.001$$

*Whole-body fat gain rate*

The fat gain rate of intact males increased linearly (P<0.001) but not quadratically (P=0.47), thus the linear regression model was chosen ($R^2$=0.750, P<0.001). The regression coefficient of the linear regression model suggested that every MJ increase of daily DE intake increased fat gain rate by 7.4 g in male pigs (Figure 13).

The fat gain rate increased both linearly (P<0.001) and quadratically (P=0.004) in response to the increased DE intake in female pigs. Adding a quadratic term in the regression model improved (P=0.007) the $R^2$ from 0.753 to 0.786, and also the BIC value was reduced from 371.1 to 363.0. A piecewise regression model achieved a slightly greater $R^2$ (0.796) than the quadratic model. The piecewise regression model achieved a similar BIC value as the quadratic model (364.4 vs 363 for piecewise vs quadratic regression model), so both the piecewise regression model ($R^2$=0.796, P<0.001) and quadratic regression model ($R^2$=0.785, P<0.001) are presented for describing the relationship between DE intake and fat gain rate in female pigs. The piecewise regression model identified a breakpoint (DE = 40.4 MJ/d) from which the regression coefficient of DE intake for predicting fat gain rate reduced from 8.51 g to -1.48 g per MJ DE per day. The best fit models are described as:

$$Fat\ gain\ rate\ (male) = -81.9\ (\pm\ 20.7\ s.e.) + 7.4\ (\pm\ 0.60\ s.e.) \times DE$$
$$R^2 = 0.750, P < 0.001$$

$$Fat\ gain\ rate\ (female) = -362.9\ (\pm\ 123.30\ s.e.) + 25.7\ (\pm\ 7.19\ s.e.) \times DE - 0.27\ (\pm\ 0.102\ s.e.) \times DE\hat{}2$$
$$R^2 = 0.786, P < 0.001, \text{BIC=363.0},$$

$$Fat\ gain\ rate\ (female) = -93.3\ (\pm\ 26.68\ s.e.) + 8.51\ (\pm\ 0.823\ s.e.) \times DE\quad when\ DE \le 40.4\ MJ;$$

or

$$= -93.3\ (\pm\ 26.68\ s.e.) + 8.51\ (\pm\ 0.823\ s.e.) \times DE - 9.99\ (\pm\ 3.37\ s.e.) \times \left(DE - 40.4\ (\pm\ 1.22\ s.e.)\right)\quad when\ DE > 40.4\ MJ;$$

$$R^2 = 0.796, P < 0.001, \text{BIC=364.4},$$

in which fat gain rate is expressed as grams per day; DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients, the constant or the breakpoint.

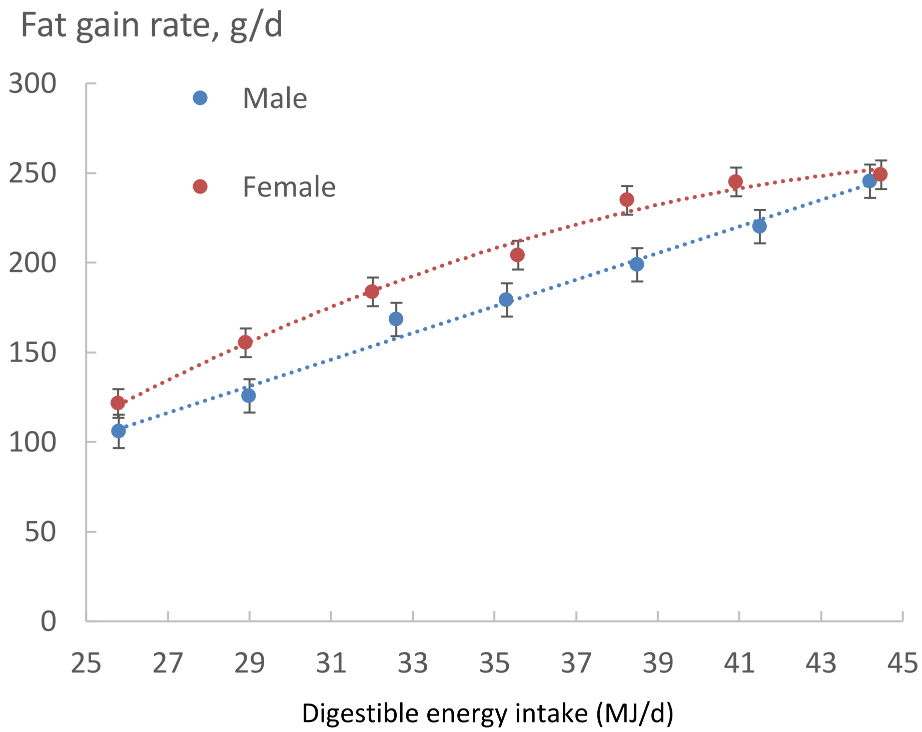


**Figure 13.** Relationship between DE intake (MJ/day) and fat gain rate (g/day) in intact male and female pigs.

$$\boldsymbol{Fat\ gain\ rate\ (male) = -81.9\ (\pm\ 20.7\ s.e.) + 7.4\ (\pm\ 0.60\ s.e.) \times DE}$$
$$\boldsymbol{R^2 = 0.750, P < 0.001}$$

$$\boldsymbol{Fat\ gain\ rate\ (female) = -362.9\ (\pm\ 123.30\ s.e.) + 25.7\ (\pm\ 7.19\ s.e.) \times DE - 0.27\ (\pm\ 0.102\ s.e.) \times DE\text{^}2;\ R^2 = 0.764, P < 0.001,\ \text{BIC=363.0,}}$$

$$\boldsymbol{Fat\ gain\ rate\ (female) = -93.3\ (\pm\ 26.68\ s.e.) + 8.51\ (\pm\ 0.823\ s.e.) \times DE\ when\ DE \leq 40.4\ MJ;\ \text{or} = -93.3\ (\pm\ 26.68\ s.e.) + 8.51\ (\pm\ 0.823\ s.e.) \times DE - 9.99\ (\pm\ 3.37\ s.e.) \times \left(DE - 40.4\ (\pm\ 1.22\ s.e.)\right)\ when\ DE > 40.4\ MJ;\ R^2 = 0.796, P < 0.001,\ \text{BIC=364.4}}$$

