EFFECTS OF BIRTH WEIGHT, FINISHING FEEDER DESIGN, AND DIETARY ASTAXANTHIN AND RACTOPAMINE HCL ON THE GROWTH, CARCASS, AND PORK QUALITY CHARACTERISTICS OF PIGS; AND META-ANALYSES TO IMPROVE THE PREDICTION OF PORK FAT QUALITY

by

JONATHAN ROBERT BERGSTROM

B. S., Iowa State University, 1992

M. S., Kansas State University, 1996

AN ABSTRACT OF A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Animal Sciences & Industry

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Abstract

Eleven-thousand one-hundred eighty-five pigs were used in 11 experiments to determine effects of birth-weight, feeder design, and dietary astaxanthin (AX) and ractopamine HCl (RAC) on growth, carcass, and pork quality characteristics of pigs. Also, data from 27 experiments were used in meta-analyses to improve prediction of pork fat iodine value (IV). In Exp. 1, increased birth-weight resulted in greater (quadratic, $P < 0.05$) pre-weaning survivability, ADG, final BW, and likelihood of achieving full-value market at 181-d of age. In Exp. 2, 3, 4, 6, 7, and 8, pigs using the wet-dry feeder (WD) had greater ($P < 0.05$) ADG, ADFI, and final BW than those using the conventional dry feeder (CD). Pigs using WD had poorer ($P < 0.05$) G:F in Exp. 3 and 4, and increased ($P < 0.05$) HCW and backfat depth in Exp. 3, 4, 6, and 7, compared to pigs fed using CD. In Exp. 5, pigs using WD from 19 to 38 kg had decreased ($P < 0.02$) ADFI and better G:F than pigs using CD. Increased feeder opening of WD increased ($P < 0.05$) ADG, ADFI, and final BW in Exp. 5, 6, and 7; as well as HCW and backfat depth in Exp. 6 and 7. Reducing WD opening at 28- and 56-d in Exp. 7 decreased ($P < 0.05$) ADG, ADFI, and backfat depth. Different openings of CD had little effect on performance in Exp. 5 and 6. In Exp. 8, changing water-source of WD to a separate location during late-finishing reduced ($P < 0.05$) overall ADG, ADFI, and final BW. Limited responses to AX were observed in Exp. 9, 10, and 11, but ADG, G:F, final BW, HCW, and fat-free lean were improved ($P < 0.05$) for pigs fed RAC in Exp. 10 and 11. Total color change during retail display of LM chops for gilts and pigs fed RAC was reduced ($P < 0.05$) in Exp. 10 and 11, indicating their color shelf-life improved. In the meta-analyses, models using dietary PUFA with ADG, BW, or backfat depth improved the fat IV prediction from $R^2 = 0.45$ to $R^2 = 0.90$.

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Major Professor

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CHAPTER 1 - The association of sow and litter characteristics with piglet birth weight; and the implications for growth, survival, and carcass characteristics of pigs on a commercial farm

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ABSTRACT

The objective of this study was to evaluate the relationships of sow and litter characteristics with piglet birth weight; and the implications for growth, survival, and carcass characteristics of pigs on a commercial farm. Data were obtained from 212 litters born during 22 consecutive days, and included individual pig identification and collection of BW at birth (n = 2,204), weaning (≈ 25 d of age), and approximately 180 d of age (weaning-to-finish, n = 1,736). All general management and feeding practices were performed according to normal farm procedures throughout the study. Fostering was practiced primarily within 24 h of birth, but the transfer or removal of individual pigs was recorded. Therefore, pigs were categorized by size of litter-of-origin (≤ 11, 12 to 14, and ≥ 15 total born), parity of birth dam (1, 2, 3, 4 and 5, and 6 to 9), fostered status (yes or no), parity of dam suckled (1, 2 and 3, and 4 to 9), birth weight (< 1.15, 1.15 to 1.35, 1.40 to 1.50, 1.55 to 1.65, 1.70 to 1.80, 1.85 to 2.05, and > 2.05 kg), and gender (barrow or gilt). Carcass data were obtained from a sample of 418 pigs harvested in a single day at a commercial processor. While birth weight decreased ($P < 0.05$) with increasing litter size, pigs born to parity 2 to 5 sows originated from larger ($P < 0.05$) litters with greater ($P < 0.05$) mean birth weight when compared to parity 1 and parity 6 to 9 sows. The SD of birth weight within litter-of-origin increased ($P < 0.05$) with litter size and parity of the birth dam. Pre-weaning ADG and survival improved ($P < 0.05$) with increasing birth weight. Weaning-to-finish and lifetime ADG, final BW (180 d of age), and likelihood of achieving full market value were improved ($P < 0.05$) for pigs with greater birth weight and for barrows. Fat-free lean index (adjusted for HCW) was improved ($P < 0.05$) for gilts and pigs with greater birth weight. Although birth weight and gender were most important, fostering revealed that parity of the sow suckled (rather than the parity of the birth dam) was also important for subsequent growth. Pre-

weaning and lifetime ADG improved ($P < 0.05$) for pigs suckling parity 2 and older sows. In conclusion, these data provide further evidence of the fundamental importance of birth weight for growth and survival of pigs on a commercial farm. Although birth weight generally decreased with larger litter sizes, these data indicate that an optimum herd parity structure and improved fostering practices may ameliorate the potential consequences of increased litter size for overall pig growth.

Key words: birth weight, carcass characteristics, litter size, pig performance, sow parity

INTRODUCTION

Research by Main et al. (2004) demonstrated the importance of both weaning age and weaning weight for subsequent performance. Thus, many swine production systems have increased weaning age by establishing critical limits for the breeding herd to reduce the likelihood of weaning pigs < 16 d of age. The desire to improve weaning weight, post-weaning growth, efficiency of growth, welfare, and economic return has resulted in an increased mean weaning age in the U.S. from 18.9 d in 1998 to 20.1 d in 2010 (PigCHAMP, 1998 and 2010).

During this same period, litter size has increased substantially (from 11.2 total born and 10.2 live born to 13.1 total born and 11.6 live born; PigCHAMP, 1998 and 2010) because of genetic selection, improvements in sow nutrition and feeding practices, and improved health management. The increase in lactation days may also be contributing to the improved reproductive performance (Hays et al., 1978).

Unfortunately, improved ovulation rates and embryonic survival have occurred without any measurable change in the uterine capacity of sows (Foxcroft, 2007). This has justifiably resulted in some concern for reduced birth weight with increased litter-size (Milligan et al., 2002a; Quiniou et al., 2002). Although the relationship of birth weight and subsequent growth is

fairly well understood (Schinckel et al., 2007; Fix et al., 2010a), relatively few studies have attempted to directly describe the relationships of litter-size and sow parity characteristics with subsequent pig performance under commercial conditions.

In addition, economically important traits are also influenced by birth weight, such as mortality and carcass characteristics (Quiniou, et al., 2002; Gondret et al., 2005; Fix et al., 2010a,b). However, the degree of association of litter and sow parity characteristics with these variables is somewhat controversial when considering the implications for pork production management and efficiency (Beaulieu et al., 2010; Schinckel et al., 2010a). A greater understanding of these relationships is necessary for continued improvement in pork production systems.

Therefore, our objective was to evaluate the relationships of sow and litter characteristics with piglet birth weight; and the implications for growth, survival, and carcass characteristics of pigs on a commercial farm.

MATERIALS AND METHODS

Procedures used in this experiment were approved by the Kansas State University Institutional Animal Care and Use Committee.

Animal Care

The experiment was conducted at a commercial farm in Kansas using a segregated, 3-site production system. A total of 2,204 pigs (PIC 327 sired; Hendersonville, TN) born to either PIC 1050 (F1) or Triumph TR4 × PIC 1050 (F2) sows (n = 212) were used. Throughout the gestation period, gilts and sows received approximately 2.05 kg/d and 2.50 kg/d, respectively, of a corn-soybean meal-based diet designed to meet or exceed the nutrient requirements of gestating sows (NRC, 1998). Sows on this farm routinely farrowed at their natural gestation length, and none of

the farrowings were induced during the experiment. During farrowing and lactation, all sows and their litters were penned in individual farrowing crates (91.4 cm × 213.4 cm for sow and 152.4 cm × 213.4 cm for pigs) located over totally slatted floors in environmentally controlled buildings.

All pigs were born between November 5, 2008 and November 25, 2008; and were individually weighed and identified with a numbered ear-tag within 18 h of birth. Unlike the practices employed in some studies and farms (Beaulieu et al., 2010), piglet viability at this farm was not based on a minimum birth weight. All pigs independently able to reach the sow's udder and attempt to suckle were included in the study, regardless of birth weight. The individual identification, gender, and birth weight of piglets was recorded; as well as the dam's identification, parity, number of total born, number of live born, and number born dead. This information was utilized to categorize piglets by their gender (male or female), the size of their litter-of-origin (3 categories; ≤ 11, 12 to 14, and ≥ 15 total born), the parity of their birth dam (5 categories; parity 1, 2, 3, 4 and 5, and 6 to 9), and their birth weight (7 categories; < 1.15, 1.15 to 1.35, 1.40 to 1.50, 1.55 to 1.65, 1.70 to 1.80, 1.85 to 2.05, and > 2.05 kg).

After weighing, and according to the normal farm procedures within 24 h of birth, litters born within the same day were equalized for number (and the piglets sized uniformly within litters) by cross-fostering. Every attempt was made to keep subsequent pig movement at a minimum; however, all necessary pig movements, fostering, removals, and mortalities were recorded. Consequently, pigs were further categorized as either non-fostered or fostered; as well as by the parity of the sow they were weaned from (3 categories; parity 1, 2 and 3, and 4 to 9). All piglets were processed (including the castration of males) according to the farm's normal procedures for optimizing sow and piglet health and welfare. During lactation, sows were

provided *ad libitum* access to feed and water. None of the pigs were given access to creep feed during lactation. At weaning (25.2 ± 1.2 d of age; range of 22 to 29 d), pigs (n = 1,995) were individually weighed upon arrival at the nursery site. Weaning occurred over 6 occasions during a 19-d period (December 1 to December 18, 2008) into 4 consecutive nursery rooms.

For the nursery phase, pigs were placed randomly in pens of 25 (0.32 m^2/pig) at weaning, where they were housed until 72.8 ± 2.4 d post-weaning. Following the nursery phase, the pigs were moved to 4 rooms in a commercial finishing barn (0.67 m^2/pig), where they were individually weighed upon arrival and again at 155.1 ± 3.0 d post-weaning (range of 132 to 163 d post-weaning; 180.2 ± 3.0 d of age, range of 157 to 189 d of age). Throughout the study, each pen was equipped with a self-feeder and an automatic cup waterer to provide *ad libitum* access to feed and water. All pigs received the farm's normal feeding program, which consisted of 10 diet phases designed to meet or exceed the pigs' nutrient requirements based on their BW (NRC, 1998). Pig removals and deaths were recorded throughout the study. At the conclusion of the study, some pigs were missing ear-tags/identification. Therefore, data from 1,736 pigs were available for the evaluation of post-weaning and lifetime performance.

Carcass data was obtained from a subsample of 418 pigs originating from a single finisher room and harvested in a single day (approximately 167 d postweaning, or 192 d of age) at a commercial processor (Triumph Foods, St. Joseph, MO). Although pigs from every category were represented in the carcass data, only pigs weighing between 95 and 150 kg at 155 d post-weaning were used. This resulted in 8 heavy pigs and 23 light pigs that were excluded to avoid weight-based penalties of the processor. The carcass data collected included the HCW, backfat thickness (BF), and longissimus muscle depth (LM) of every individual pig. Dressing percentage was not determined because the processor weighed carcasses and not live pigs. The fat-free lean

index (FFLI; National Pork Producers Council, 2000) of every harvested pig was calculated from the carcass data collected.

Statistical Analysis

The Mixed procedure of SAS (v. 9.2; SAS Institute Inc., Cary, NC) was used to analyze the relationships of sow, litter, and pig characteristics with pig growth data. The Satterthwaite adjustment for degrees of freedom was used in all models. The authors of similar peer-reviewed and published studies have analyzed data and interpreted their results using various methods (Beaulieu et al., 2010; Fix et al., 2010ab). Therefore, analyses of the variables of interest were performed using several methods in our study.

The first method used the categories created and described previously to characterize their relationships with pig performance. Fixed effects used in the categorical analyses were the litter-of-origin total born category and sow parity category, as well as the pig gender, birth weight category, foster status (fostered, 34.2% vs. non-fostered, 65.8%), and the parity category suckled. Significant litter-of-origin total born category × parity category interactions were found for all characteristics of the litter-of-origin. Nevertheless, the main effects are reported in the categorical analyses because the interactions resulted primarily from differences in the magnitude of change of each variable with increasing litter-size category across parities (data not shown). Therefore, covariates were used to analyze the litter-of-origin characteristics of interest when appropriate. For pig growth characteristics, interactions among birth weight category, gender, and foster status were evaluated and included in the categorical models when appropriate, as well as the random effects of birth litter, nursery room, and finisher room. When significant ($P < 0.05$), covariates were utilized for comparisons of interest. Least squares means

were computed for the variables of interest, with differences determined using the TUKEY adjustment for *P*-values.

A second method utilized step-wise regression to model the effects of gender, foster status, litter-of-origin characteristics (total born; dam parity; and litter birth weight standard deviation), birth weight, parity of dam suckled, and appropriate covariates on pre-weaning ADG, weaning weight, wean-to-finish ADG, lifetime ADG, final BW, HCW, BF, LM, and FFLI. The quadratic effects of litter-of-origin total born, dam-of-origin parity, parity of dam suckled, birth weight, and litter birth weight standard deviation (SD) were also tested in the models, as well as the interactions of variables. Additionally, linear and quadratic characteristics of the parity of the dam and the size of the litter-of-origin (as well as their interactions) were evaluated to model their effects on birth weight and litter birth weight SD. The Covtest option and fit statistic (AIC) were used to determine whether the birth litter and/or dam suckled needed to be included as random effect(s) for each model. Final models were developed by removing variables with $P > 0.05$.

The Glimmix procedure of SAS was used with the logit link function to evaluate the binary distributions and estimate the likelihoods of foster status, pre-weaning survival, wean-to-finish survival, and achieving full-value at market (> 98 kg BW at ≈ 180 d of age). This was applied similarly to the Mixed procedures and methods of analyses described above. Least squares means were computed with differences determined using the TUKEY adjustment for *P*-values. The ILINK option was also used to obtain estimates of LSmeans and confidence limits on the inverse linked scale (to obtain means for the percent survival/mortality).

Additionally, a simple correlation analysis (using the CORR procedure of SAS) was also performed with the birth-to-finish data set (1,736 pigs) to provide descriptions of the

relationships of litter size, parity of the birth dam, birth weight, litter birth weight SD, weaning weight, litter-of-origin weaned BW SD, parity of the dam suckled, weaning age, and final BW. For all analyses, differences with a *P*-value of less than 0.05 were considered to be statistically significant.

RESULTS

Effects of Parity of the Dam-of-Origin

Pigs born from third parity sows also originated from litters with the greatest ($P < 0.05$) number of total born and pigs born live (Table 1-1). The litter-of-origin total born for pigs from parity category 4 and 5 sows was greater ($P < 0.05$) than that of pigs from parity 2 sows, and pigs from parity 2 sows had a greater ($P < 0.05$) litter-of-origin total born than pigs from parity 1 sows. Pigs born of parity category 6 to 9 sows originated from litters with a similar, intermediate number of total born as pigs born of parity 1 and 2 sows. The number born live in the litter-of-origin was greater ($P < 0.05$) for pigs from parity category 4 and 5 sows when compared to pigs from parity category 6 to 9 and parity 1 sows. Pigs born of parity 2 sows originated from litters with an intermediate number born live that was also greater ($P < 0.05$) than that of pigs from parity 1 sows. The number of stillborn pigs of the litter-of-origin was greatest ($P < 0.05$) for pigs from parity category 4 and 5 sows when compared to pigs from parity 1 and parity 2 sows, and was intermediate for pigs from parity category 6 to 9 and parity 3 sows.

Birth weight was greatest ($P < 0.05$) for pigs from second parity sows, followed by pigs from parity category 3 and parity category 4 and 5, which were also heavier than ($P < 0.05$) pigs from parity category 6 to 9 and 1, respectively. The litter birth weight SD of pigs increased ($P < 0.05$) with each increase in parity category up to parity 3, and remained greater for pigs from parity categories 4 to 5 and 6 to 9 when compared to parity 1 and 2 sows, despite their

similarities in litter size. This, combined with the reduced mean birth weight of pigs born to parity category 6 to 9 sows, resulted in pigs from parity category 6 to 9 having a greater ($P < 0.05$) likelihood of being cross-fostered (48.3% fostered) compared to pigs from other sow parities (32.6 to 34.3% fostered).

Generally, low birth weight pigs were visually selected from older parity sows by the herdsperson and cross-fostered to younger parity sows, whose largest pigs were then cross-fostered to older parity sows. This was done to obtain litters with similar numbers of uniformly sized pigs, and was believed to reduce the likelihood of large sows crushing low birth weight pigs (Weary et al., 1998). Because a significant number of pigs were cross-fostered in this manner, the mean parity of the dam suckled increased for pigs born to parity 1 and 2 sows, remained essentially the same for pigs from parity 3 sows, and decreased for pigs born to parity categories 4 and 5 and 6 to 9.

Fostering of piglets likely resulted in a greater ($P < 0.05$) number of birth littermates weaned for pigs originating from parity categories with larger litters at birth. Also, fostering resulted in similar numbers of pigs weaned from the dam-of-origin and the dam suckled across parity-of-origin categories, although these numbers were slightly reduced ($P < 0.05$) for pigs from parity 1 and parity category 6 to 9 because they also had a reduced ($P < 0.05$) likelihood of pre-weaning survival. Fostering, however, did not appear to result in any improvements in the SD of BW among birth littermates at weaning. Similar to the differences observed in litter birth weight SD of pigs originating from different parity categories, the litter-of-origin weaned BW SD increased ($P < 0.05$) as the litter-of-origin parity category increased.

Pre-weaning, weaning-to-finish, and lifetime ADG, as well as weaning and final BW, increased numerically as parity category increased to 2, and then decreased ($P < 0.05$) for pigs

from parity categories 4 and 5 and 6 to 9. The post-weaning likelihood of survival was improved ($P < 0.05$) for pigs from parity categories 2 and 3, and was poorest for pigs from parity category 6 to 9. Similarly, the likelihood of surviving pigs achieving full market value at 180 d of age increased ($P < 0.05$) as parity category increased to 3, and then fell to the lowest likelihood for pigs from parity categories 4 and 5 and 6 to 9. There were no differences in the carcass characteristics of pigs originating from the various parity categories.

Interactions of the parity of the dam-of-origin (linear and quadratic) with the size of the litter-of-origin were significant ($P < 0.05$) for modeling birth weight and litter birth weight SD (Table 1-6, Figure 1-1, and Figure 1-2). However, the parity of the dam-of-origin was not significant for modeling the growth, survival, and carcass characteristics of the progeny (Tables 1-6 and 1-7). The parity of the dam-of-origin was correlated ($P < 0.05$) with litter-of-origin weaned BW SD, litter birth weight SD, litter-of-origin total born, and weaning weight ($r = 0.277$, 0.227, 0.054, and 0.050, respectively; Table 1-8).

Effects of Size of the Litter-of-Origin

Sow parity was not different among the 3 litter-of-origin total born categories in this study (Table 1-2). As mandated by the categorical constraints, the number of total born of the dam-of-origin increased ($P < 0.05$) with increasing total born category. The number of pigs born live and stillborn from the litter-of-origin also increased ($P < 0.05$) with increasing total born category.

Birth weight of live born pigs was greatest ($P < 0.05$) for those from total born category $\leq$ 11, followed by pigs from total born category 12 to 14, and was lowest ($P < 0.05$) for pigs from total born category $\geq$ 15. The litter birth weight SD of pigs increased ($P < 0.05$) as total born category increased. Collectively, the number of live pigs relative to the apparently functional

teats per dam-of-origin, the reduced mean birth weight, and the greater litter birth weight SD of pigs from total born category ≥ 15 resulted in these pigs having a greater ($P < 0.05$) likelihood of being cross-fostered compared to pigs from the smaller total born categories. However, a considerable proportion of the pigs originating from smaller litters were also cross-fostered to obtain uniformly sized pigs within each litter.

The fostering practices resulted in a greater ($P < 0.05$) mean parity of the dam suckled for pigs originating from total born category ≤ 11. Fostering likely resulted in a greater ($P < 0.05$) number of birth littermates being weaned for pigs originating from larger litters at birth. A relatively similar numbers of pigs were weaned from the dam-of-origin and the dam suckled across total born categories, although these numbers were slightly reduced ($P < 0.05$) for pigs from total born category ≤ 11. Combined with the reduced ($P < 0.05$) likelihood of pre-weaning survival for pigs from the larger total born categories, fostering may have been responsible for the relative similarity in litter-of-origin weaned BW SD of pigs from the different litter sizes.

Pre-weaning ADG and weaning weight were greatest ($P < 0.05$) for pigs originating from total born category ≤ 11. Weaning-to-finish ADG, lifetime ADG, and final BW were not different among the total born categories, but numerically decreased ($P > 0.10$) as the size of the litter-of-origin increased. The post-weaning likelihood of survival was improved ($P < 0.05$) for pigs from total born categories ≤ 11 and ≥ 15. Similarly, the likelihood of surviving pigs achieving full market value at 180 d of age was improved ($P < 0.05$) for pigs from total born category ≤ 11, and was the lowest for pigs from total born category 12 to 14. There were no differences in the carcass characteristics of pigs originating from the litter size categories.

The size of the litter-of-origin was most effective for modeling birth weight and litter birth weight SD, although interactions with the parity of the dam were also significant ($P < 0.05$,

Table 1-6, Figure 1-1, and Figure 1-2). However, size of the litter-of-origin was not different for modeling the growth, survival, and carcass characteristics of the progeny (Tables 1-6 and 1-7). The size of the litter-of-origin was correlated ($P < 0.05$) with litter birth weight SD, birth weight, weaning weight, litter-of-origin weaned BW SD, final BW, and parity of the dam-of-origin (r = 0.266, -0.257, -0.138, 0.106, -0.079, and 0.054, respectively; Table 1-8).

Effects of Fostering and the Parity of the Dam Suckled

As would be expected, the litter characteristics for non-fostered pigs within each suckled parity group reflected the same differences ($P < 0.05$) across parity groups as observed for the corresponding litter-of-origin parity categories (Table 1-3). The birth weight of non-fostered pigs nursed by parity 1 sows was intermediate, but lighter ($P < 0.05$) than that of non-fostered pigs suckling older parity sows. Pigs fostered onto first parity sows had the lowest ($P < 0.05$) birth weight, and originated from large litters born of older parity sows with the greatest litter birth weight SD. The birth weight of pigs fostered onto parity 2 and 3 sows was intermediate, but lighter ($P < 0.05$) than that of non-fostered pigs nursed by the same sows. Pigs fostered onto parity 2 and 3 sows also originated from large litters with greater ($P < 0.05$) litter birth weight SD. Fostered pigs nursed by parity 4 to 9 sows had a heavier ($P < 0.05$) birth weight than pigs fostered to younger sows, but originated from smaller litters born of younger parity sows with a lower ($P < 0.05$) litter birth weight SD than pigs fostered to first parity sows.

The litter-of-origin weaned BW SD of all fostered pigs was similar to that of non-fostered pigs nursed by parity 4 to 9 sows, but greater ($P < 0.05$) than that of non-fostered pigs nursed by younger sows. The litter-of-origin weaned BW SD of non-fostered pigs nursed by parity 2 and 3 sows was also greater ($P < 0.05$) than that of non-fostered pigs nursed by first parity sows.

There was a parity group suckled × foster status interaction ($P < 0.01$) for the number of birth littermates weaned. This occurred because pigs fostered onto first parity sows, all pigs nursed by parity 2 and 3 sows, and non-fostered pigs of parity 4 to 9 sows had a greater ($P < 0.05$) number of birth littermates weaned than non-fostered pigs of first parity sows; with an intermediate number for pigs fostered onto parity 4 to 9 sows. Despite the interaction, fostered pigs had a greater ($P < 0.01$) number of birth littermates weaned, and pigs nursed by parity 2 and 3 sows had a greater ($P < 0.05$) number of birth littermates weaned than pigs nursed by the other parity groups. Also, pigs nursed by parity 4 to 9 sows had a greater ($P < 0.05$) number of birth littermates weaned than pigs nursed by first parity sows.

Parity group suckled × foster status interactions ($P < 0.01$) were observed for pre-weaning ADG and weaning weight in the categorical analysis. This occurred because pigs fostered to first parity and parity 2 and 3 sows had numerically poorer pre-weaning ADG and weaning weight than the non-fostered pigs in the same parity groups, but the opposite was observed for pigs weaned from parity 4 to 9 sows. Regardless, pre-weaning ADG and weaning weight were increased ($P < 0.01$) for pigs nursed by older parity sows when birth weight category and the litter-of-origin parity category were used as covariates. The parity of the dam suckled was also significant ($P < 0.05$) for modeling pre-weaning ADG and weaning weight, but the interactions were not (Table 1-6 and Figure 1-3).

An increased ($P < 0.01$) likelihood of pre-weaning survival was observed for pigs weaned from parity group 2 and 3 compared to pigs weaned from first parity sows and parity 4 to 9 sows. Although birth weight was used as a covariate in this categorical analysis, other factors associated with birth weight may not be accounted for, such as differences in suckling behavior and nutrient intake. Therefore, the lower birth weight of pigs nursed by first parity sows may

have indirectly contributed to their reduced likelihood of survival. The regression analysis indicated that the interactions ($P < 0.05$) of birth weight, foster status, and gender had a greater effect on the likelihood of pre-weaning survival than the negative quadratic effect of increasing parity of the dam suckled (Figure 1-4). Although the final models of pre-weaning survival also included positive linear and quadratic effects of litter birth weight SD, the differences in the litter birth weight SD between fostered and non-fostered pigs in this study suggest that the litter birth weight SD was a significant component of the birth weight × foster status interaction.

Fostering had no effect on weaning-to-finish ADG, lifetime ADG, and final BW. Although differences in weaning-to-finish ADG were not different among pigs weaned from the different parity groups, lifetime ADG and final BW were greater ($P < 0.05$) for pigs weaned from parity groups 2 and 3 and 4 to 9 compared to pigs weaned from first parity sows. These effects were also apparent in the final regression models, with linear and quadratic ($P < 0.05$) effects of the parity of the dam suckled for lifetime ADG and final BW (Figure 1-5). Carcass characteristics were not influenced by the parity of the dam suckled or foster status (Table 1-7).

A parity group suckled × foster status interaction ($P < 0.01$) was also observed for the likelihood of surviving pigs achieving full market value at ≈180 d of age. This likely occurred because of the indirect effects of the birth weight differences described above. Regardless of the reduced likelihood of fostered pigs weaned from first parity and parity 2 and 3 sows, the likelihood of achieving full market value was most improved ($P < 0.01$) for pigs weaned from parity groups 2 and 3 and 4 to 9. The final model describing the likelihood of achieving full market value included ($P < 0.05$) the interactive effects of birth weight, foster status, and gender, as well as the linear and quadratic effects of the parity of the dam suckled (Figure 1-6).

In the categorical analysis, a parity group suckled × foster status interaction ($P < 0.01$) was observed for the post-weaning likelihood of survival. This occurred because non-fostered pigs nursed by first parity and parity group 2 and 3 sows had a greater ($P < 0.05$) likelihood of post-weaning survival than fostered pigs suckling the same sows, but no differences were observed between non-fostered and fostered pigs suckling parity group 4 to 9 sows. Although birth weight category was used as a covariate, other related factors described previously may be responsible for the reduced likelihood of survival observed for fostered pigs weaned from first parity and parity 2 and 3 sows. Despite the interaction, post-weaning likelihood of survival was improved ($P < 0.05$) for pigs weaned from parity groups 2 and 3 and 4 to 9 compared to pigs weaned from first parity sows. The predominant importance of the parity of the dam suckled (linear, $P < 0.10$) for improving post-weaning survival was evident in the final model.

The parity of the dam suckled was correlated ($P < 0.05$) with weaning weight, birth weight, litter-of-origin weaned BW SD, and litter birth weight SD ($r = 0.329$, 0.236, 0.234, and 0.140, respectively; Table 1-8).

Effects of Birth weight

The parity of the dam-of-origin was not different among the 7 birth weight categories in this study (Table 1-4). However, other differences in the litter-of-origin characteristics were observed. Pigs in the 2 heaviest birth weight categories (1.85 to 2.05 and > 2.05 kg), especially those with a birth weight > 2.05 kg, originated from smaller ($P < 0.05$) litters. As would be expected, pigs in the lightest (< 1.15 kg) and heaviest (1.85 to 2.05 and > 2.05 kg) birth weight categories were from litters with the greatest ($P < 0.05$) litter birth weight SD. Because the farm protocol for fostering was based on forming equally sized litters of uniform pigs, the size of the litter-of-origin and litter birth weight SD of pigs in the lightest birth weight category greatly

reduced ($P < 0.05$) their odds of not becoming fostered. The odds of not becoming a fostered pig were also lower ($P < 0.05$) for the 1.15 to 1.35 kg birth weight category, and then gradually increased as the birth weight category increased. Fostering (and the greater size of the litter-of-origin) likely facilitated the greater number of birth littermates weaned for pigs from the 6 lightest birth weight categories compared to pigs in the heaviest birth weight category, and successfully resulted in a similar number of pigs weaned from both the dam-of-origin and the dam suckled across birth weight categories.

As mandated by the categorical constraints, birth weight increased ($P < 0.05$) with increasing birth weight category. Because the fostering practices resulted in differences ($P < 0.05$) in the mean parity of the dam suckled among the birth weight categories, the parity of the dam suckled and foster status were used as covariates for the analysis of pre-weaning pig performance. The mean parity of the dam suckled was lowest ($P < 0.05$) for pigs in the lightest birth weight category, and was also lower ($P < 0.05$) for pigs in the 1.15 to 1.35 kg birth weight category, compared to heavier categories. Foster status was also used as a covariate for the analysis of post-weaning and lifetime growth performance. Pre-weaning ADG, weaning weight, weaning-to-finish ADG, lifetime ADG, and final BW all increased ($P < 0.05$) with increasing birth weight category. The final regression models also demonstrated the ($P < 0.05$) positive linear and quadratic relationships of birth weight with these growth performance variables (Table 1-6, Figure 1-3, and Figure 1-5).

A birth weight category × gender interaction ($P < 0.05$, data not shown) was observed for the likelihood of pre-weaning survival. At low-birth weights, gilts had a greater likelihood of pre-weaning survival compared to barrows at low-birth weights. However, the likelihood of pre-weaning survival improved ($P < 0.05$) dramatically as birth weight category increased. The

greatest improvement occurred when birth weight category increased ($P < 0.05$) from the lightest category (< 1.15 kg) to the next heaviest category (1.15 to 1.35 kg), and then continued to improve up to the 1.55 to 1.65 kg birth weight category. The final regression models also demonstrate the positive linear and quadratic ($P < 0.05$) relationships of birth weight with pre-weaning survival, as well as the interactions with gender and foster status (Figure 1-4).

Although the effect of birth weight category on the weaning-to-finish likelihood of survival was found to be significant ($P < 0.05$), no clear relationship was evident. The final regression model demonstrated the preeminent trend ($P < 0.10$) for increasing parity of the dam suckled to improve the likelihood of post-weaning survival.

A birth weight category × gender interaction ($P < 0.05$) was observed for the likelihood of surviving pigs to achieve full market value at 180 d of age. This occurred because the likelihood of achieving full market value was greatly reduced ($P < 0.05$) for gilts compared to barrows in the lightest birth weight categories. Despite these differences, the likelihood of achieving full market value improved for both genders as birth weight category increased, but the gender differences were not as apparent in the heaviest birth weight categories. As mentioned earlier, the final model describing the likelihood of achieving full market value included ($P < 0.05$) the interactive effects of birth weight, foster status, and gender, as well as the positive linear and quadratic effects of the parity of the dam suckled (Figure 1-6).

While only 418 of the 1,736 pigs finished in this study were evaluated for carcass characteristics, differences were observed. As expected, HCW was lowest ($P < 0.05$) for pigs in the lightest birth weight category, with gradual improvements associated with increasing birth weight category thereafter. Longissimus muscle depth did not differ among the birth weight categories when HCW was used as a covariate. Birth weight category × gender interactions ($P <$

0.05) were observed for the remaining carcass variables. When HCW was used as a covariate, backfat depth was greatest ($P < 0.05$) for barrows in the lightest birth weight categories, and became similar to that of gilts as birth weight category increased. The differences in backfat depth resulted in reduced ($P < 0.05$) FFLI for barrows in the lightest birth weight categories, but FFLI was similar to that of gilts in the heaviest birth weight categories. The final regression models also demonstrated the significant ($P < 0.05$) positive linear and quadratic relationships of birth weight with HCW; as well as the gender interactions for backfat depth, and FFLI (Table 1-7).

The birth weight was correlated ($P < 0.05$) with weaning weight, final BW, parity of the dam suckled, and litter-of-origin weaned BW SD ($r = 0.601$, 0.443, 0.236, and -0.061, respectively; Table 1-8).

Effects of Pig Gender

Male piglets tended to have a greater ($P < 0.05$) birth weight than gilts (1.57 vs. 1.51 kg, Table 1-5). However, there were no differences in the pre-weaning ADG or weaning BW between barrows and gilts. After weaning, barrows had greater ($P < 0.05$) ADG from weaning-to-finish, which resulted in greater ($P < 0.05$) lifetime ADG and final BW at 180 d of age. Consequently, barrows also had a greater ($P < 0.05$) likelihood of achieving full market value at 180 d of age, and this difference was increasingly evident with decreasing birth weight (as described earlier, gender × birth weight category, Table 1-4). The significance of the relationship of gender with these measures of growth performance was also demonstrated in the regression analyses (Table 1-6, Figure 1-5, and Figure 1-6).

As expected, barrows had greater ($P < 0.05$) HCW and BF, and reduced FFLI compared to gilts. When HCW was used as a covariate, LM of barrows was less ($P < 0.05$) than that of gilts, and the differences in BF and FFLI remained.

Despite having a slightly lower mean birth weight, gilts had a greater ($P < 0.05$) likelihood of survival (birth weight category × gender, data not shown). Regression analyses also demonstrated the increased likelihood for pre-weaning survival of gilts, as well as the interactive relationships of gender with foster status and birth weight (Table 1-6, Figure 1-4). Gender was not an effective variable for modeling the likelihood of survival post-weaning.

DISCUSSION

In the present study, the litter and pre-weaning pig characteristics associated with parity of the dam-of-origin were consistent with those observed by others. In an analysis of 30 farms over a 52 week period, Rix and Ketchem (2010) reported that the average total born per litter increased from parity 1 to parity 3, and then gradually decreased from parity 4 to parity ≥ 7. With data from 52 sows over 8 consecutive parities, Milligan et al. (2002) reported similar associations in the number of total born and born alive across parity groups (parity 1, 2, 3 to 5, and 6 to 8), as well as the stillborn per litter. The differences and numeric trends that they reported for mean birth and weaning weight, variation in birth and weaning weight, number of littermates weaned, and survival to weaning are also similar to the data reported herein. Damgaard et al. (2003) reported data from 22,521 pigs originating from 2,003 litters born of 1,074 sows and further provided conclusive evidence for these relationships of sow parity with litter characteristics.

There is relatively little information pertaining to differences in the performance of progeny from different parity sows. Larriestra et al. (2002), Moore (2003), Miller et al. (2008),

and Smits and Collins (2009) have reported improved nursery and finisher growth for the progeny of parity ≥ 2 sows compared to the progeny of first parity sows. However, information describing the lifetime performance of pigs from multiple specific parities greater than 2 is lacking. Smith et al. (2007) reported greater BW at weaning (either 15 or 20 d of age) and 42 d post-weaning for pigs born to parity 2, 3, 4, 5, and ≥ 6 sows, compared to first parity sows, regardless of birth weight category (9 categories). Although they utilized cross-fostering to equalize the number of pigs across litters, the effects of the birth dam and the dam suckled were not separated. Carney et al. (2009a) reported that pig BW was greater for the progeny of fourth parity sows compared to first parity sows throughout a 19 d pre-weaning period, and these differences were maintained during the 42 d post-weaning period (Carney et al., 2009b). Although the birth weight of pigs originating from parity 4 and 5 dams was greater than that of pigs born of first parity sows in the current study, subsequent growth performance and BW were similar. Carney et al. (2009a) observed a greater difference in birth weight between progeny of the 2 parity groups, and this is likely due to the similar number of total born and born alive between the parity groups in their study. In the current study, pigs from parity 4 and 5 sows also originated from larger litters than pigs from first parity sows, which likely resulted in a much smaller difference in the birth weight.

Similar to the findings of Miller et al. (2008) and Smits and Collins (2009), the considerable number of pigs fostered in the current study to dams differing in parity from the birth dam provides evidence that the parity of the sow suckled may be more important for subsequent growth than the parity of the birth dam. Miller et al. (2008) identified differences in the passive immunity provided by first-litter gilts and sows, and used fostering to determine that it was the parity of the dam suckled that influenced piglet immune system development. Most

often, differences in performance of progeny from first parity and older parity sows have been attributed to the immature immunological status of gilts and their progeny, as well as the lighter birth weight mentioned previously. Several have reported poorer performance of gilt progeny without consideration for fostering across parities and the associated mothering ability of the dam suckled (Moore, 2003; Smith et al., 2007; and Carney et al., 2009a,b). Based on such observations, some have suggested that large production systems (≥ 10,000 sows) could benefit by segregating farms for gilts and their first parity progeny from those for older sows and their progeny (parity segregation; Moore, 2003). Smaller farms, however, may not find it feasible to practice parity segregation. Also on smaller farms, if fostering is limited to within 24-h of parturition, it may not be possible (or beneficial) to foster across litters born only to dams of the same parity.

In addition to the differences in the immunological development of gilts and the lower birth weight of their first parity progeny, Beyer et al. (2007) and Miller et al. (2008) have also identified differences in the potential milk yield of first parity and older sows. Although piglet BW and litter-size influence the milk yield of sows, inherent differences in the potential milk yield of first parity and older sows may also be responsible for the reduced performance of pigs suckling first parity sows (King et al., 1997; Auldist et al. 1998; Beyer et al., 2007). In the current study, the improved pre-weaning and lifetime performance of pigs suckling older parity sows was evident regardless of the parity of their birth dam, even when adjusted for birth weight, and support the conclusion that the progeny born of gilts do not appear to have an inherent pre- or post-weaning growth or health limitation (Smits and Collins, 2009).

On the farm in the present study, pigs with a low birth weight born of older parity sows were fostered primarily onto first parity sows to reduce pre-weaning mortality associated with

small pigs becoming crushed by older parity sows (Weary et al., 1998; Smits and Collins, 2009). Conversely, pigs with a heavy birth weight were fostered from younger to older sows. The data indicate that this practice should be re-evaluated. The differences in BW and growth of light- and heavy-birth weight pigs within a group may be exacerbated by fostering light pigs to first parity sows and heavier pigs to older sows. To reduce BW variation within a group, pigs with heavy birth weight should likely be fostered to first parity sows, and pigs with low birth weight should likely be fostered to suitable second or third parity sows (Smits and Collins, 2009).

It is particularly important to consider that the greater potential milk yield of older parity sows is also dependent upon their environment, nutritional status, and feed intake during lactation. In the current study, although individual sow BW and lactation feed intake were not recorded; sows were provided *ad libitum* access to feed throughout lactation using individual self-feeders with ≈11 kg feed storage capacity. None of the feeders were permitted to become empty at any time during lactation, and all farrowings and lactations occurred between November 5 and December 18. Miller et al. (2008) reported that the BW of sow progeny was greater than that of gilt progeny out to 10 weeks of age in a winter farrowed replicate (21°C mean ambient temperature), but that there were no differences in BW by 28 d of age in a summer replicate (26°C mean ambient temperature) when adjusted for birth weight. They suggested that the increased summer temperature had greater negative effects on sows than lighter BW gilts, resulting in a greater reduction in the potential milk yield of sows.

Cross-fostering of piglets is common practice on swine farms, with an emphasis on reducing pre-weaning mortality to maintain the economic advantages of increased mean litter-size. Marcatti (1986) reported that pre-weaning mortality of cross-fostered litters was half that of non-fostered litters (6.7 vs. 13.4%). Fostering has successfully reduced pre-weaning mortality

when compared to litters left to suckle their birth dam, primarily because fostered pigs are often placed in litter groups with similar numbers of uniformly-sized pigs. This is particularly important in cases of increased litter-size, where variation (SD or CV) in birth weight within the birth litter is greater and the pigs (especially those with low-birth weight) are subject to greater risk of pre-weaning mortality (English and Bampton, 1982; and Marcatti, 1986). Successful fostering to improve the pre-weaning performance and welfare of pigs generally involves a single fostering event across litters of similar age within the first few days of life. Uniformly-sized litters of not more than 10 pigs are preferred to improve stability in the teat order, and reduce the fighting among pigs and disruption of suckling bouts (Hemsworth et al., 1976; Giroux et al., 2000; and Robert and Martineau, 2001).

Unlike studies where the mortality of fostered pigs was compared to pigs remaining with their intact birth litters, non-fostered pigs with extremely low-birth weight in the current study had a greater likelihood for survival compared to fostered pigs of the same birth weight. One possible explanation for this is that non-fostered pigs with low-birth weight may have been able to access more productive anterior teats after their heavier littermates were fostered off and replaced with lower BW pigs. Several studies have demonstrated a positive, albeit weak, correlation between pre-weaning growth and suckling anterior and middle mammary glands when compared to posterior teats (Fraser and Jones, 1975; Kim et al., 2000; and Miller et al., 2008). Also, pigs with heavier birth weight within a litter are more likely to suckle from the preferred, anterior teats; and Miller et al. (2008) indicated that fostered pigs were more likely to suckle from posterior teats after adjusting for birth weight. These effects, combined with a probable interruption in the intake of colostrum from primarily first parity sows, probably

contributed to the greater survival of non-fostered pigs of low-birth weight compared to fostered pigs with the same birth weight.

The regression analysis indicated that pigs with heavier birth weight obtained a greater benefit in pre-weaning ADG from suckling older parity sows, and that may reflect a greater ability to stimulate milk production as well as suckle from more productive teats. The importance of pig BW, size of the litter nursed, and previous teat productivity for current and future milk yield of sows have been demonstrated (Fraser et al., 1992; King et al., 1997; Auldist et al. 1998). Piglets have usually demonstrated a preference for anterior teats, and underutilized posterior teats are more prone to becoming non-productive in subsequent lactations. Based on the collective observations, Miller et al. (2008) suggested that preferentially fostering heavier pigs might facilitate better development of the posterior udder sections, while providing lighter pigs' access to the higher yielding anterior sections without seriously compromising subsequent milk yield. Also, fostering heavier piglets onto first parity sows might facilitate greater milk production in subsequent parities. Clearly, further research is needed to validate fostering strategies among gilts and sows that may reduce future variation in pig BW while maximizing the productive longevity of sows.

Despite the greater mean birth weight and pre-weaning growth rate of pigs suckling older parity sows in the current study, their likelihood of pre-weaning survival was slightly reduced. Subjective reasons for pre-weaning mortality were recorded, but they were not analyzed. However, it is reasonable to suspect that a reduced likelihood of pre-weaning survival may have occurred from an increased risk of crushing with older sows, some of which may have occurred after the collection of birth weight but before fostering (Weary et al., 1998). As described previously, the reduced likelihood for survival may also have resulted from a reduction

in the number of fully functional teats with older sows, and limited use of 'nurse sows' during the study. After weaning, however, survival tended to be improved for pigs that had suckled from older parity sows. This agrees with the observations reported by Moore (2003), but differs somewhat from the observations of Larriestra et al. (2002). Larriestra et al. (2002) reported that weaning weight and gender were the only factors associated with mortality through 7 wk post-weaning, but they did not record individual BW at birth and the pigs were considerably lighter at weaning (3.6 kg, presumably a younger weaning age). The heavier weaning weight in the current study, coupled with the greater pre-weaning growth of pigs suckling older parity sows and their potential for improved immunological development, probably contributed to the trend for improved post-weaning survival of pigs suckling older sows.

Not surprisingly, increased litter size resulted in reduced mean birth weight. Several have reported this relationship previously, and provide estimated reductions in mean birth weight of 33 g to 59 g for each additional pig born per litter (Quiniou et al., 2002; Knol and Mathur, 2009; and Beaulieu et al., 2010). Modeling of the data indicated parity differences in this estimate, with an estimated reduction of 44 g for each additional pig born to a first parity sow, 38 g for a parity 2 and 7 sow, and 32 – 34 g for a parity 3 to 6 sow. Also, despite the overall decrease in birth weight with increasing litter size, the data indicated that the birth weight of pigs born to parity 2 and 7 sows with a total born of 13, and parity 3 to 5 sows with a total born of 15, was similar to that of pigs born to first parity sows with a total born of 11. Milligan et al. (2002) described similar relationships in litter size and birth weight across parities, and attributed the concomitant increase in litter size and birth weight of parity 2 to 5 sows to greater available uterine space compared to first parity sows. However, mean litter size and birth weight of pigs born to parity 6 to 9 sows in the current study was not different than that of pigs born to first parity sows.

As reported by others, variation in birth weight within the litter-of-origin became greater with increasing litter size (Milligan et al., 2002; Quiniou et al., 2002; Boulot et al., 2008). Using 3 litter size categories similar to those in the current study, Beaulieu et al. (2010) did not observe any differences in BW variation at birth with increasing litter size. However, they excluded pigs with a birth weight ≤ 750 g, and the average parity of sows in their smallest litter size category was considerably greater than that of the medium and large litter size categories (mean parity of 4.0 vs. 3.1 and 3.2, respectively). As demonstrated, and described earlier with considerable evidence, variation in birth weight within a litter also increases in litters born of older parity sows, independent of litter size. The greater variation in birth weight within larger litters generally represents an increase in the number of pigs with a birth weight < 1.0 kg, but also a greater number of pigs with a birth weight ≥ 1.0 and 1.4 kg when compared to litters with ≤ 11 total born (Boulot et al., 2008).

The weaning weight and likelihood of pre-weaning survival reflected the differences in mean birth weight, and were greatest for pigs from the smallest litter category. This agrees with the findings of Milligan et al. (2002) and Beaulieu et al. (2010), although the differences between the medium and large litter categories reported by Milligan et al. (2002) were significantly greater than that observed in the current study. However, the data of Milligan et al. (2002) were derived from non-fostered litters, and the higher pre-weaning mortality associated with large litters having increased BW variation (and more low birth weight pigs) resulted in a relatively similar number of pigs weaned from the large and small litters. The association of increased pre-weaning mortality with greater variation in birth weight within a litter was mentioned previously, but this is primarily caused by the reduced capacity for survival of the low-birth weight pigs in the litter group. Similar to the observations of Beaulieu et al. (2010), fostering likely facilitated a

greater number of birth littermates to be weaned from larger litter sizes in the current study. When pigs were selected for fostering, they were generally either considerably smaller or considerably larger than most of their littermates, and were fostered to form litters of more uniformly sized pigs. Therefore, the greater SD of birth weight of the litter-of-origin that was characteristic of the pigs selected for fostering had little to do with the variation in BW among pigs on the litter that they suckled. Regardless, it appears that the fostering of pigs from litters with a greater SD of birth weight served to improve their likelihood of survival.

Despite the differences in pre-weaning growth of pigs from the small vs. larger litter size categories, there was no apparent effect of litter size category on subsequent or lifetime growth performance and carcass characteristics. This is in agreement with the findings of Bérard et al. (2008) and Beaulieu et al. (2010). However, there was a negative (albeit weak) correlation of final BW with increasing number of total born in the current study. Fostering and the greater pre-weaning mortality of primarily low birth weight pigs from large litters are likely responsible for the lack of differences in final BW among the litter size categories, as well as the weak correlation of final BW with litter size. Nevertheless, more pigs were weaned from larger litters, and the lack of an appreciable difference in mortality from weaning-to-finish indicates that the largest litter size category produced ≈ 56% more pigs finished of full value when compared to the smallest litter size category.

Recently, Schinckel et al. (2010a) used a stochastic model to demonstrate the effects of litter size and parity of the dam on pig performance and profitability. They simulated growth of 5,000 barrows and 5,000 gilts for each parity (1 thru 6) × litter size (6 to 14 total born) combination without the utilization of fostering, and repeated the simulation for pigs fostered within parity category (parities 1, 2, and > 2) to obtain 11 pigs nursed for litter sizes of 6 to 20

total born. A comparison of the 2 simulations underscored the benefits of fostering to equalize litters when litter size is increased. However, even with fostering, their modeled reduction of approximately 0.39 kg in BW at 150 d of age for every additional pig born (from 6 – 16 total born) is very similar to the numeric differences we observed in final BW (180 d of age) between the 3 total born categories. While the economic benefits of increased litter size have not been disputed, the evidence suggests that technologies and management practices to improve survival and growth of pigs from large litters are worthy of continued investigation.

Whether analyzed categorically (Powell and Aberle, 1980; Smith et al., 2007; Beaulieu et al., 2010) or as a continuous trait (Klindt, 2003; Schinckel et al., 2007, 2010b), numerous others have also demonstrated the significant relationship of birth weight with subsequent growth rate and BW of growing-finishing pigs at various ages. The data overwhelming indicate that incremental increases in pig birth weight at lighter BWs resulted in greater increases in growth rate and BW at weaning and 180 d of age than incremental increases in birth weight at heavier BWs.

The continued disparity in postnatal growth and development of pigs differing significantly in birth weight is not surprising. Pigs with low birth weight are less developed, having a lower fixed number of myofibers at birth (Wigmore and Stickland, 1983; Gondret et al., 2005; and Bérard et al., 2010). There is also evidence for other potentially permanent differences in the development of low birth weight pigs, such as immature intestinal development at birth and disproportionately smaller internal organs (Ashworth et al., 2001; and D'Inca et al., 2010). Asymmetrical organ weights have been observed in low birth weight pigs, and the levels of some important regulatory hormones and growth factors may be reduced in pigs with low birth weight. The severity or potential permanence of immature development is likely exacerbated by

postnatal factors that restrict the intake of nutrients and important bioactive components found in colostrum and milk (e.g., immunoglobulins and growth factors; Morise et al., 2008). Because pigs are precocial and polytocous, underdeveloped pigs are abruptly required to compete with littermates postpartum for nutrients and passive antibodies from the sow. Therefore, low birth weight pigs are subject to greater risk of becoming crushed by the sow, starvation, hypothermia (> surface:body volume ratio of smaller pigs), and disease; particularly during the first 3 d of life (Shankar et al., 2009).

The influence of birth weight on measures of lean characteristics has also received considerable attention. Differences in experimental design, as well as measurements and methods of data collection, have resulted in various interpretations of this relationship. As suggested by Fix et al. (2010a), the effects of birth weight (and interpretation of the results) appear to be dependent upon the feeding practices (restricted vs. *ad libitum*) and whether comparisons were performed at a common age or a common BW. Although carcass data was obtained from a subset of pigs in the current study, the results are generally similar to larger sets of data obtained with *ad libitum* feeding (Matthews et al., 2009; Fix et al., 2010a; and Schinckel et al., 2010).

In conclusion, these data provide further evidence of the fundamental importance of birth weight for subsequent growth and survival of pigs on a commercial farm. Although mean birth weight decreased with increasing litter size, greater litter size and birth weight were observed for pigs from parity 2 to 5 sows compared to parity 1 and parity 6 to 9 sows. Variation in birth weight within the litter-of-origin increased with litter size and parity of the birth dam. The parity of the sow suckled was more important for growth and survival than the parity of the birth dam. Pre-weaning and lifetime growth performance of pigs suckling parity 2 and older sows was

improved, and was more important for overall growth in this study than weaning age (when the mean = 25 d, with a range of 22 to 29 d). However, crushing and/or starvation due to a shortage of fully functional teats may have resulted in greater pre-weaning mortality of pigs suckling parity 4 to 9 sows. Despite relatively permanent differences in the growth and development of pigs born lighter at birth, further research is needed to improve the implementation and success of techniques (e.g., fostering, management of colostrum intake, creep feeding, and milk supplementation) that may improve the performance and management of low BW pigs on commercial farms. Genetic selection for greater birth weight, pre-weaning survival, and growth rate is possible (Knol et al., 2002; Canario et al., 2010; Roehe et al., 2010); but further emphasis on management, genetics, and nutrition is also needed to improve the fitness of sows for reproductive longevity.

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Table 1-1. The association of the dam-of-origin parity category with the litter-of-origin characteristics, pig performance and carcass characteristics

	Sow Parity category for litter-of-origin					
Item	1	2	3	4-5	6-9	SE
Pre-weaning performance (2,171 pigs)						
n	569	383	411	535	273	
Parity[1]	1.0[a]	2.0[b]	3.0[c]	4.4[d]	7.1[e]	0.03
Total born/litter	12.2[a]	12.8[b]	14.2[d]	13.5[c]	12.6[ab]	0.24
Live born/litter	11.2[a]	11.9[bc]	13.1[d]	12.2[c]	11.5[ab]	0.22
Stillborn/litter	1.0[a]	0.9[a]	1.1[ab]	1.3[b]	1.2[ab]	0.10
SD of birth BW, kg	0.24[a]	0.28[b]	0.30[c]	0.31[c]	0.30[c]	0.007
Birth littermates weaned[2]	10.6[a]	11.2[b]	12.4[d]	11.9[c]	10.4[a]	0.24
SD of weaning BW (birth littermates), kg[2,3]	1.24[a]	1.36[b]	1.36[b]	1.47[c]	1.60[d]	0.040
Total weaned from dam-of-origin[2]	9.9[b]	10.3[c]	10.4[c]	10.1[bc]	8.9[a]	0.15
Birth BW, kg	1.47[a]	1.69[c]	1.54[b]	1.54[b]	1.47[ab]	0.030
Fostered, %	33.3	34.3	33.4	32.6	48.3	
Odds ratio for non-fostered	0.70[bc]	0.65[b]	0.69[bc]	0.73[c]	0.08[a]	0.039
Parity of dam suckled	1.9[a]	2.6[b]	3.0[c]	3.8[d]	4.9[e]	0.14
Total weaned from dam suckled[2]	9.9[ab]	10.3[c]	10.4[c]	10.1[bc]	9.6[a]	0.15
Pre-weaning ADG, g[2,3,4]	232[bc]	245[c]	243[bc]	225[ab]	213[a]	8.0
Weaned BW, kg[2,3,4]	7.40[bc]	7.90[c]	7.68[bc]	7.16[ab]	6.75[a]	0.236
Pre-weaning mortality, %	10.6	5.7	8.4	8.4	13.1	
Odds ratio for survival[3]	2.13[b]	2.80[d]	2.40[c]	2.39[c]	1.90[a]	0.072
Post-weaning and Lifetime performance (1,713 pigs)						
n	444	315	327	420	207	
Weaning-to-finish ADG, g[2,3,5]	721[ab]	745[b]	726[ab]	712[a]	695[a]	13.4
Lifetime ADG, g[2,3,5]	653[ab]	675[b]	660[ab]	645[a]	628[a]	12.2
Final BW, kg[2,3,5]	119.3[ab]	123.6[b]	120.6[ab]	117.8[a]	114.5[a]	2.22
Weaning-to-finish mortality, %	3.5	2.0	2.4	3.3	5.6	
Odds ratio for survival[3]	3.32[b]	3.89[c]	3.70[c]	3.39[b]	2.83[a]	0.099
Weaning-to-finish culls & <98 kg final BW, %	7.9	6.5	5.4	9.2	10.7	
Odds ratio for full-value market[2,3,5]	2.46[b]	2.67[c]	2.87[d]	2.29[a]	2.13[a]	0.072
Carcass data (418 pigs)						
n	116	87	56	120	39	
HCW, kg[3,5]	93.4	97.0	93.6	94.7	91.5	2.91
Backfat depth, mm[3,5]	17.7	19.2	16.8	18.6	18.0	1.59
Longissimus muscle depth, mm[3,5]	57.0	57.8	56.4	57.6	54.6	1.86
FFLI (fat-free lean index)[3,5]	52.0	51.0	52.5	51.6	51.8	1.09

[1] Means with different superscripts differ ($P < 0.05$).
[2] Age at weaning as a covariate.
[3] Parity suckled as a covariate.
[4] Total born category for litter-of-origin as a covariate.
[5] Days from weaning until determination of final BW as a covariate.

Table 1-2. The association of the litter-of-origin total born category with the litter-of-origin characteristics, pig performance and carcass characteristics

	Total Born category for litter-of-origin, no. per litter			
Item	≤11	12-14	≥15	SE
Pre-weaning performance (2,204 pigs)				
n	644	903	657	
Parity	3.2	3.0	3.3	0.11
Total born/litter[1]	9.3[a]	12.8[b]	16.4[c]	0.07
Live born/litter[1]	8.5[a]	11.7[b]	14.4[c]	0.09
Stillborn/litter[1]	0.8[a]	1.1[b]	1.9[c]	0.07
SD of birth BW, kg[1]	0.29[a]	0.31[b]	0.33[c]	0.005
Birth littermates weaned[1,2]	8.5[a]	11.4[b]	13.6[c]	0.12
SD of weaning BW (birth littermates), kg[1,2,3]	1.36	1.39	1.37	0.027
Total weaned from dam-of-origin[1,2]	9.9[a]	10.1[ab]	10.2[b]	0.11
Birth BW, kg[1]	1.63[c]	1.47[b]	1.41[a]	0.021
Fostered, %	35.4	31.7	40.3	
Odds ratio for non-fostered	0.60[b]	0.77[c]	0.40[a]	0.027
Parity of dam suckled	3.3[b]	2.9[a]	3.0[ab]	0.11
Total weaned from dam suckled[1,2]	10.0[a]	10.5[b]	10.4[b]	0.11
Pre-weaning ADG, g[1,2,3]	242[b]	229[a]	230[ab]	5.6
Weaned BW, kg[1,2,3]	7.71[b]	7.27[a]	7.23[a]	0.166
Pre-weaning mortality, %	7.2	10.8	11.0	
Odds ratio for survival[1,3,4]	2.55[b]	2.11[a]	2.09[a]	0.052
Post-weaning and Lifetime performance (1,713 pigs)				
n	518	678	517	
Weaning-to-finish ADG, g[2,3,5]	727	720	712	9.4
Lifetime ADG, g[2,3,5]	659	651	645	8.6
Final BW, kg[2,3,5]	120.6	119.0	117.7	1.57
Weaning-to-finish mortality, %	3.0	3.5	2.9	
Odds ratio for survival[3]	3.49[b]	3.31[a]	3.51[b]	0.069
Weaning-to-finish culls & <98 kg final BW, %	5.4	9.6	7.9	
Odds ratio for full-value market[2,3,5]	2.86[c]	2.25[a]	2.45[b]	0.049
Carcass data (418 pigs)				
n	120	219	79	
HCW, kg[2,5]	96.8	92.9	94.3	2.11
Backfat depth, mm[2,5]	18.1	18.4	17.5	1.20
Longissimus muscle depth, mm[2,5]	57.4	57.1	56.2	1.37
FFLI (fat-free lean index)[2,5]	51.7	51.7	52.2	0.82

[1] Parity category of dam-of-origin as a covariate. Means with different superscripts differ ($P < 0.05$).
[2] Age at weaning as a covariate.
[3] Parity suckled as a covariate.
[4] Foster status as a covariate.
[5] Days from weaning until determination of final BW as a covariate.

Table 1-3. The association of the parity category of the dam suckled and foster status with the litter-of-origin characteristics, pig performance and carcass characteristics

Parity Group suckled:	1		2 – 3		4 – 9			*P*<		
Item / Fostered:	No	Yes	No	Yes	No	Yes	SE	Parity suckled × Foster	Parity suckled	Foster
Pre-weaning performance (2,134 pigs)										
n	373	257	520	241	487	256				
Litter-of-origin										
Parity[1]	1.0[a]	3.9[d]	2.5[b]	3.3[c]	5.1[e]	2.8[b]	0.13	0.02	0.01	0.01
Total born/litter	12.0[a]	13.6[b]	13.4[b]	13.7[b]	13.2[b]	12.2[a]	0.27	0.01	0.01	0.01
Live born/litter	11.2[a]	12.4[b]	12.3[b]	12.4[b]	12.0[b]	11.4[a]	0.25	0.01	0.01	0.01
Stillborn/litter	0.9[ab]	1.2[c]	1.1[bc]	1.3[c]	1.2[c]	0.8[a]	0.11	---	---	0.01
SD of birth BW, kg	0.23[a]	0.32[d]	0.28[b]	0.30[cd]	0.30[c]	0.29[bc]	0.007	---	---	0.01
Birth littermates weaned[2]	10.6[a]	11.6[b]	11.6[b]	11.8[b]	11.5[b]	11.0[ab]	0.27	0.01	0.01	0.01
SD of weaning BW (birth littermates), kg[2,3,4,5]	1.05[a]	1.60[c]	1.29[b]	1.50[c]	1.51[c]	1.53[c]	0.042	---	---	0.01
Total weaned from dam-of-origin[2]	10.2[b]	9.7[bc]	10.7[d]	9.0[a]	10.0[bc]	9.6[b]	0.18	0.01	0.01	0.01
Birth BW, kg	1.46[b]	1.22[a]	1.65[c]	1.43[b]	1.66[c]	1.63[c]	0.032	0.01	0.01	0.01
Parity of dam suckled	1.0[a]	1.0[a]	2.5[b]	2.5[b]	5.1[c]	5.6[d]	0.08	0.01	0.01	0.01
Total weaned from dam suckled[2]	10.2[b]	9.5[a]	10.7[c]	10.1[b]	9.9[b]	9.3[a]	0.17	---	---	0.01
Pre-weaning ADG, g[2,3,5]	211[a]	202[a]	255[b]	246[b]	252[b]	260[b]	6.7	0.01	0.01	0.02
Weaned BW, kg[2,3,5]	6.90[a]	6.65[a]	8.04[b]	7.79[b]	7.92[b]	8.15[b]	0.170	0.01	0.01	0.02
Pre-weaning mortality, %	11.8	13.9	8.1	8.1	14.0	10.7				
Odds ratio for survival[3,5]	2.01[ab]	1.82[a]	2.44[c]	2.44[c]	1.82[a]	2.12[b]	0.097	---	0.01	---
Post-weaning and Lifetime performance (1,695 pigs)										
n	284	172	429	197	403	210				
Weaning-to-finish ADG, g[2,5,6]	721	708	732	730	723	724	10.3	---	---	---
Lifetime ADG, g[2,5,6]	650[ab]	637[a]	664[b]	661[ab]	657[ab]	658[ab]	9.1	---	0.03	---
Final BW, kg[2,5,6]	118.9[ab]	116.5[a]	121.5[b]	120.9[ab]	120.0[ab]	120.4[ab]	1.63	---	0.03	---
Weaning-to-finish mortality, %	1.1	1.6	0.6	0.8	0.6	0.5				
Odds ratio for survival[5]	4.58[b]	4.12[a]	5.20[c]	4.83[b]	5.15[c]	5.30[c]	0.111	0.01	0.01	0.01
Weaning-to-finish culls & <98 kg final BW, %	9.0	11.5	4.8	5.7	4.6	4.3				
Odds ratio for full-value market[2,5,6]	2.32[b]	2.04[a]	2.99[cd]	2.81[c]	3.03[d]	3.10[d]	0.082	0.01	0.01	0.01
Carcass data (413 pigs)										
n	76	27	99	49	108	54				
HCW, kg[2,5,6]	93.6	93.1	95.2	98.4	93.9	92.9	2.60	---	---	---
Backfat depth, mm[2,5,6]	17.8	19.1	18.2	18.5	18.1	17.5	1.31	---	---	---
Longissimus muscle depth, mm[2,5,6]	56.5	55.6	57.5	58.9	56.7	56.6	1.88	---	---	---
FFLI (fat-free lean index)[2,5,6]	52.0	51.0	51.8	51.7	51.7	52.1	0.85	---	---	---

[1] Means with different superscripts differ ($P < 0.05$).
[2] Age at weaning as a covariate.
[3] Parity category of the dam-of-origin as a covariate.
[4] Total born category for litter-of-origin as a covariate.
[5] Birth BW category as a covariate.
[6] Days from weaning until determination of final BW as a covariate.

Table 1-4. The association of birth weight category with the litter-of-origin characteristics, pig performance and carcass characteristics

	Birth BW category, kg							
Item	< 1.15	1.15 to 1.35	1.40 to 1.50	1.55 to 1.65	1.70 to 1.80	1.85 to 2.05	> 2.05	SE
Pre-weaning performance (2,204 pigs)								
n	359	365	315	331	288	288	258	
Litter-of-origin								
Parity	3.3	3.1	3.1	3.0	3.1	3.4	3.0	0.17
Total born/litter[1]	13.7^{c}	13.4^{c}	13.4^{c}	13.4^{c}	13.4^{c}	12.6^{b}	10.7^{a}	0.26
Live born/litter	12.6^{c}	12.2^{c}	12.2^{c}	12.3^{c}	12.2^{bc}	11.6^{b}	10.1^{a}	0.24
Stillborn/litter	1.2^{b}	1.2^{b}	1.1^{b}	1.1^{b}	1.1^{b}	1.1^{b}	0.6^{a}	0.11
SD of birth BW, kg	0.30^{c}	0.26^{a}	0.26^{a}	0.28^{ab}	0.28^{b}	0.30^{c}	0.30^{bc}	0.008
Birth littermates weaned[2]	11.7^{bc}	11.6^{bc}	11.5^{bc}	11.9^{c}	11.6^{bc}	11.1^{b}	9.7^{a}	0.25
SD of weaning BW (birth littermates), kg[1,2]	1.57^{b}	1.39^{a}	1.32^{a}	1.32^{a}	1.32^{a}	1.40^{a}	1.37^{a}	0.042
Total weaned from dam-of-origin[2]	9.8	10.0	10.1	10.1	10.1	10.0	9.9	0.17
Birth BW, kg	0.97^{a}	1.28^{b}	1.46^{c}	1.59^{d}	1.72^{e}	1.89^{f}	2.16^{g}	0.009
Fostered, %	56.2	42.4	31.1	30.4	29.9	27.1	23.1	
Odds ratio for non-fostered	-0.25^{a}	0.31^{b}	0.80^{c}	0.83^{c}	0.85^{c}	0.99^{d}	1.21^{e}	0.048
Parity of dam suckled	1.7^{a}	2.6^{b}	3.3^{c}	3.4^{c}	3.5^{c}	3.5^{c}	3.6^{c}	0.17
Total weaned from dam suckled[2]	9.9	10.1	9.8	10.2	10.3	10.1	10.1	0.16
Pre-weaning ADG, g[2,3]	192^{a}	223^{b}	225^{b}	234^{bc}	240^{c}	256^{d}	265^{d}	5.0
Weaned BW, kg[2,3]	5.82^{a}	6.89^{b}	7.11^{b}	7.47^{c}	7.75^{c}	8.33^{d}	8.84^{e}	0.128
Pre-weaning mortality, %	21.8	10.6	8.6	4.0	5.6	3.9	5.3	
Odds ratio for survival[2]	1.28^{a}	2.14^{b}	2.37^{c}	3.18^{e}	2.82^{d}	3.20^{e}	2.89^{d}	0.099
Post-weaning and Lifetime performance (1,734 pigs)								
n	231	273	246	287	236	248	213	
Weaning-to-finish ADG, g[3,4,5]	638^{a}	680^{b}	702^{bc}	718^{c}	735^{cd}	751de	763^{e}	9.1
Lifetime ADG, g[3,4,5]	573^{a}	615^{b}	635^{bc}	650^{cd}	665de	681^{ef}	693^{f}	8.0
Final BW, kg[3,4,5]	104.4^{a}	112.2^{b}	115.9^{c}	118.8^{c}	121.7^{cd}	124.7^{de}	127.3^{e}	1.44
Weaning-to-finish mortality, %	3.5	3.7	2.9	4.9	3.4	3.2	2.8	
Odds ratio for survival	3.33^{b}	3.27^{b}	3.53^{b}	2.97^{a}	3.35^{b}	3.40^{b}	3.54^{b}	0.105
Gender[6]	G B	G B	G B	G B	G B	G B	G B	
Weaning-to-finish culls & <98 kg final BW, %	32.9 7.3	15.3 6.8	5.1 5.0	11.8 3.3	1.8 4.0	3.0 1.7	1.9 2.7	
Odds ratio for full-value market[3,5]	0.71^{a} 2.54^{b}	1.71^{b} 2.61^{bd}	2.92^{df} 2.94^{df}	2.01^{e} 3.39^{g}	4.02^{hi} 3.19^{fg}	3.47^{g} 4.07^{hi}	4.74^{i} 3.57^{gh}	0.222
Carcass data (418 pigs)								
n	58	68	62	60	55	59	56	
HCW, kg[3,5]	86.3^{a}	92.3^{b}	94.4^{bc}	96.5^{bc}	95.4^{bc}	96.8^{bc}	99.6^{c}	1.95
Gender	G B	G B	G B	G B	G B	G B	G B	
Backfat depth, mm[3,5,7]	18.1^{ab} 21.5^{c}	17.4^{a} 21.2^{c}	16.9^{a} 21.1^{bc}	16.6^{a} 19.8^{bc}	17.0^{a} 18.0^{ab}	16.9^{a} 18.3^{ab}	16.8^{a} 17.6^{a}	1.04
Longissimus muscle depth, mm[3,5,7]	59.0 56.1	58.1 55.9	59.1 55.2	58.0 55.8	59.9 56.2	57.6 54.9	58.0 55.3	1.73
FFLI (fat-free lean index)[3,5,7]	52.1^{cd} 49.5^{a}	52.2^{d} 49.7^{ab}	52.5^{d} 49.7^{ab}	52.7^{d} 50.7^{b}	52.7^{d} 51.8^{d}	52.5^{d} 51.6^{bcd}	52.8^{d} 52.1^{d}	0.67

[1] Means with different superscripts differ ($P < 0.05$).
[2] Parity of dam suckled as a covariate.
[3] Age at weaning as a covariate.
[4] Foster status as a covariate.
[5] Days from weaning until determination of final BW as a covariate.
[6] Birth BW category × Gender interaction ($P < 0.01$), G = gilts and B = barrows.
[7] HCW as a covariate.

Table 1-5. The effect of gender on pig performance and carcass characteristics.

	Gender		
Item	Barrow	Gilt	SE
Pre-weaning performance (2,204 pigs)			
n	1,092	1,112	
Birth BW, kg[1]	1.57[b]	1.51[a]	0.017
Fostered, %	35.6	35.0	
Odds ratio for non-fostered	0.59	0.62	0.021
Pre-weaning ADG, g[2]	235	233	2.5
Weaned BW, kg[2]	7.51	7.39	0.069
Pre-weaning mortality, %	9.6	8.3	
Odds ratio for survival	2.25[a]	2.41[b]	0.036
Post-weaning and Lifetime performance (1,736 pigs)			
n	843	893	
Weaning-to-finish ADG, g[2,3]	757[b]	688[a]	4.2
Lifetime ADG, g[2,3]	684[b]	625[a]	3.7
Final BW, kg[2,3]	125.1[b]	114.2[a]	0.68
Weaning-to-finish mortality, %	2.0	1.5	
Odds ratio for survival	3.89[a]	4.19[b]	0.059
Weaning-to-finish culls & < 98 kg final BW, %	4.9	11.3	
Odds ratio for full-value market[2,3]	2.96[b]	2.06[a]	0.037
Carcass data (418 pigs)			
n	202	216	
HCW, kg[2,3]	97.5[b]	91.3[a]	0.96
Backfat depth, mm[2,3,4]	19.7[b]	17.0[a]	0.36
Longissimus muscle depth, mm[2,3,4]	55.6[a]	58.5[b]	0.61
FFLI (fat-free lean index) [2,3,4]	50.7[a]	52.5[b]	0.23

[1] Birth BW of male piglets was obtained prior to the farms normal castration procedures performed within the first 7 d post-partum. Means with different superscripts differ ($P < 0.05$).
[2] Age at weaning as a covariate.
[3] Days from weaning until determination of final BW as a covariate.
[4] HCW as a covariate.