***Ratio of lean:fat gain rate***
The ratio of lean:fat gain rate of male pigs reduced linearly (P<0.001) but not quadratically (P=0.63) in response to the increased daily DE intake, thus the linear regression model was used ($R^2$=0.174, P=0.001). The coefficient of the linear regression model suggested that every MJ increase in DE intake reduced the ratio of lean:fat gain rate by 0.011 (Figure 14).

In female pigs the ratio reduced linearly (P<0.001) and quadratically (P=0.011) in response to the increased daily DE intake. Adding a quadratic term in the regression model improved (P=0.020) $R^2$ from 0.178 to 0.258 and reduced BIC from -52.5 to -54.3. The piecewise regression model achieved a similar $R^2$ (0.276) but a higher BIC (-51.6) than the quadratic model. Thus, the quadratic model ($R^2$=0.258, P=0.001) was chosen for describing the relationship between DE intake and the ratio of lean:fat gain rate in female pigs.

$$Ratio\ of\ lean{:}fat\ gain\ rate\ \ (male) = 5.04\ (\pm\ 0.536\ s.e.) - 0.50\ (\pm\ 0.015\ s.e.) \times DE$$
$$R^2 = 0.174, P = 0.001$$

$$Ratio\ of\ lean{:}fat\ gain\ rate\ \ (female) = 10.4\ (\pm\ 2.73\ s.e.) - 0.42\ (\pm\ 0.159\ s.e.) \times DE + 0.005\ (\pm\ 0.0022\ s.e.) \times DE\hat{}2$$
$$R^2 = 0.258, P = 0.001,$$

in which DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients, the constant or the breakpoint.

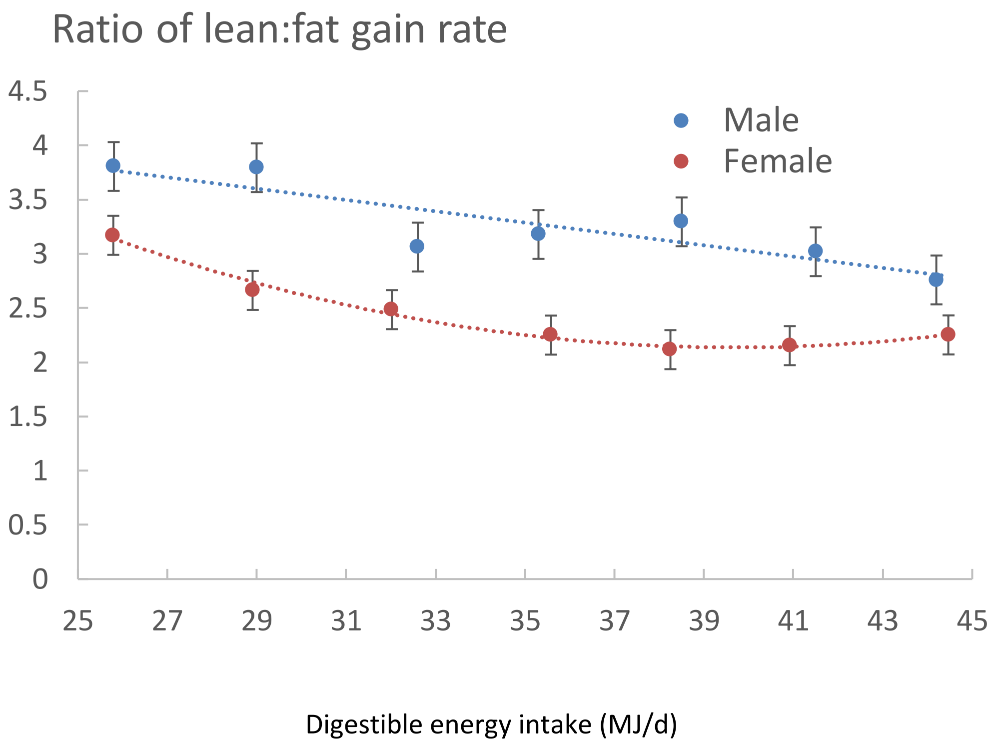


**Figure 14.** Relationship between DE intake (MJ/day) and ratio of lean:fat gain rate in intact male and female pigs.

$$\boldsymbol{Ratio\ of\ lean{:}fat\ gain\ rate\ \ (male) = \ 5.04\ (\pm\ 0.536\ s.e.) - 0.50\ (\pm\ 0.015\ s.e.) \times DE;\ R^2 =\ 0.174, P = 0.001}$$

$$\boldsymbol{Ratio\ of\ lean{:}fat\ gain\ rate\ \ (female) = \ 10.4\ (\pm\ 2.73\ s.e.) - 0.42\ (\pm\ 0.159\ s.e.) \times DE + 0.005\ (\pm\ 0.0022\ s.e.) \times DE^2;\ R^2 =\ 0.258, P = 0.001}$$

***Ash gain rate***
In male pigs, the rate of ash gain increased linearly (P<0.001) and quadratically (P=0.036) in response to increased daily DE intake (Figure 15). Adding a quadratic term tended to improve (P=0.069) $R^2$ from 0.739 to 0.755, and no piecewise regression models improved $R^2$, hence the quadratic regression model was used ($R^2$=0.755, P<0.001) (Figure 8).