Table 1-6. Modeled relationships of birth weight and growth performance responses with effective variables

Pig variable of interest	Modeled relationship with effective variables of interest	Fit Statistic[1]
Birth BW, kg	2.054 – 0.052*total born + 0.009*(total born*parity) – 0.001*(total born*parity^2)	AIC = 1,277.8
SD of Birth weight within litter-of-origin	0.1104 + 0.01451*total born – 0.00043*total born^2 + 0.002082*(total born*parity) – 0.00001*(total born^2*parity^2)	AIC = -4,626.7
Pre-weaning ADG, g	12.38 + 179.61*birth weight (kg) – 39.22*birth weight^2 + 21.38*parity suckled – 3.93*parity suckled^2 + 1.28*(birth weight*parity suckled^2)	AIC = 20,306.8
Weaning BW, kg	-4.79 + 5.54*birth weight (kg) – birth weight^2 + 0.54*parity suckled – 0.10*parity suckled^2 + 0.03*(birth weight*parity suckled^2) + 0.20*wean age	AIC = 6,037.7
Pre-weaning likelihood of survival		Gen. X^2 = 1,423.4
non-fostered barrow	-4.51 + 6.22*birth weight (kg) – 1.57*birth weight^2 – 0.02*parity suckled^2 + 12.01*Litter birth weight SD – 4.45*Litter birth weight SD^2	
non-fostered gilt	-4.51 + 6.52*birth weight (kg) – 1.57*birth weight^2 – 0.02*parity suckled^2 + 12.01*Litter birth weight SD – 4.45*Litter birth weight SD^2	
fostered barrow	-6.12 + 7.60*birth weight (kg) – 1.57*birth weight^2 – 0.02*parity suckled^2 + 12.01*Litter birth weight SD – 4.45*Litter birth weight SD^2	
fostered gilt	-6.12 + 7.72*birth weight (kg) – 1.57*birth weight^2 – 0.02*parity suckled^2 + 12.01*Litter birth weight SD – 4.45*Litter birth weight SD^2	
Wean-to-Finish ADG, g		AIC = 19,020.7
barrow	-420.24 + 268.55*birth weight (kg) – 51.88*birth weight^2 + 11.29*wean age (d) + 3.91*wean-to-finish d	
gilt	-482.86 + 268.55*birth weight (kg) – 51.88*birth weight^2 + 11.29*wean age (d) + 3.91*wean-to-finish d	
Lifetime ADG, g		AIC = 18,584.3
barrow	-322.19 + 242.49*birth weight (kg) – 45.97*birth weight^2 + 11.28*parity suckled – 1.28*parity suckled^2 + 6.95*wean age (d) + 3.57*wean-to-finish d	
gilt	-375.94 + 242.49*birth weight (kg) – 45.97*birth weight^2 + 11.28*parity suckled – 1.28*parity suckled^2 + 6.95*wean age (d) + 3.57*wean-to-finish d	
Final BW, kg		AIC = 12,990.7
barrow	-168.25 + 44.67*birth weight (kg) – 8.28*birth weight^2 + 2.02*parity suckled – 0.228*parity suckled^2 + 1.88*wean age (d) +1.25*wean-to-finish d	
gilt	-177.96 + 44.67*birth weight (kg) – 8.28*birth weight^2 + 2.02*parity suckled – 0.228*parity suckled^2 + 1.88*wean age (d) +1.25*wean-to-finish d	
Wean-to-Finish likelihood of survival	2.97 + 0.13*parity suckled (P < 0.10)	Gen. X^2 = 1,565.3
Likelihood of achieving full value market, > 98 kg		Gen. X^2 = 1,434.5
non-fostered barrow	-43.78 + 3.01*birth weight (kg) + 0.53*parity suckled – 0.06*parity suckled^2 + 0.37*wean age (d) + 0.21*wean-to-finish d	
non-fostered gilt	-43.78 + 2.36*birth weight (kg) + 0.53*parity suckled – 0.06*parity suckled^2 + 0.37*wean age (d) + 0.21*wean-to-finish d	
fostered barrow	-43.78 + 2.69*birth weight (kg) + 0.53*parity suckled – 0.06*parity suckled^2 + 0.37*wean age (d) + 0.21*wean-to-finish d	
fostered gilt	-43.78 + 2.46*birth weight (kg) + 0.53*parity suckled – 0.06*parity suckled^2 + 0.37*wean age (d) + 0.21*wean-to-finish d	

[1] AIC = Akaike's information criterion for Mixed models. Gen. X^2 = Generalized Chi-squared for Glimmix models of odds ratios.

Table 1-7. Modeled relationships of carcass characteristics with effective variables

Carcass characteristic of interest	Modeled relationship with effective variables of interest	Fit Statistic, AIC[1]
HCW, kg		2,998.0
barrow	65.80 + 31.03*birth weight (kg) – 6.52*birth weight^2	
gilt	59.51 + 31.03*birth weight (kg) – 6.52*birth weight^2	
Backfat depth, mm		2,237.2
barrow	-0.40 – 4.27*birth weight (kg) + 0.35*wean age (d) + 0.19*HCW	
gilt	-7.74 – 1.27*birth weight (kg) + 0.35*wean age (d) + 0.19*HCW	
Longissimus muscle depth, mm		2,650.9
barrow	42.85 – 0.90*wean age (d) + 0.37*HCW (kg)	
gilt	45.72 – 0.90*wean age (d) + 0.37*HCW (kg)	
FFLI (fat-free lean index)		-1,853.7
barrow	62.95 + 2.74*birth weight (kg)– 0.29*wean age (d) – 0.10*HCW	
gilt	68.00 + 0.67*birth weight (kg)– 0.29*wean age (d) – 0.10*HCW	

[1] AIC = Akaike's information criterion.

Table 1-8. Correlation coefficients for sow, litter, and pig characteristics of the pigs finished (n = 1,736)

	Parity-of-origin	Birth weight	Litter BW SD (birth)	Weaned BW	Litter BW SD (weaning)	Parity Suckled	Wean Age	Final BW
Total Born[1]	***0.054***	***-0.257***	***0.266***	***-0.138***	***0.106***	-0.017	***0.102***	***-0.079***
Parity-of-origin		-0.032	***0.227***	***0.050***	***0.277***	***0.502***	***-0.067***	0.007
Birth weight			0.046	***0.601***	***-0.061***	***0.236***	-0.041	***0.443***
Litter BW SD (birth)				0.008	***0.452***	***0.140***	***0.099***	-0.021
Weaned BW					0.040	***0.329***	***0.149***	***0.437***
Litter BW SD (weaning)						***0.234***	***0.112***	-0.020
Parity Suckled							-0.036	***0.138***
Wean Age								***0.062***

[1] Numbers italicized in bold are significant at $P < 0.05$.

Figure 1-1. Effects of litter size and parity on mean birth weight. Derived using the model in Table 1-6.

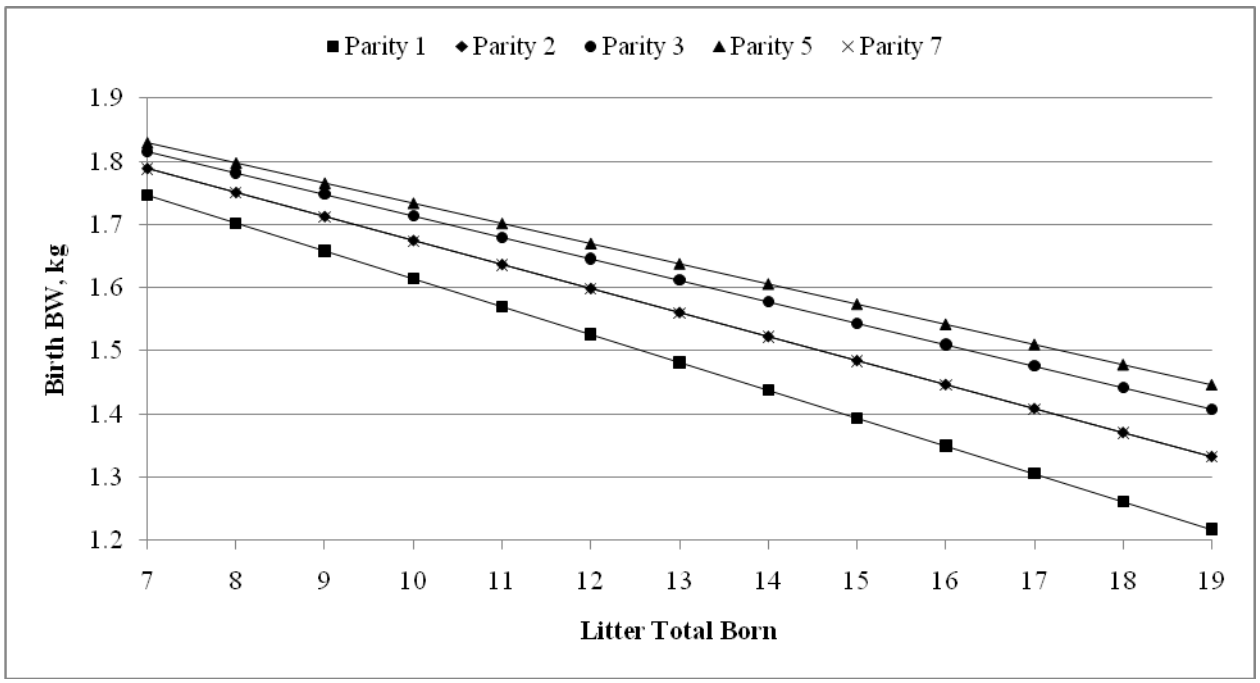


Figure 1-2. Effects of litter size and parity on the SD of birth weight within the litter-of-origin. Derived using the model in Table 1-6.

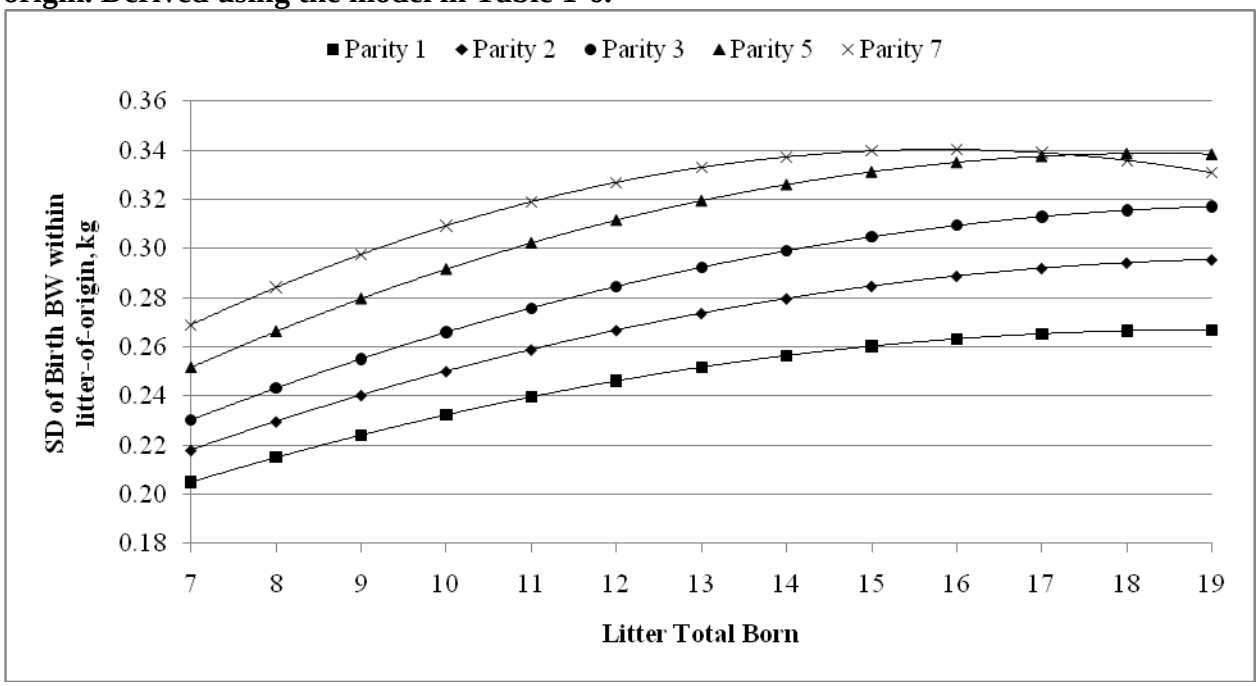


Figure 1-3. Effects of pig birth weight and the parity of the dam suckled on pre-weaning ADG. Derived using the model in Table 1-6.

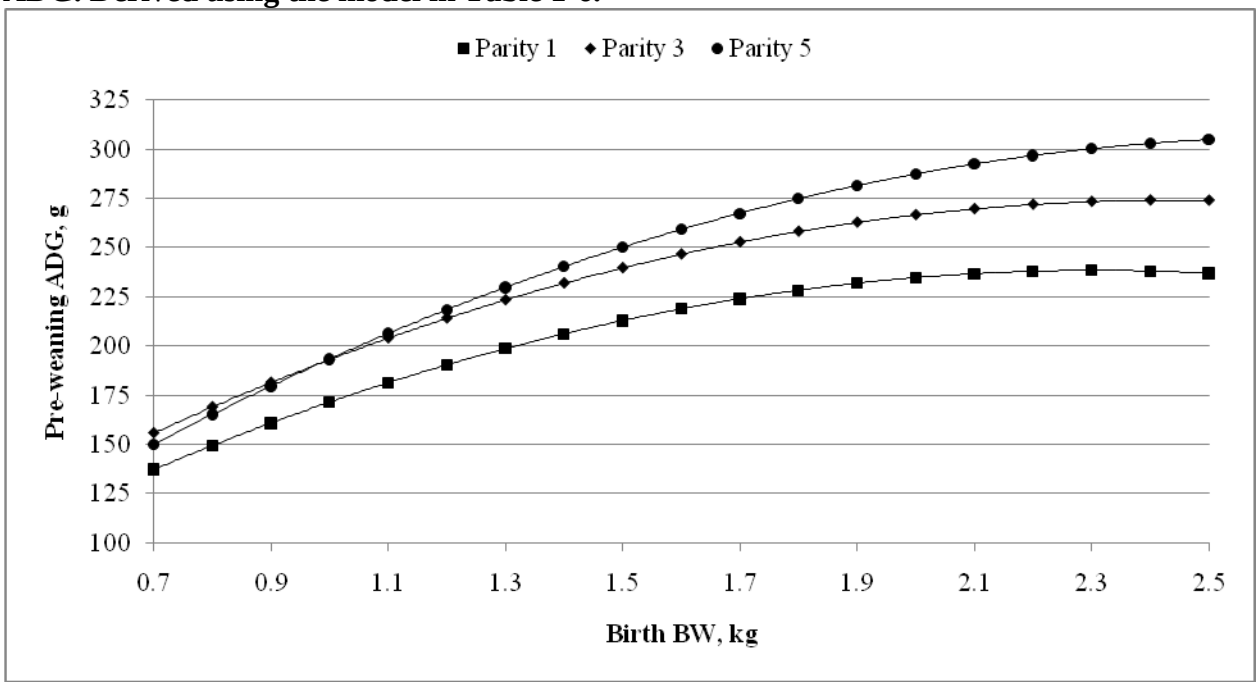


Figure 1-4. Effects of pig birth weight, foster status, and gender on pre-weaning survival. Derived using the model in Table 1-6, with pigs weaned from parity 3 sows and a litter birth weight SD of 0.27.

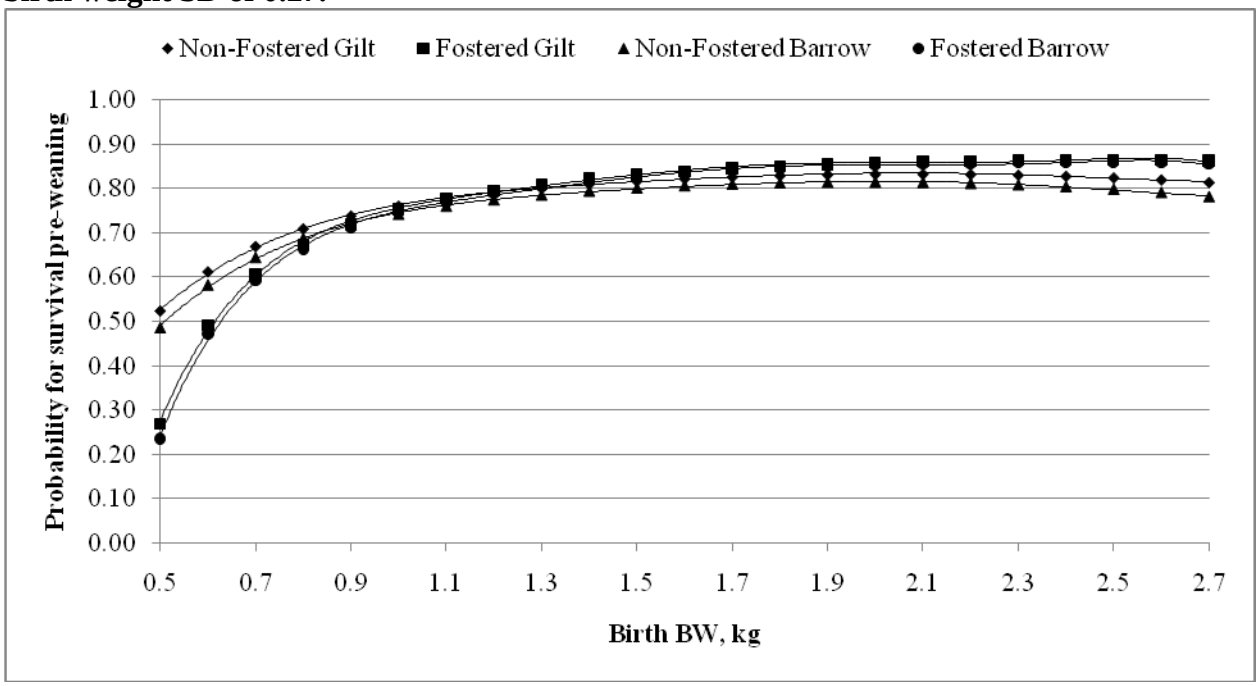


Figure 1-5. Effects of pig birth weight and gender on lifetime ADG. Derived using the model in Table 1-6, with pigs weaned from parity 3 sows at 25 d of age and fed for 155 d from weaning-to-finish.

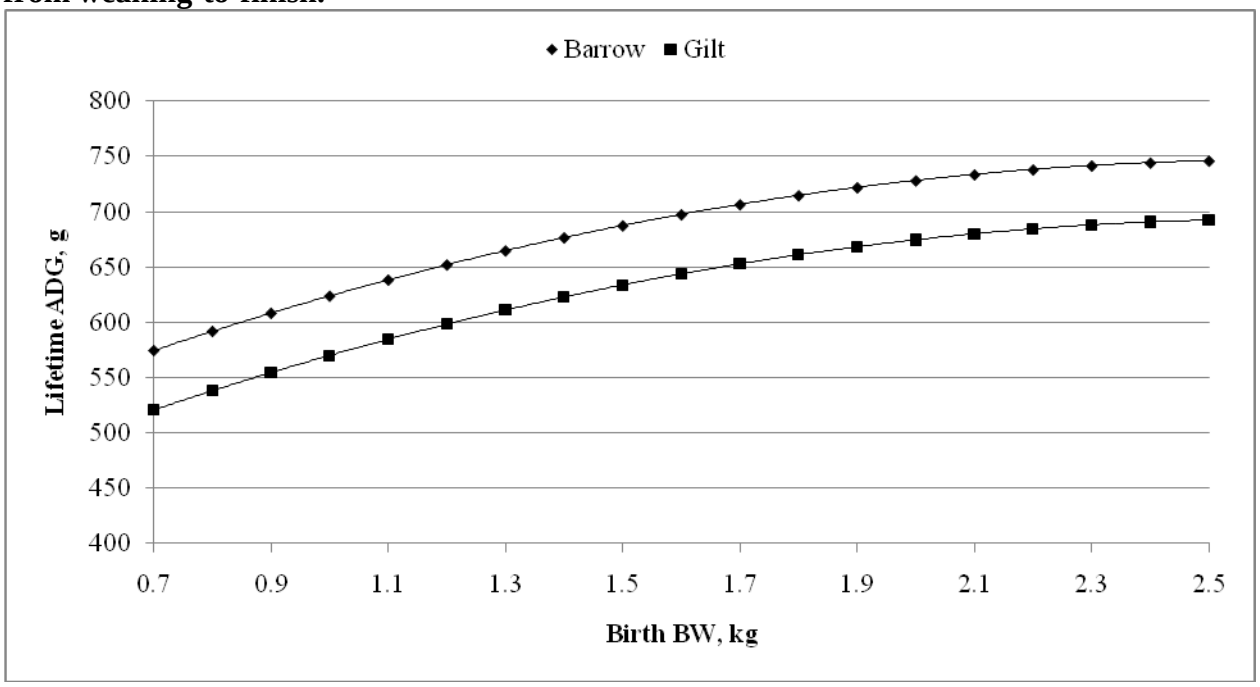
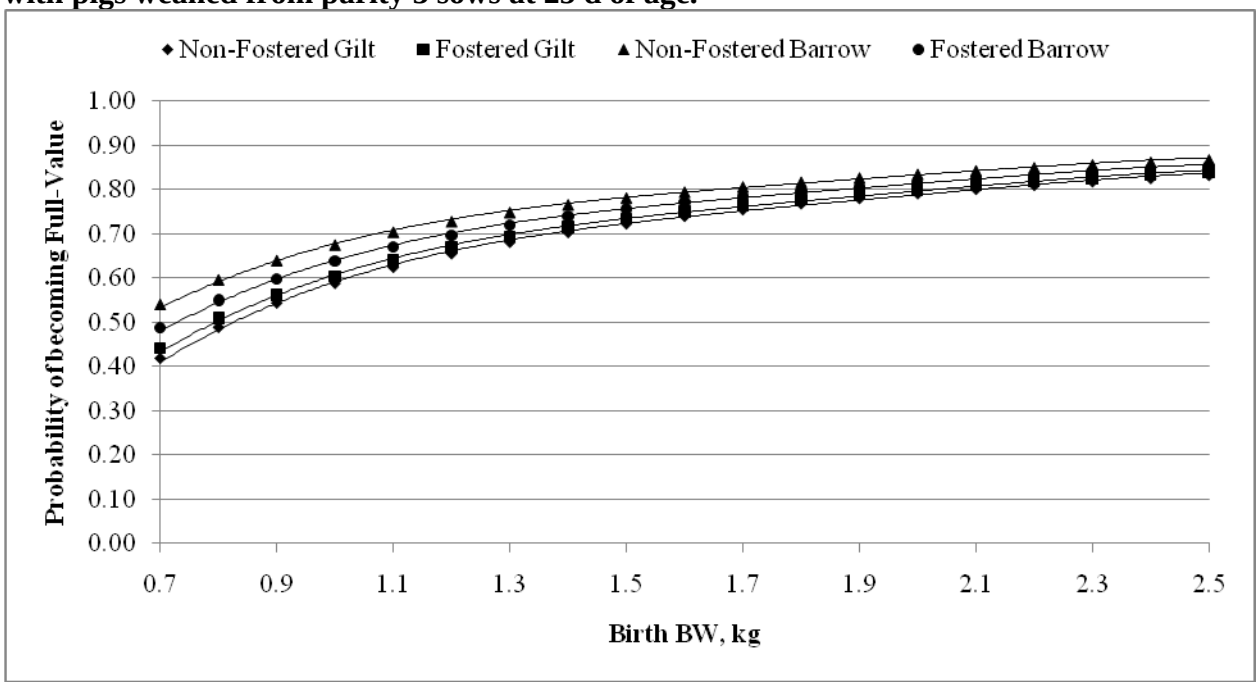


Figure 1-6. Effects of pig birth weight, foster status, and gender on the probability of surviving pigs achieving full-value at 180 d of age. Derived using the model in Table 1-6, with pigs weaned from parity 3 sows at 25 d of age.



CHAPTER 2 - The effects of feeder design, dietary level of dried distillers' grains with solubles, and gender on the performance and carcass characteristics of finishing pigs

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ABSTRACT

The objectives of this research were to compare the effects of a conventional dry (152.4 cm-wide, 5-space, Staco® Inc.) and a wet-dry (double-sided, each side = 38.1 cm space, Crystal Springs®, GroMaster Inc.) finishing feeder on performance and carcass characteristics; and evaluate the effects of feeder design, dietary level of dried distillers grains with solubles (DDGS), and gender on performance and carcass characteristics of finishing pigs. Three experiments were conducted, with a completely randomized assignment of treatments in each. In Exp. 1, 1,186 pigs (32.1 kg BW) were used in a 69-d experiment. There were 26 to 28 pigs/pen and 22 pens/feeder design, and all pigs received the same diets in 4 phases. In Exp. 2, 1,236 pigs (28.7 kg BW) were used in a 104-d experiment, with 25 to 28 pigs/pen and 23 pens/feeder design. All pigs were fed the same diets in 4 phases from d 0 to 84. On d 84, the 3 largest pigs in each pen were removed for harvest, and remaining pigs were placed on a diet containing 5 ppm ractopamine HCl until the end of the experiment. Carcass measurements were obtained from 11 pens of each feeder design after harvest on d 104. In Exp. 3, 1,080 pigs (35.1 kg BW) were used in a 99-d, 2 × 2 × 2 factorial with dry vs. wet-dry feeders, barrows vs. gilts, and 20 vs. 60% dietary DDGS for treatment factors. There were 5 pens of 27 pigs for each of the 8 treatments, with 20 pens for each of the main effects. Diets were fed in 3 phases to d 78. On d 78, the 2 largest pigs in each pen were removed for harvest. Remaining pigs were fed a common diet with 20% DDGS and 5 ppm ractopamine HCl until carcass data were obtained on d 99. Jowl fat samples were collected from 2 pigs/pen on d 78 and 99 for fatty acid analysis and iodine value (IV) determination. In all experiments, pigs fed with the wet-dry feeder had greater ($P < 0.05$) ADG, ADFI, and final BW. In Exp. 2 and 3, HCW and backfat depth were increased ($P < 0.05$) for pigs fed with a wet-dry feeder; but G:F and FFLI were reduced. Jowl IV was also reduced (*P*

< 0.05) with a wet-dry feeder in Exp. 3. Pigs fed 60% DDGS from d 0 to 78 in Exp. 3 had decreased ($P < 0.05$) ADG, G:F, final BW, HCW, and backfat; but increased jowl IV and a tendency ($P < 0.07$) for greater FFLI. Barrows had greater ($P < 0.01$) ADG, ADFI, final BW, HCW, and backfat; but reduced G:F, FFLI, and jowl IV. In conclusion, ADG and ADFI were greater with a wet-dry feeder, but poorer G:F and increased backfat depth occurred when pigs were fed longer or to heavier BW with a wet-dry feeder.

Key words: dried distillers grains with solubles, feeder design, finishing pigs

INTRODUCTION

Finishing feed costs represent a significant portion of the cost of production, and swine producers are continually evaluating technologies that may improve the performance of finishing pigs and income over feed cost. Considerable improvements in growth and efficiency have been made in the areas of genetics and nutrition. However, studies which demonstrate an improved understanding of feeder designs and their effects on performance, feeding behavior, and efficiency have not kept pace.

Barns for growing-finishing pigs are commonly equipped with various types of feeders and waterers designed to provide pigs with *ad libitum* access to feed and water with minimal waste. Feed is often presented in its original dry form; with water provided separately in a nipple waterer, cup waterer, or water trough located in close proximity. However, some barns are equipped with a wet-dry feeder that provides pigs' access to dry feed and water at the same location with the opportunity to consume wet feed.

In previous research, some have reported that using a wet-dry feeder improved the growth rate of finishing pigs (Amornthewaphat et al., 2000; Brumm et al., 2000; Gonyou and Lou, 2000), and some have not identified any benefits in pig performance with using a wet-dry

feeder design (Patterson, 1991). These studies compared the differences in performance between pigs fed with wet-dry feeders and dry feeders with water provided separately. More research is needed to compare the effects dry vs. wet-dry feeder designs on finishing pig performance in modern commercial pig facilities.

Therefore, the objectives of this research were to 1) determine the effects of a dry vs. a wet-dry feeder on growth performance, 2) determine the effects of a dry vs. a wet-dry feeder on carcass characteristics, and 3) determine the effects of feeder design, dietary level of DDGS, and gender on performance and carcass characteristics of finishing pigs raised in commercial conditions. A series of 3 experiments were completed to fulfill these objectives.

MATERIALS AND METHODS

Procedures used in the experiments were approved by the Kansas State University Institutional Animal Care and Use Committee.

Animal Care

The research was conducted in a commercial finishing research facility in southwestern Minnesota. The facility was double curtain sided with pit fans for minimum ventilation and completely slatted flooring over a deep pit for manure storage. Individual pens were 3.0 × 5.5 m. One half of the pens were equipped with a single-sided, 152.4-cm-wide, 5-hole, stainless steel dry feeder (STACO, Inc., Schaefferstown, PA) and 1 cup waterer in each pen. The remaining pens were each equipped with a double-sided, stainless steel wet-dry feeder (Crystal Springs, GroMaster, Inc., Omaha, NE) with a 38.1-cm-wide feeder opening on both sides that provided access to feed and water, with water supplied from a single nipple waterer located under a feed ‘shelf’ located over the center of the feed pan. Every feeder was positioned along the fence-line with an adjacent pen.

Although the pens equipped with a wet-dry feeder also contained the remaining cup waterer, these were shut off during the experiments. Therefore, the only source of water for pigs in these pens was through the wet-dry feeder. In addition, water was delivered to all the pens of each feeder design independently, and each of the 2 water lines was equipped with a single water meter to monitor total water disappearance for each feeder design.

Experiment 1

A total of 1,186 pigs (PIC 337 × 1050, Hendersonville, TN) were weighed and allotted to the 2 feeder designs in a 69-d experiment. There were 22 pens per treatment in a completely randomized design. Each pen contained 26 to 28 pigs with the average number of gilts and barrows per pen and initial weight (32.1 kg) balanced across treatments. All pigs were fed the same sequence of diets with 4 dietary phases (d 0 to 10, 10 to 28, 28 to 50, and 50 to 69; Table 2-1). The diets were formulated to meet or exceed the nutrient requirements of pigs for each diet phase (NRC, 1998). On d 14, 28, 42, 56, and 69, pigs were weighed and feed disappearance was measured to determine ADG, ADFI, G:F, and mean BW. This experiment was conducted from December 20, 2007 to February 27, 2008.

Experiment 2

A total of 1,236 pigs (PIC 337 × 1050) were weighed and allotted to the 2 feeder designs in a 104-d experiment. There were 23 pens per treatment in a completely randomized design. Each pen contained 25 to 28 pigs with the average number of gilts and barrows per pen and initial weight (28.7 kg) balanced across treatments. Unlike Exp. 1, all pigs were fed by using a feed budget (diet 1 = 26.8 kg/pig, diet 2 = 39.9 kg/pig, diet 3 = 54.9 kg/pig, and diet 4 = 59.0 kg/pig; Table 2-2). The diets were formulated to meet or exceed the nutrient requirements of pigs for each diet phase (NRC, 1998). On d 84, the 3 largest pigs per pen were marketed. Afterward,

all the remaining pigs were fed a fifth diet containing 5 ppm ractopamine HCl (Paylean; Elanco Animal Health, Indianapolis, IN) until d 104. On d 0, 14, 28, 42, 56, 70, 84, and 104, pigs were weighed and feed disappearance was measured to determine ADG, ADFI, G:F, and mean BW.

On d 104, all remaining pigs were individually tattooed and shipped approximately 96 km to a commercial processing plant (Swift, Worthington, MN), where they were harvested and carcass data were obtained from 494 pigs (11 pens per feeder design). Carcass data included HCW, yield, and the backfat and longissimus muscle depth measurements; which were obtained by optical probe between the 3rd and 4th rib from the last rib at 7 cm from the dorsal midline. The fat-free lean index was calculated according to National Pork Producers Council (2000) procedures. This experiment was conducted from April 8, 2008, to July 21, 2008.

Experiment 3

A total of 1,080 pigs (PIC 337 × 1050) were used in a 99-d experiment. A 2 × 2 × 2 factorial arrangement of treatments was used to evaluate the interactive effects of feeder design (conventional dry vs. wet-dry feeder), dietary concentration of DDGS (20% vs. 60%), and gender (barrow vs. gilt) on finishing pig performance. Pigs were sorted by gender (barrows and gilts) into groups of 27, weighed (35.1 kg initial BW), allotted to pens containing 1 of the 2 feeder designs, and assigned to a corn-soybean meal-DDGS-based feeding program of either 20% or 60% DDGS from d 0 to 78 (Table 2-3). A completely randomized design was used to evaluate the 8 treatment combinations, with 5 pens per treatment. This provided 20 pens per treatment for each of the 3 main effects (feeder design, DDGS concentration, and gender).

All pigs were fed their assigned level of DDGS in 3 dietary phases (d 0 to 28, 28 to 56, and 56 to 78). The 2 diets within each of the 3 feeding phases were formulated to an equal lysine concentration on a standardized ileal digestible basis. Digestibility values for AA were obtained

from the NRC (1998) and used for all ingredients except DDGS. For DDGS, AA digestibility values from Stein et al. (2006) were used. An ME value of 3,420 kcal/kg was used for both corn and DDGS. All dietary nutrient levels were formulated to meet or exceed the requirements of pigs for each diet phase. Pig weights and feed disappearance were recorded by pen on d 0, 14, 28, 42, 56, 78, and 99 to determine ADG, ADFI, G:F, and mean BW.

On d 78, the 2 largest pigs in each pen were weighed and removed for harvest. Jowl fat samples were collected from these pigs for fatty acid analysis and the calculation of iodine value (IV). All remaining pigs were fed a common diet from d 78 to 99 that contained 20% DDGS and 5 ppm of ractopamine HCl. On d 99, remaining pigs were individually tattooed and shipped approximately 96 km to a commercial processing plant (Swift, Worthington, MN), where they were harvested and carcass data were obtained from 885 pigs. Carcass data included HCW, yield, and the backfat and longissimus muscle depth measurements; which were obtained by optical probe between the 3rd and 4th rib from the last rib at 7 cm from the dorsal midline. The fat-free lean index was calculated according to National Pork Producers Council (2000) procedures. Jowl fat samples were also collected from the carcasses of 2 average-sized pigs within each pen for fatty acid analysis and the calculation of IV.

All jowl fat samples collected were obtained 24-h postmortem and stored frozen at 0°C until sample preparation and fatty acid analysis. Fat (50 μg) was combined with 2 mL of methanolic-HCl and 3 mL of internal standard (2 mg/mL of methyl Heptadecanoic acid (C17:0) in benzene) and subsequently heated in a water bath for 120 min at 70°C for transmethylation. After cooling, the addition of 2 mL of benzene and 3 mL of K_2CO_3 facilitated the extraction of the methyl esters for quantification of methylated fatty acids by gas chromatography. An IV was calculated from the fatty acid analysis using the following equation (AOCS, 1998): IV = [C16:1]

× 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723, where the brackets indicate the percentage concentration of the specified fatty acid. This experiment was conducted from August 8 to November 12, 2008.

Statistical Analysis

For both Exp. 1 and Exp. 2, data were analyzed as a completely randomized design using the PROC MIXED procedure of SAS (v. 8.2; SAS Institute Inc., Cary, NC) with pen as the experimental unit.

The data for Exp. 3 were analyzed as 2 × 2 × 2 factorial arrangement in a completely randomized design using the PROC MIXED procedure of SAS (v. 8.2; SAS Institute Inc., Cary, NC). Pen was the experimental unit. Because there were differences in the initial BW of barrows and gilts, the initial BW was used as a covariate in data analysis. For all analyses, differences with a *P*-value of less than 0.05 were considered to be statistically significant, and trends are reported with a *P*-value of less than 0.15.

RESULTS

Experiment 1

During each period, ADG was improved ($P < 0.02$) for pigs fed using the wet-dry feeder (Table 2-4). From d 0 to 14, ADFI was not different between the 2 feeder designs, but G:F tended ($P < 0.11$) to be improved for pigs fed with the wet-dry feeder. Thereafter, the ADFI and BW at the end of each period was greater ($P < 0.0001$) for pigs fed with the wet-dry feeder, but G:F was not different than that obtained with the conventional dry feeder.

Overall (d 0 to 69) ADG, ADFI, and final BW were greater ($P < 0.0001$) for pigs fed using a wet-dry feeder than for those fed using the conventional dry feeder. Feed efficiency was not different between pigs fed with either feeder design. Although a single water meter reading

was obtained daily during the experiment to monitor the total water disappearance of pigs on each feeder treatment, water disappearance did not appear to differ between the 2 feeder designs.

Experiment 2

From d 0 to 84, the results obtained were very similar to those observed in Exp. 1 (Table 2-5). Pigs fed using a wet-dry feeder had greater ($P < 0.0001$) ADG, ADFI, and final BW than those fed with the conventional dry feeder. Feed efficiency was not different between pigs fed with either feeder design.

When the pigs were switched to a diet containing 5 ppm ractopamine HCl from d 84 to 104, ADG of pigs fed with the 2 feeder designs was not different. However, pigs eating from the wet-dry feeder had greater ($P < 0.0001$) ADFI and reduced ($P < 0.0001$) G:F compared to those fed using the conventional dry feeder.

Overall (d 0 to 104) ADG, ADFI, and final BW were increased ($P < 0.0001$), but G:F was poorer ($P < 0.002$), for pigs fed using the wet-dry feeder. Water disappearance was numerically greater for the pens equipped with the conventional dry feeder and cup waterer (6.45 vs. 5.68 L/pig/d). Hot carcass weight tended ($P < 0.06$) to be greater for pigs fed using the wet-dry feeder. No differences in longissimus muscle depth were observed, but average backfat depth was greater ($P < 0.002$) for pigs fed with the wet-dry feeder. Therefore, carcass yield and FFLI were decreased ($P < 0.03$) for pigs fed using the wet-dry feeder.