Ash gain rate increased linearly (P<0.001) but not quadratically (P=0.14) with the increased daily DE intake in female pigs, thus the linear regression model was chosen ($R^2$=0.758, P<0.001). Every MJ increase of daily DE intake increased ash gain rate by 0.55 g per MJ DE intake per day. The best fit models are described as:

$$Ash\ gain\ rate\ \ (male) = -18.2\ (\pm\ 10.68\ s.e.) + 1.75\ (\pm\ 0.623\ s.e.) \times DE - 0.016\ (\pm\ 0.0088\ s.e.) \times DE\hat{}2$$
$$R^2 = \ 0.755, P < 0.001$$

$$Ash\ gain\ rate\ \ (female) = \ 1.13\ (\pm\ 1.515\ s.e.) + 0.55\ (\pm\ 0.042\ s.e.) \times DE$$
$$R^2 = \ 0.758, P = 0.001,$$

in which ash gain rate is expressed as grams per day; DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients, the constant or the breakpoint.

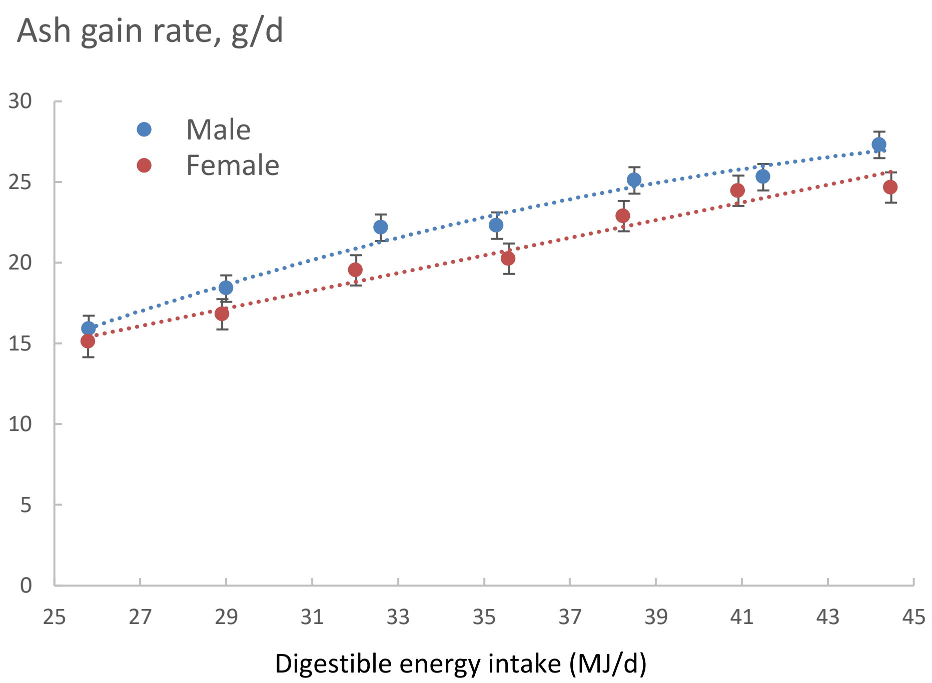


**Figure 15.** Relationship between DE intake (MJ/day) and ash gain rate (g/day) in intact male and female pigs.

$$\boldsymbol{Ash\ gain\ rate\ (male) = -18.2\ (\pm\ 10.68\ s.e.) + 1.75\ (\pm\ 0.623\ s.e.) \times DE - 0.016\ (\pm\ 0.0088\ s.e.) \times DE^2;\ R^2 = 0.739, P < 0.001}$$

$$\boldsymbol{Ash\ gain\ rate\ (female) = 1.13\ (\pm\ 1.515\ s.e.) + 0.55\ (\pm\ 0.042\ s.e.) \times DE;\ R^2 = 0.758, P = 0.001}$$

***Carcass weight of pigs at 108 kg live weight***

The hot standard carcass weight (standardised at 108.6 kg live weight) increased linearly (P=0.004) but not quadratically (P=0.49) with the increased DE in intact males. The quadratic regression model has a higher BIC than the linear regression model (47.6 vs 44.3 for quadratic vs linear regression model), thus the linear regression model ($R^2$=0.736, P<0.001) was chosen for describing the relationship between DE intake and hot carcass weight at a given pre-slaughter live weight. The regression coefficient suggests that every MJ increase of DE intake increased carcass weight by 0.088 kg.

The hot standard carcass weight (standardised at 108.6 kg live weight) did not respond to dietary DE intake in female pigs (Linear, P=0.61; Quadratic, P=0.055) (Figure 16). The best fit model is described as:

$$\begin{aligned} &Hot\ standard\ carcass\ weight\ \ (male) \\ &\quad = 17.7\ (\pm\ 8.56\ s.e.) + 0.088\ (\pm\ 0.0303\ s.e.) \times DE \\ &\quad + 0.579\ (\pm\ 0.077\ s.e.)\ \times LW \\ &\qquad R^2 = 0.736, P < 0.001, \end{aligned}$$

in which backfat thickness of live animals is measured at P2 site (mm); DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficient or the constant; LW is the pre-slaughter live weight

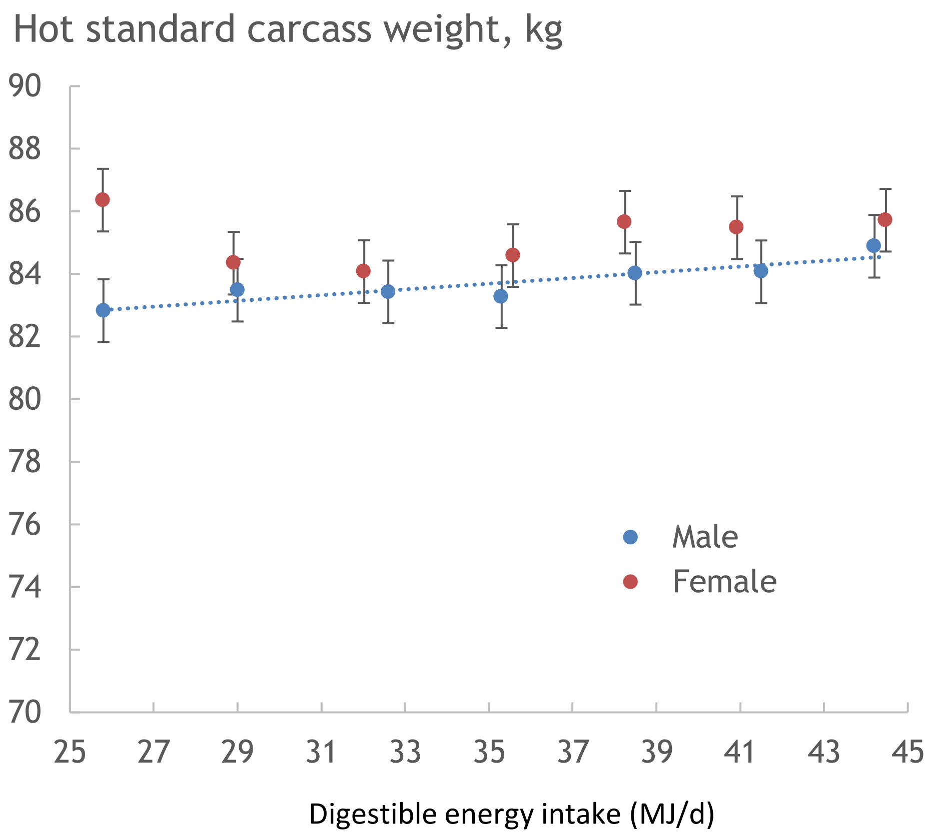


**Figure 16.** Relationship between daily DE intake (MJ/day) and hot standard carcass weight (measured at 108 kg live weight, head on, trotters on, visceral off) in female and male pigs.

$$\boldsymbol{Hot\ standard\ carcass\ weight\ (male) = 17.7\ (\pm\ 8.56\ s.e.) + 0.088\ (\pm\ 0.0303\ s.e.) \times DE + 0.579\ (\pm\ 0.077\ s.e.) \times Live\ weight}$$

$$\boldsymbol{R^2 = 0.736, P < 0.001}$$

The relationship is not significant in female pigs, therefore no equation is presented.

***Carcass dressing %***

Dressing percentage of intact male pigs increased linearly (P=0.001) with increased DE intake at a regression coefficient of 0.10 per MJ DE intake per day, whereas dressing percentage of female pigs was not affected by DE intake (Linear, P=0.67; Quadratic, P=0.13) (Figure 17). The best fit model is described as:

$$Dress\ \%\ (male) = 73.6\ (\pm\ 1.07\ s.e.) + 0.100\ (\pm\ 0.0301\ s.e.) \times DE$$
$$R^2 = 0.156, P = 0.002,$$

in which dressing percentage is expressed as %; DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficient or the constant.