Experiment 3

From d 0 to 78 (Table 2-6), feeder design × gender ($P < 0.05$) interactions were observed for ADG and d-78 BW. This occurred because the ADG and d-78 BW of barrows and gilts using the wet-dry feeder were similar. However, with the conventional dry feeder, the ADG and d-78 BW of barrows were greater than that of gilts. Despite the interactions, ADG, ADFI, and d-78

BW were greater ($P < 0.0001$), and G:F was poorer ($P < 0.0001$), for pigs using the wet-dry feeder. Pigs fed 20% DDGS had greater ($P < 0.0001$) ADG and d-78 BW, and better ($P < 0.001$) G:F than those fed 60% DDGS. Barrows tended ($P < 0.06$) to have greater ADG than gilts, but had greater ($P < 0.01$) ADFI and d-78 BW with poorer ($P < 0.0001$) G:F than gilts.

From d 78 to 99, when all pigs received a common diet containing 20% DDGS and 5 ppm ractopamine HCl, a trend ($P < 0.06$) for a feeder design × gender interaction was observed for ADFI. This occurred because the difference in ADFI between barrows and gilts was greater with the wet-dry feeder. Despite the interaction, ADG and ADFI were greater ($P < 0.03$) for pigs using the wet-dry feeder compared with the dry feeder, and for pigs fed 60% DDGS compared with 20% DDGS in the previous period. Barrows also had greater ($P < 0.0001$) ADFI and poorer ($P < 0.01$) G:F than gilts.

Overall (d 0 to 99), pigs using the wet-dry feeder had greater ($P < 0.0001$) ADG, ADFI, final BW, HCW (Table 2-7), and backfat depth; poorer ($P < 0.0001$) G:F; and decreased ($P < 0.001$) FFLI and jowl fat IV when compared to pigs fed with the conventional dry feeder. Feeding 60% DDGS from d 0 to 78 resulted in decreased ($P < 0.04$) ADG, final BW, HCW, and backfat depth; poorer ($P < 0.002$) G:F; a tendency ($P < 0.07$) for increased FFLI; and greater ($P < 0.001$) jowl fat IV when compared to feeding 20% DDGS throughout the experiment. Barrows had greater ($P < 0.04$) ADG, ADFI, final BW, HCW, and backfat depth; poorer ($P < 0.0001$) G:F; and decreased ($P < 0.0001$) FFLI and jowl fat IV than gilts.

DISCUSSION

These data demonstrated consistent improvements in the ADG and ADFI of finishing pigs fed meal diets *ad libitum* with a wet-dry feeder, when compared to a conventional dry feeder. This occurred despite the dry feeder providing twice the amount of feeder space per pig.

Gonyou and Lou (2000) indicated that both the number of feeding spaces and availability of water at the feeder are the principle design features that influence the performance of the pig group. They compared 6 models of dry feeders and 6 models of wet-dry feeders, and also observed greater ADG and ADFI for pigs fed using wet-dry feeders. Although there were only 12 pigs/pen in their study, Gonyou (1999) utilized feeding behavior data from single-space and multiple-space models to estimate the number of pigs required to keep each feeder space occupied 80% of the time. This was a conservative estimate to obtain optimal use of a feeder without decreasing performance. Gonyou (1999) estimates indicated that a 20 to 35% greater stocking rate was appropriate for a wet-dry feeder space (14 to 15 pigs/feeding space) when compared to an equal amount of dry feeder space (11 to 12 pigs/feeding space).

Gonyou and Lou (2000) reported that pigs eating from wet-dry feeders spent less total time eating and had less feeder entrances per day than those fed with dry feeders. In an experiment with restricted feeding, they determined that eating speed was increased nearly 3-fold for pigs consuming wet feed. Miyawaki et al. (1996) also observed a reduction in the total daily time spent eating for pigs fed with wet-dry feeders, but this occurred with a similar number of shorter visits to the feeder than that of pigs eating from the dry feeder. Hurst et al. (2008) also reported a considerably faster eating rate for wet-fed compared to dry-fed pigs with restricted feeding. In an experiment with *ad libitum* feeding, they observed greater ADG in pigs offered a 1:3 feed and water mixture. Although not different, ADFI was also 6% greater for the wet-fed compared to dry-fed pigs. However, there were only 4 pens of 8 pigs for each treatment in their 6-wk experiment. In the present experiments, the presentation of both feed and water in the feeder was likely responsible for the greater ADG and ADFI observed with the wet-dry feeder.

Water is an essential nutrient, and its availability must not be overlooked when making comparisons between feeder designs that include differences in providing water. Although replicated measurements were not obtained within the experiments, the total water disappearance measured for pigs on each feeder design in the first 2 experiments indicates that water was not limiting. The calculated water:feed ratios exceeded the minimum requirement suggested by the NRC (approximately 2 kg water:kg feed, 1998). However, data from Exp. 1 by itself do not provide conclusive evidence that the availability of water from the cup waterer was not limiting feed intake of pigs fed with the dry feeder. Only one nipple waterer was provided in the double-sided wet-dry feeder, but 2 separate and opposing trough spaces permitted 2 pigs to access the trough containing feed and water at any time. Only one pig could drink at a time from the cup waterer provided in the pens with the dry feeder. However, the greater apparent water disappearance observed for pigs provided a single cup waterer and dry feeder in Exp. 2 (during spring and summer months) suggest that water was not limiting. Previous research in these facilities did not identify a benefit to providing more than one cup waterer per pen with the dry feeder (S. S. Dritz, Kansas State University, Manhattan, unpublished results). Therefore, it is unlikely that the availability of water by itself was limiting in any of these experiments.

Other studies have also demonstrated improved ADG with *ad libitum* feeding of meal diets using wet-dry feeders (Patterson, 1989; Anderson et al., 1990; Walker, 1990) sometimes associated with greater ADFI, sometimes associated with improved G:F, and sometimes associated with additive numeric differences reported for both (Rantanen et al., 1995; Amornthewaphat et al., 2000; Brumm et al., 2000). In a few studies, differences in the ADG of pigs fed with wet-dry and dry feeders have not been observed. In one such report, Rantanen et al. (1994) repeated a feeder design experiment twice, with 5 replicates in the summer and another 5

replicates during the winter. Although pigs fed with a single-space wet-dry feeder were heavier at the end of the study than those fed with either a double-space dry or a round 8-space dry feeder during the summer (108.3 vs. 104.3 and 104.1 kg, respectively), they reported no differences in ADG or ADFI during either season. However, regardless of season, feed efficiency was improved with the wet-dry feeder. Patterson (1991) did not observe any differences in growth performance when comparing 2 different wet-dry feeders with a conventional dry feeder.

Various other design features may be responsible for the different responses observed among experiments comparing different feeders. Baxter (1991) reported that both a head and shoulder or head barrier between each feeding space reduced aggression and feed wastage. Morrow and Walker (1994a) also reported that, with 20 pigs per pen, fitting a stall to a single-space wet-dry feeder reduced aggression and the occurrence of tail biting. Although the number of daily feeder visits was reduced and the duration of each visit increased, differences in growth performance and feed wastage were not observed. Gonyou (1999) included a multiple-space 'tube' feeder in their study and reported that intake and growth were equal to that of other multiple-space wet-dry feeders, but the data seem to indicate that the lack of protected and well defined feeder spaces may result in a reduced stocking rate relative to other wet-dry feeders. Nevertheless, it is likely that the provision of a head barrier around the feeding spaces of the wet-dry feeder contributed to the differences in performance between the 2 feeder designs in the current studies. The feeding spaces of the conventional dry feeder were only separated by a nose barrier in the trough.

Another very important design feature (or mechanism) that may result in differences in feeding behavior and growth is the method and adjustment for regulating the gravity flow and

access to feed in the trough. Morrow and Walker (1994b) used a single-space wet-dry feeder with an operating flap in 2 finishing experiments, and calibrated it to dispense either 1.4, 2.7, or 5.3 g each time the flap was pushed by a pig with its nose in the first experiment. They reported that ADFI was reduced at the lowest dispensing rate in the first experiment, but that ADG increased with each increase in the dispensing rate. Although the total time spent eating was considerably greater at the low setting, the feeders were not fully occupied throughout the day and night. They indicated that the pigs at the lowest setting were not willing to work harder to achieve the intakes observed at higher settings. Additionally, the overall carcass-based feed efficiency improved and final backfat depth increased with each increase in dispensing rate. Their second experiment evaluated dispensing rates of 4.8, 6.9, and 9.3 g per push. None of the performance criteria were influenced by the further increases in dispensing rate employed in their second experiment, but the accumulation of feed in the trough continued to increase. On occasions when more than half the trough became filled with wet feed in their second experiment, they indicated that the feed supply was temporarily closed to encourage consumption of the accumulated feed. Therefore, any potential for increased feed conversion and wastage at their highest setting was not evident. These data support our recent observation that the growth of pigs fed with a wet-dry feeder, which generally provides less eating spaces and is more prone to plugging than a conventional dry feeder, may be more sensitive to differences in feeder adjustment (Bergstrom, J. R., 2011).

Feed efficiency responses in experiments comparing different feeder designs have been more variable than the gain and feed intake responses reported. As indicated previously, Rantanen et al. (1994) observed better feed efficiency with a wet-dry feeder, but Gonyou and Lou (2000) indicated there were no differences in feed efficiency between wet-dry and dry

feeder designs in their study. Similar to Exp. 2 and 3, Brumm et al. (2000) observed poorer G:F with the wet-dry compared to the conventional dry feeder. Although feed wastage was not visually considered to be a problem in their study, they did report that a single delivery of coarse-ground feed made adjustment of the wet-dry feeder difficult during the period that this feed was consumed.

In Exp. 3, we experienced difficulties in achieving a feeder setting that provided access to feed without filling the trough, particularly with the diet containing 60 % DDGS and the wet-dry feeder. The dry feeder was initially adjusted to a setting determined to be optimal in previous experiments. The wet-dry feeder was adjusted to an opening suggested by the manufacturer, which had been utilized in Exp. 1 and 2. Differences in the composition and flowability of the meal diets between experiments may have contributed to the problem, but the feeders were subsequently adjusted daily as needed to obtain trough coverage of approximately 50% (Duttlinger et al., 2009). Although more difficult initially, maintaining feeders at the desired pan coverage became much easier as the pigs grew larger.

Besides apparent differences in managing feed access and wastage among feeder designs, other underlying differences may be important for understanding the various feed efficiency responses observed. Differences described previously in the eating behavior of pigs fed with wet-dry and dry feeders may occur throughout the growing-finishing period (Gonyou and Lou, 2000). Additionally, younger and lighter pigs fed *ad libitum* visit the feeder more frequently for longer meals, which results in a greater time budget for feeding than older and larger pigs (Hyun et al., 1997). This, combined with the slower eating rate of younger pigs to achieve a greater level of *ad libitum* feed intake relative to BW, indicates that younger pigs using wet-dry feeders may expend less energy to achieve *ad libitum* intake due to a faster eating rate and reduced time

budget for feeding. Such a relationship could result in improved feed efficiency during early growth, and this may explain the tendency for improved G:F during the first 2 wk in Exp.1 and other experiments (Bergstrom, J. R., 2011). However, pigs with greater ADFI and ADG also approach physiological maturity faster, which eventually results in measurable differences in the relative accretion of muscle and fat when compared to slower growing pigs of similar age or BW (Braude et al., 1959; Barber et al., 1972; Kanis, 1988). Therefore, experiments which identify feeder designs that increase ADFI and ADG and conclude at heavier BWs may observe poorer overall G:F, increased backfat depth, and reduced percent carcass lean.

Differences in performance between pigs fed 20% and 60% DDGS in Exp. 3 are consistent with previous experiments comparing various levels of dietary DDGS. Whitney et al. (2006) reported linear decreases in ADG and G:F when DDGS was increased from 0 to 30% of the diet, with no differences in ADFI. Linneen et al. (2008) also reported decreased ADG with increasing levels of DDGS, but this was associated with reductions in ADFI rather than differences in G:F in their experiments. In Exp. 3, it is interesting that the ADG and ADFI of pigs fed 60% DDGS from d 0 to 78 was greater from d 78 to 99, after they were switched to the diet containing 20% DDGS, when compared to those fed 20% DDGS throughout the experiment. Given the difficulties encountered with feeder adjustment described previously, it is likely that the differences in G:F from d 0 to 78 between pigs fed 20% and 60% DDGS reflect differences in the amount of feed wasted. Similar to the diets used by Linneen et al. (2008), the diets used in Exp. 3 were formulated to the same lysine level within each phase on a standardized ileal digestible basis. Xu et al. (2010a) also compared diets formulated on a standardized ileal digestible AA basis that contained 0 to 30% DDGS, and observed reduced ADFI and improved

G:F with increased DDGS. It is possible that the actual amount of feed consumed was reduced for pigs receiving the 60% DDGS diet, but unknown.

In Exp. 3, reducing the dietary level of DDGS from 60% to 20% for the last 21 days was successful in mitigating the negative effects on yield commonly associated with feeding greater levels of DDGS to harvest (Whitney et al., 2006; and Linneen et al., 2008; Xu et al., 2010a). The reduced HCW for pigs fed 60% DDGS from d 0 to 78, compared to those fed 20% DDGS throughout the experiment, reflect the differences in overall ADG and final BW. Linneen et al. (2008) reported tendencies for reduced backfat and increased FFLI when feeding up to 20% DDGS. With the reduced growth rates associated with feeding increased levels of DDGS, it is not surprising that the carcasses of pigs fed 60% DDGS tended to be leaner based on the evidence presented previously.

The differences in jowl fat IV observed are also supported in the literature. Benz et al. (2010) reported increased jowl fat IV with increasing dietary levels of DDGS. Xu et al. (2010b) demonstrated that reducing the dietary level of DDGS from either 15 or 30% to 0% for up to 6 weeks did not restore the IV of belly fat to that of the control, and a recent meta-analysis by Bergstrom et al. (2011) indicated that the effects of polyunsaturated fatty acid concentrations in earlier diets are primarily important for determining the final IV of pork fat depots. Wood et al. (2008) have also reported on the relationship of backfat depth and gender with the concentrations of polyunsaturated fatty acids in pork carcass fat. Therefore, it is not surprising that jowl fat IV was lower for pigs with greater backfat depth, such as barrows and pigs fed with the wet-dry feeder.

The overall differences in growth performance between barrows and gilts in Exp. 3 are typical for that obtained with *ad libitum* feeding in commercial facilities. However, it is

interesting that the d 0 to 78 ADG and d 78 BW of barrows and gilts were similar with the wet-dry feeder, whereas the d 0 to 78 ADG and d 78 BW of barrows was greater than that of gilts fed with the conventional dry feeder. During the last 21 d, when all pigs received a diet containing 20% DDGS and 5 ppm ractopamine HCl, ADFI of barrows fed with the wet-dry feeder was considerably greater than that of gilts. Barrows fed with the wet-dry feeder also had greater ADG than gilts during the final period.

In conclusion, these experiments demonstrate that ADG and ADFI of finishing pigs are improved with a wet-dry feeder. The improved growth rate of gilts with a wet-dry feeder represents an opportunity for the industry to identify specialized feeding methods that may enhance the growth of slower growing pigs within a group. Pigs fed with wet-dry feeders and high levels of DDGS may have growth rates equal to (or greater than) that of pigs fed low levels of DDGS with a conventional dry feeder. However, with the differences in growth observed in these studies, feeding to a heavier BW may result in poorer overall G:F and fatter carcasses with a wet-dry feeder. These negative responses may offset any economic advantages obtained from improvements in growth. Further research is necessary to identify wet-dry feeder designs or management strategies that will sustain benefits in growth while minimizing the potential negative effects on feed efficiency and carcass lean.

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Table 2-1. Diet composition, Exp. 1

	Dietary phase[1]			
Ingredient, %	d 0 to 10	d 10 to 28	d 28 to 50	d 50 to 69
Corn	58.88	52.09	55.31	57.93
Soybean meal, 46.5% CP	22.25	18.95	15.92	13.20
DDGS[2]	9.00	20.00	20.00	20.00
Bakery by-product	5.00	5.00	5.00	5.00
Choice white grease	2.55	2.05	2.10	2.25
Monocalcium P, 21% P	0.25	---	---	---
Limestone	0.80	0.80	0.80	0.80
VTM, amino acids, phytase[3]	1.27	1.11	0.87	0.82
TOTAL	100.00	100.00	100.00	100.00
Calculated analysis				
Standardized ileal digestible (SID) amino acids				
Lys, %	1.11	1.05	0.95	0.86
Ile:lys, %	59	63	64	66
Leu:lys, %	138	158	168	177
Met:lys, %	32	31	30	31
Met & Cys:lys, %	58	60	60	64
Thr:lys, %	62	62	64	63
Trp:lys, %	16	16	16	16
Val:lys, %	68	74	77	79
CP, %	18.9	19.7	18.5	17.4
Total lys, %	1.24	1.20	1.09	0.99
ME, kcal/kg	3,494	3,483	3,485	3,494
SID lys:ME, g/Mcal	3.19	3.02	2.72	2.46
Ca, %	0.45	0.40	0.39	0.38
P, %	0.45	0.43	0.42	0.41
Available P, %	0.26	0.26	0.25	0.25

[1] Each dietary phase was fed to all pigs during the periods described in the table.
[2] Dried distillers' grains with solubles.
[3]Vitamin and trace mineral premix, amino acids, and phytase added by the feed supplier to meet the desired nutrient specifications.

Table 2-2. Diet composition, Exp. 2

	Dietary Phase[1]				
Ingredient, %	1	2	3	4	5
Corn	61.60	54.56	50.05	52.76	59.61
Soybean meal, 46.5% CP	21.60	18.55	13.10	10.45	16.45
DDGS[2]	9.00	20.00	30.00	30.00	17.00
Bakery by-product	5.00	5.00	5.00	5.00	5.00
Choice white grease	0.65	---	---	---	---
Monocalcium P, 21% P	0.13	---	---	---	---
Limestone	0.80	0.85	0.85	0.85	0.80
VTM, amino acids, phytase[3]	1.22	1.04	1.00	0.94	1.14
TOTAL	100.00	100.00	100.00	100.00	100.00
Feed budget, kg/pig	26.8	39.9	54.9	59.0	to d 104
Calculated analysis					
Standardized ileal digestible amino (SID) acids					
Lys, %	1.11	1.05	0.90	0.81	0.94
Ile:lys, %	59	63	69	71	65
Leu:lys, %	139	159	190	204	167
Met:lys, %	32	30	33	35	32
Met & Cys:lys, %	59	60	68	72	62
Thr:lys, %	62	62	64	66	65
Trp:lys, %	16	16	17	17	17
Val:lys, %	68	74	84	87	77
CP, %	18.9	19.7	19.4	18.4	18.3
Total lys, %	1.24	1.20	1.06	0.97	1.08
ME, kcal/kg	3,411	3,388	3,391	3,393	3,391
SID lys:ME, g/Mcal	3.25	3.10	2.66	2.39	2.77
Ca, %	0.42	0.41	0.40	0.39	0.39
P, %	0.42	0.44	0.46	0.45	0.41
Available P, %	0.23	0.26	0.31	0.30	0.24

[1] Each dietary phase was fed to all the pigs in the sequence, and according to the feed budget, outlined in the table.
[2] Dried distillers' grains with solubles.
[3]Vitamin and trace mineral premix, amino acids, and phytase added by the feed supplier to meet the desired nutrient specifications. Paylean (Elanco, Greenfield, IN) was also added in the last diet phase to obtain 5 ppm ractopamine HCl in the complete diet.

Table 2-3. Diet composition, Exp. 3

	Dietary phase[1]						
	d 0 to 28		d 28 to 56		d 56 to 78		d 78 to 99
DDGS,%[2]:	20	60	20	60	20	60	20
Ingredient, %							
Corn	60.07	26.45	63.00	29.90	66.84	33.55	58.36
Soybean meal, 46.5% CP	18.06	11.20	15.25	7.83	11.49	4.24	19.85
DDGS	20.00	60.00	20.00	60.00	20.00	60.00	20.00
Limestone	1.00	1.40	0.95	1.35	0.90	1.35	1.00
Salt	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Liquid lysine, 60%	0.40	0.50	0.35	0.48	0.33	0.43	0.33
VTM, phytase[3]	0.12	0.10	0.10	0.09	0.09	0.08	0.08
Ractopamine HCl, 20 g/kg[4]	---	---	---	---	---	---	0.025
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis							
Standardized ileal digestible (SID) amino acids							
Lys, %	0.95	0.95	0.85	0.85	0.74	0.74	0.95
Ile:lys, %	68	77	70	80	72	85	71
Leu:lys, %	175	231	188	249	204	278	180
Met:lys, %	31	40	33	43	35	48	32
Met & Cys:lys, %	63	81	67	86	72	96	65
Thr:lys, %	61	73	64	76	67	82	64
Trp:lys, %	17	18	18	18	18	18	18
Val:lys, %	81	97	85	101	89	110	84
CP, %	18.9	23.8	17.9	22.5	16.5	21.1	19.6
Total lys, %	1.10	1.18	0.99	1.07	0.87	0.94	1.10
ME, kcal/kg	3,364	3,353	3,366	3,355	3,371	3,358	3,364
SID lys:ME, g/Mcal	2.82	2.83	2.52	2.53	2.20	2.17	2.82
Ca, %	0.47	0.60	0.44	0.57	0.41	0.56	0.47
P, %	0.43	0.58	0.42	0.56	0.41	0.55	0.44
Available P, %	0.27	0.32	0.25	0.32	0.23	0.31	0.22

[1]Each dietary phase was fed to both feeder designs during the periods described in the table.
[2]Dried distillers grains with solubles.
[3]Vitamin and trace mineral premix. Phytase provided 0.07% to 0.12% available P.
[4]Paylean, Elanco Animal Health, Greenfield, IN.

Table 2-4. The effects of feeder design on growth performance of finishing pigs, Exp. 1

	Feeder design			
Item[1]	Conventional dry	Wet-dry	SE	*P* <
d 0 to 14				
ADG, kg	0.95	0.98	0.009	0.02
ADFI, kg	1.86	1.88	0.021	---[2]
G:F	0.51	0.52	0.005	0.11
d 14 BW, kg	45.4	45.8	0.36	---
d 14 to 28				
ADG, kg	0.98	1.06	0.008	0.0001
ADFI, kg	2.22	2.41	0.021	0.0001
G:F	0.44	0.44	0.003	---
d 28 BW, kg	59.2	60.7	0.42	0.02
d 28 to 42				
ADG, kg	0.99	1.08	0.010	0.0001
ADFI, kg	2.42	2.67	0.018	0.0001
G:F	0.41	0.41	0.005	---
d 42 BW, kg	73.0	75.9	0.42	0.0001
d 42 to 56				
ADG, kg	0.92	0.99	0.016	0.002
ADFI, kg	2.60	2.87	0.029	0.0001
G:F	0.35	0.35	0.004	---
d 56 BW, kg	85.8	89.9	0.52	0.0001
d 56 to 69				
ADG, kg	0.95	1.02	0.020	0.02
ADFI, kg	2.56	2.86	0.035	0.0001
G:F	0.37	0.36	0.007	---
d 0 to 69				
ADG, kg	0.95	1.03	0.005	0.0001
ADFI, kg	2.33	2.53	0.015	0.0001
G:F	0.41	0.41	0.002	0.13
d 69 BW, kg	98.2	103.2	0.47	0.0001
Total water disappearance[3]				
L/pig/d	5.30	5.53	NR[4]	NR
L/kg gain	5.58	5.37	NR	NR
water:feed, kg:kg	2.27	2.19	NR	NR

[1] A total of 1,186 pigs (PIC 337 × 1050; initial BW = 32.1 kg) with 26 to 28 pigs per pen and 22 pens per treatment were used in a 69-d experiment to compare the growth performance of pigs fed from either a conventional dry feeder with a cup waterer or a wet-dry feeder. This experiment was conducted from December 20, 2007 to February 27, 2008.

[2] Not significant ($P > 0.15$).

[3] Separate water meters were utilized to record water disappearance for all pens within the 2 feeder designs.

[4] NR = not replicated.

Table 2-5. The effects of feeder design on growth performance and carcass characteristics of finishing pigs, Exp. 2

	Feeder design			
Item[1]	Conventional dry	Wet-dry	SE	*P* <
d 0 to 84 growth performance				
ADG, kg	0.85	0.92	0.006	0.0001
ADFI, kg	2.21	2.39	0.015	0.0001
G:F	0.39	0.39	0.002	---[2]
d 84 BW, kg	100.6	106.4	0.60	0.0001
d 84 to 104 growth performance				
ADG, kg	0.89	0.88	0.017	---
ADFI, kg	2.48	2.75	0.030	0.0001
G:F	0.36	0.32	0.004	0.0001
d 0 to 104 growth performance				
ADG, kg	0.86	0.91	0.006	0.0001
ADFI, kg	2.25	2.45	0.015	0.0001
G:F	0.38	0.37	0.002	0.002
d 104 BW, kg	118.6	123.8	0.69	0.0001
Total water disappearance[3]				
L/pig/d	6.45	5.68	NR[4]	NR
L/kg gain	7.50	6.24	NR	NR
water:feed, kg:kg	2.88	2.32	NR	NR
Carcass characteristics[5]				
HCW, kg	88.5	90.8	0.81	0.06
Yield, %	76.9	75.2	0.43	0.02
Backfat depth, mm	16.3	17.8	0.28	0.002
Longissimus muscle depth, cm	6.13	6.21	0.104	---
Fat-free lean index	50.5	49.9	0.16	0.03

[1] A total of 1,236 pigs (PIC 337 × 1050; initial BW = 28.7 kg) with 25 to 28 pigs per pen and 23 pens per treatment were used in a 104-d experiment to compare the growth performance of pigs fed from either a conventional dry feeder with a cup waterer or a wet-dry feeder. This experiment was conducted from April 8, 2008, to July 21, 2008.

[2] Not significant ($P > 0.15$).

[3] Separate water meters were utilized to record water disappearance for all pens within the 2 feeder designs.

[4] NR = not replicated.

[5] Carcass data from 494 pigs (11 pens/feeder-type) were obtained for the comparison of carcass characteristics.

Table 2-6. The effects of feeder design, dietary level of dried distillers' grains with solubles (DDGS), and gender on growth performance of finishing pigs, Exp. 3

	Feeder design												
	Wet-Dry				Conventional dry								
	20% DDGS		60% DDGS		20% DDGS		60% DDGS			*P* <			
Item[1,2]	Barrow	Gilt	Barrow	Gilt	Barrow	Gilt	Barrow	Gilt	SEM	Feeder design	DDGS	Gender	Feeder × Gender
d 0 to 78													
ADG, kg	0.92	0.91	0.86	0.87	0.85	0.82	0.82	0.79	0.010	0.0001	0.0001	0.06	0.05
ADFI, kg	2.53	2.37	2.49	2.36	2.21	2.06	2.20	2.03	0.028	0.0001	---[3]	0.0001	---
G:F	0.36	0.38	0.35	0.37	0.39	0.40	0.37	0.39	0.005	0.0001	0.001	0.0001	---
d 78 BW, kg	108.6	106.6	102.7	103.3	103.0	99.3	99.9	97.5	0.79	0.0001	0.0001	0.01	0.05
d 78 to 99	20% DDGS												
ADG, kg	1.11	1.07	1.21	1.14	1.06	1.02	1.10	1.10	0.035	0.03	0.01	---	---
ADFI, kg	3.41	3.02	3.51	3.09	3.00	2.80	3.19	3.01	0.079	0.0001	0.02	0.0001	0.06
G:F	0.33	0.35	0.34	0.37	0.35	0.37	0.34	0.37	0.010	---	---	0.01	---
d 0 to 99													
ADG, kg	0.96	0.94	0.93	0.92	0.89	0.86	0.88	0.85	0.011	0.0001	0.02	0.04	---
ADFI, kg	2.69	2.50	2.69	2.50	2.35	2.20	2.39	2.22	0.029	0.0001	---	0.0001	---
G:F	0.36	0.38	0.34	0.37	0.38	0.39	0.37	0.38	0.004	0.0001	0.002	0.0001	---
d 99 BW, kg	130.4	128.1	127.7	126.4	124.8	120.3	122.3	119.9	1.17	0.0001	0.04	0.005	---

[1]A total of 1,080 pigs (PIC 337 × 1050; initial BW = 35.1 kg) were placed in 40 pens containing 27 pigs each and were used in a 99-d experiment to compare the growth performance of barrows and gilts fed diets containing 20% or 60% DDGS with either a conventional dry feeder with a cup waterer or a wet-dry feeder. This experiment was conducted from Aug. 8 to Nov. 12, 2008.

[2]There were no feeder × DDGS × gender, feeder × DDGS or DDGS × gender interactions ($P > 0.05$) observed for these criteria.

[3]Not significant ($P > 0.15$).

Table 2-7. The effects of feeder design, dietary level of dried distillers' grains with solubles (DDGS), and gender on carcass characteristics of finishing pigs, Exp. 3

	Feeder design												
	Wet-Dry				Conventional dry								
	20% DDGS		60% DDGS		20% DDGS		60% DDGS			*P* <			
Item[1,2]	Barrow	Gilt	Barrow	Gilt	Barrow	Gilt	Barrow	Gilt	SEM	Feeder design	DDGS	Gender	Feeder × Gender
HCW, kg	98.1	95.1	94.9	92.1	92.8	89.1	90.8	88.9	1.38	0.0001	0.03	0.004	---[3]
Yield, %	74.6	75.1	75.3	74.9	74.7	75.0	75.0	75.4	0.33	---	---	---	---
Backfat depth, mm	21.2	17.5	19.9	16.5	18.3	14.8	17.7	14.4	0.48	0.0001	0.01	0.0001	---
LM[4] depth, cm	5.92	6.05	5.90	5.90	5.98	6.22	5.91	6.02	0.116	---	---	---	---
Fat-free lean index	48.8	50.4	49.3	50.7	49.9	51.2	50.0	51.5	0.22	0.0001	0.07	0.0001	---
Jowl IV[5]													
d 78 (n = 72)	68.7	70.8	80.2	81.3	71.0	74.1	81.2	86.2	1.5	0.001	0.001	0.001	---
d 99 (n = 72)	70.3	73.8	79.3	81.4	72.0	75.0	81.0	82.9	1.2	0.05	0.001	0.001	---

[1]A total of 885 pigs (PIC 337 × 1050) were used to compare carcass characteristics of barrows and gilts fed 20% or 60% DDGS with either a conventional dry feeder with a cup waterer or a wet-dry feeder.

[2]There were no feeder × DDGS × gender, feeder × DDGS or DDGS × gender interactions (P > 0.05) observed for these criteria.

[3]Not significant (*P* > 0.15).

[4] LM = longissimus muscle.

[5]A DDGS × day interaction (P < 0.02) was observed for jowl IV. Jowl IV was greater on d 99 for pigs that were fed 20% DDGS throughout the experiment but was greater on d 78 for pigs fed 60% DDGS from d 0 to 78.

CHAPTER 3 - The effects of feeder design and adjustment strategies on the growth performance and carcass characteristics of growing-finishing pigs

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ABSTRACT

The objectives of this research were to compare the effects of a conventional dry (CD, 152.4 cm-wide, 5-space, Staco Inc., Schaefferstown, PA) and a wet-dry (WD, double-sided, each side = 38.1 cm space, Crystal Springs, GroMaster Inc., Omaha, NE) feeder using various feeder adjustment openings on the growth performance and carcass characteristics of growing-finishing pigs. Three experiments were conducted, with a completely randomized assignment of treatments to 48 pens of 26 or 27 pigs in each. In Exp. 1, 1,296 pigs (initial BW 19 kg) were used in a 27-d study to evaluate 3 feeder openings nested within each feeder design. The openings were ≈1.8-, ≈2.4-, and ≈3.1-cm for the CD feeder and 1.3-, 1.9-, and 2.5-cm for the WD feeder. From d 0 to 27, pigs fed with a WD feeder had similar ADG, but lower ($P < 0.02$) ADFI and better G:F, compared to pigs fed with a CD feeder. Increased adjustment opening increased (linear, $P < 0.01$) ADG and ADFI of pigs fed with a WD feeder, and increased (linear, $P < 0.01$) ADFI of pigs fed with a CD feeder. In Exp. 2, 1,248 pigs (initial BW 33 kg) were used to evaluate 3 feeder openings nested within each feeder design in a 93-d study. Openings for the CD feeder were the same as Exp. 1, and 1.9-, 2.5-, and 3.2-cm for the WD feeder. Pigs fed with a WD feeder had greater ($P < 0.05$) ADG, ADFI, final BW, HCW, and backfat, but decreased fat-free lean index (FFLI), compared with those fed with a CD feeder. Increased opening of the WD feeder resulted in greater (linear, $P < 0.05$) ADG, ADFI, HCW, and backfat, but lower FFLI. No differences among CD feeder openings were observed, and G:F was similar among all feeder treatments. In Exp. 3, 1,287 pigs (initial BW 38 kg) were used in a 92-d factorial experiment with 4 feeder treatments and 2 diet types. Feeder treatments were CD at ≈2.4-cm opening, WD at 3.2-cm opening, WD changed to 2.5-cm opening on d 56, and WD changed to 2.5-cm opening on d 28 and 1.9-cm opening on d 56. The 2 diet types were a corn-soybean meal-15% dried

distillers grains with solubles (DDGS) diet and a corn-25% DDGS-20% bakery by-product-soybean meal diet. Performance was similar among the 2 diet types. Pigs fed with a WD feeder had greater ($P < 0.01$) ADG, ADFI, HCW, and backfat, but decreased FFLI, than pigs fed with a CD feeder. Reducing the WD feeder opening during the study decreased ($P < 0.05$) ADG. Pigs with the WD feeder opening reduced to 1.9-cm had decreased ($P < 0.05$) ADFI and backfat, but increased FFLI, compared to pigs with a WD feeder opening of 3.2-cm. Feed efficiency was similar among treatments. In conclusion, ADG, ADFI, HCW, and backfat were increased with a WD feeder, but the growth of pigs fed with a WD feeder was more sensitive to differences in feeder adjustment than that of pigs fed with a CD feeder.

Key words: dry feeder, feeder adjustment, feeder design, finishing pigs, wet-dry feeder

INTRODUCTION

Previous research has demonstrated that, compared to a conventional dry feeder, a wet-dry feeder may increase the ADG and ADFI of finishing pigs (Amornthewaphat et al., 2000; Brumm et al., 2000; Gonyou and Lou, 2000). However, differences in G:F of pigs fed with dry and wet-dry feeders have not been as consistent. Experiments indicate that differences in pig performance might also be influenced by feeder adjustment (Smith et al., 2004; Duttlinger, et al. 2009). Feeder adjustment affects the ease or difficulty with which pigs are able to access feed from a feeder and feeding behaviors; which may also affect ADFI, ADG, G:F, and carcass backfat depth (Braude et al., 1959; Barber et al., 1972; Kanis, 1988). Differences in the amount of feed wasted can result from differences in feeder design, but reductions in ADFI and G:F can occur when the amount of effort required to obtain feed is increased (Morrow and Walker, 1994a; Gonyou, 1998).

Relatively little information is available to assist producers in determining the optimum adjustment of feeders with *ad libitum* feeding. Smith et al. (2004) and Duttlinger et al. (2009) have reported that a multiple-space, conventional dry feeder should be adjusted to provide feed covering approximately 40 to 75% and 61% of the bottom of the feed trough during nursery and finisher stages, respectively. Whether or not similar recommendations are appropriate for a wet-dry feeder has not been determined.

Therefore, we conducted 2 experiments to evaluate the effects of feeder adjustment with both a wet-dry feeder and a conventional dry feeder on the performance and carcass characteristics of growing-finishing pigs. A third experiment was conducted using 2 diet-types to determine if changing adjustment of the wet-dry feeder during growing-finishing would improve G:F and reduce backfat with a sustained improvement in ADG compared to pigs fed with a conventional dry feeder.

MATERIALS AND METHODS

Procedures used in the experiments were approved by the Kansas State University Institutional Animal Care and Use Committee.

Animal Care

The research was conducted in a commercial finishing research facility in southwestern Minnesota. The facility was double curtain sided with pit fans for minimum ventilation and completely slatted flooring over a deep pit for manure storage. Individual pens were 3.0 × 5.5 m. One half of the pens were equipped with a single-sided, 152.4-cm-wide, 5-hole, stainless steel dry feeder (Figure 3-1; STACO, Inc., Schaefferstown, PA) and 1 cup waterer in each pen. The remaining pens were each equipped with a double-sided, stainless steel wet-dry feeder (Figure 3-2; Crystal Springs, GroMaster, Inc., Omaha, NE) with a 38.1-cm-wide feeder opening on both

sides that provided access to feed and water, with water supplied from a single nipple waterer located under a feed 'shelf' located over the center of the feed pan. Every feeder was positioned along the fence-line with an adjacent pen.

Although the pens equipped with a wet-dry feeder also contained a cup waterer, these were shut off during the experiments. Therefore, the only source of water for pigs in these pens was through the wet-dry feeder. In addition, water was delivered to all the pens of each feeder design independently, and each of the 2 water lines was equipped with a single water meter to monitor total water disappearance for each feeder design.