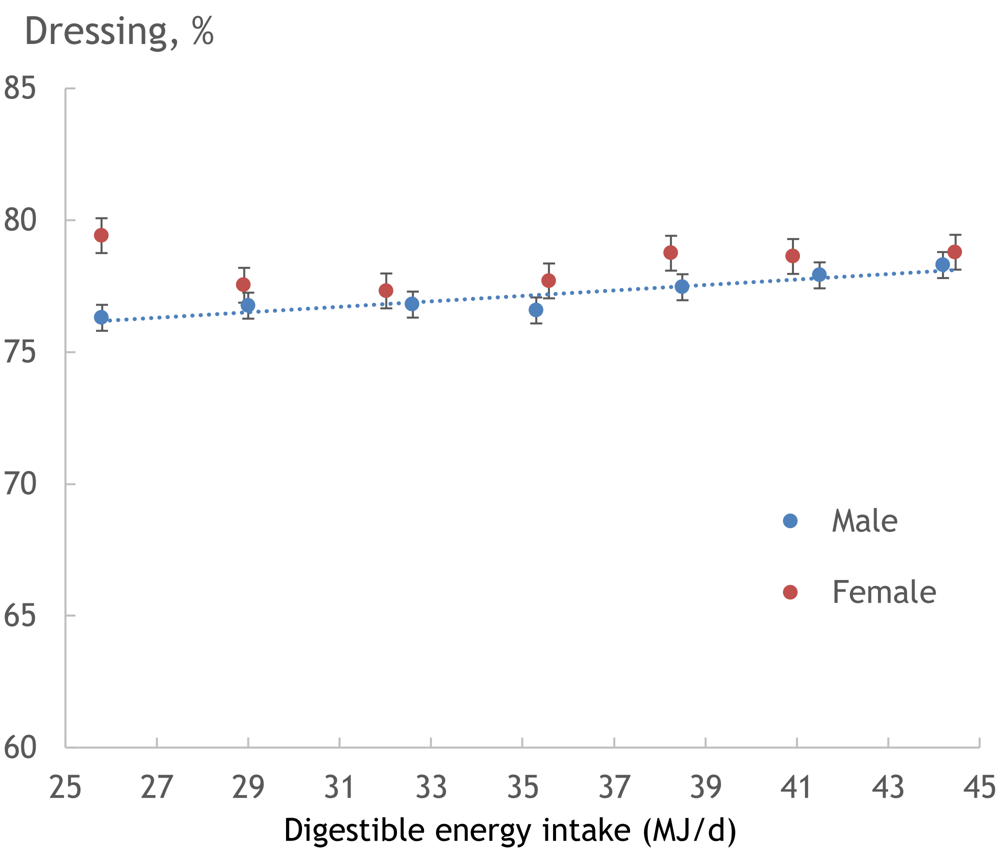


**Figure 17.** Relationship between DE intake (MJ/day) and dressing percentage (%) in intact male and female pigs.

$\boldsymbol{Dress}\ \%\ (\boldsymbol{male}) = \ \mathbf{73.6}\ (\pm\ \mathbf{1.07}\ \boldsymbol{s.e.}) + \mathbf{0.100}\ (\pm\ \mathbf{0.0301}\ \boldsymbol{s.e.}) \times \boldsymbol{DE};\ \boldsymbol{R}^2 = \ \mathbf{0.156}, \boldsymbol{P} = \mathbf{0.002}.$

The relationship is not significant in female pigs, therefore no equation is presented.

*Backfat thickness of carcass*

Carcass backfat (P2, mm) thickness increased linearly (P=0.003) with increased DE intake in intact males at a regression coefficient of 0.125 mm per MJ DE intake per day, whereas carcass backfat thickness did not respond (Linear, P=0.51; Quadratic, P=0.61) to DE intake in females (Figure 18). The best fit model is described as:

$$Carcass\ backfat\ (P2\ site)\ \ (male) = 7.59\ (\pm\ 1.477\ s.e.) + 0.125\ (\pm\ 0.0414\ s.e.) \times DE$$
$$R^2 = 0.130, P = 0.004,$$

in which carcass backfat thickness is measured at P2 site (mm); DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficient or the constant.

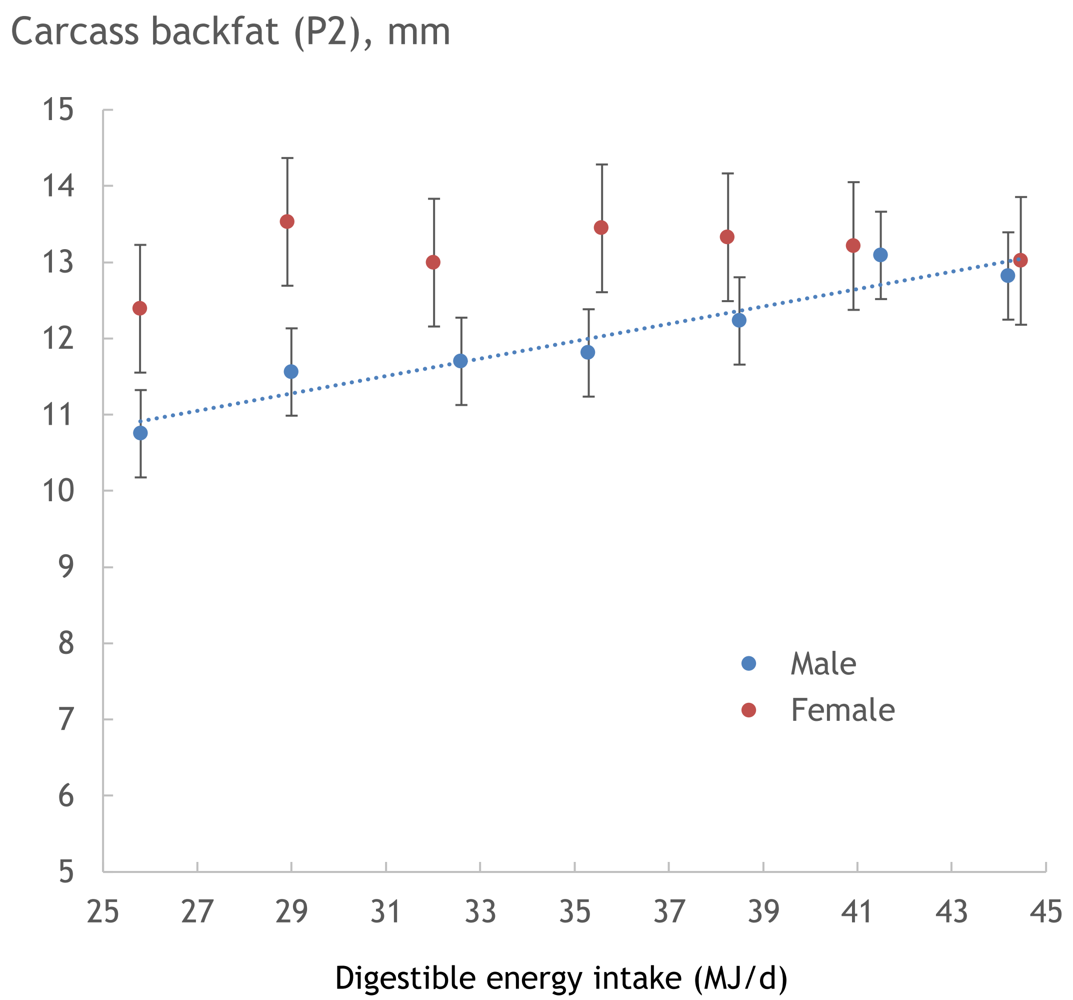


**Figure 18.** Relationship between DE intake (MJ/day) and carcass backfat (P2 site, mm) in intact male and female pigs at 108 kg live weight.

$\boldsymbol{Carcass\ backfat\ (P2\ site)\ (male) = \ 7.59\ (\pm\ 1.477\ s.e.) + 0.125\ (\pm\ 0.0414\ s.e.) \times DE;\ R^2 = 0.130, P = 0.004}$

The relationship is not significant in female pigs, therefore no equation is presented.

***Loin depth***

Loin depth measured in carcasses increased quadratically (P=0.032) with the increased DE intake (Figure 19). The analysis using piecewise regression achieved a lower $R^2$ than the quadratic model, hence was not used.

Loin depth was not affected by DE intake in female pigs (Linear, P=0.24, Quadratic, P=0.42). The best fit model is described as:

$$Carcass\ loin\ depth\ (P2\ site)\ (male) = 104.4\ (\pm\ 24.47\ s.e.) - 3.00\ (\pm\ 1.427\ s.e.) \times DE + 0.041\ (\pm\ 0.0203\ s.e.) \times DE^{\wedge}2$$

$$R^2 = 0.097, P = 0.070,$$

in which carcass loin depth was measured at P2 site (mm); DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficients or the constant.

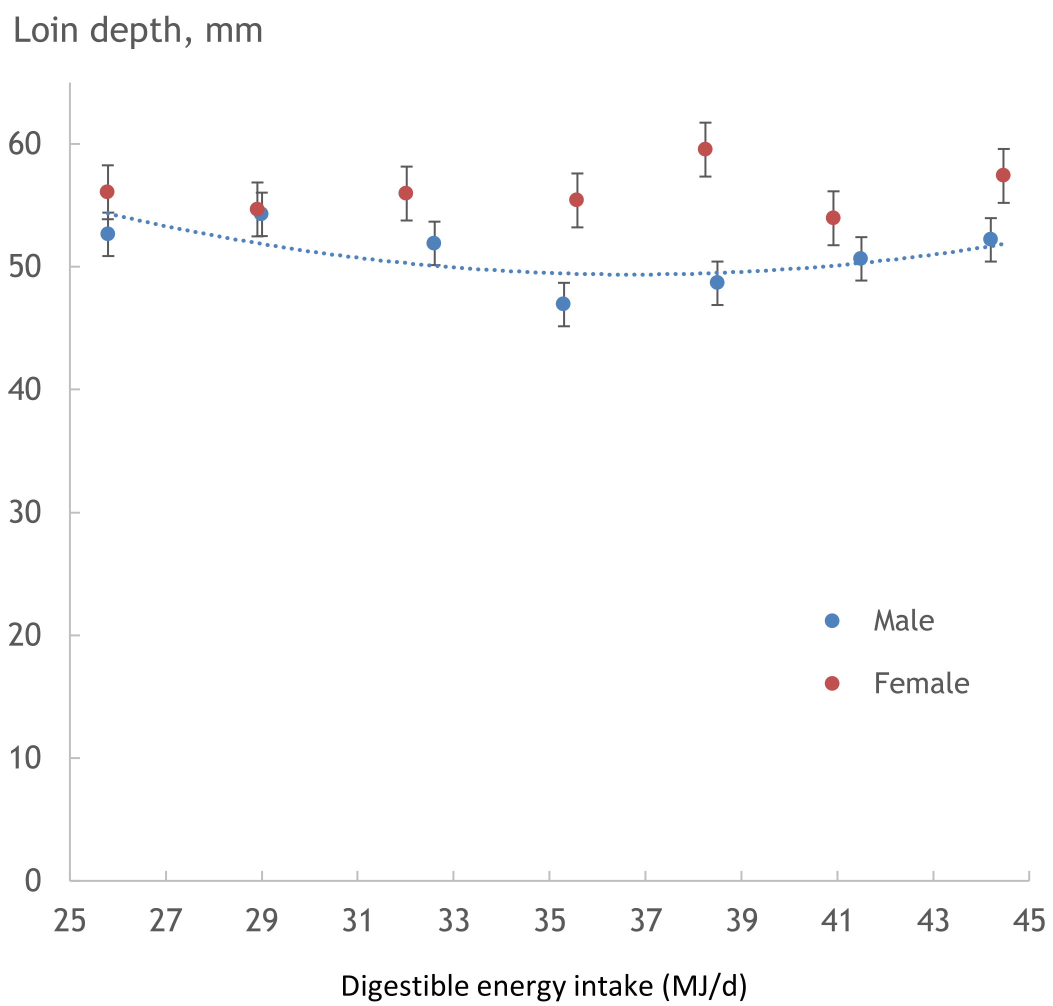


**Figure 19.** Relationship between DE intake (MJ/day) and carcass loin depth (P2 site, mm) in intact male and female pigs.

$\boldsymbol{Carcass\ loin\ depth}\ (\boldsymbol{P2\ site})\ (\boldsymbol{male}) = \ \mathbf{104.4}\ (\pm\ \mathbf{24.47}\ \boldsymbol{s.e.}) - \mathbf{3.00}\ (\pm\ \mathbf{1.427}\ \boldsymbol{s.e.}) \times \boldsymbol{DE} + \mathbf{0.041}\ (\pm\ \mathbf{0.0203}\ \boldsymbol{s.e.}) \times \boldsymbol{DE}^{\mathbf{2}};\ \boldsymbol{R}^2 = \ \mathbf{0.097}, \boldsymbol{P} = \mathbf{0.070}.$

The relationship is not significant in female pigs, therefore no equation is presented.