Experiment 1

A total of 1,296 pigs (PIC 337 × 1050, Hendersonville, TN; initially 19 kg BW) were used in a 27-d experiment to evaluate the effects of feeder design (conventional dry vs. wet-dry feeder) and initial feeder adjustment on grower pig performance. Pigs were placed into pens of 27, with each pen consisting of 14 barrows and 13 gilts. Pens of pigs were weighed and allotted to the 2 feeder designs and 3 initial feeder openings within each feeder type. There were 24 pens per feeder design and 8 pens for each of the 3 feeder openings within each feeder type.

The 3 openings used for the wet-dry feeder were 1.3-, 1.9-, and 2.5-cm (Figures 3-3, 3-4, and 3-5). For the conventional dry feeder, the 'agitation plate' was designed so that it could be moved up and down by the pigs at any particular feeder setting, and provided for a range of opening (approximately 0.72-cm) for pigs to access feed. Therefore, the 3 openings used for the conventional dry feeder were ≈1.8-, ≈2.4-, and ≈3.1-cm (Figures 3-6, 3-7, and 3-8).

On d 19, measurements of the feeder opening were obtained for all feeders. For the wet-dry feeder, the mean gap opening for each feeder was determined with two measurements (one from each side of the feeder) from the top of the feeder shelf to the bottom edge of the feed

storage hopper. For the dry feeder, a narrow and wide measurement of the gap opening between the bottom of the feeder trough and bottom edge of the 'agitation plate' was obtained from each end of the feeder. Therefore, a mean narrow, mean wide, and mean overall gap opening were determined for each dry feeder. A digital photo of the trough of each feeder was also taken on d 19. Afterward, the pictures were independently scored for percentage trough coverage by a trained panel of 6 people. The mean trough coverage of each feeder was determined to evaluate the relationship between feeder opening and percentage feed coverage in the trough.

Pens of pigs were weighed and feed disappearance was measured on d 0, 13, and 27 to determine ADG, ADFI, G:F, and mean BW. All pigs were fed the same corn-soybean meal diets containing 15% DDGS (Table 3-1). The diet was formulated to meet or exceed the nutrient requirement estimates (NRC, 1998).

Experiment 2

A total of 1,248 pigs (PIC 337 × 1050, initially 33 kg BW) were used in a 93-d experiment to evaluate the effects of feeder design (conventional dry vs. wet-dry feeder) and adjustment on growing-finishing pig performance and carcass characteristics. Pigs were placed into pens of 26, with each pen consisting of 13 barrows and 13 gilts. Pens of pigs were weighed and allotted to the 2 feeder types and 3 feeder openings within each feeder type. There were 24 pens per feeder type and 8 pens for each of the 3 feeder openings within each feeder type.

The 3 openings used for the wet-dry feeders were 1.9-, 2.5-, and 3.2-cm (Figures 3-4, 3-5, and 3-9). The 3 openings used for the dry feeder were ≈1.8-, ≈2.4-, and ≈3.1-cm. The feeder opening treatments were maintained throughout the experiment (d 0 to 93).

Pens of pigs were weighed and feed disappearance was measured on d 0, 14, 28, 42, 58, 79, and 93 to determine ADG, ADFI, G:F, and mean BW. All pigs were fed the same corn-

soybean meal diets containing 15% DDGS during 4 dietary phases (Table 3-1). Diet phases were fed from d 0 to 14, d 14 to 42, d 42 to 72, and the final diet containing 5 ppm ractopamine HCl (Paylean, Elanco, Greenfield, IN) was fed from d 72 to 93. Diets were formulated to meet or exceed the nutrient requirement estimates of pigs during each diet phase (NRC, 1998).

On d 79, 3 pigs (2 barrows and 1 gilt) from each pen were weighed and removed for marketing. At the conclusion of the experiment on d 93, the remaining pigs were individually tattooed and shipped approximately 96 km to a commercial processing plant (Swift, Worthington, MN), where they were harvested and carcass data were obtained. Carcass data included HCW, carcass yield, and the backfat and longissimus muscle depth measurements; which were obtained by optical probe (Fat-O-Meater; SFK Technology A/S, Denmark) inserted between the 3rd and 4th rib from the last rib at 7 cm from the dorsal midline. The fat-free lean index (FFLI) was calculated according to National Pork Producers Council (2000) procedures.

On d 41 and 84, measurements of the feeder opening were obtained for all feeders as in Exp. 1, and a photo of the trough of each feeder was taken. As in Exp. 1, the pictures were scored for percentage trough coverage so that the relationship between feeder opening and feed coverage of the trough could be determined.

Experiment 3

A total of 1,287 pigs (PIC 337 × 1050, initially 38 kg BW) were used in a 92-d experiment to compare the effects of the conventional dry feeder, 3 wet-dry feeder adjustment strategies, and 2 diet types (in a 4 × 2 factorial arrangement of treatments) on growing-finishing pig performance and carcass characteristics. We hypothesized that a possible difference in the flow-ability of the 2 diet types might interact with feeder opening. There were 27 pigs per pen (13 or 14 barrows and 13 or 14 gilts) and 6 replications for each of the 8 treatments. To obtain an

equal number of replications across the 4 feeder treatments, 12 pens were equipped with the conventional dry feeder, and 36 pens were equipped with a wet-dry feeder to evaluate the 3 wet-dry feeder adjustment strategies.

The first wet-dry strategy consisted of maintaining an opening of 3.2-cm throughout the study. The second wet-dry strategy consisted of an initial opening of 3.2-cm until d 56, followed by a reduced opening of 2.5-cm for the remainder of the experiment. The third wet-dry strategy consisted of an initial opening of 3.2-cm until d 28, followed by an opening of 2.5-cm until d 56, and an opening of 1.9-cm for the remainder of the experiment. The conventional dry feeder was maintained at an opening of ≈2.4-cm throughout the study (Figure 3-10). Pen and feeder weights were measured on d 14, 28, 42, 56, 72, and 92 to determine ADG, ADFI, G:F, and mean BW.

The 2 diet types evaluated in this study were a corn-soybean meal-15% DDGS diet (CS) and a corn-25% DDGS-20% bakery by-product-soybean meal diet (BY). Both diets were fed over 4 dietary phases (Table 3-2). The 2 diets within each of the 4 feeding phases were formulated to a similar standardized ileal digestible lysine:ME ratio (g/Mcal). Digestibility values for AA were obtained from the NRC (1998) and used for all ingredients except DDGS and bakery by-product. For DDGS, AA digestibility values from Stein et al. (2006) were used. For the bakery by-product, the AA digestibility values from the NRC (1998) for soft, red winter wheat were used. An ME value of 3,420 kcal/kg was used for both corn and DDGS. All dietary nutrient levels were formulated to meet or exceed the requirement estimates of pigs for each diet phase (NRC, 1998).

On d 72, 3 pigs (2 barrows and 1 gilt) from each pen were weighed and removed for marketing. On d 94 (approximately 48 h after collecting the final pen weights), the remaining pigs were individually tattooed and shipped approximately 96 km to a commercial processing

plant (Swift, Worthington, MN), where they were harvested and carcass data were obtained similar to previously described in Exp. 2.

On d 20 and 83, measurements of the feeder opening were obtained for all feeders as in the previous experiments, and a photo of the trough of each feeder was taken and scored as described in Exp. 2.

Statistical Analysis

For both Exp. 1 and Exp. 2, data were analyzed as a completely randomized design using the PROC MIXED procedure of SAS (v. 8.2; SAS Institute Inc., Cary, NC) with the 3 feeder openings nested within each of the 2 feeder designs. Linear and quadratic polynomial contrasts were used to evaluate the effects of increasing the feeder opening within each feeder design. Pen served as the experimental unit. In Exp. 2, HCW was used as a covariate for the comparison of other carcass characteristics.

The data for Exp. 3 were analyzed as 4 × 2 factorial arrangement of treatments with 4 feeder treatments (1 dry feeder and 3 wet-dry feeder adjustment strategies) and the 2 diet types in a completely randomized design using the PROC MIXED procedure of SAS (v. 8.2; SAS Institute Inc., Cary, NC). Preplanned orthogonal contrasts were used to compare the overall effects of feeder design, as well as compare feeder adjustment strategies among pigs fed with the wet-dry feeder. Pen served as the experimental unit. Hot carcass weight was used as a covariate for the comparison of other carcass characteristics. For all analyses, differences with a *P*-value of less than 0.05 were considered to be statistically significant.

RESULTS

Experiment 1

The mean opening of the conventional dry feeder was greater ($P < 0.001$) than that of the wet-dry feeder on d 19 (Table 3-3). However, the percentage trough coverage of the conventional dry feeder was less ($P < 0.001$) than that of the wet-dry feeder. The openings of both feeder designs increased (linear, $P < 0.001$) with greater feeder adjustment setting. The openings achieved were 1.49 to 2.04-, 2.03 to 2.72-, and 2.76 to 3.44-cm for the conventional dry feeder and 1.27-, 1.91-, and 2.54-cm for the wet-dry feeder, respectively. The percentage trough coverage of the conventional dry feeder increased (quadratic, $P < 0.01$) with greater feeder opening, as did that of the wet-dry feeder (linear, $P < 0.001$).

From d 0 to 27, pigs fed with the wet-dry feeder had decreased ($P < 0.02$) ADFI and better G:F than pigs using the conventional dry feeder. Increased feeder opening of the wet-dry feeder increased (quadratic, $P < 0.02$) ADG, ADFI, and d-27 BW. Increased feeder opening of the conventional dry feeder also increased (linear, $P < 0.01$) ADFI.

Experiment 2

The mean openings of the conventional dry feeder and wet-dry feeder were the same on d 41 and 84 for each feeder setting (2.5-cm). The openings of both feeder types increased (Table 3-4; linear, $P < 0.001$) with greater feeder adjustment setting. The openings achieved were 1.47 to 2.08-, 2.11 to 2.84-, and 2.80 to 3.45-cm for the conventional dry feeder and 1.91-, 2.54-, and 3.18-cm for the wet-dry feeder. The percentage trough coverage for both feeder types increased (linear, $P < 0.001$) with greater feeder opening on both d 41 and 84. However, the percentage trough coverage of the conventional dry feeder was less ($P < 0.02$) than that of the wet-dry feeder on d 41, but they were not different on d 84.

Overall (d 0 to 93), pigs fed with the wet-dry feeder had increased ($P < 0.05$) ADG, ADFI, final BW, HCW, and backfat depth; but decreased ($P < 0.001$) FFLI; compared with pigs fed with the conventional dry feeder. Neither feeder type nor opening influenced overall G:F. Increased feeder opening of the wet-dry feeder also resulted in increased (linear, $P < 0.05$) ADG, ADFI, final BW, HCW, and backfat depth; but decreased ($P < 0.02$) FFLI. However, increasing the feeder opening of the conventional dry feeder had no effect on growth performance and carcass characteristics.

Experiment 3

The mean opening of the wet dry feeder was greater ($P < 0.001$) than that of the conventional dry feeder on d 20 and 83, but the mean opening of the conventional dry feeder was greater ($P < 0.05$) on d 83 than that of the wet-dry feeder with a reduced opening of 1.9-cm (Table 3-5). The mean opening of the wet-dry feeder decreased ($P < 0.05$) with each reduction in the mechanical setting, from 3.2-cm to 2.5-cm to 1.9-cm. There was a feeder design × diet type interaction ($P < 0.01$) observed for the percentage trough coverage on d 20. This occurred because trough coverage of the wet-dry feeder was relatively similar between the 2 diet-types, but trough coverage of the conventional dry feeder was considerably greater with the BY diet than with the CS diet. There were no differences in trough coverage on d 83, but the trough coverage for the wet-dry feeder with an opening of 1.9-cm and the conventional dry feeder were numerically lowest.

No feeder × diet type interactions observed for growth and carcass characteristics during the experiment. Overall growth performance and carcass characteristics of pigs fed the 2 diet-types were similar (data not shown). From d 0 to 28, pigs fed with the wet-dry feeder had greater

($P < 0.02$) ADG and ADFI than pigs fed with conventional dry feeder (Table 3-6). However, there were no differences in G:F or d-28 BW among treatments.

From d 28 to 56, all pigs fed using the wet-dry feeder continued to have greater ($P < 0.001$) ADG and ADFI compared with pigs fed using the conventional dry feeder, and the performance of pigs fed with a wet-dry feeder at a reduced opening of 2.5-cm remained similar to that of pigs fed with a wet-dry feeder opening of 3.2-cm. This resulted in a heavier ($P < 0.002$) d-56 BW for pigs fed with the wet-dry feeder compared with pigs fed using the conventional dry feeder. There were no differences in G:F among feeder treatments.

From d 56 to 92 and overall (d 0 to 92), all pigs fed using the wet-dry feeder had greater ($P < 0.001$) ADG, ADFI, and final BW than pigs fed with the conventional dry feeder. However, within the wet-dry feeder treatments, pigs fed using a wet-dry feeder with the opening reduced to 2.5-cm and 1.9-cm had decreased ($P < 0.05$) ADG compared to pigs using the wet-dry feeder with an opening maintained at 3.2-cm. Additionally, pigs fed using a wet-dry feeder with the opening reduced to 1.9-cm had decreased ($P < 0.05$) ADFI than that of pigs using the wet-dry feeder maintained at an opening of 3.2-cm. The ADFI of pigs fed using a wet-dry feeder with the opening reduced to 2.5-cm was intermediate. There were no differences in G:F among feeder treatments.

Pigs fed using the wet-dry feeder had greater ($P < 0.02$) HCW, carcass yield, and backfat depth than pigs fed with the conventional dry feeder, but loin depth of pigs fed with the wet-dry feeder was less ($P < 0.04$) than that of pigs fed with the dry feeder. The differences in backfat and loin depth resulted in pigs fed with the wet-dry feeder having lower ($P < 0.001$) FFLI than pigs fed with the dry feeder. However, within the wet-dry feeder treatments, pigs fed with a feeder opening reduced to 1.9-cm had decreased ($P < 0.05$) backfat depth and increased ($P <$

0.05) FFLI compared to those fed with a feeder opening maintained at 3.2-cm. The backfat depth and FFLI of pigs fed using the wet-dry feeder with a final opening of 2.5-cm were intermediate.

DISCUSSION

As demonstrated in previous studies with growing-finishing pigs fed meal diets *ad libitum*; ADG, ADFI, and final BW were generally improved for pigs fed with a wet-dry feeder (Amornthewaphat et al., 2000; Brumm et al., 2000; Gonyou and Lou, 2000). However, the magnitude of differences in ADG and final BW (compared to a dry feeder) within various studies appears to be dependent on the differences in ADFI and G:F. These can be influenced by other feeder design features (Baxter, 1991; Lou and Gonyou, 1997), the number of pigs per feeder space (Walker, 1990; Morrow and Walker, 1994b), the size and age of the pigs, and the association of these variables with feeding behavior (Hyun et al., 1997; Gonyou and Lou, 2000).

The current studies were performed specifically to evaluate the effects of different feeder openings (settings) of the dry and wet-dry feeder design on the performance and carcass characteristics of pigs in a commercial research barn. The mechanical adjustment of the feeder opening is the only feature of a feeder that can be readily changed. Presumably, the feeder opening is designed to be adjustable so that it can accommodate differences in the flowability of feeds and provide unrestricted access to feed with little wastage. However, despite an emphasis placed on feeder adjustment to obtain the best possible feed efficiency, relatively little data are available to establish recommendations for an ‘ideal’ feeder adjustment.

The settings evaluated for the conventional dry feeder in Exp. 1 and 2 were selected to validate results previously obtained at the same facility by Duttlinger et al. (2009), but for lighter pigs (Exp. 1) and for a longer duration (Exp. 2). After 2 experiments, Duttlinger et al. (2009) concluded that the ‘ideal’ feeder setting provided feed covering slightly more than half of the

bottom of the feed trough, regardless of diet type. In their experiments, the difference in ADG between a trough coverage of 45 to 70% and a trough coverage of >70% were minimal, and ADFI was the only criteria that increased consistently with each increase of the feeder opening in both experiments. Feed efficiency was numerically the best with a trough coverage of 45 to 70% in their experiments, with slightly poorer G:F at a trough coverage < 45% and > 70%, corresponding to a 2.0- to 2.9-cm gap opening.

Myers et al. (2010a) compared 3 feeder settings with a dry feeder, which were obtained by adjusting the feeder agitation plate to a minimum opening of 1.27-, 1.91-, or 2.54-cm. Similar to the dry feeder used in the current studies, the agitation plate was designed so that it could be moved precisely 0.64-cm upward, which provided a range of opening for pigs to access feed. They reported ADG and ADFI responses similar to that observed by Duttlinger et al. (2009), but G:F was best at the lowest opening (1.27- to 1.91-cm). Based on numerically greater ADG from d 0 to 28 (41 to 68 kg) and improved G:F from d 28 to 89 (68 to 128 kg), they suggested that the optimum feeder opening may change during the finisher phase. They indicated that a trough coverage of approximately 58% (1.91- to 2.54-cm opening) for pigs up to 68 kg, followed by a reduced trough coverage of approximately 28% (1.27- to 1.91-cm opening), might provide the best overall performance. However, they used a dry feeder with 2 feeding spaces and 3 or 4 pigs per feeder space (approximately 8.9-cm linear trough space/pig). In another experiment, Myers et al. (2010b) compared a narrow feeder opening (1.27- to 1.91-cm) to a wide opening (2.54- to 3.18-cm opening) at two trough densities (4.4-cm vs. 8.9-cm linear trough space/pig) from 37 kg to 129 kg BW. Although ADG was not different, pigs fed at the narrow opening had reduced ADFI and better G:F. This was associated with 42.9% trough coverage at the greater trough

density and 54.1% trough coverage at the lower trough density, compared to corresponding trough coverage's of 83.3% and 86.5% at the wide opening.

Similar to the previous experiments, an increased feeder opening of the conventional dry feeder in Exp. 1 and 2 did not result in appreciable differences in the ADG of growing-finishing pigs. Collectively, however, these experiments imply that a trough coverage of approximately 30 to 50% for pigs > 70 kg, and 50 to 70% for pigs < 70 kg, will provide sufficient access to feed for growth with a dry self-feeder; but that exceeding this range could result in poorer G:F. Therefore, an opening of 1.9- to 2.7-cm was used for the conventional dry feeder in Exp. 3, which served as a control treatment for the evaluation of wet-dry feeder management strategies.

These experiments demonstrate a contrast in the response to different feeder openings with the conventional dry and wet-dry feeder. In both Exp. 1 and 2, increasing the opening of the wet-dry feeder resulted in greater ADG, ADFI, and final BW. Increasing the feeder opening of the dry feeder failed to improve ADFI and ADG to that obtained with the wet-dry feeder at increased openings. This implies that the presentation of feed and water together might be required for any further increase in ADFI and ADG, and that decreased settings of the wet-dry feeder successfully limited the accessibility of feed and reduced ADFI and ADG.

The manner that pigs were able to obtain access to feed from each of the feeder designs also may have caused differences in the sensitivity of pig performance to the feeder openings. With the conventional dry feeder design, each feeder setting provided a range of opening with a hanging, stainless steel agitation plate that pigs could manipulate to access feed. The wet-dry feeder design utilized an adjustable feed shelf located above the feed trough, and each feeder setting provided a precise, fixed opening from which feed could be accessible.

In Exp. 1, pigs fed using the wet-dry feeder at the lowest opening (1.27-cm opening) from d 0 to 27 had reduced ADG and ADFI. This was potentially associated with the observation that the feeder opening for this feeder treatment was frequently plugged during the first 10 d of the experiment, but this problem had abated by the time that trough coverage was evaluated on d 19. The ADG and ADFI of pigs using the wet-dry feeder at the 1.91-cm and 2.54-cm openings were only slightly greater than that of pigs fed with the dry feeder, but G:F was improved. As a result; when all pigs fed with the wet-dry feeder were compared to those fed with the dry feeder; ADG was similar, ADFI was reduced, and G:F was improved for pigs fed with the wet-dry feeder. In an earlier experiment initiated at a heavier BW (initially 32 kg BW; J. R. Bergstrom, 2011), pigs fed with the wet-dry feeder (3.18-cm gap opening) had slightly greater ADG, similar ADFI, and a tendency for improved G:F during the first 2 wk when compared to those using the conventional dry feeder. Similar to other studies, the magnitude of differences in ADG and ADFI between the wet-dry and dry feeder were greater during later periods of growth. Differences (or changes) in feeding behavior, such as a faster eating rate and reduced time budget for feeding, might be responsible for the improved G:F in the early growing-finishing period when pigs were placed on the wet-dry feeder (Gonyou and Lou, 2000; J. R. Bergstrom, 2011). The numeric improvements in overall G:F that were associated with a reduced wet-dry feeder opening in Experiments 2 and 3 indicates that this type of feeder management strategy may be particularly important during the late finishing stages.

Differences in the backfat depth and FFLI of pigs fed with the wet-dry feeder and dry feeder are also consistent with earlier research. The linear reduction in backfat depth and concomitant increase in FFLI observed with decreased wet-dry feeder openings indicates that the differences observed between pigs using the 2 feeder designs are related to the differences in

ADG and ADFI (Braude et al., 1959; Barber et al., 1972; Kanis, 1988). Although the backfat depth and FFLI of pigs fed using a reduced wet-dry feeder opening in Experiments 2 and 3 were still poorer than that obtained with the dry feeder, these data demonstrated that (with *ad libitum* feeding) feeder management strategies can be used to manipulate the growth and carcass characteristics of growing-finishing pigs fed with the wet-dry feeder.

The carcass yield differences observed between pigs fed with the wet-dry and dry feeder in Exp. 3 likely resulted from differences in the amount of time that feed was withheld before their arrival at the processor for harvest, which occurred after weighing pigs at the farm. The wet-dry feeder had substantially less feed storage capacity (≈134 kg less) than the conventional dry feeder. Although the withholding of feed was preplanned to reduce unnecessary feed wastage, the differences in feeder capacity and inherent differences in ADFI were not fully accounted for. It was estimated that pigs fed with the wet-dry feeder were withheld from feed for approximately 27 h prior to harvest, whereas pigs fed with the dry feeder were withheld from feed for approximately 15 h prior to harvest.

In conclusion, pigs fed with a wet-dry feeder had greater ADG, ADFI, final BW, HCW, and backfat, but reduced FFLI, compared to pigs fed with a conventional dry feeder. Although lighter BW pigs in Exp.1 had improved G:F with a wet-dry feeder, the G:F was similar when the initial BW was >33 kg. Using different feeder openings for the conventional dry feeder did not result in appreciable differences in overall growth performance or carcass characteristics. Trough coverage of 30 to 50% for pigs > 70 kg, and 50 to 70% for pigs < 70 kg, appears to be optimal for a conventional dry feeder. Contrary to the results obtained with the dry feeder, the growth performance and carcass characteristics of pigs fed with a wet-dry feeder were significantly influenced by differences in the feeder opening. An increased feeder opening of the wet-dry

feeder resulted in further increases in ADG, ADFI, final BW, HCW, and backfat, but decreased FFLI. Numerical improvements in G:F were associated with decreased openings of the wet-dry feeder. Staged reductions in the wet-dry feeder opening during growth resulted in a final BW similar to that obtained when the wet-dry feeder remained at a constant opening; but the overall feed intake was reduced and carcass characteristics improved. Regardless of diet type, the optimal trough coverage for the wet-dry feeder appeared to be approximately 65 to 85% for pigs up to 90 kg. Thereafter, reduced trough coverage of approximately 50 to 65% appeared optimal to decrease unnecessary feed utilization and improve the percentage carcass lean.

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Figure 3-1. Conventional dry feeder with cup waterer.

Figure 3-2. Wet-dry feeder.

Note: the cup waterer was shut-off so that the only source of water was through the feeder

Figure 3-3. Wet-dry feeder with a 1.27-cm opening (setting 6) and ≈35% trough coverage.

Figure 3-4. Wet-dry feeder with a 1.91-cm opening (setting 10) and ≈57% trough coverage.

Figure 3-5. Wet-dry feeder with a 2.54-cm opening (setting 14) and ≈65% trough coverage.

Figure 3-6. Conventional dry feeder with a 1.49- to 2.04-cm opening (setting 6) and ≈9% trough coverage.

Figure 3-7. Conventional dry feeder with a 2.03- to 2.72-cm opening (setting 8) and ≈21% trough coverage.

Figure 3-8. Conventional dry feeder with a 2.76- to 3.44-cm opening (setting 10) and ≈79% trough coverage.

Figure 3-9. Wet-dry feeder with a 3.18-cm opening (setting 18) and ≈84% trough coverage.

Figure 3-10. Conventional dry feeder with a 2.11- to 2.84-cm opening (setting 8) and ≈57% trough coverage.

Table 3-1. Diet composition, Exp. 1 & 2

	Dietary phase[1]			
Item	23 to 45 kg	45 to 73 kg	73 to 102 kg	102 kg to mkt.
Ingredient, %				
Corn	61.46	66.53	71.45	63.35
Soybean meal, 46.5% CP	21.43	16.64	11.85	19.80
DDGS[2]	15.00	15.00	15.00	15.00
Monocalcium P, 21% P	0.15	---	---	---
Limestone	1.00	0.95	0.90	1.00
Salt	0.35	0.35	0.35	0.35
Liquid lysine, 60%	0.45	0.40	0.35	0.35
L-Threonine	0.05	0.03	0.01	0.01
VTM + phytase[3]	0.11	0.10	0.09	0.085
Ractopamine HCl, 20 g/kg[4]	---	---	---	0.025
Total	100.00	100.00	100.00	100.00
Calculated analysis				
Standardized ileal digestible (SID) amino acids				
Lys, %	1.05	0.90	0.75	0.95
Ile:lys, %	64	66	69	68
Leu:lys, %	158	172	191	170
Met:lys, %	28	30	33	30
Met & Cys:lys, %	57	62	68	61
Thr:lys, %	62	63	64	62
Trp:lys, %	17	17	17	18
Val:lys, %	75	79	84	80
CP, %	19.3	17.5	15.7	18.7
Total lys, %	1.19	1.03	0.87	1.09
ME, kcal/kg	3,358	3,366	3,371	3,364
SID lys:ME, g/Mcal	3.13	2.67	2.23	2.82
Ca, %	0.50	0.44	0.41	0.47
P, %	0.46	0.41	0.39	0.42
Available P, %	0.29	0.25	0.23	0.21

[1] Each dietary phase was formulated to meet the requirements for the BW ranges described in the table.
[2] Dried distillers grains with solubles.
[3] VTM = Vitamin and trace mineral premix. Phytase provided 0.12% available P.
[4] Paylean, Elanco Animal Health, Greenfield, IN.

Table 3-2. Diet composition, Exp. 3

	Dietary phase[1]							
	36 to 59 kg		59 to 84 kg		84 to 107 kg		107 kg to mkt.	
Item	CS[2]	BY[2]	CS	BY	CS	BY	CS	BY
Ingredient, %								
Corn	65.02	37.31	68.51	40.74	72.14	44.45	63.30	35.62
Soybean meal, 46.5% CP	17.80	15.60	14.60	12.25	11.05	8.60	19.80	17.35
DDGS[3]	15.00	25.00	15.00	25.00	15.00	25.00	15.00	25.00
Bakery by-product	---	20.00	---	20.00	---	20.00	---	20.00
Monocalcium P, 21% P	0.15	---	---	---	---	---	---	---
Limestone	1.00	1.00	0.95	1.00	0.95	1.00	1.00	1.05
Salt	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Lysine sulfate	0.54	0.62	0.48	0.56	0.42	0.51	0.42	0.51
L-Threonine	0.03	0.01	0.01	---	---	---	0.01	---
VTM + phytase[4]	0.11	0.11	0.10	0.10	0.09	0.09	0.09	0.09
Ractopamine HCl, 20 g/kg[5]	---	---	---	---	---	---	0.025	0.025
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis								
Standardized ileal digestible (SID) amino acids								
Lys, %	0.96	0.98	0.85	0.86	0.73	0.74	0.95	0.96
Ile:lys, %	64	66	66	69	69	72	68	70
Leu:lys, %	164	169	176	183	194	201	171	177
Met:lys, %	29	30	31	33	34	36	30	32
Met & Cys:lys, %	59	62	63	67	69	74	62	65
Thr:lys, %	60	60	62	62	63	66	62	63
Trp:lys, %	17	17	17	17	17	17	18	18
Val:lys, %	76	79	80	83	85	88	80	83
CP, %	17.9	19.4	17.1	18.5	15.7	17.1	19.0	20.4
Total lys, %	1.10	1.13	0.98	1.01	0.85	0.88	1.09	1.12
ME, kcal/kg	3,360	3,422	3,371	3,428	3,373	3,428	3,366	3,424
SID lys:ME, g/Mcal	2.86	2.86	2.52	2.52	2.16	2.17	2.82	2.81
Ca, %	0.49	0.48	0.44	0.47	0.42	0.46	0.47	0.50
P, %	0.44	0.44	0.40	0.43	0.39	0.41	0.42	0.45
Available P, %	0.28	0.29	0.25	0.26	0.23	0.25	0.21	0.26

[1] Each dietary phase was formulated to meet the requirements for the BW ranges described in the table.
[2] CS = Corn-soybean meal-15% dried distillers grains with solubles (DDGS), BY = Corn-DDGS-bakery by-product-soybean meal.
[3] Dried distillers grains with solubles.
[4] VTM = Vitamin and trace mineral premix. Phytase provided 0.07 to 0.12% available P.
[5] Paylean, Elanco Animal Health, Greenfield, IN.

Table 3-3. Effects of feeder design and initial feeder setting on the trough coverage and growth performance of grower pigs, Exp. 1

	Feeder design							*P* <			
	Wet-dry			Conventional dry					Wet-dry		Conventional dry	
Initial feeder opening, cm:	1.3	1.9	2.5	≈1.8	≈2.4	≈3.1	SEM	Feeder type	linear	quadratic	linear	quadratic
Feeder data, d 19[1]												
Maximum opening, cm[2]	1.27	1.91	2.54	2.04	2.72	3.44	0.058	0.0001	0.0001	---[3]	0.0001	---
Minimum opening, cm[4]	1.27	1.91	2.54	1.49	2.03	2.76	0.068	0.01	0.0001	---	0.0001	---
Avg. opening, cm	1.27	1.91	2.54	1.77	2.37	3.10	0.061	0.0001	0.0001	---	0.0001	---
Trough coverage, %	34.9	57.3	64.5	9.0	21.1	79.0	5.70	0.01	0.001	---	0.0001	0.01
Live performance												
d 0 to 27												
ADG, kg	0.59	0.71	0.75	0.66	0.68	0.69	0.012	---	0.0001	0.01	---	---
ADFI, kg	1.07	1.28	1.34	1.22	1.26	1.30	0.016	0.02	0.0001	0.001	0.01	---
G:F	0.55	0.55	0.56	0.54	0.54	0.53	0.006	0.01	---	---	---	---
d 27 BW, kg	35.2	38.5	39.7	37.3	37.8	38.1	0.33	---	0.0001	0.02	---	---

[1] A total of 1,296 pigs with an initial BW of 19.4 kg were placed in 48 pens containing 27 pigs each.
[2] Measured from the bottom of the feed pan (dry) or shelf (wet-dry) to the bottom of the feed agitation plate (dry) or feeder hopper (wet-dry) at the narrowest position.
[3] Not significant ($P > 0.05$).
[4] Measured from the bottom of the feed pan (dry) or shelf (wet-dry) to the bottom of the feed agitation plate (dry) or feeder hopper (wet-dry) at the widest position.

Table 3-4. Effects of feeder design and feeder setting on the trough coverage, growth performance, and carcass characteristics of growing-finishing pigs, Exp. 2

	Feeder design							*P* <			
	Wet-dry			Conventional dry					Wet-dry		Conventional dry	
Initial feeder opening, cm:	1.9	2.5	3.2	≈1.8	≈2.4	≈3.1	SEM	Feeder type	linear	quadratic	linear	quadratic
Feeder data[1]												
Maximum opening[2], cm	1.91	2.54	3.18	2.08	2.84	3.45	0.058	0.001	0.001	---[3]	0.001	---
Minimum opening[4], cm	1.91	2.54	3.18	1.47	2.11	2.80	0.068	0.001	0.001	---	0.001	---
Avg. opening, cm	1.91	2.54	3.18	1.78	2.47	3.13	0.059	---	0.001	---	0.001	---
d 41 trough coverage, %	52.5	63.1	84.9	23.6	58.4	83.0	5.85	0.02	0.001	---	0.001	---
d 84 trough coverage, %	52.9	72.0	82.3	40.4	66.3	83.0	5.87	---	0.001	---	0.001	---
Live performance, d 0 to 93												
ADG, kg	0.94	0.97	1.01	0.89	0.92	0.92	0.017	0.0001	0.01	---	---	---
ADFI, kg	2.51	2.64	2.77	2.38	2.45	2.42	0.067	0.0001	0.01	---	---	---
G:F	0.38	0.37	0.36	0.37	0.38	0.38	0.008	---	---	---	---	---
Final BW, kg	119.3	121.8	126.1	114.5	117.7	117.8	2.51	0.01	0.05	---	---	---
Carcass characteristics[5]											---	---
HCW, kg	87.2	89.8	92.7	85.5	87.3	87.8	1.80	0.05	0.04	---	---	---
Backfat depth, mm	16.9	17.1	18.3	16.5	16.3	16.2	0.38	0.001	0.02	---	---	---
Loin depth, cm	6.18	6.16	6.09	6.13	6.11	6.03	0.135	---	---	---	---	---
FFLI[6]	50.2	50.1	49.5	50.4	50.5	50.5	0.19	0.001	0.02	---	---	---

[1] A total of 1,248 pigs with an initial BW of 33.1 kg were placed in 48 pens containing 26 pigs each.

[2] Measured from the bottom of the feed pan (dry) or shelf (wet-dry) to the bottom of the feed agitation plate (dry) or feeder hopper (wet-dry) at the narrowest position.

[3] Not significant ($P > 0.05$).

[4] Measured from the bottom of the feed pan (dry) or shelf (wet-dry) to the bottom of the feed agitation plate (dry) or feeder hopper (wet-dry) at the widest position.

[5] A total of 1,021 pigs were used to determine the carcass characteristics of the feeder treatments. Hot carcass weight was used as a covariate in the analysis of other carcass characteristics.

[6] FFLI = fat-free lean index.

Table 3-5. Effect of feeder design, diet-type, and changing the feeder setting of a wet-dry feeder on feeder gap opening and trough coverage during the growing-finishing period, Exp. 3

Feeder design[1]:	Wet-dry						Conventional dry						
Feeder opening strategy, cm:	3.2		3.2 - 2.5		3.2 - 2.5 - 1.9		≈2.4			*P* <			
Diet-type[2]:	CS	BY	CS	BY	CS	BY	CS	BY	SEM	Feeder design × diet type	Feeder design	Diet type	Wet-dry opening
Feeder data	3.2-cm		2.5-cm		1.9-cm								
Maximum opening, cm[3,4]	3.18[a]		2.54[b]		1.91[c]		2.71[d]		0.070	N/A[5]	0.001	N/A	0.001
Minimum opening, cm[6]	3.18[a]		2.54[b]		1.91[c]		1.88[c]		0.085	N/A	0.001	N/A	0.001
Avg. opening, cm	3.18[a]		2.54[b]		1.91[c]		2.30[d]		0.076	N/A	0.001	N/A	0.001
d 20 trough coverage, %	73	80	N/A	N/A	N/A	N/A	41	86	7.0	0.01	---[7]	0.001	N/A
d 83 trough coverage, %	76	89	78	84	64	62	58	69	10.1	---	---	---	---

[1] A total of 24 pens containing 27 pigs each were used, with 6 pens containing the conventional dry feeder and 18 pens containing the wet-dry feeder.
[2] CS = corn-soybean meal-15% dried distillers grains with solubles (DDGS), BY = corn-soybean meal-25% DDGS-20% bakery by-product.
[3] Means within a row with different superscripts differ ($P < 0.05$).
[4] Measured from the bottom of the feed pan (dry) or shelf (wet-dry) to the bottom of the feed agitation plate (dry) at the narrowest position or feeder hopper (wet-dry).
[5] N/A = not applicable.
[6] Measured from the bottom of the feed pan (dry) or shelf (wet-dry) to the bottom of the feed agitation plate (dry) at the widest position or feeder hopper (wet-dry).
[7] Not significant ($P > 0.05$).