## Plasma urea nitrogen

Plasma urea nitrogen concentration was not affected (Linear, P=0.63, Quadratic, P=0.90) by DE intake in intact male pigs, but it reduced linearly (P=0.021) with increased DE intake in female pigs at a regression coefficient of -0.029 mm per MJ DE intake per day (Figure 20). The best fit model is described as:

$$PUN\ \ (female) = \ 20.2\ (\pm\ 0.42\ s.e.) - 0.029\ (\pm\ 0.012\ s.e.) \times DE$$
$$R^2 = \ 0.100, P = 0.021,$$

in which plasma urea nitrogen (mM) is measured at 108 kg live weight; DE is the daily digestible energy intake (MJ/day); s. e. is the standard error of the regression coefficient or the constant.

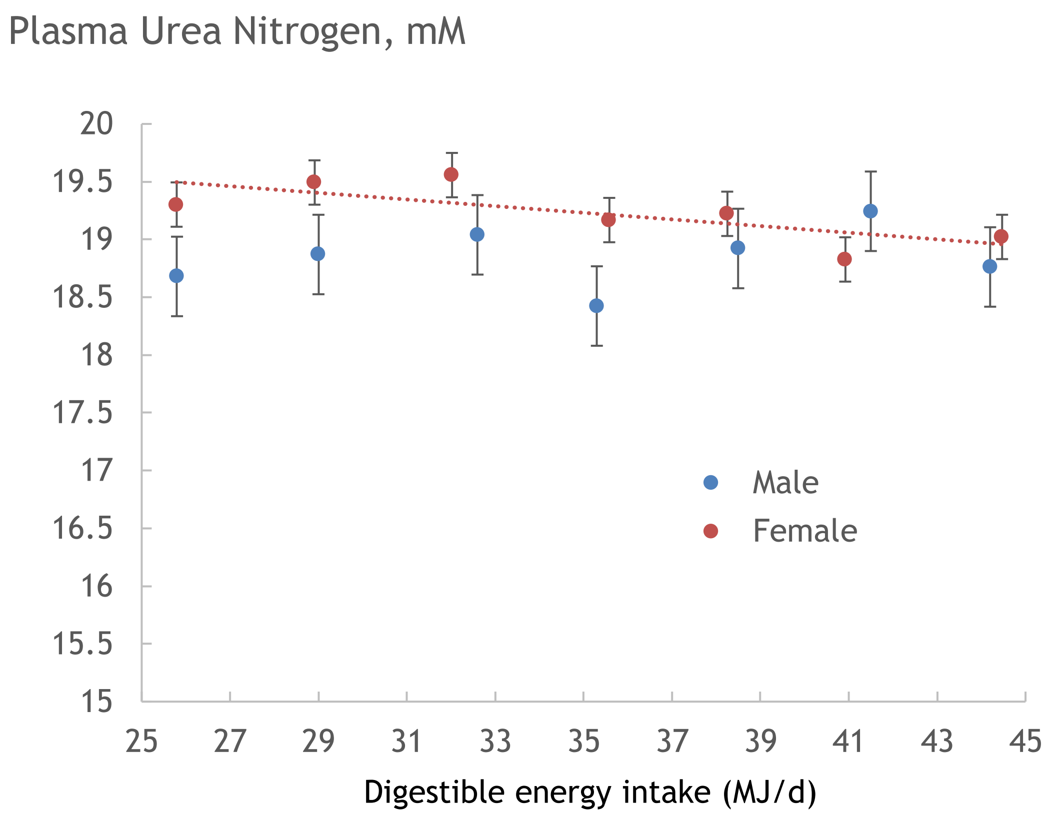


**Figure 20.** Relationship between DE intake (MJ/day) and plasma urea nitrogen (measured at 108 kg live weight) in intact male and female pigs.

$\boldsymbol{PUN\ (female) = 20.2\ (\pm\ 0.42\ s.e.) - 0.029\ (\pm\ 0.012\ s.e.) \times DE;\ R^2 = 0.100, P = 0.021}$.

The relationship is not significant in female pigs, therefore no equation is presented.

Table 2. Comparison of body composition of finisher pigs (PrimeGro™ Genetics) between studies conducted in 00s and 2019.

| Sex | Publications | Start BW, kg | Final BW, kg | ADG, kg/d | Voluntary DE intake/kg $BW^{0.75}$, MJ/kg | Whole-body lean% | Whole-body fat% | Whole-body ash% | Carcass backfat (P2), mm |
|---|---|---|---|---|---|---|---|---|---|
| Boar | McCauley *et al*. (2003) | 81 | 116 | 1.38 | 1.71 | 65% | 24% | 2.2% | 20.0 |
| | Suster *et al*. (2004) | 60 | 101 | 1.34 | 1.75 | 70% | 16% | 2.6% | 13.8 |
| | Suster *et al*. (2006a) | 55 | 112 | 1.02 | NA | 67% | 19% | NA | 15.9 |
| | Dunshea *et al*. (2003) | 70 | 102 | 1.13 | 1.59 | 73% | 17% | 1.9% | 18.0 |
| | Oliver *et al*. (2003) | 65 | 99 | 1.18 | 1.57 | 70% | 20% | 2.5% | 14.7 |
| | Average of trials in 2000 | 66 | 106 | 1.21 | 1.66 | 69% | 19% | 2.3% | 16.5 |
| | Current study 2019 | 60 | 108 | 1.14 | 1.59 | 69% | 16% | 2.5% | 12.8 |
| | *Deviation (2019-2000)* | *-9%* | *2%* | *-5%* | *-4%* | *0%* | *-16%* | *8%* | *-22%* |
| Gilt | McCauley *et al*. (2003) | 80 | 110 | 1.07 | 1.73 | 61% | 26% | 2.1% | 18.6 |
| | Oliver *et al*. (2003) | 64 | 92 | 1.06 | 1.48 | 67% | 24% | 2.6% | 14.2 |
| | Suster *et al*. (2005) | 80 | 112 | 1.17 | 1.64 | 63% | 20% | 2.7% | 15.9 |
| | Suster *et al*. (2006b) | 60 | 91 | 1.10 | 1.68 | 66% | 20% | 2.7% | 17.1 |
| | Average of trials in 2000 | 69 | 100 | 1.10 | 1.57 | 65% | 21% | 2.4% | 15.3 |
| | Current study 2019 | 60 | 108 | 1.04 | 1.60 | 67% | 18% | 2.5% | 13.0 |
| | *Deviation (2019-2000)* | *-13%* | *8%* | *-6%* | *2%* | *2%* | *-15%* | *4%* | *-15%* |

*Ad libitum* feeding was practiced in all the cited experiments
BW: body weight
DE: digestible energy, MJ
NA: no data were available

# 4. Application of Research

The key finding from the current experiment was that every MJ increase of daily DE intake increased the rate of protein gain by 3.8 g/d in intact male pigs and by 2.5 g/d in female pigs throughout the tested range of daily DE intakes (25.8-44.5 MJ/d). The linear relationship between protein deposition rate and DE intake agreed with the most recent study conducted on the same breed of pigs (King et al. 2004). Some early studies suggested that the selection emphasis on protein gain rate had changed the relationship between protein gain rate and dietary energy intake to a linear manner (i.e. no plateau phase) in British (Rao and McCracken 1991) and Australian (Dunshea *et al.* 1993; King *et al.* 2004) genetics. Quadratic (or linear-plateau) relationships between protein deposition rate and dietary energy in male pigs was only reported in some early genetics and castrated males in the 1980s and 90s in Australia (Campbell *et al.* 1985; Campbell and Taverner 1988), France (Quiniou *et al.* 1996) and The Netherlands (Bikker 1994).

Surprisingly, the results in this experiment showed that fat gain rate and whole-body fat composition of female pigs increased linearly from 25.7 to 40.4 MJ DE per day and then reached a plateau phase from 40.4 MJ DE per day. This plateau phase in female pigs was not reported elsewhere, and we cannot explain the finding. We cannot exclude the possibility that some female pigs with a lower fat gain potential were randomly selected into the *ad libitum* group. The linear response of fat gain rate to DE intake in male pigs was similar as reported before (King *et al.* 2004).

Backfat thickness, one of the most economically important carcass traits in the Australasian pig market, increased by 0.125 mm for every MJ daily DE intake in intact male pigs but did not respond to DE intake in female pigs, as shown in regression analysis of the current study. By comparison, in the study conducted by King *et al.* (2004), every MJ increase in DE intake increased carcass backfat thickness by 0.20 mm and 0.30 mm in males and females, respectively. The blunted response of carcass backfat thickness to dietary DE intake in the modern genetics examined herein is likely to be the outcome of the genetic selection on lower backfat thickness in the sire line over the past two decades.

Given that the carcass backfat thickness of male pigs still responds to DE intake, feed restriction remains a viable strategy to reduce backfat thickness in male pigs. With regard to female pigs, *ad libitum* feeding (i.e., up to 44.5 MJ DE/day in the current study) is recommended, for achieving a shorter duration to reach marketable body weight, because *ad libitum* feeding in female pigs is not likely to increase carcass backfat thickness and the protein deposition rate increased linearly throughout the wide DE intake range. The lack of response of backfat thickness of female pigs is likely to be an outcome of a direct genetic selection for the pigs with less backfat thickness. It is worthwhile to mention that the backfat measurement on carcasses only explained less than 40% variation of whole-body fat composition measured by DXA method in the experiment (data not shown). The whole-body fat composition (DXA method) in male and female pigs both increased linearly in response to energy intake, but this fact does not have an economic impact in the current carcass grading system in Australia.

Overall, the whole-body fat composition of finisher pigs (Primegro™ Genetics) with modern genetics reduced from 18% to 16% in intact male pigs and from 21% to 18% in female pigs compared with the same breed measured using DXA scanner in the past two decades (Table 2). Nevertheless, the voluntary dietary DE intake of finisher pigs was maintained at 1.59 MJ DE per kg and 1.60 MJ DE per kg metabolic body weight for male and female pigs, respectively, compared with the past studies. Unfortunately, we were unable to compare tissue gain rate with previous literature due to the different methods used for quantifying tissue mass in the past (wet chemistry on carcasses) and current study (DXA on whole body).

Future experiments should re-evaluate the economics of unrestricted and restricted feeding strategy in female and male pigs under commercial conditions, particularly, to investigate whether the benefits from the carcass backfat reduction through energy restriction outweigh the cost associated with prolonged age-derived mortality and facility turn-over.

# 5. Conclusion

Pigs with modern genetics (Primegro™ Genetics, as of 2019) have less whole-body fat and backfat thickness, whereas the voluntary energy intake has not changed significantly compared to the same breed two decades ago. The protein deposition rate of intact male and female pigs both increased linearly with the increased DE intake in the tested range. Carcass backfat thickness increased linearly in response to the increased daily DE intake in male pigs but not in female pigs.

# 6. Limitations/Risks

The limitation of the research was the lack of castrated male pigs as an experimental treatment.

# 7. Recommendations

Based on the experimental results, the following recommendations have been made on the assumption that finisher pigs can be marketed by body weight:

- Restricting dietary energy intake in male pigs can reduce carcass backfat (slaughtered at a fixed body weight).
- Unrestricted feeding in female pigs should be considered, because the protein tissue deposition rate of female pigs increased linearly in response to increased dietary energy, and feed restriction did not effectively reduce carcass backfat thickness in female pigs.

- The economics of restricted and unrestricted feeding should be evaluated in intact male and female respectively under commercial conditions with the cost of duration of growth and mortality rate taken into considerations.

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**Appendix 1 - Notes**

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