Table 3-6. Effects of feeder design and changing the feeder setting of a wet-dry feeder on the growth performance and carcass characteristics of growing-finishing pigs, Exp. 3

Feeder design:	Wet-dry			Dry		*P* <	
Feeder opening strategy, cm:	3.2	3.2 - 2.5	3.2 - 2.5 - 1.9	≈2.4	SEM	Feeder design	Wet-dry setting
Live performance[1]							
d 0 to 28 feeder opening, cm:	3.2	3.2	3.2	≈2.4			
ADG, kg	0.97	0.95	0.95	0.90	0.012	0.001	N/A[2]
ADFI, kg	2.12	2.13	2.13	2.06	0.025	0.02	N/A
G:F	0.45	0.44	0.45	0.44	0.004	---[3]	N/A
d 28 BW, kg	64.5	63.8	64.3	62.9	0.93	---	N/A
d 28 to 56 feeder opening, cm:	3.2	3.2	2.5	≈2.4			
ADG, kg	0.99	0.98	0.99	0.89	0.011	0.001	---
ADFI, kg	2.89	2.84	2.83	2.56	0.033	0.001	---
G:F	0.34	0.35	0.35	0.35	0.003	---	---
d 56 BW, kg	92.4	91.3	92.1	87.7	1.07	0.002	---
d 56 to 92 feeder opening, cm:	3.2	2.5	1.9	≈2.4			
ADG[4], kg	1.15[a]	1.10[b]	1.08[b]	1.04[c]	0.014	0.001	0.05
ADFI, kg	3.27[a]	3.16[ab]	3.05[b]	2.93[c]	0.039	0.001	0.05
G:F	0.35	0.35	0.36	0.35	0.003	---	---
Overall (d 0 to 92)							
ADG, kg	1.04[a]	1.01[b]	1.01[b]	0.95[c]	0.008	0.001	0.05
ADFI, kg	2.79[a]	2.74[ab]	2.70[b]	2.54[c]	0.028	0.001	0.05
G:F	0.37	0.37	0.38	0.37	0.003	---	---
Final BW, kg	132.5[a]	129.1[a]	129.8[a]	123.4[b]	1.25	0.001	---
Carcass characteristics[5]							
HCW, kg	95.1[a]	93.2[a]	94.2[a]	89.9[b]	1.11	0.01	---
Yield, %[6]	76.5[ab]	76.7[a]	76.9[a]	75.9[b]	0.26	0.02	---
Backfat depth, mm	19.5[a]	19.2[ab]	18.6[b]	17.6[c]	0.30	0.001	0.05
Loin depth, cm	6.32[ab]	6.27[a]	6.35[ab]	6.54[b]	0.085	0.04	---
FFLI[7]	49.3[a]	49.4[ab]	49.7[b]	50.2[c]	0.14	0.001	0.05

[1] A total of 1,287 pigs with an initial BW of 37.5 kg were placed in 48 pens containing 27 pigs each.
[2] N/A = not applicable.
[3] Not significant ($P > 0.05$).
[4] Means within a row with different superscripts differ ($P < 0.05$).
[5] On d 94, carcass data were obtained for 1,097 pigs. Hot carcass weight was used as a covariate for comparison of backfat depth, loin depth, and FFLI.
[6] Yield differences likely reflect differences in the time that feed was withheld prior to harvest, and the associated effects on differences in BW and HCW determined by the processor. This resulted from differences in feed storage capacity between the 2 feeder designs.
[7] FFLI = fat-free lean index.

CHAPTER 4 - The effects of feeder design and changing the source of water to a location separate from the wet-dry feeder at 4 or 8 weeks prior to harvest on the growth, feeding behavior, and carcass characteristics of finishing pigs

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ABSTRACT

Our objectives were to compare a conventional dry (CD, 152.4 cm-wide, 5-space, STACO Inc., Schaefferstown, PA) and a wet-dry (WD, double-sided, each side = 38.1 cm space, Crystal Springs, GroMaster Inc., Omaha, NE) feeder, and determine if changing the source of water to a location separate from a wet-dry feeder during the finishing period would result in improved G:F and carcass characteristics. A total of 1,296 pigs (PIC, 337 × 1050; initially 19.4 kg BW) were used, with 27 pigs per pen (14 barrows and 13 gilts) and 24 pens per feeder design. Pigs were fed identical corn-soybean meal diets with 15% dried distillers' grains with solubles (DDGS). Pens with a WD feeder had a separate cup waterer, but the feeder provided the sole water source until d 69. The water supply to the WD feeder was shut-off in 8 pens on d 69 (WD69) and another 8 pens on d 97 (WD97), and the cup waterer was turned-on. For the remaining 8 pens, the WD feeder provided the sole water source for the entire experiment (WD124). From d 0 to 69, pigs fed with the WD feeder had increased ($P < 0.05$) ADG, ADFI, G:F, and d 69 BW compared to those using the CD. Overall (d 0 to 124), pigs using WD124 had greater ($P < 0.05$) ADG, ADFI, final BW, and HCW than all other treatments. Pigs fed with WD97 had greater ($P < 0.05$) ADG than pigs that used a CD feeder, with WD69 being intermediate. Pigs using WD97 had greater ($P < 0.05$) ADFI than WD69, with CD being intermediate. Pigs fed with WD124 had poorer ($P < 0.05$) G:F than WD69, and pigs using WD97 and CD were intermediate. Backfat depth of pigs using WD69 was reduced ($P < 0.05$) compared to all other treatments, and LM depth was greater ($P < 0.05$) than that of pigs using a CD feeder and WD97. The LM depth of pigs using WD124 was also greater ($P < 0.05$) than that of pigs fed with the CD feeder. The fat-free lean index of pigs using WD69 was greater ($P < 0.05$) than WD97, and pigs that used the CD feeder and WD124 were intermediate. Pigs fed using the WD

feeder visited the feeder less frequently ($P < 0.05$) and spent less total time at the feeder ($P < 0.05$) than those fed with the CD feeder. These differences in feeding pattern remained even after the access to water was removed from the WD feeder, with no change in the amount of aggressive behavior observed at the feeder. In conclusion, pigs fed with a WD feeder had increased growth rate compared with a CD feeder. Although measures of carcass leanness were improved by changing the location of the water, removing the water from the feeder also eliminated any net improvement in BW from using a WD feeder.

Key words: dry feeder, feeding behaviors, finishing pig, growth, water, wet-dry feeder

INTRODUCTION

Previous research has demonstrated that a wet-dry feeder may increase the ADG and ADFI of finishing pigs when compared to a conventional dry feeder, (Amornthewaphat et al., 2000a; Brumm et al., 2000; and Gonyou and Lou, 2000). However, differences in the G:F and carcass characteristics of pigs fed with dry and wet-dry feeders have not been as consistent. Comparing 12 different *ad libitum* feeders (6 dry and 6 wet-dry), Gonyou and Lou (2000) found increased ADG and ADFI, and lower carcass lean percent with wet-dry feeders, with no differences in G:F. Brumm et al. (2000) also observed greater ADG and ADFI with a wet-dry feeder, but reported lower G:F with no differences in percentage carcass lean.

Differences in the G:F of pigs using different feeder designs are usually attributed to differences in feed wastage, which is influenced by feeder design, presence of water, number of pigs and feeding spaces, pig size and age, feeder adjustment, and associated feeding behaviors (Baxter, 1991; Lou and Gonyou, 1997). However, greater ADFI and ADG of pigs throughout the finishing period can also result in differences in G:F and increased backfat depth (Barber et al., 1972; Kanis, 1988; Morrow and Walker, 1994). Recent studies indicate that the differences in

G:F and carcass lean between pigs fed with a wet-dry feeder and dry feeder may be related to the differences in ADFI and ADG, particularly when pigs are fed to a heavier BW (Bergstrom, J. R., 2011).

Similar to the feeding space requirements suggested by Gonyou and Lou (2000), Amornthewaphat et al. (2000b) reported that using a single-space wet-dry feeder as a dry feeder (with water provided separately) for 12 pigs resulted in performance similar to that obtained with a two-space, conventional dry feeder from 54 to 115 kg BW. Collectively, it appears that using a wet-dry feeder may provide greater benefits for growth early in the finishing period, but the possibility of using the same feeder and changing the presentation of feed from wet-dry to dry during the late finishing period may improve the efficiency of growth.

Therefore, our objectives were to determine if changing the source of water to a location separate from the wet-dry feeder at 4 or 8 weeks before harvest would improve feed efficiency and carcass characteristics of pigs fed with a wet-dry feeder, while sustaining an improvement in overall ADG compared to pigs fed with a dry feeder.

MATERIALS AND METHODS

Procedures used in this experiment were approved by the Kansas State University Institutional Animal Care and Use Committee.

Animal Care

The research was conducted in a commercial finishing research facility in southwestern Minnesota. The facility was double curtain sided with pit fans for minimum ventilation and completely slatted flooring over a deep pit for manure storage. Pens were 3.0 × 5.5 m, with half of the pens equipped with a single-sided, 152.4-cm-wide, 5-hole, stainless steel dry feeder (STACO, Inc., Schaefferstown, PA) and 1 cup waterer. The remaining pens were each equipped

with a double-sided, stainless steel wet-dry feeder (Crystal Springs, GroMaster, Inc., Omaha, NE) with a 38.1-cm-wide feeder opening on both sides that provided access to feed and water, with water supplied from a single nipple waterer located under a feed 'shelf' located over the center of the feed pan. Wet-dry feeders were positioned along the fence-line with both feeder openings accessible to pigs within the same pen.

All pens equipped with a wet-dry feeder also contained a cup waterer. Both sources of water for these pens were equipped with individual shut-off valves so that the water source could be controlled. The cup waterer in the pens containing a wet-dry feeder was shut-off at the beginning of the experiment. From d 0 to 69, the only source of water for pigs in these pens was through the wet-dry feeder. In addition, water was delivered to all the pens of each feeder design independently, and each of the 2 water lines was equipped with a single water meter to monitor total water disappearance for each feeder design.

Data Collection

Growth

A total of 1,296 pigs (PIC 337 × 1050, Hendersonville, TN; initially 19.4 kg BW) were used to evaluate the effects of feeder design (conventional dry vs. wet-dry feeder) and changing the source of water from a wet-dry feeder to a location separate from the feeder during the late-finishing period on pig performance. Pigs were placed into pens of 27, with each pen consisting of 14 barrows and 13 gilts. Pens of pigs were weighed and allotted to one of the 2 feeder designs. There were 24 pens per feeder design with 8 pens used for each of the water-source treatments within the wet-dry feeder.

On d 69, the water source at the wet-dry feeder was shut-off and the cup waterer turned-on in 8 of the pens with a wet-dry feeder. This process was repeated with an additional 8 pens

equipped with a wet-dry feeder on d 97. For the remaining 8 pens with a wet-dry feeder, the feeder provided the sole source of water for the entire experiment.

Pens of pigs were weighed and feed disappearance was measured on d 0, 14, 28, 42, 56, 69, 97, and 124 to determine ADG, ADFI, G:F, and mean BW. All pigs were fed the same corn-soybean meal diets containing 15% DDGS during 4 dietary phases from d 0 to 39, d 39 to 69, d 69 to 97, and d 97 to 124, respectively (Table 4-1). During the last dietary phase, the diet contained 5 ppm of ractopamine HCl. All diets were formulated to meet or exceed the nutrient requirement estimates of pigs during each diet phase (NRC, 1998).

On d 104, 3 pigs (2 barrows and 1 gilt) from each pen were weighed and removed for marketing. At the conclusion of the experiment on d 124, the remaining pigs were individually tattooed and shipped approximately 96 km to a commercial processing plant (Swift, Worthington, MN), where they were harvested and carcass data were obtained. Carcass data included HCW, carcass yield, and the backfat and longissimus muscle depth measurements; which were obtained by optical probe between the 3rd and 4th rib from the last rib at 7 cm from the dorsal midline. The fat-free lean index (FFLI) was calculated according to the National Pork Producers Council (2000) procedures.

Feeding Behaviors

To determine whether changing the source of water to a location separate from a wet-dry feeder would affect feeding behaviors, video recordings were taken from d 94 to 96, d 97 to 99, and d 109 to 111. These periods were selected to represent the feeding behaviors associated with 3 of the feeder treatments shortly before, shortly after, and 2 wk after the change in water source for the wet-dry feeders switched on d 97. Nine pens were randomly selected for repeated, continuous video recording during the 3 time periods, with 3 pens chosen to represent each of 3 of the treatments: the conventional dry feeder, the wet-dry feeder with water continuously

available at the feeder, and the wet-dry feeder with the water source switched to the cup waterer on d 97. A video camera (Panasonic, Model no. SDR-H40P-Hard Disk Drive) was suspended from the ceiling and positioned to capture approximately 24-h of digital video around the feeder trough of the first pen for each treatment on d 94, the second pen for each treatment on d 95, and the third pen for each treatment on d 96 (d 94 to 96). This process was repeated again on d 97, 98, and 99 (d 97 to 99); and again on d 109, 110, and 111 (d 109 to 111). Immediately before initiation of video recording, 4 barrows and 4 gilts in each pen were randomly selected and identified with a unique identification number. Aerosolized livestock marking paint was used to apply the number to each pig's back so that it was easily visible in the video recording. Each recording was initiated at approximately noon on each of the predetermined days, and concluded at approximately noon on the following day. Video recordings were stored on an external hard drive after each session.

The behaviors at the feed trough of the identified pigs in each pen were observed continuously for two 3-h time blocks during each of the 3 periods (d 94 to 96, d 97 to 99, and d 109 to 111); one 3-h block was selected between 13:00- to 18:00-h and the second 3-h block was selected between 06:00- to 11:00-h. Video was reviewed using the combined 6-h period, and the number of visits to the feeder trough (head positioned in or above the feeder trough), length of each visit (min), and total time at the feeder trough (min) were recorded for each of the 8 identified pigs. Additionally, the number and duration (s) of aggressive interactions (pushing, nudging, and/or biting directed towards a pen-mate) involving an identified pig at the feeder were recorded.

Statistical Analysis

The data were analyzed as a completely randomized design using the PROC MIXED procedure of SAS (v. 8.2; SAS Institute Inc., Cary, NC) to compare the growth performance of pigs fed with the wet-dry and dry feeder from d 0 to 69, as well as the growth performance and carcass characteristics for the 3 wet-dry feeder and single dry feeder treatments from d 69 to 124 and overall (d 0 to 124). Additionally, the behavioral data were analyzed as repeated measures to compare the average number of feeder visits, duration of each feeder visit, total time at the feeder, number of aggressive occurrences, and duration of each aggressive occurrence for each feeder treatment by period (d 94 to 96, 97 to 99, and 109 to 111). Pen served as the experimental unit in this study. For all analyses, differences with a *P*-value of less than 0.05 were considered to be statistically significant.

RESULTS

Growth

From d 0 to 69, pigs fed using the wet-dry feeder had greater ($P < 0.05$) ADG, ADFI, G:F, and d 69 BW than those fed with the conventional dry feeder (Table 4-2). When the availability of water was removed from the wet-dry feeder and provided by a cup waterer beginning on d 69, pigs fed using this arrangement had reduced ($P < 0.05$) ADG, ADFI, and G:F from d 69 to 97 when compared to those fed with a wet-dry feeder that continued to provide the sole source of water or a dry feeder and separate cup waterer. Additionally, pigs fed using a wet-dry feeder with water in the feeder had greater ($P < 0.05$) ADG, ADFI, and d 97 BW than those fed with a conventional dry feeder; but G:F was not different between these treatments. Although pigs fed using a wet-dry feeder with water in the feeder had greater ($P < 0.05$) d 97 BW than

those fed using a wet-dry feeder with a separate water source, the d 97 BW of pigs using the dry feeder and wet-dry feeder with a separate water source was similar.

From d 97 to 124, when the source of water was removed from the wet-dry feeder and provided by a cup waterer beginning on d 97, these pigs had reduced ($P < 0.05$) ADG compared to all other treatments. Also, pigs fed with a wet-dry feeder that provided water throughout the study had greater ($P < 0.05$) ADG than those fed with a conventional dry feeder, and the ADG of pigs fed using the wet-dry feeder with the water source changed to the cup waterer on d 69 was intermediate. Pigs using a wet-dry feeder that provided water throughout the study had greater ($P < 0.05$) ADFI from d 97 to 124 than all other feeder treatments. Also, from d 97 to 124, pigs fed with the wet-dry feeder used as a dry feeder beginning on d 69 had improved ($P < 0.05$) G:F compared to those fed with a wet-dry feeder that provided water in the feeder until d 97 or throughout the study, and the G:F of pigs fed with a conventional dry feeder was intermediate.

Overall (d 0 to 124), pigs fed using a wet-dry feeder that provided water in the feeder throughout the study had greater ($P < 0.05$) ADG, ADFI, and final BW than all other treatments. However, pigs fed with a wet-dry feeder that provided water in the feeder from d 0 to 97 had greater ($P < 0.05$) ADG than those fed using a conventional dry feeder, and the ADG of pigs fed with a wet-dry feeder that provided water in the feeder from d 0 to 69 was intermediate. Also, pigs fed with a wet-dry feeder that provided water in the feeder from d 0 to 97 had greater ($P < 0.05$) ADFI than those fed with a wet-dry feeder that provided water in the feeder from d 0 to 69, and the ADFI of pigs fed with a conventional dry feeder was intermediate. Pigs fed using the wet-dry feeder as a dry feeder beginning on d 69 had improved ($P < 0.05$) G:F compared to those fed with a wet-dry feeder that provided water throughout the study, and the G:F of pigs fed using the wet-dry feeder as a dry feeder beginning on d 97 or a conventional dry feeder was

intermediate. The final BW of pigs fed with the wet-dry feeder used as a dry feeder beginning on either d 69 or 97 was not different than those fed with a conventional dry feeder.

Pigs fed using a wet-dry feeder that provided water in the feeder throughout the study had greater ($P < 0.05$) HCW than those using all other feeder treatments. For carcass traits, there were no differences in the carcass yield between treatments. However, backfat depth was reduced ($P < 0.05$) for pigs fed with a wet-dry feeder that was used as a dry feeder beginning on d 69 when compared to those fed using all other feeder treatments. The LM depth of pigs fed with a wet-dry feeder that was used as a dry feeder beginning on d 69 was greater ($P < 0.05$) than that of pigs fed using a wet-dry feeder that provided water from d 0 to 97 or a conventional dry feeder. Also, the LM depth of pigs using a wet-dry feeder that provided water throughout the study was greater ($P < 0.05$) than that of pigs fed with a conventional dry feeder, and the LM depth of pigs fed using a wet-dry feeder that provided water from d 0 to 97 was intermediate. Pigs fed using a wet-dry feeder that provided water from d 0 to 69 had a greater ($P < 0.05$) FFLI than pigs fed using a wet-dry feeder that provided water from d 0 to 97, and the FFLI of pigs fed with either a wet-dry feeder providing water throughout the study or a conventional dry feeder was intermediate.

Feeding Behaviors

Overall, there were no feeder treatment × period interactions observed for the feeding behaviors evaluated in this study (Table 4-3). For the d 94 to 96 period, pigs visited the feeder more frequently ($P < 0.05$) during the 6-h of time sampled than on d 109 to 111, but the duration of each feeder visit and total time spent at the feeder did not differ between periods. For the d 94 to 96 period and overall (d 94 to 96, d 97 to 99, and d 109 to 111 periods combined), pigs fed with a wet-dry feeder visited the feeder less frequently ($P < 0.05$) and spent less total time ($P <$

0.05) at the feeder than pigs fed with a conventional dry feeder, with no differences observed in the duration of each feeder visit. For each period and overall, there were no differences in the feeding behaviors measured for pigs fed with the wet-dry feeder that provided water throughout the experiment and those fed using a wet-dry feeder with water provided separately beginning on d 97. There was no treatment, period, or overall differences in the number and duration of aggressive occurrences that occurred near the feeder.

DISCUSSION

Similar to previous experiments, pigs fed with a wet-dry feeder that provided water in the feeder had greater ADG, ADFI, and subsequent BW than pigs fed using a dry feeder and separate water source (Brumm et al. 2000; Gonyou and Lou, 2000; Bergstrom, J. R., 2011). Although G:F was slightly improved for pigs fed with the wet-dry feeder from d 0 to 69, there was no difference in the overall G:F of pigs fed with access to water in the wet-dry feeder throughout the study and those fed using the conventional dry feeder. The absence of expected differences in the G:F, backfat depth, and carcass FFLI between pigs fed with access to water in the wet-dry feeder throughout the study and those fed using the conventional dry feeder could reflect the magnitude of differences in ADG and ADFI when compared to some other studies. Payne (1991) suggested that the greater feed intake obtained with a single-space wet-dry feeder can lead to increased carcass fat in some pig genotypes, and that a loss in value with some carcass grading systems may negate the growth benefits observed. Other experiments conducted by our group support that conclusion, but have also demonstrated that ADG, ADFI, subsequent BW, and carcass backfat depth can be reduced, and G:F improved, with a decreased feeder opening of the wet-dry feeder (i.e., reduced accessibility of feed; Bergstrom, J. R., 2011). Based on results of these experiments (where ADG, ADFI, final BW, HCW, and carcass backfat depth

increased and G:F was reduced with an increased feeder opening), a feeder opening of 2.54-cm was used for the wet-dry feeder in the current experiment.

As suggested by Amornthewaphat et al. (2000b) and Gonyou and Lou (2000), these data indicate that the availability of water with feed in the wet-dry feeder was responsible for the increase in ADFI, ADG, and subsequent BW. Despite a considerable reduction in ADFI and ADG during d 69 to 97 for pigs with the source of water removed from the wet-dry feeder to a separate source on d 69, the subsequent (d 97 to 124) and overall growth performance of these pigs was not different than those fed using a conventional dry feeder. Therefore, when utilized as a dry feeder, the 2 feeding spaces provided by the wet-dry feeder were sufficient to achieve growth performance similar to that with the conventional dry feeder that provided double the amount of feeder space for 24 to 27 pigs. Likewise, Amornthewaphat et al. (2000b) and Gonyou and Lou (2000) indicated that a single-space feeder with a separate waterer could maintain the growth performance of up to 12 pigs. However, the reduced performance observed during the first 28-d that the water source was removed from the wet-dry feeder on d 69 eliminated the net benefit in whole body growth that had been obtained with the wet-dry feeder up to that point.

Compared to all other feeder treatments during d 97 to 124, pigs fed using the wet-dry feeder with access to water removed to a separate source on d 97 also experienced a considerable reduction in ADG during the following 27-d. Although the overall ADG of these pigs remained slightly greater than that of pigs fed using the conventional dry feeder, the overall ADFI, G:F, final BW, and carcass characteristics were not different. Therefore, despite the demonstrated ability of the wet-dry feeder to function as a dry feeder and slow late finishing growth when the availability of water was removed from the feeder, it appears that the abrupt removal of water from the feeder during the late finishing period requires a substantial modification in the pigs'

feeding and/or drinking behavior in order to maintain any previous benefit in whole body growth.

Any difference in ADG observed between pigs fed with the wet-dry and dry feeder primarily resulted from a difference in ADFI. Differences in ADFI are demonstrated to be associated with important differences in feeding behaviors. Regardless of the feeder design, when feeding spaces do not appear to be limiting, growing-finishing pigs in groups fed *ad libitum* have demonstrated a diurnal pattern of feeding similar to that observed for individually-housed pigs (de Haer and Merks, 1992; Nielsen et al., 1995a; Bornett et al., 2000). Several have also reported that two peak periods of feeding activity may occur during the day, a morning period and an afternoon period (Walker, 1991; de Haer and Merks, 1992; Nielsen et al., 1995a). Although approximately 24-h of continuous video were recorded during each of the 3 periods of interest in the current study, the barn lighting was lowered during the night to reduce the number of insects during periods of natural ventilation, which made it difficult to observe any discernable behaviors during this time period. However, the ability to observe feeding behaviors during the assumed peak feeding times was both practical and suitable for evaluating potential differences among the selected treatments.

Similar to the observations reported by Gonyou and Lou (2000), pigs eating from the wet-dry feeder spent less total time eating and had less feeder entrances than those fed with the conventional dry feeder during the periods observed. However, little information is available on how these differences in feeding behavior may have developed. All pigs used in the current experiment were received from a commercial nursery where every pen was equipped with a multi-space, conventional dry feeder. Magowan et al. (2008) reported that, when compared to pigs maintained on the same type of feeder, ADFI was reduced during the first 2-wk in the

finisher when groups of 20 pigs were moved from pens with a 4-space dry feeder in the nursery to pens with a single-space wet-dry feeder, or vice-versa. In their study, the reduced ADFI during the first 2-wk after pigs were moved from the multi-space dry feeder to the single-space wet-dry feeder probably reflected the need to adapt to an increased number of pigs per feeding space. Although Magowan et al. (2008) did not report feeding behaviors on a per pig basis, the feeder occupancy rate and aggressive behaviors at the feeder during the first- and fourth-wk in the finisher were greatest for pigs moved from the multi-space dry feeder to the single-space wet-dry feeder. However, there were nearly 50% more pigs per wet-dry feeder space than in the current study, yet the pigs moved from the multi-space dry feeder to the single-space wet-dry feeder in their study had slightly greater ADG during the finishing period and overall when compared to the other treatments. Although pelleted diets were fed throughout their experiment, the reduced ADFI during the first 2-wk after pigs were moved from the single-space wet-dry feeder to the multi-space dry feeder indicates that a period of adaptation may have been required to adjust for a reduced eating rate.

Using meal diets to compare the eating rate of individual small (41 to 54 kg BW) and large (85 to 94 kg BW) pigs fed with 6 dry and 6 wet-dry feeder designs, Gonyou and Lou (2000) used pigs previously fed from a dry feeder and found no differences in the amount of feed consumed in 10-min from dry and wet-dry feeders following a 6-h fast; but large pigs ate faster than small pigs. However, in another experiment using large pigs fasted for 6-h, they found that pigs consumed 500 g of feed nearly 3 times faster when it was pre-mixed with an equal amount of water. Hsia and Lu (1985) and Hurst et al. (2008) have also reported a considerably faster eating rate for wet-fed compared to dry-fed pigs. In the current experiment, it is likely that providing access to water with feed increased the eating speed for pigs using the wet-dry feeder.

This probably resulted in larger meals and the greater ADFI observed, despite the apparent adaptation to fewer meals (or feeder visits) and reduced total time spent feeding compared to those fed with the conventional dry feeder during the late finishing periods (Nielsen, 1999). When access to water with feed was abruptly removed from the wet-dry feeder during the late finishing period, the eating speed of these pigs was most likely reduced, with no apparent adaptation in meal frequency or duration to sustain ADFI.

The food intake and feeding behavior of growing-finishing pigs fed *ad libitum* are generally influenced by genotype, age and BW, physiological needs, experiences, preferences, and social and environmental constraints (Torrallardona and Roura, 2009). The social and environmental constraints are especially relevant in studies evaluating *ad libitum* feeders for group-housed finishing pigs. Individually-housed pigs achieve greater ADG and ADFI than pigs in groups by consuming feed more frequently in smaller meals of shorter duration at a slower eating rate (de Haer and Merks, 1992; Bornett et al., 2000). When pigs are group-housed, a decreased number of feeding spaces and/or an increased degree of protection of the feeder space (or difficulty of access) can also lead to a reduced number of daily meals that are longer in duration, with no differences in ADFI or growth performance (Morrow and Walker, 1994; Nielsen et al., 1995a; Nielsen et al., 1996). However, Walker (1991) reported that there was no difference in the number of daily feeder visits per pig when the number of pigs using a single-space wet-dry feeder was increased from 10 to 30, but the mean duration of each visit decreased as the number of pigs increased. In spite of this, ADG was similar, but ADFI was greater and feed efficiency poorer when there were 20 or 30 pigs per feeder when compared to 10. These responses indicate that there may have been an increase in eating rate, feed wastage, or both when there were 20 or 30 pigs per feeder space. Nielsen et al. (1995b) reported there were fewer,

longer feeder visits and an increased eating rate when there were 20 pigs grouped per single-space dry feeder when compared to 5, 10, and 15 pigs per feeder; but ADG, ADFI, and G:F were similar.

The eating rate of individual pigs in a group offered a particular diet *ad libitum* has been reported to be relatively stable, regardless of the meal size (Nielsen, 1999). However, eating rate does increase during growth (i.e. increased body size), with a concomitant decrease in the daily number of feeder visits and/or total eating time (Hyun et al., 1997; Nielsen, 1999; Gonyou and Lou, 2000). Also, as mentioned previously, the eating rate may be influenced by the type or form of the feed presented to the pig (i.e. eating rate for wet feed > pelleted feed > meal feed; Hsia and Lu, 1985), which can result in a reduced time budget for feeding that is accomplished with fewer visits to the feeder (Gonyou and Lou, 2000).

Being social animals, it appears that the number, duration, and size of meals established by pigs fed *ad libitum* in a group represent adaptations in feeding motivation to attempt to achieve synchrony and/or cohesion in feeding and other behaviors (Nielsen, 1999; Bornett et al., 2000). In the current experiment, the reduction in ADFI (and ADG) observed after pigs were abruptly changed from wet to dry feeding in the late finishing period did not appear to induce changes in the feeding pattern when they were maintained on the same feeder and provided a separate water source. Also, the amount of aggression observed at the feeder did not increase, and was numerically lower for pigs with the wet-dry feeder design overall. This was probably due to the protected head-space provided by the sides of the wet-dry feeder, whereas the 5 feeding spaces of the conventional dry feeder were simply divided by nose barriers (Baxter, 1991). It appears that several weeks may have been required for these pigs to adapt an eating rate which resulted in ADFI similar to those fed with the conventional dry feeder.

In conclusion, pigs fed with the wet-dry feeder that provided access to water with feed throughout the experiment had greater ADG, ADFI, final BW, and HCW when compared to pigs fed with the conventional dry feeder or wet-dry feeder with access to water removed to a separate source. The greater ADFI and ADG obtained when access to water was provided in the wet-dry feeder appeared to result from an increased eating rate. Abruptly changing the source of water in the wet-dry feeder to a separate cup waterer during the finishing period was followed by a 4-wk period of reduced growth that eliminated the net benefit in growth that had been previously obtained with the wet-dry feeder. Differences in the feeding behaviors of pigs fed with the wet-dry and dry feeders were observed, but the differences may also be associated with other design features that were independent of the provision or separation of the water source. Removing the access to water at the wet-dry feeder to a separate water source did not result in changes in the feeding pattern or aggression, but probably required an adaptation to an increased eating speed to achieve ADFI and ADG similar to that obtained with the conventional dry feeder. This research provides useful information for the further development of novel feeding concepts to manipulate growth, and perhaps improve the efficiency, of growing-finishing pigs fed *ad libitum*.

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Table 4-1. Diet composition

	Dietary phase[1]			
Item	23 to 45 kg	45 to 73 kg	73 to 102 kg	102 kg to mkt.
Ingredient, %				
Corn	61.46	66.53	71.45	63.35
Soybean meal, 46.5% CP	21.43	16.64	11.85	19.80
DDGS[2]	15.00	15.00	15.00	15.00
Monocalcium P, 21% P	0.15	---	---	---
Limestone	1.00	0.95	0.90	1.00
Salt	0.35	0.35	0.35	0.35
Liquid lysine, 60% Lys	0.45	0.40	0.35	0.35
L-Threonine	0.05	0.03	0.01	0.01
VTM, phytase[3]	0.11	0.10	0.09	0.085
Ractopamine HCl , 20 g/kg[4]	---	---	---	0.025
Total	100.00	100.00	100.00	100.00
Calculated analysis				
Standardized ileal digestible (SID) amino acids				
Lys, %	1.05	0.90	0.75	0.95
Ile:lys, %	64	66	69	68
Leu:lys, %	158	172	191	170
Met:lys, %	28	30	33	30
Met & Cys:lys, %	57	62	68	61
Thr:lys, %	62	63	64	62
Trp:lys, %	17	17	17	18
Val:lys, %	75	79	84	80
CP, %	19.3	17.5	15.7	18.7
Total Lys, %	1.19	1.03	0.87	1.09
ME, kcal/kg	3,358	3,366	3,371	3,364
SID Lys:ME, g/Mcal	3.13	2.67	2.23	2.82
Ca, %	0.50	0.44	0.41	0.47
P, %	0.46	0.41	0.39	0.42
Available P, %	0.29	0.25	0.23	0.21

[1] Each dietary phase was formulated to meet the requirements for the BW ranges described in the table.
[2] Dried distillers grains with solubles.
[3] VTM = Vitamin and trace mineral premix. The phytase source provided 0.12% available P.
[4] Paylean, Elanco Animal Health, Greenfield, IN.

Table 4-2. The effects of feeder design and changing the water source to a location separate from the wet-dry feeder at 4 and 8 wk prior to harvest on the growth performance and carcass characteristics of growing-finishing pigs

Feeder design:	Wet-dry feeder			Dry feeder		Wet-dry vs. Dry
Water with feed:	throughout	to d 97	to d 69	w/separate cup waterer	SEM	*P* <
Growth performance[1]						
d 0 to 69						
ADG, kg	0.83	0.82	0.82	0.79	0.012	0.001
ADFI, kg	1.90	1.85	1.83	1.80	0.030	0.02
G:F	0.44	0.44	0.45	0.44	0.003	0.05
d 69 BW, kg	77.6	76.5	76.1	74.1	0.82	0.001
d 69 to 97[2]						
ADG, kg	0.87[a]	0.90[a]	0.74[b]	0.83[c]	0.017	---[3]
ADFI, kg	2.78[a]	2.76[a]	2.40[b]	2.58[c]	0.031	---
G:F	0.32[ab]	0.33[a]	0.31[b]	0.32[a]	0.005	---
d 97 BW, kg	102.2[a]	101.7[a]	96.9[b]	97.3[b]	0.80	---
d 97 to 124						
ADG, kg	1.06[a]	0.91[b]	1.01[ac]	0.99[c]	0.029	---
ADFI, kg	3.09[a]	2.66[b]	2.77[b]	2.78[b]	0.061	---
G:F	0.34[a]	0.34[a]	0.37[b]	0.36[ab]	0.007	---
d 0 to 124						
ADG, kg	0.89[a]	0.86[b]	0.84[bc]	0.84[c]	0.007	---
ADFI, kg	2.33[a]	2.21[b]	2.14[c]	2.17[bc]	0.019	---
G:F	0.38[a]	0.39[ab]	0.39[b]	0.39[ab]	0.003	---
final BW, kg	128.7[a]	124.7[b]	122.2[b]	122.5[b]	1.08	---
Carcass characteristics[4]						
HCW, kg	96.0[a]	93.2[b]	91.6[b]	92.4[b]	1.02	---
Carcass yield, %	75.4	75.4	75.4	75.9	0.41	---
Backfat depth, mm	19.6[a]	19.7[a]	17.7[b]	18.9[a]	0.47	---
Longissimus muscle depth, cm	6.18[ab]	5.86[bc]	6.48[a]	5.84[c]	0.165	---
FFLI[5]	49.5[ab]	49.2[a]	50.0[b]	49.6[ab]	0.24	---

[1] A total of 1,296 pigs (PIC, 337 × 1050, initially 19.4 kg) were placed in 48 pens containing 27 pigs each.

[2] Means within the same row having different superscripts differ ($P < 0.05$).

[3] The main effects of feeder design were not compared for response criteria beginning on d 69, and the differences between feeder treatments were determined using the PDIFF option of SAS.

[4] Carcass data were obtained for 829 pigs from 38 pens (20 conventional dry and 18 wet-dry feeders) to determine the effects of feeder treatment on carcass characteristics.

[5] FFLI = fat-free lean index.

Table 4-3. The effects of feeder design and changing the water source to a location separate from the wet-dry feeder at d 97 on the feeding behaviors and aggression of finishing pigs on d 94 to 96, d 97 to 99, and d 109 to 111

Feeder design:	Wet-dry feeder		Dry feeder	
Water with feed:	throughout	to d 97	w/cup waterer	SEM
Feeding behaviors (per pig)[1]				
d 94 to 96				
no. of feeder visits[2]	5.7[a]	6.5[a]	12.4[b]	1.85
duration/visit, min	4.3	5.3	4.3	1.74
total time at feeder, min	18.0[a]	20.0[a]	41.6[b]	5.58
d 97 to 99				
no. of feeder visits	4.1	3.9	6.8	1.49
duration/visit, min	4.2	5.5	4.7	1.46
total time at feeder, min	13.8[a]	15.8[a]	30.0[b]	4.47
d 109 to 111				
no. of feeder visits[3]	2.8[A]	3.3[A]	7.6[B]	1.85
duration/visit, min	6.3	5.8	5.1	1.74
total time at feeder, min	16.2	18.3	30.2	5.58
Overall				
no. of feeder visits	4.2[a]	4.6[a]	9.0[b]	0.75
duration/visit, min	4.9	5.5	4.7	1.18
total time at feeder, min	16.0[a]	18.0[a]	33.9[b]	2.49
Feeding aggression (per pig)				
d 94 to 96				
no. of occurrences	1.8	2.5	4.8	1.27
duration/occurrence, s	2.6	2.2	4.0	1.07
d 97 to 99				
no. of occurrences	4.7	2.1	4.0	1.01
duration/occurrence, s	4.8	3.6	4.0	0.86
d 109 to 111				
no. of occurrences	2.2	1.8	3.5	1.27
duration/occurrence, s	2.9	3.2	2.6	1.07
Overall				
no. of occurrences	2.9	2.1	4.1	0.69
duration/occurrence, s	3.4	3.0	3.5	0.59

[1] A total of 9 pens (3 from each feeder treatment) were randomly selected for repeated video recording of feeding behaviors at d 94 to 96, d 97 to 99, and d 109 to 111. There were 8 pigs per pen (4 barrows and 4 gilts) observed continuously for 6-h (3-h morning + 3-h afternoon) within each period. No treatment × day interactions were observed.

[2] Means within the same row having different lower-case superscripts differ ($P < 0.05$). Those having different upper-case superscripts tended to differ ($P < 0.10$).

[3] The number of feeder visits was less ($P < 0.05$) during the 6-h sampled in the d 109 to 111 period when compared to the d 94 to 96 period.

CHAPTER 5 - The effects of dietary astaxanthin and ractopamine HCl on the growth performance, carcass characteristics, and color shelf-life of longissimus chops from barrows and gilts

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ABSTRACT

The objectives of this research were to evaluate the effects of dietary astaxanthin (AX) and ractopamine HCl (RAC) on the growth, carcass characteristics, LM color, and color shelf-life of LM chops of barrows and gilts. Pigs were TR4 × C22 (PIC, Hendersonville, TN) and diets were corn-soybean meal-based in all experiments. In Exp. 1, 48 barrows (98 kg initial BW) were fed 26-d to evaluate the effects of AX, with 2 pigs/pen and 6 pens/treatment. The 4 dietary treatments consisted of 0, 5, 10, and 20 ppm AX from *Xanthophyllomyces dendrorhous* (yeast). No differences in growth performance were observed in this experiment; however, pigs fed increasing AX tended (quadratic, $P < 0.08$) to have decreased backfat depth and increased fat-free lean index. After 30-min bloom at 24-h postmortem, the 10th-rib LM surface of pigs fed AX tended ($P < 0.08$) to be darker (lower CIE L*) and less yellow (lower CIE b*). In Exp. 2, 72 barrows and 72 gilts (102 kg initial BW) were fed 26-d to evaluate the effects of AX and RAC. Pigs were blocked by BW with 2 barrows or gilts/pen and 4 pens of each gender/treatment. The 9 dietary treatments consisted of 0, 5, 7.5, and 10 ppm AX from yeast, 5 ppm synthetic AX, and 10 ppm RAC with 0, 2.5, 5, and 7.5 ppm AX from yeast. Feeding RAC increased ADG, G:F, final BW, HCW, and LM area; but there were no differences associated with feeding AX. There were no differences in initial color scores, but discoloration scores of LM chops increased (linear, $P < 0.01$) during 7-d of retail display, and were greater ($P < 0.01$) for barrow chops on d 7 (d × gender and interaction, $P < 0.01$). Also, overall discoloration scores and d 0 to 3 objective total color change were lower ($P < 0.01$) for gilt chops and those from pigs fed RAC. In Exp. 3, 80 barrows and 80 gilts (90 kg initial BW) were fed 26-d to evaluate the effects of AX and RAC, with 1 barrow and gilt/pen and 10 pens/treatment. The 8 treatments were 0, 7.5, 15, 30, 60, and 120 ppm AX from yeast, and 10 ppm RAC with 7.5 and 20 ppm AX from yeast. Feeding RAC

increased ADG, G:F, final BW, HCW, and LM area. Among non-RAC fed pigs, there was improved (quadratic, $P < 0.05$) G:F and increased (quadratic, $P < 0.06$) ADG with increasing AX up to 60 ppm. As in Exp. 2, discoloration scores of LM chops did not differ initially, but increased (linear, $P < 0.01$) during display and were greater ($P < 0.02$) for chops from barrows and non-RAC fed pigs on d 6 (d × gender and d × treatment, $P < 0.04$). Also, overall discoloration scores and total color change during 6-d retail display were lower ($P < 0.02$) for chops from gilts and pigs fed RAC. These results suggest that color shelf-life of LM chops from gilts and pigs fed 10 ppm RAC was extended, but was not influenced by feeding AX.
Key words: astaxanthin, color shelf-life, finishing pigs, pork, ractopamine HCl

INTRODUCTION

Astaxanthin is a carotenoid without potential for vitamin A activity in mammals, and exists naturally in various plants, algae, and seafood. Its unique molecular structure (a xanthophyll) may impart a potent antioxidant capacity (Yuan et al., 2011). Although used primarily for the pigmentation of farmed salmonids, astaxanthin may also improve their growth, immunity, and survival (Goodwin, 1986; Christiansen et al., 1995a). Research and interest in the potential benefits of astaxanthin for human health has increased, and environmentally-friendly technologies can produce large quantities of "natural" astaxanthin (Montanti et al., 2011; Yuan et al., 2011).

There is little information on the effects of dietary astaxanthin on pig performance and fresh pork color and quality. Yang et al. (2006) reported a linear reduction in 10^{th}-rib backfat depth, and increases in carcass yield and LM area, with the addition of 1.5 and 3 ppm dietary astaxanthin for 14-d preharvest. However, they did not observe any differences in measures of fresh pork color or quality. Using higher levels of astaxanthin, other researchers have reported

improved growth, carcass, and pork quality characteristics for pigs fed 48 ppm for 90-d preharvest (Kim et al., 2008) and improved pork color shelf-life for pigs fed 66.7 ppm for 42-d preharvest (Carr et al., 2010).

The effects of ractopamine HCl and gender on the color shelf-life of fresh pork have not been clarified. Despite observing an increased PUFA:SFA ratio and iodine value for backfat samples from pigs fed 10 mg/kg ractopamine HCl, Apple et al. (2008) reported that the LM quality of these pigs may have been enhanced during 5 d of retail display. Additionally, studies that differentiate the color shelf-life characteristics of fresh pork from barrows and gilts are lacking.

Therefore, we conducted 3 experiments to determine the effects of feeding various levels of astaxanthin and ractopamine HCl on growth and carcass characteristics of finishing pigs and color-shelf life characteristics of LM chops from barrows and gilts during simulated retail display.

MATERIALS AND METHODS

Procedures used in the experiments were approved by the Kansas State University Institutional Animal Care and Use Committee.

Animal Care

In each experiment, pigs were housed in pens within an environmentally controlled finishing building at the Kansas State University Swine Teaching and Research Center. The pens (each 1.22 m × 1.52 m) had a totally slatted floor and were each equipped with a dry self-feeder and nipple waterer to accommodate 2 finishing pigs per pen (0.93 m^2 per pig) with *ad libitum* access to feed and water. The facility was a mechanically ventilated room with a pull-plug manure storage pit.

Experiment 1

A total of 48 barrows (TR4 × C22, PIC, Hendersonville, TN) with an average initial BW of 98 kg were used in this study. Pigs were blocked by weight and randomly allotted to 1 of 4 dietary treatments with 2 pigs per pen and 6 pens per treatment. Dietary treatments consisted of a corn-soybean meal-based control diet formulated to meet or exceed the nutrient requirements for barrows of this genotype (NRC, 1998), and the control diet with 5, 10, and 20 ppm astaxanthin from *Xanthophyllomyces dendrorhous* yeast (Aquasta, IGENE Biotechnology, Columbia, MD) added at the expense of cornstarch to achieve the dietary treatments (Table 5-1). Pigs and feeders were weighed on d 0, 7, 14, 21, and 26 to determine ADG, ADFI, G:F, and BW.

On d 27, one pig per pen was transported to the Kansas State University Meats Lab for humane slaughter and the collection of carcass data. Hot carcass weights were collected immediately after evisceration. First-rib, 10^{th}-rib, last-rib, and last-lumbar backfat depths, as well as LM area at the 10^{th}-rib, were collected from the left side of each pig carcass 24-h postmortem. The fat-free lean index (FFLI) of each carcass was calculated according to the National Pork Producers Council (2000) procedures. Additionally, the CIE L*, a*, and b* values of the LM surface at the 10^{th}- and 11^{th}-rib interface were determined from the mean of 3 random readings taken after 30 min of bloom with a HunterLab Miniscan™ XE Plus spectrophotometer (Model 45/0 LAV, 2.54-cm-diameter aperture, 10° standard observer, Illuminant D65, Hunter Associates Laboratory, Inc., Reston, VA).

The data were analyzed as a randomized complete block design using the PROC MIXED procedure of SAS (v. 8.2; SAS Institute Inc., Cary, NC) with pen as the experimental unit. Linear and quadratic polynomial contrasts were used to determine the effects of increasing dietary astaxanthin, and an orthogonal contrast was performed to compare the responses of pigs fed all astaxanthin treatments to those fed the control diet. For all analyses, differences with a *P*-value

of less than 0.05 were considered to be statistically significant, and trends were considered to have a *P*-value of less than 0.10.

Experiment 2

A total of 72 barrows and 72 gilts (TR4 × C22, PIC, Hendersonville, TN) with an initial BW of 102 kg were used in this study. Pigs were blocked by weight and randomly allotted to 1 of 9 dietary treatments. There were 2 pigs per pen and 4 pens per treatment × gender combination (8 replications of each dietary treatment). Dietary treatments consisted of a corn-soybean meal-based control diet formulated to contain 0.95% standardized ileal digestible (SID) lysine; the control with 5, 7.5, and 10 ppm astaxanthin from *Xanthophyllomyces dendrorhous* yeast (Aquasta, IGENE Biotechnology, Columbia, MD); the control with 5 ppm pure synthetic astaxanthin (Carophyll Pink, DSM Nutritional Products, Basel, Switzerland); and the control with 10 ppm ractopamine HCl and 0, 2.5, 5, and 7.5 ppm astaxanthin from *Xanthophyllomyces dendrorhous* yeast (Table 5-1). Experimental diets were fed in meal form, and astaxanthin and/or ractopamine HCl were added to the control diet at the expense of cornstarch to achieve the dietary treatments. The diets were formulated to meet or exceed the nutrient requirements for pigs of this genotype (NRC, 1998). Pigs and feeders were weighed weekly and approximately 18 h before harvest to determine ADG, ADFI, G:F, and BW.

To ensure that the harvest procedures would occur in accordance with IACUC standards and the capabilities of the Kansas State University Meats Laboratory, the barrow feeding period ended when all barrows were transported to the abattoir on d 22 for humane slaughter. The gilt feeding period ended one week later, when they were all transported for humane slaughter on d 29. This resulted in a similar final BW for barrows and gilts.

After evisceration, HCW was measured and recorded. First-rib, 10^{th}-rib, last-rib, and last-lumbar backfat depth, as well as LM area at the 10^{th}- and 11^{th}-rib interface, were collected from the right half of each carcass 24-h postmortem. After obtaining carcass measurements, a 20-cm section of the LM caudal to the 10^{th}- 11^{th}-rib interface was removed from the carcass of 1 randomly selected pig per pen and vacuum-packaged and frozen at -20°C.

After 7 or 14 d of frozen storage, the LM sections were thawed for 24-h at 4°C and a 2.54-cm thick boneless LM chop was fabricated from the center of each LM section. Each LM chop was placed on a 1 S styrofoam tray (Dyne-A-Pak Inc., LAVAL, QC, Canada) with an absorbent pad and overwrapped with a polyvinylchloride film (23,250 mL of O_2/m^2/24 h oxygen permeability/flow rate). The packages were placed in an open-top retail display case (unit model DMF8, Tyler Refrigeration Corp., Niles, MI) at 2 ± 1.5°C for a maximum of 7 d. The display case was illuminated with continuous fluorescent lighting (3,000 K, Bulb model F32T8/ADV830/Alto, Philips, Bloomfield, NJ) that emitted an average of 2,249 lx. Packages were rotated daily to compensate for any variation in temperature and lighting within the case.

On d 0, 1, 2, and 3 of retail display, objective measures of lean color were determined for all packages using a HunterLab Miniscan™ XE Plus spectrophotometer (Model 45/0 LAV, 2.54-cm-diameter aperture, 10° standard observer, Illuminant D65, Hunter Associates Laboratory, Inc., Reston, VA) to measure CIE L*, a*, and b*. The spectrophotometer was calibrated daily against a standard white tile (Hunter Associates Laboratory) and 3 locations of the lean surface of each sample package were measured and averaged to determine the CIE L*, a*, and b* values. Additionally, the change in total color (ΔE) from d 0 to 3 was calculated as: $\sqrt{((\Delta L^*)^2+(\Delta a^*)^2+(\Delta b^*)^2)}$ (Minolta, 1998).

Subjective lean color scores (1 = white to pale pinkish gray to 6 = dark purplish red, National Pork Producers Council, 2000) were also determined on d 0 of retail display from the average of scores provided by 11 trained panelists. The same panelists provided scores for lean surface discoloration (1 = no discoloration, very bright pinkish red to 7 = total discoloration, extremely dark pinkish gray/tan; Hunt et al., 1991) on d 0 to 7 of retail display. When an individual package received a mean discoloration score > 4, it was classified as having an unacceptable appearance and removed from display. Also, the number of days that each package maintained an acceptable appearance (mean discoloration score ≤ 4) was used to determine the color shelf-life. Packages removed for an unacceptable appearance were assigned a discoloration score of 5 for the remaining d of retail display.

The data were analyzed as a randomized complete block design using the PROC MIXED procedure of SAS (v. 8.2; SAS Institute, Inc., Cary, NC) to evaluate the effects of dietary treatment, gender, and their interactions. Pen was the experimental unit. Color shelf-life data collected for the LM chops during retail display were analyzed as repeated measures, with d as the repeated variable and LM chop as the subject. Preplanned orthogonal contrasts were used to evaluate the effects of gender, astaxanthin, astaxanthin from *Xanthophyllomyces dendrorhous* yeast, synthetic astaxanthin, and ractopamine HCl; and linear and quadratic polynomial contrasts were used to determine the effects of increasing astaxanthin from *Xanthophyllomyces dendrorhous* yeast within the non-ractopamine HCl and ractopamine HCl treatments. For all analyses, differences with a *P*-value of less than 0.05 were considered to be statistically significant, and trends were considered to have a *P*-value of less than 0.10.

Experiment 3

A total of 80 barrows and 80 gilts (TR4 × C22, PIC, Hendersonville, TN) with an initial BW of 90 kg were used in this study. Pigs were weighed and allotted to 1 of 9 dietary treatments, with 1 barrow and gilt per pen and 10 pens for each of 8 dietary treatments. Dietary treatments consisted of a corn-soybean meal-based control diet formulated to 0.66% SID lysine, the control diet formulated to contain 7.5, 15, 30, 60, and 120 ppm astaxanthin from *Xanthophyllomyces dendrorhous* yeast (Nāturxan, IGENE Biotechnology, Columbia, MD); and 2 diets formulated to contain 0.95% SID lysine and 10 ppm ractopamine HCl with 7.5 and 20 ppm astaxanthin from *Xanthophyllomyces dendrorhous* yeast (Table 5-2). Experimental diets were fed in meal form, and astaxanthin and/or ractopamine HCl were added to the control diet at the expense of corn to achieve the dietary treatments. The diets were formulated to meet or exceed the nutrient requirements for pigs of this genotype (NRC, 1998). Pigs and feeders were weighed weekly and approximately 18-h before harvest to determine ADG, ADFI, G:F, and BW.

To ensure that the harvest procedures would occur in accordance with IACUC standards and the capabilities of the Kansas State University Meats Laboratory, 6 pigs per treatment on d 23, 7 pigs per treatment on d 28, and 7 pigs per treatment on d 30 were transported to the abattoir for humane slaughter. This resulted in a mean feeding duration of 26-d, with all pigs harvested at approximately 27-d after the initiation of the experiment.

Immediately after evisceration, the heart, kidneys, liver, and spleen of every pig were weighed and inspected for abnormalities by a veterinarian from the Department of Diagnostic Medicine/Pathobiology in the College of Veterinary Medicine at Kansas State University, and the HCW was recorded. First-rib, 10^{th}-rib, last-rib, and last-lumbar backfat depth, as well as the LM area and mean of 2 pH readings obtained at the 10^{th}- and 11^{th}-rib interface, were collected from the left side of each pig carcass 24-h postmortem. After obtaining carcass measurements, a

20-cm section of the LM caudal to the 10^{th}- 11^{th}-rib interface was removed from the carcass of both pigs (1 barrow and 1 gilt) from each of 9 pens per treatment and vacuum-packaged and refrigerated at 4°C.

After 7-d of refrigerated storage, two 2.54-cm thick boneless LM chops were fabricated from each LM section. One LM chop was placed on simulated retail display for 6 d as in Exp. 2. The second chop was vacuum-packaged and frozen at -20°C immediately after fabrication. After 6 d of display, the chops on display were vacuum-packaged and frozen at -20°C prior to shipping both chops from each carcass to an outside laboratory (IGENE Biotechnology, Columbia, MD) for the determination of astaxanthin concentration in the LM.

On d 0 to 6 of retail display, objective measures of lean color were determined daily from 2 locations of the lean surface of each sample package using a HunterLab Miniscan™ XE Plus spectrophotometer to measure CIE L*, a*, and b* as in Exp. 2. Additionally, the change in total color (ΔE) from d 0 to 6 was calculated as: $\sqrt{((\Delta L^*)^2+(\Delta a^*)^2+(\Delta b^*)^2)}$ (Minolta, 1998).

Subjective lean color scores (1 = white to pale pinkish gray to 6 = dark purplish red, National Pork Producers Council, 2000) and marbling scores (1 = very lean to 5 = highly marbled, National Pork Producers Council, 2000) were also determined on d 0 of retail display from the average of scores provided by 8 trained panelists. The same panelists provided scores for lean surface discoloration (1 = no discoloration, very bright pinkish red to 7 = total discoloration, extremely dark pinkish gray/tan; Hunt et al., 1991) on d 0 to 6 of retail display.

The data were analyzed as a completely randomized design using the PROC MIXED procedure of SAS (v. 8.2; SAS Institute, Inc., Cary, NC) to evaluate the effects of the dietary treatments, and preplanned orthogonal contrasts were performed to compare the effects of pigs fed treatments containing 0 and 10 ppm ractopamine HCl. Linear and quadratic polynomial

contrasts were also used to determine the effects of increasing astaxanthin within the non-ractopamine HCl treatments. Pen served as the experimental unit. Additionally, data collected from the LM chops during retail display were analyzed as a split-plot to evaluate the effects of gender using repeated measures, with d as the repeated variable and LM chop as the subject. For all analyses, differences with a *P*-value of less than 0.05 were considered to be statistically significant, and trends were considered to have a *P*-value of less than 0.10.

RESULTS

Experiment 1

Overall (d 0 to 26), ADG and G:F of pigs fed astaxanthin were not different than those of control pigs (Table 5-3). However, ADFI tended (linear; $P < 0.10$) to decrease with increasing astaxanthin. Although there were no differences in the final BW or carcass yield, the HCW tended (linear, $P < 0.08$) to decrease with increasing astaxanthin. Therefore, the HCW was used as a covariate for the comparison of backfat depth, LM area, and FFLI. Dietary astaxanthin decreased ($P < 0.03$) average backfat depth, and tended ($P < 0.06$) to decrease 10^{th}-rib backfat depth. The reductions in average and 10^{th}-rib backfat depth tended (quadratic; $P < 0.08$) to be greatest at the 5 and 10 ppm level of astaxanthin. No differences were observed in LM area. However, the differences in backfat depth resulted in a trend ($P < 0.10$) for increased FFLI for pigs fed astaxanthin, and pigs fed 5 or 10 ppm astaxanthin tended (quadratic; $P < 0.08$) to have the greatest FFLI.

The objective measurements of LM color demonstrated that the cut LM surface from pigs fed astaxanthin tended to be darker (lower CIE L* values; $P < 0.06$) and less yellow (lower CIE b* values; $P < 0.08$) than that of the pigs fed the control diet. Measurements of redness (CIE a* values) and yellowness (CIE b* values) were lowest (quadratic; $P < 0.02$ and $P < 0.06$,

respectively) at the 10 ppm level of astaxanthin; however, the CIE a* of pigs fed 5 and 20 ppm astaxanthin were numerically greater than that of the controls.

Experiment 2

No treatment × gender interactions were observed for growth and carcass characteristics during the study. Overall, barrows had greater ($P < 0.001$) ADG and ADFI than gilts (Table 5-4). However, the gilts achieved a similar final BW at harvest because they were fed 1 wk longer before harvest. Pigs fed ractopamine HCl had greater ($P < 0.001$) ADG and final BW, and improved G:F ($P < 0.001$), compared with non-ractopamine HCl-fed pigs (Table 5-5). There were no differences in growth for pigs supplemented with the various levels of astaxanthin.

Barrows had greater ($P < 0.001$) backfat depth and reduced ($P < 0.01$) LM area and FFLI compared to gilts. Pigs fed ractopamine HCl had greater ($P < 0.03$) HCW, yield, LM area, and FFLI than non-ractopamine HCl-fed pigs.

The initial subjective color scores of LM chops placed on retail display were not different (Table 5-6). However, the discoloration scores of the LM chops increased (quadratic, $P < 0.001$) from d 0 to 7 of retail display. Although the discoloration scores were not different among the dietary treatments or genders on d 0, the discoloration scores of LM chops from gilts were lower (d × gender, $P < 0.001$; barrow vs. gilt, $P < 0.001$) than those of barrows on d 3 to 7 of retail display and overall. The discoloration scores of chops from pigs fed ractopamine HCl were lower ($P < 0.001$) than those of pigs not fed ractopamine HCl on d 3 to 7 and overall, but the gender differences in discoloration score were less among the LM chops that originated from pigs fed ractopamine HCl (dietary treatment × gender, $P < 0.001$). Among LM chops from pigs fed ractopamine HCl, the discoloration score was lowest (quadratic, $P < 0.001$) from d 3 to 7 and

overall for pigs fed the highest level of astaxanthin (7.5 ppm) from *Xanthophyllomyces dendrorhous* yeast.

The repeated, subjective evaluations for discoloration were also utilized to determine the average color shelf-life of LM chops. Chops from gilts had a greater ($P < 0.001$) color shelf-life than those from barrows, and chops from pigs fed ractopamine HCl had a greater ($P < 0.001$) color shelf-life than those from non-ractopamine HCl-fed pigs.

When comparing the objective color measurements of LM chops, there were no differences observed in the CIE L* (measure of lightness/darkness, white = 100 and black = 0) measured over 7 d (Table 5-7). However, there was a dietary treatment × gender interaction ($P < 0.001$) for the CIE a* (measure of redness, larger value = more red). This occurred because, among the chops from pigs fed the non-ractopamine HCl diets, the decrease (linear, $P < 0.01$) in the CIE a* with increasing concentration of astaxanthin from *Xanthophyllomyces dendrorhous* was more evident among barrows. A d × gender interaction ($P < 0.001$) was also observed for the CIE a* because the decrease (linear, $P < 0.001$) in CIE a* values during the 7 d of retail display was greater for barrows when compared to those of gilts. Nevertheless, the CIE a* of LM chops from ractopamine HCl-fed pigs was reduced ($P < 0.001$) compared to those from non-ractopamine HCl-fed pigs. Among the chops from pigs fed ractopamine HCl, the CIE a* was reduced (quadratic, $P < 0.001$) as the concentration of astaxanthin from *Xanthophyllomyces dendrorhous* rose to 5 ppm before it increased at 7.5 ppm astaxanthin. The CIE b* (measure of yellowness, larger value = more yellow) of the LM chops decreased (linear, $P < 0.001$) during the 7 d of retail display, and was lower ($P < 0.001$) for chops from pigs fed ractopamine HCl. Among the chops from pigs fed the non-ractopamine HCl diets, the CIE b* decreased (linear, $P < 0.001$) with increasing concentration of astaxanthin from *Xanthophyllomyces dendrorhous*.

Collectively, the changes in CIE L*, a*, and b* of LM chops from d 0 to 3 resulted in differences in the change in total color (ΔE) from d 0 to 3 of simulated retail display. Chops from pigs fed ractopamine HCl and gilts had less ($P < 0.001$) ΔE than pigs fed non-ractopamine HCl diets and barrows, respectively.

Experiment 3

Overall, pigs fed ractopamine HCl had greater ($P < 0.001$) ADG and final BW, and improved G:F ($P < 0.001$), compared with non-ractopamine HCl-fed pigs (Table 5-8). Among pigs fed the non-ractopamine HCl diets, there was a tendency (quadratic, $P < 0.06$) for greater ADG and an improvement (quadratic, $P < 0.05$) in G:F with increasing dietary astaxanthin to 30 and 60 ppm, respectively. However, there were no differences in the final BW of pigs fed the various levels of astaxanthin, and ADFI was similar among all the dietary treatments.

Notable differences or abnormalities of the heart, kidneys, liver, and spleen were not observed during their gross inspection at harvest. Although the absolute weight of the heart or spleen of pigs was not different among the dietary treatments, the relative weight (% of final BW) of the heart was reduced ($P < 0.01$) for pigs fed ractopamine HCl. Also, the liver and kidney weights of pigs fed ractopamine HCl were greater ($P < 0.001$), and tended ($P < 0.07$) to have a greater relative weight (% of final BW), than that of pigs not fed ractopamine HCl. There were no differences in organ weights associated with feeding astaxanthin, but the relative kidney weight (% of final BW) tended (quadratic, $P < 0.08$) to be reduced for pigs fed 30 and 60 ppm astaxanthin.

Pigs fed ractopamine HCl had greater ($P < 0.03$) HCW, LM area, 24-h LM pH, and FFLI than non-ractopamine HCl-fed pigs. Among pigs fed the non-ractopamine HCl diets, the carcass characteristics of those fed astaxanthin were not different from those fed the diet without astaxanthin.

There were no treatment × gender interactions observed for any of the simulated retail display criteria, and negligible amounts of astaxanthin were detected in the assayed samples of LM chops. The initial subjective color scores were reduced (quadratic, $P < 0.01$) for LM chops from pigs fed increasing levels of astaxanthin in the diets without ractopamine HCl (Table 5-9). Also, LM chops from gilts had a slightly greater ($P < 0.03$) initial color score than those from barrows, but no differences were observed in the initial color score of chops from pigs fed 0 and 10 ppm ractopamine HCl. The marbling score was slightly greater ($P < 0.05$) for LM chops from pigs fed ractopamine HCl, but no differences were observed between barrows and gilts or with increasing dietary astaxanthin. Discoloration scores of the LM chops increased (linear, $P < 0.001$) from d 0 to 6 of simulated retail display. Although the discoloration scores were not different among the dietary treatments or genders on d 0, the discoloration scores of LM chops from gilts were lower (d × gender, $P < 0.001$; barrow vs. gilt, $P < 0.001$) than those of barrows on d 4 to 6 of retail display and overall. Also, the discoloration scores of chops from pigs fed ractopamine HCl were lower (d × treatment, $P < 0.001$; ractopamine HCl vs. non-ractopamine HCl, $P < 0.001$) than those of pigs not fed ractopamine HCl on d 3 to 6 and overall. No differences in discoloration scores were observed among LM chops from pigs fed increasing levels of astaxanthin without ractopamine HCl.

When comparing the objective color measurements of LM chops, the CIE L* was increased (quadratic, $P < 0.01$) for chops from pigs fed increasing astaxanthin in the diets without ractopamine HCl throughout the simulated retail display (Table 5-10). There were no gender differences in the CIE a* of LM chops, but the CIE a* of chops from pigs fed ractopamine HCl was decreased ($P < 0.02$) compared to that of chops from pigs fed non-ractopamine HCl diets. Although the CIE a* of chops from all pigs decreased (quadratic, $P <$

0.001) from d 0 to 6 of retail display, the change in CIE a* was greater (d × treatment and d × gender, $P < 0.02$) for chops from pigs fed non-ractopamine HCl diets and barrows. The CIE b* of LM chops was lower ($P < 0.04$) for chops from pigs fed ractopamine HCl and gilts, but these differences were greater (d × treatment and d × gender, $P < 0.02$) on d 0 of retail display than on d 6. There were no differences in the CIE a* or CIE b* values of LM chops from pigs fed increasing astaxanthin without ractopamine HCl. Overall, the differences and changes in the CIE L*, a*, and b* of LM chops from d 0 to 6 of simulated retail display resulted in differences in the change in total color (ΔE, d 0 to 6). Chops from pigs fed ractopamine HCl and gilts had a lower ($P < 0.01$) ΔE than pigs fed non-ractopamine HCl diets and barrows, respectively.

DISCUSSION

Although few studies have reported on the effects of feeding diets with added astaxanthin on the growth performance of finishing pigs, these results generally agree with that observed in previous studies. Yang et al. (2006) reported that there were no differences in the growth performance of finishing pigs fed 0, 1.5, and 3 ppm dietary astaxanthin during 14-d pre-harvest. More recently, Carr et al. (2010) indicated there were no differences in the growth performance of pigs fed 0 and 66.7 ppm of natural astaxanthin from *Haematococcus pluvialis* algae for 42-d pre-harvest. However, Kim et al. (2008) suggested that feeding a probiotic mixture which provided 48 ppm of astaxanthin from *Xanthophyllomyces dendrorhous* yeast for 90-d improved the growth performance of finishing pigs. They observed similar improvements in ADG and G:F as that obtained in Exp. 3 for pigs fed 30 and 60 ppm astaxanthin from *Xanthophyllomyces dendrorhous*. It is not clear, however, whether the improvements in G:F observed in these 2 studies resulted from improved intestinal health or digestibility from the astaxanthin of *Xanthophyllomyces dendrorhous* yeast or the yeast itself.

With synthetic astaxanthin (Carophyll Pink, DSM Nutritional Products, Basel, Switzerland), Christiansen et al. (1995a) observed that a minimum of 5 ppm dietary astaxanthin was required to improve the growth and survivability of Atlantic salmon fry. However, they indicated this may have resulted from the pro-vitamin A activity of astaxanthin for this species and the poor bioavailability of the synthetic vitamin A palmitate/acetate used in the purified basal diet for fry. Larger Atlantic salmon have demonstrated an ability to utilize synthetic vitamin A esters (Storebakken et al., 1993; Thompson et al., 1994). Although astaxanthin is primarily included in the diets of farmed salmonids to improve their pigmentation, Atlantic salmon supplemented with astaxanthin may have an improved immunological status that is associated with increased concentrations of vitamin A and E in muscle, as well as vitamin C in liver (Torrissen, 1989; Christiansen et al, 1995b). Despite the high tolerance for dietary astaxanthin (1,000 ppm) demonstrated by rainbow trout, the highest level approved by the European Food Safety Authority (EFSA) and United States Food and Drug Administration (US-FDA) for feed of farmed salmonids is 100 ppm (The EFSA Journal, 2007) and 80 ppm (US-FDA Code of Federal Regulations - 21CFR73.35), respectively. Astaxanthin is typically included in the diets of farmed salmonids at 50 to 80 ppm, which results in increased concentrations of astaxanthin in flesh that is more red (greater CIE *a**) and yellow (greater CIE *b**; Storebakken et al., 2004).

Astaxanthin has not demonstrated pro-vitamin A activity in birds and mammals and, despite increasing evidence for numerous potential health benefits, few studies have reported improvements in the performance of broiler or layer birds fed astaxanthin (Goodwin, 1986; Inborr, 1998; Yuan et al., 2011). However, because β-carotene is primarily converted into vitamin A, there is considerable interest in the use of non-pro-vitamin A carotenoids for the

pigmentation of broilers and egg yolks to improve consumer acceptance (Hencken, 1992). Numerous studies have reported differences in color (greater *a** values, more red) or improvements in color shelf-life of the egg yolks from layers (Kim et al., 1996; Akiba et al., 2000a,b,c; Yang et al., 2006) and muscles of broilers fed astaxanthin (Matsushita et al., 2000; Akiba et al., 2001a,b; An et al., 2004;). Relatively low levels of 0.7 to 16 ppm astaxanthin were reported to be efficacious for affecting the color of egg yolks, and levels of 15 to 30 ppm were efficacious for affecting the color of broiler muscles.

The effects of astaxanthin on pork carcass and color characteristics are inconsistent. Despite the relatively low dietary levels of astaxanthin (0, 1.5, and 3 ppm) evaluated by Yang et al. (2006), they are the only ones who have reported a linear improvement in the carcass yield of pigs fed increasing astaxanthin. They did not indicate whether the astaxanthin used in their experiment was provided as synthetic or from a natural source, such as *Haematococcus pluvialis* or *Xanthophyllomyces dendrorhous*. However, they also reported a linear reduction in backfat thickness and a greater LM area with increasing astaxanthin, similar to the quadratic trends for decreased backfat depth associated with feeding greater concentrations of 5, 10, and 20 ppm astaxanthin in Exp. 1. Regardless, there were no differences in the backfat depth and LM area of pigs fed 0 to 10 ppm of astaxanthin in Exp. 2 or 0 to 120 ppm in Exp. 3. Kim et al. (2008) also reported no differences in the backfat thickness or LM area of pigs fed 0 and 48 ppm astaxanthin from *Xanthophyllomyces dendrorhous* for 90-d. Although Carr et al. (2010) indicated that pigs fed 66.7 ppm astaxanthin from *Haematococcus pluvialis* for 42-d tended to have decreased backfat depth compared to the control pigs, the pigs fed astaxanthin were also 6 kg lighter at the beginning and end of their study.

During 5 and 10 d of cold storage, Yang et al. (2006) did not observe differences in either the subjective or objective color of vacuum-packaged LM chops from pigs fed 0, 1.5, and 3 ppm astaxanthin. Although pigs fed 5, 10, and 20 ppm astaxanthin in Exp. 1 tended to have a darker (decreased *L**) and less yellow (decreased *b**) LM surface than that of control pigs after 30-min bloom at 24-h postmortem, Carr et al. (2010) fed pigs 0 and 66.7 ppm astaxanthin for 42-d pre-harvest and did not observe differences in the subjective color score and objective measures of darkness (*L**), redness (*a**), and yellowness (*b**) of the LM surface after a 15-min bloom at 24-h postmortem. However, Carr et al. (2010) reported that the color of LM chops from pigs fed astaxanthin was improved during 7 d of retail display with darker (decreased *L**) and less yellow (decreased *b**) color values. These color differences of the LM from feeding astaxanthin are similar to that observed in Exp. 1 at 24-h postmortem. Despite these indications that feeding astaxanthin to finishing pigs might improve the color and length of consumer acceptability of fresh retail pork products, there were no beneficial effects observed for the color shelf-life of LM chops from feeding either relatively low levels in Exp. 2 or high levels in Exp. 3.

The lack of appreciable and consistent differences in the color of pork from pigs fed astaxanthin may be related to differences in the levels and digestibility of the sources evaluated. Information on the absorption and utilization of carotenoids in pigs is lacking, and the absorption of carotenoids in mammals is generally considered to be relatively poor (Parker, 1996; During and Harrison, 2004). Various factors can influence the digestibility of carotenoids within an animal species, including the age/BW of the animal, the composition of the diet (e.g. fat, vitamin A, and vitamin E concentrations; and carotenoid content, types, geometrical isomers, and proportions), level of feed intake, and growth rate (Christiansen et al., 1993; Ytrestøyl et al., 2006; Bjerkeng et al., 2007). Although the previously reported color responses to astaxanthin in

poultry have occurred with corn-soybean meal-based diets, it is not known whether the zeaxanthin and lutein in corn may affect the absorption of astaxanthin in pigs (Parker, 1996; Yang et al., 2006). Increased carotenoid intake can result in decreased digestibility (During and Harrison, 2004; Ytrestøyl et al., 2006).

The primary enantiomer of astaxanthin found in *Haematococcus pluvialis* is the (3*S*,3'*S*)-isomer, which is different than the (3*R*,3'*R*)-isomer found in *Xanthophyllomyces dendrorhous* and the 1:2:1 mixture of (3*R*,3'*R*)-, (3*R*,3'*S*)-, and (3*S*,3'*S*)-isomers in synthetic astaxanthin. Salmonids can deposit these isomers at nearly the same rate, but that may not be true for all species (Hencken, 1992). Also, it has been suggested that the esterified astaxanthin of *Haematococcus pluvialis* may have greater bioavailability in some species but not others (Torrissen, 2000; Yuan et al., 2011). Greater fractionation of the yeast cell wall has resulted in improved utilization of astaxanthin from *Xanthophyllomyces dendrorhous* for both rainbow trout and layer birds (Akiba et al, 2000b; Storebakken et al., 2004). Astaxanthin from fractionated *Xanthophyllomyces dendrorhous* can be as effective as synthetic astaxanthin for obtaining improved coloration of egg yolks and Atlantic salmon (Akiba et al., 2000b; Bjerkeng et al, 2007).

Although feeding astaxanthin has resulted in differences in the color of animal tissues, there is relatively little information on its tissue distribution. The flesh of Atlantic salmon fed 60 ppm astaxanthin has been reported to contain 4 to 5 ppm astaxanthin, and astaxanthin in the flesh of trout has been reported to increase from 5 to 13 ppm as the dietary level increased from 20 to 100 ppm (The EFSA Journal, 2007). With Atlantic salmon that were force-fed radio-labeled astaxanthin, Torrissen and Ingebrigtsen (1992) reported the greatest radioactivity in the dorsal cutis, bile, intestinal mucosa, liver, posterior of the kidney, developing eggs, uveal tract of the

eye, and meninges of the spinal cord; with less present in the muscle and cranial kidney. Similarly, after feeding 0, 50, and 100 ppm astaxanthin to 2-wk old male broiler chicks for 14 d, Takahashi et al. (2004) reported that concentrations were greatest in the small intestine and subcutaneous fat and lowest in the muscles.

The improved ADG, G:F, final BW, HCW, LM area, and leanness of pigs fed 10 ppm ractopamine HCl in Exp. 2 and 3 are consistent with that previously reported in the literature (Carr et al., 2005a; Weber et al., 2006). Also, the greater pH of the LM observed 24-h postmortem for pigs fed 10 ppm ractopamine HCl in Exp. 3 is similar to the differences reported by Carr et al. (2005a) for LM chops, and the 48-h pH of the LM reported by Apple et al. (2008). However, Carr et al. (2005a,b) and Weber et al. (2006) did not observe differences in the pH of the LM at 24-h postmortem. In contrast to previous research which demonstrated that feeding 10 ppm ractopamine HCl had no influence on LM marbling scores (Carr et al., 2005a,b; Weber et al., 2006), the increased LM marbling associated with feeding ractopamine HCl in Exp. 3 is similar to that reported by Apple et al. (2008).

In both Exp. 2 and 3, the influence of feeding ractopamine HCl to pigs on the subjective and objective color of their LM is consistent with the literature. Although the initial subjective color scores for the LM chops from pigs fed ractopamine HCl were similar to those from pigs that were not fed ractopamine, the chops from pigs not fed ractopamine HCl had greater discoloration scores after 3 d of retail display. The lack of difference in the initial subjective color score agrees with the findings of Carr et al., (2005a,b) and Weber et al. (2006), but the reduced subsequent discoloration scores for LM chops from pigs fed ractopamine HCl seems to agree with the increased subjective color scores observed across 5 d of retail display reported by Apple et al. (2008). Using illuminant C for measurement of objective color, Apple et al. (2008)

reported that LM chops from pigs fed ractopamine HCl were darker (decreased L* value) than those from pigs not fed ractopamine HCl. However, most research has not detected differences in L* values when using illuminant D65 (Stoller et al., 2003; Carr et al., 2005a,b). Several have reported that the LM chops from pigs fed ractopamine HCl are less red (decreased a* value) and yellow (decreased b* value; Carr et al., 2005a,b; Apple et al., 2008; de Almeida et al., 2010). These differences are generally considered advantageous for improved consumer acceptance and color shelf-life. In the current experiments, the consistent decrease in the change in total objective color of LM chops from pigs fed ractopamine HCl indicated that the color shelf-life of these chops was improved during retail display. Collectively, the decreased subjective discoloration scores and change in total objective color of LM chops from pigs fed 10 ppm ractopamine HCl could result in greater consumer acceptance of fresh pork during retail display.

Although differences in the growth performance and carcass characteristics of barrows and gilts in Exp. 2 were typical and not unexpected, the differences in LM color and color shelf-life characteristics that were observed in Exp. 2 and 3 have not been reported in the literature. Differences in LM characteristics between barrows and gilts, or between pigs fed 10 ppm ractopamine HCl and those not fed ractopamine HCl, may explain the differences in the measures of LM color shelf-life that were observed.

Gilts generally have a greater cross-sectional LM area than barrows, which is associated with a greater cross-sectional area of the individual myofibers rather than a difference in the number of myofibers (Miller et al., 1975; Larzul et al., 1997). Studies by Miller et al. (1975) and Larzul et al. (1997) also indicate that, although there were no differences between barrows and gilts in the percentage or relative cross-sectional area of the myofiber types, the cross-sectional area of the individual type IIBw (non-oxidative fast twitch) myofibers was greater in LM from

gilts. Additionally, Larzul et al. (1997) reported that the LM of gilts had greater glycolytic potential than the LM of barrows. These differences in the LM characteristics of barrows and gilts are similar to the differences reported between pigs fed non-ractopamine HCl or ractopamine HCl diets. Both Depreux et al. (2002) and Gunawan et al. (2007) have reported that there is an increased number of type IIB myosin heavy chain isoforms (at the expense of type IIA) in the muscles of pigs fed ractopamine HCl.

The implications of differences in the proportions of muscle fiber types between barrows and gilts or pigs fed ractopamine HCl for the retail color shelf-life characteristics of pork products have not been determined directly. However, Gentry et al. (2004) reported a reduced percentage of type IIA fibers and increased percentage of type IIB/X fibers in the LM and semimembranosus muscle of pigs reared indoors when compared to pigs reared outdoors. These differences were associated with the LM chop from indoor reared pigs having a greater subjective color score, decreased redness (reported as Minolta a*), and a tendency for reduced discoloration during 4 d of retail display. Although the environmental variables responsible for the differences in their study are unclear, the evidence for the relationship of the relative proportions of muscle fiber types with differences in the color shelf-life of fresh pork are worthy of continued investigation.

In conclusion, feeding astaxanthin to finishing pigs in these experiments had little effect on the growth performance, carcass characteristics, and color shelf-life of LM chops during retail display. However, in addition to the expected differences in the growth performance and carcass characteristics of gilts and barrows or pigs fed 10 ppm ractopamine HCl, the color shelf-life characteristics of LM chops during retail display were improved for chops from gilts and pigs fed ractopamine HCl. These studies demonstrate that the utilization of practices known to

increase production of lean pork and improve production efficiency, such as feeding gilts or 10 ppm ractopamine HCl in late finishing, may also improve the consumer acceptance of fresh pork during a longer period of retail display.

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Table 5-1. Composition of the experimental control diets, Exp. 1 & 2

Ingredient, %[1]	Exp. 1	Exp. 2
Corn	85.40	72.85
Soybean meal, 46.5% CP	12.44	25.14
Monocalcium P, 21% P	0.45	0.35
Limestone	0.85	0.85
Salt	0.35	0.35
L-lysine HCl	0.15	0.15
Vitamin premix[2]	0.08	0.08
Trace mineral premix[3]	0.08	0.08
Cornstarch[4,5]	0.20	0.15
Total	100.00	100.00
Calculated analysis		
Standardized ileal digestible (SID) amino acids, %		
Lys, %	0.63	0.95
Ile:lys, %	71	70
Leu:lys, %	188	156
Met:lys, %	33	28
Met & Cys:lys, %	68	58
Thr:lys, %	64	61
Trp:lys, %	18	19
Val:lys, %	85	79
Total lys, %	0.72	1.07
CP, %	13.2	18.1
ME, kcal/kg	3,355	3,353
SID lys:ME, g/Mcal	1.88	2.83
Ca, %	0.47	0.50
P, %	0.42	0.45
Available P, %	0.15	0.20

[1]Experimental diets were fed for 26 d before harvest.

[2]The vitamin premix supplied the following nutrients per kg of feed: 3,527 IU of vitamin A as retinyl acetate; 440 IU of vitamin D_3; 14 IU of vitamin E as DL-α-tocopherol acetate; 1.4 mg of vitamin K as menadione dimethylpyrimidinol bisulfite; 2.6 mg of riboflavin; 15.9 mg of niacin; 8.8 mg of pantothenic acid as D-calcium pantothenate; and 12.3 μg of vitamin B_{12}.

[3]The trace mineral premix supplied the following nutrients per kg of feed: 0.16 mg of iodine as ethylenediamine dihydriodide; 0.16 mg of selenium as sodium selenite; 88.1 mg of zinc as zinc sulfate; 88.1 mg of iron as ferrous sulfate; 8.8 mg of copper as copper sulfate; and 21.2 mg of manganese as manganese oxide.

[4]Astaxanthin (Aquasta, 10,000 ppm from *Xanthophyllomyces dendrorhous* yeast, IGENE Biotechnology, Columbia, MD) replaced cornstarch in the control diet to achieve the experimental diets containing 5, 10, and 20 ppm astaxanthin in Exp. 1.

[5]Astaxanthin (Aquasta, 10,000 ppm from *Xanthophyllomyces dendrorhous* yeast; or pure synthetic, Carophyll Pink, DSM Nutritional Products, Basel, Switzerland) and/or ractopamine HCl (Paylean, Elanco, Greenfield, IN) replaced cornstarch in the control diet to achieve dietary treatments with 2.5, 5, 7.5, and 10 ppm AX and/or 10 ppm ractopamine HCl in Exp. 2.

Table 5-2. Composition of the experimental diets, Exp. 3

Ingredient, %[1]	Control diet	Ractopamine HCl diet
Corn[2]	83.80	70.71
Soybean meal, 46.5% CP	12.30	25.44
Soybean oil	2.00	2.00
Monocalcium P, 21% P	0.225	0.10
Limestone	0.90	0.90
Salt	0.35	0.35
L-lysine HCl	0.20	0.15
L-threonine	0.025	0.025
Vitamin premix w/phytase[3]	0.10	0.10
Trace mineral premix[4]	0.10	0.10
Ractopamine HCl, 20 g/kg[5]	---	0.05
Nāturxan (10,000 ppm astaxanthin)[6]	---	0.075
Total	100.00	100.00
Calculated analysis		
Standardized ileal digestible (SID) amino acids, %		
Lys, %	0.66	0.95
Ile:lys, %	67	69
Leu:lys, %	176	155
Met:lys, %	31	30
Met & Cys:lys, %	63	60
Thr:lys, %	64	63
Trp:lys, %	17	19
Val:lys, %	80	78
Total lys, %	0.74	1.07
CP, %	13.0	18.0
ME, kcal/kg	3,457	3,452
SID lys:ME, g/Mcal	1.91	2.75
Ca, %	0.45	0.48
P, %	0.37	0.40
Available P, %	0.21	0.21

[1]Experimental diets were fed for approximately 26 d before slaughter.
[2]Astaxanthin (Nāturxan, 10,000 ppm from *Xanthophyllomyces dendrorhous*, IGENE Biotechnology, Columbia, MD) replaced corn in the control diet to achieve dietary treatments with 7.5, 15, 30, 60, and 120 ppm astaxanthin.
[3]The vitamin premix supplied the following nutrients per kg of feed: 4,409 IU of vitamin A as retinyl acetate; 550 IU of vitamin D_3; 17 IU of vitamin E as DL-α-tocopherol acetate; 1.7 mg of vitamin K as menadione dimethylpyrimidinol bisulfite; 3.2 mg of riboflavin; 19.9 mg of niacin; 11.0 mg of pantothenic acid as D-calcium pantothenate; 15.4 μg of vitamin B_{12}; and 300 FTU of phytase.
[4]The trace mineral premix supplied the following nutrients per kg of feed: 0.16 mg of iodine as ethylenediamine dihydriodide; 0.16 mg of selenium as sodium selenite; 88.1 mg of zinc as zinc sulfate; 88.1 mg of iron as ferrous sulfate; 8.8 mg of copper as copper sulfate; and 21.2 mg of manganese as manganese oxide.
[5]Provided 10 ppm ractopamine HCl in the complete diet (Paylean, Elanco, Greenfield, IN).
[6]Additional astaxanthin (Nāturxan, 10,000 ppm from *Xanthophyllomyces dendrorhous*, IGENE Biotechnology, Columbia, MD) replaced corn in the Ractopamine HCl diet containing 7.5 ppm astaxanthin to achieve the dietary treatment with 20 ppm astaxanthin.

Table 5-3. Growth performance and carcass characteristics of pigs fed increasing astaxanthin, Exp. 1

	Astaxanthin, ppm[2]					Probability, *P* <		
Item[1]	0	5	10	20	SEM	Control vs. Astaxanthin	Linear	Quadratic
Growth performance, d 0 to 26								
ADG, kg	0.96	1.01	0.92	0.90	0.054	---[3]	---	---
ADFI, kg	3.03	3.07	2.83	2.81	0.108	---	0.10	---
G:F	0.32	0.33	0.33	0.32	0.014	---	---	---
Final BW, kg	122.5	123.9	121.6	121.2	1.73	---	---	---
Carcass characteristics[4]								
Live BW, kg	122.8	123.6	122.9	119.7	2.16	---	---	---
HCW, kg	87.2	87.3	86.8	83.4	1.96	---	0.08	---
Yield, %	71.0	70.6	70.6	69.6	0.67	---	---	---
Average backfat depth, mm[5]	23.8	20.6	20.2	20.8	1.15	0.03	---	0.08
10th-rib backfat depth, mm	20.4	16.1	16.3	17.9	1.58	0.06	---	0.07
LM area, cm^2	46.9	49.3	48.7	46.7	1.81	---	---	---
FFLI[6]	53.3	55.8	55.6	54.4	0.96	0.10	---	0.08
LM color[7]								
CIE L*	60.3	55.3	58.9	56.2	1.42	0.06	---	---
CIE a*	9.4	10.1	8.2	10.3	0.31	---	---	0.02
CIE b*	15.8	14.8	14.4	15.1	0.47	0.08	---	0.06

[1]A total of 48 barrows (TR4 × C22, PIC, Hendersonville, TN) with an initial BW of 98 kg were used, with 2 pigs per pen and 6 pens per treatment. Data were obtained from 1 pig per pen for the determination of carcass characteristics.
[2]Aquasta (astaxanthin from *Xanthophyllomyces dendrorhous*), IGENE Biotechnology, Columbia, MD.
[3]Not significant ($P > 0.10$).
[4]One pig per pen (24 barrows) was used to evaluate carcass characteristics, and HCW was used as a covariate for the comparison of backfat depth, LM area, and FFLI.
[5]Average of the backfat depth measured at the first-rib, 10th-rib, last-rib, and last lumbar.
[6]FFLI = fat-free lean index.
[7]Measured as the mean of 3 readings of the cut surface at the 10th- and 11th-rib interface after 30-min for bloom. The range for CIE L* is 0 to 100 (0 = black, 100 = white). A positive CIE a* indicates the degree of redness. A positive CIE b* indicates the degree of yellowness.

Table 5-4. Growth performance and carcass characteristics of barrows and gilts, Exp. 2

Item[1]	Barrows	Gilts	SEM	*P* <
Growth performance				
Feeding period, d	22	29		
Initial BW, kg	103.9	100.7	3.14	---[2]
ADG, kg	1.22	1.14	0.015	0.001
ADFI, kg	3.82	3.47	0.064	0.001
G:F	0.32	0.33	0.005	---
Final BW, kg	131.2	133.7	2.65	---
Carcass characteristics				
HCW, kg	93.7	95.6	2.03	---
Yield, %	71.4	71.6	0.21	---
Average backfat depth, mm	26.9	22.8	0.55	0.001
10^{th}-rib backfat depth, mm	22.9	17.0	0.59	0.001
LM area, cm^2	48.6	53.4	1.11	0.01
FFLI[3]	52.0	55.4	0.35	0.001

[1] A total of 72 barrows and 72 gilts (TR4 × C22, PIC, Hendersonville, TN) were blocked by weight, with 2 pigs per pen and 36 pens per gender.
[2] Not significant ($P > 0.10$).
[3] FFLI = fat-free lean index.

Table 5-5. Growth performance and carcass characteristics of finishing pigs fed various levels of astaxanthin with or without ractopamine HCl, Exp. 2

Ractopamine HCl, ppm[1,2]:	None					10					
Astaxanthin source:	*Xanthophyllomyces dendrorhous*[3]				Synthetic[4]	*Xanthophyllomyces dendrorhous*					*P* <
Astaxanthin level, ppm:	0	5	7.5	10	5	0	2.5	5	7.5	SEM	Ractopamine HCl[5]
Growth performance											
ADG, kg	1.13	1.06	1.11	1.09	1.05	1.28	1.31	1.31	1.28	0.035	0.001
ADFI, kg	3.66	3.65	3.64	3.63	3.56	3.65	3.71	3.75	3.53	0.102	---[6]
G:F	0.31	0.29	0.31	0.30	0.30	0.35	0.35	0.35	0.36	0.008	0.001
Final BW, kg	131.1	130.4	130.4	129.8	128.9	134.8	135.5	135.5	135.7	2.06	0.001
Carcass characteristics											
HCW, kg	92.7	91.9	92.3	91.8	91.4	97.0	98.0	97.7	98.9	1.60	0.001
Yield, %	70.7	70.4	71.5	70.8	70.9	72.0	72.4	72.1	72.9	0.36	0.001
Average backfat, mm[7]	24.4	26.7	24.5	24.6	23.7	25.4	25.0	25.1	24.1	0.87	---
10th-rib backfat, mm	19.8	21.4	20.5	19.4	19.7	20.6	19.8	20.8	17.7	1.26	---
LM area, cm^2	46.8	48.7	47.5	48.6	50.2	53.5	53.2	52.8	57.6	1.64	0.001
FFLI[8]	53.0	52.8	52.9	53.7	54.0	53.8	54.1	53.6	55.7	0.75	0.03

[1]A total of 144 barrows and gilts (TR4 × C22, PIC, Hendersonville, TN; initially 103 kg) were blocked by weight and provided 2 pigs per pen and 8 pens per dietary treatment to evaluate the effects of various levels of astaxanthin with or without 10 ppm Paylean for approximately 26 d pre-harvest.
[2]Paylean, Elanco, Greenfield, IN.
[3]Aquasta, IGENE Biotechnology, Columbia, MD.
[4]Carophyll Pink, DSM Nutritional Products, Basel, Switzerland.
[5]No ractopamine HCl × astaxanthin interactions or astaxanthin effects (linear or quadratic) were observed for any of the growth and carcass criteria measured.
[6]Not significant ($P > 0.10$).
[7]Average of the backfat depth measured at the first-rib, 10th-rib, last-rib, and last lumbar.
[8]FFLI = fat-free lean index.

Table 5-6. Subjective color and color shelf-life evaluation of pork LM chops from barrows and gilts fed various levels of astaxanthin with or without ractopamine HCl, Exp. 2

Ractopamine HCl, ppm[1,2]:	None										10								
Astaxanthin source:	*Xanthophyllomyces dendrorhous*[3]								Synthetic[4]		*Xanthophyllomyces dendrorhous*								
Astaxanthin level, ppm:	0		5		7.5		10		5		0		2.5		5		7.5		
Gender[5]:	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	SEM
Initial color[6], d 0	3.3	3.2	3.6	3.5	3.3	3.6	3.2	3.4	3.3	3.6	3.3	3.3	3.4	3.4	3.4	3.3	3.5	3.6	0.22
Discoloration score[7, 8]																			
d 0	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.1	1.2	1.1	1.1	1.1	1.1	1.1	1.2	1.1	1.2	1.1	0.22
d 1	1.4	1.6	1.4	1.3	1.4	1.5	1.6	1.4	1.4	1.3	1.4	1.4	1.2	1.4	1.5	1.4	1.3	1.4	0.22
d 2	2.5	2.5	2.4	2.4	2.7	2.4	2.8	2.1	3.2	2.3	2.6	2.1	2.3	2.3	3.4	2.3	2.0	2.1	0.22
d 3	3.5	3.3	3.6	3.2	3.6	3.2	3.5	2.8	3.3	3.0	3.5	2.8	2.8	3.0	3.3	2.9	2.7	2.7	0.22
d 4	4.2	3.8	4.3	3.7	4.3	3.7	4.3	3.5	3.9	3.6	4.0	3.2	3.3	3.5	3.9	3.5	3.0	3.0	0.22
d 5	4.8	4.2	4.8	3.9	4.9	3.8	4.9	4.0	4.5	4.0	4.4	3.6	3.8	3.9	4.5	3.8	3.5	3.4	0.22
d 6	5.0	4.4	5.0	4.5	5.0	4.5	5.0	4.4	5.0	4.3	5.0	4.0	4.1	4.6	5.0	4.4	4.4	4.0	0.22
d 7	5.0	4.7	5.0	4.9	5.0	4.9	5.0	4.8	5.0	4.9	5.0	4.9	4.7	4.9	5.0	4.9	5.0	4.5	0.22
Overall	3.4	3.2	3.5	3.1	3.5	3.1	3.5	3.0	3.4	3.1	3.4	2.9	2.9	3.1	3.5	3.0	2.9	2.8	0.08
Color shelf-life, d[9,10]	3.3	4.5	3.0	5.0	3.0	4.3	3.0	4.8	3.8	4.8	3.5	5.5	5.3	4.5	3.8	5.3	5.3	5.5	0.54

[1]Longissimus muscle chops from barrows (36) and gilts (36) were visually evaluated daily by a trained panel during 7 d of retail display.
[2]Paylean, Elanco, Greenfield, IN.
[3]Aquasta, IGENE Biotechnology, Columbia, MD.
[4]Carophyll Pink, DSM Nutritional Products, Basel, Switzerland.
[5]B = barrow and G = gilt.
[6]Color score: 1 = white to pale pinkish gray to 6 = dark purplish red (National Pork Producers Council, 2000).
[7]Discoloration score: 1 = no discoloration, very bright pinkish red to 7 = total discoloration, extremely dark pinkish gray/tan (Hunt et al., 1991). Individual sample packages that received a mean discoloration score ≥ 4 were deemed to have an unacceptable appearance and removed from display for the remainder of the experiment. Sample packages removed for an unacceptable appearance were assigned a discoloration score of 5 for the remaining days of retail display.
[8]Discoloration statistics: dietary treatment × gender ($P < 0.001$), d × gender ($P < 0.001$), d (linear, $P < 0.001$; quadratic, $P < 0.001$), barrow vs. gilt ($P < 0.001$), ractopamine HCl vs. non-ractopamine HCl ($P < 0.001$), astaxanthin from *Xanthophyllomyces dendrorhous* within ractopamine HCl (linear, $P < 0.03$; quadratic, $P < 0.01$).
[9]Color shelf-life = average days of acceptable appearance during simulated retail display.
[10]Color shelf-life statistics: barrow vs gilt ($P < 0.0001$), ractopamine HCl vs non-ractopamine HCl ($P < 0.001$).

Table 5-7. Objective color measurements of pork LM chops from barrows and gilts fed various levels of astaxanthin with or without ractopamine HCl, Exp. 2

Ractopamine HCl, ppm[1,2]:	None										10								
Astaxanthin source:	*Xanthophyllomyces dendrorhous*[3]								Synthetic[4]		*Xanthophyllomyces dendrorhous*								
Astaxanthin level, ppm:	0		5		7.5		10		5		0		2.5		5		7.5		
Gender[5]:	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	SEM
CIE L*[6]																			
d 0	54.5	57.2	57.3	54.3	55.5	54.7	57.3	55.8	56.1	54.0	55.2	54.3	55.5	55.0	55.2	55.0	54.3	54.2	1.33
d 1	54.5	55.8	55.8	53.8	55.0	53.5	55.0	54.6	55.9	53.5	54.3	54.6	54.8	53.7	54.5	54.8	52.9	53.6	1.33
d 2	54.9	56.3	56.2	54.1	55.4	53.7	55.4	54.3	55.5	53.1	54.1	53.9	54.3	53.9	54.8	53.8	52.9	53.6	1.33
d 3	54.0	56.0	55.7	54.0	55.3	53.3	55.2	53.6	55.4	53.2	53.8	54.0	53.6	54.0	54.2	54.4	53.0	54.1	1.33
Overall	54.5	56.3	56.2	54.0	55.3	53.8	55.7	54.6	55.7	53.4	54.4	54.2	54.5	54.1	54.7	54.5	53.3	53.9	0.67
CIE a*[7,8]																			
d 0	11.5	10.0	10.4	10.2	10.7	9.1	8.9	10.4	10.2	10.0	9.9	9.2	9.7	8.8	9.1	8.4	9.9	9.1	0.44
d 1	10.6	10.2	10.0	10.1	9.9	9.1	9.0	10.4	9.8	10.0	9.5	9.1	9.6	9.0	8.7	8.4	10.0	9.4	0.44
d 2	8.6	8.9	8.4	9.0	8.3	8.4	7.6	9.5	8.6	9.3	8.4	8.7	8.9	8.4	7.8	8.0	9.2	9.1	0.44
d 3	8.4	8.5	8.1	8.7	7.6	8.2	7.3	9.4	8.2	9.0	8.1	8.7	8.7	8.3	7.5	7.8	9.4	9.0	0.44
Overall	9.8	9.4	9.2	9.5	9.1	8.7	8.2	9.9	9.2	9.6	9.0	8.9	9.2	8.6	8.3	8.1	9.6	9.1	0.22
CIE b*[9,10]																			
d 0	17.5	16.9	16.3	16.5	17.3	15.7	15.9	15.9	17.1	16.4	16.1	16.0	16.5	15.4	15.7	15.5	16.3	15.6	0.42
d 1	17.0	17.1	16.6	16.6	16.4	16.0	16.4	16.3	16.5	16.3	16.1	15.8	16.3	15.7	15.6	15.5	15.9	15.7	0.42
d 2	15.8	16.5	15.7	15.8	15.4	15.2	15.7	15.9	16.1	15.8	15.5	15.7	15.6	15.3	14.9	15.3	15.2	15.5	0.42
d 3	16.0	15.9	15.6	15.2	14.9	15.2	15.0	15.8	16.0	15.7	15.4	15.6	15.7	15.2	14.6	14.9	15.1	15.3	0.42
Overall	16.6	16.6	16.1	16.0	16.0	15.5	15.8	15.9	16.4	16.0	15.8	15.8	16.0	15.4	15.2	15.3	15.6	15.5	0.21
ΔE, d 0 to 3[11,12]	3.6	2.4	3.1	2.3	4.2	2.6	3.7	2.7	2.6	1.7	2.6	1.2	2.4	2.5	2.5	1.5	2.1	1.7	0.40

[1]Longissimus muscle chops from barrows (36) and gilts (36) were measured daily for objective lean color analysis (CIE L*, a*, and b*) during 7 d of retail display using a HunterLab Miniscan™ XE Plus spectrophotometer (Model 45/0 LAV, 2.54-cm-diameter aperture, 10° standard observer, Illuminant D65, Hunter Associates Laboratory, Inc., Reston, VA).
[2]Paylean, Elanco, Greenfield, IN.
[3]Aquasta, IGENE Biotechnology, Columbia, MD.
[4]Carophyll Pink, DSM Nutritional Products, Basel, Switzerland.
[5]B = barrow and G = gilt.
[6]CIE L* = measure of darkness to lightness (black = 0 to white = 100).
[7]CIE a* = measure of redness (a larger value indicates a more red color).
[8]CIE a* statistics: dietary treatment × gender ($P < 0.001$), d × gender ($P < 0.001$), d (linear, $P < 0.001$), ractopamine HCl vs. non-ractopamine HCl ($P < 0.001$), controls vs. astaxanthin from *Xanthophyllomyces dendrorhous* ($P < 0.03$), astaxanthin from *Xanthophyllomyces dendrorhous* within non-ractopamine HCl (linear, $P < 0.01$), astaxanthin from *Xanthophyllomyces dendrorhous* within ractopamine HCl (quadratic, $P < 0.001$).
[9]CIE b* = measure of yellowness (a larger value indicates a more yellow color).
[10]CIE b* statistics: d (linear, $P < 0.001$), ractopamine HCl vs. non-ractopamine HCl ($P < 0.001$), controls vs. all astaxanthin ($P < 0.001$), controls vs. astaxanthin from *Xanthophyllomyces dendrorhous* ($P < 0.001$), astaxanthin from *Xanthophyllomyces dendrorhous* within non-ractopamine HCl (linear, $P < 0.001$).
[11]ΔE = total color change, calculated as $\sqrt{((d\ 0\ L^* - d\ 3\ L^*)^2 + (d\ 0\ a^* - d\ 3\ a^*)^2 + (d\ 0\ b^* - d\ 3\ b^*)^2)}$ (Minolta, 1998).
[12]ΔE statistics: ractopamine HCl vs. non-ractopamine HCl ($P < 0.001$), barrow vs. gilt ($P < 0.001$).

Table 5-8. Growth performance, selected organ weights, and carcass characteristics of finishing pigs fed various levels of astaxanthin with or without ractopamine HCl, Exp. 3

Ractopamine HCl, ppm[1,2]:	0						10			*P* <		
										Astaxanthin within 0 ppm Ractopamine HCl		Ractopamine HCl vs. Non-Ractopamine HCl
Astaxanthin, ppm[3]:	0	7.5	15	30	60	120	7.5	20	SEM	linear	quadratic	
Pre-harvest growth performance, 26 d												
ADG, kg	0.97	0.95	0.96	1.04	1.03	0.99	1.19	1.20	0.030	---[4]	0.06	0.001
ADFI, kg	2.82	2.83	2.78	2.90	2.82	2.82	2.93	2.79	0.079	---	---	---
G:F	0.35	0.33	0.34	0.36	0.37	0.35	0.41	0.43	0.009	---	0.05	0.001
Final BW, kg	115.8	115.3	115.5	117.8	117.3	116.3	121.5	121.7	1.23	---	---	0.001
Post-harvest organ weights												
Heart, g	429.4	414.6	418.2	433.1	420.3	418.0	416.5	416.8	9.15	---	---	---
Heart, % of BW	0.37	0.36	0.36	0.37	0.36	0.36	0.34	0.34	0.007	---	---	0.01
Kidney, g	176.2	169.3	174.6	168.2	167.6	169.4	188.7	184.4	0.010	---	---	0.001
Kidney, % of BW	0.15	0.15	0.15	0.14	0.14	0.15	0.15	0.15	0.003	---	0.08	0.06
Liver, g	1,642	1,629	1,653	1,704	1,679	1,665	1,772	1,813	37.7	---	---	0.001
Liver, % of BW	1.42	1.41	1.43	1.45	1.43	1.43	1.46	1.49	0.026	---	---	0.07
Spleen, g	187.3	182.2	184.5	201.1	192.2	202.9	198.3	207.5	10.15	---	---	---
Spleen, % of BW	0.16	0.16	0.16	0.17	0.16	0.17	0.16	0.17	0.008	---	---	---
Carcass characteristics												
HCW, kg	83.2	83.3	84.4	85.8	84.7	84.5	88.4	88.8	0.96	---	---	0.001
Yield, %	71.9	72.3	73.1	72.8	72.2	72.6	72.8	72.9	0.36	---	---	---
Avg. backfat depth, mm	22.3	23.6	22.8	22.4	22.8	23.3	22.0	22.0	0.74	---	---	---
10^{th} – rib backfat depth, mm	19.3	20.1	19.9	18.8	19.7	20.7	18.4	18.2	0.98	---	---	---
10^{th} – rib LM area, cm^2	49.5	47.2	48.1	49.9	47.7	48.1	52.5	53.6	1.23	---	---	0.001
10^{th} – rib LM pH, 24-h	5.50	5.49	5.47	5.50	5.49	5.52	5.57	5.53	0.015	---	---	0.001
FFLI[5]	54.7	53.9	54.0	54.8	54.0	53.6	55.4	55.7	0.66	---	---	0.03

[1]A total of 160 barrows and gilts (TR4 × C22, PIC, Hendersonville, TN; initially 90 kg) were used with 2 pigs per pen (1 barrow and gilt) and 10 pens per treatment to evaluate the effects of various levels of dietary astaxanthin with or without 10 ppm ractopamine HCl.
[2]Paylean, Elanco, Greenfield, IN.
[3]Nāturxan (astaxanthin from *Xanthophyllomyces dendrorhous*), IGENE Biotechnology, Columbia, MD.
[4]Not significant ($P > 0.10$).
[5]FFLI = fat-free lean index.

Table 5-9. Subjective color evaluation during simulated retail display of LM chops from barrows and gilts fed various levels of astaxanthin with or without ractopamine HCl, Exp. 3

													P <			
													Astaxanthin within 0 ppm Ractopamine HCl			
Ractopamine HCl, ppm[1,2]:	0						10			Gender					Ractopamine HCl vs.	
Astaxanthin, ppm[3] :	0	7.5	15	30	60	120	7.5	20	SEM	Barrow	Gilt	SEM	linear	quadratic	Non-Ractopamine HCl	Gender
Pigs, n	18	18	18	18	18	18	18	18		72	72					
Color score, d 0[4]	3.6	3.2	3.4	3.4	3.1	3.4	3.4	3.3	0.08	3.3	3.4	0.04	---[5]	0.002	---	0.03
Marbling score, d 0[6]	1.6	1.4	1.5	1.5	1.5	1.6	1.7	1.5	0.08	1.6	1.5	0.04	---	---	0.05	---
Discoloration scores[7,8]																
d 0	1.2	1.5	1.4	1.3	1.4	1.4	1.3	1.4	0.11	1.4	1.3	0.05				
d 1	1.5	1.7	1.7	1.6	1.7	1.6	1.5	1.7	0.11	1.7	1.6	0.05				
d 2	1.8	2.2	2.2	2.0	2.2	2.0	1.8	2.1	0.11	2.1	2.0	0.05				
d 3	2.2	2.7	2.6	2.4	2.6	2.3	2.1	2.3	0.11	2.5	2.3	0.05				
d 4	2.7	3.1	3.0	2.8	3.0	2.7	2.3	2.6	0.11	2.9	2.6	0.05				
d 5	3.0	3.5	3.3	3.1	3.3	3.0	2.5	2.7	0.11	3.2	2.9	0.05				
d 6	3.3	3.8	3.7	3.4	3.6	3.3	2.8	2.9	0.11	3.5	3.2	0.05				
Overall	2.2	2.6	2.6	2.4	2.5	2.3	2.0	2.2	0.10	2.5	2.3	0.05	---	---	0.001	0.02

[1]Longissimus muscle chops from barrows (72) and gilts (72) were visually evaluated daily by a trained panel during 6 d of retail display.
[2]Paylean, Elanco, Greenfield, IN.
[3]Nāturxan (astaxanthin from *Xanthophyllomyces dendrorhous*), IGENE Biotechnology, Columbia, MD.
[4]Color score: 1 = white to pale pinkish gray to 6 = dark purplish red (National Pork Producers Council, 2000).
[5]Not significant ($P > 0.10$).
[6]Marbling score: 1 = very lean to 5 = highly marbled (National Pork Producers Council, 2000).
[7]Discoloration score: 1 = no discoloration, very bright pinkish red to 7 = total discoloration, extremely dark pinkish gray/tan (Hunt et al., 1991).
[8]Effect of d (linear, $P < 0.001$; quadratic, $P < 0.05$), treatment × d ($P < 0.001$), gender × d ($P < 0.04$).

Table 5-10. Objective color measurements during simulated retail display of LM chops from barrows and gilts fed various levels of astaxanthin with or without ractopamine HCl, Exp. 3

														P <			
Ractopamine HCl, ppm[1,2]:	0						10			Gender			Astaxanthin within 0 ppm Ractopamine HCl		Ractopamine HCl vs. Non-Ractopamine HCl	
Astaxanthin, ppm[3] :	0	7.5	15	30	60	120	7.5	20	SEM	Barrow	Gilt	SEM	linear	quadratic		Gender
Pigs, n	18	18	18	18	18	18	18	18		72	72					
CIE L*[4,5]																
d 0	56.4	59.3	58.3	58.3	59.0	57.7	57.2	58.6	0.52	58.6	57.6	0.26				
d 1	56.4	59.2	58.6	58.5	59.1	58.0	57.4	58.8	0.52	58.7	57.8	0.26				
d 2	56.3	59.2	58.3	58.5	59.1	58.0	57.4	59.0	0.52	58.5	57.8	0.26				
d 3	56.8	59.5	58.7	58.6	59.3	58.2	57.5	59.0	0.52	58.8	58.1	0.26				
d 4	56.6	59.2	58.4	58.5	59.1	58.0	57.4	58.7	0.52	58.5	58.0	0.26				
d 5	56.7	59.3	58.4	58.5	59.2	57.9	57.5	58.6	0.52	58.5	58.0	0.26				
d 6	57.1	59.4	58.6	58.9	59.3	58.3	57.8	59.0	0.52	58.8	58.3	0.26				
Overall	56.6	59.3	58.5	58.5	59.2	58.0	57.5	58.8	0.51	58.6	58.0	0.25	---[6]	0.01	---	0.06
CIE a*[7,8]																
d 0	10.9	10.6	10.7	10.4	10.4	10.6	9.3	9.0	0.25	10.4	10.1	0.13				
d 1	11.1	10.6	10.7	10.6	10.4	10.7	9.9	9.5	0.25	10.4	10.4	0.13				
d 2	10.6	9.9	10.0	10.0	9.8	10.2	9.7	9.2	0.25	9.9	10.0	0.13				
d 3	9.9	9.2	9.5	9.4	9.2	9.6	9.3	8.8	0.25	9.3	9.4	0.13				
d 4	9.5	8.7	8.9	8.9	8.7	9.0	9.1	8.5	0.25	8.8	9.0	0.13				
d 5	9.0	8.2	8.5	8.5	8.2	8.7	8.8	8.3	0.25	8.4	8.6	0.13				
d 6	8.5	7.7	8.0	8.0	7.8	8.2	8.6	7.8	0.25	7.9	8.2	0.13				
Overall	9.9	9.3	9.5	9.4	9.2	9.6	9.2	8.7	0.23	9.3	9.4	0.12	---	0.10	0.02	---
CIE b*[8,9]																
d 0	17.2	17.5	17.4	17.2	17.2	17.1	16.3	16.5	0.16	17.2	16.8	0.08				
d 1	17.2	17.5	17.4	17.1	17.1	17.0	16.5	16.7	0.16	17.2	17.0	0.08				
d 2	16.9	17.2	17.2	16.9	17.0	16.8	16.4	16.5	0.16	17.0	16.8	0.08				
d 3	16.6	17.0	16.9	16.7	16.8	16.6	16.3	16.3	0.16	16.8	16.5	0.08				
d 4	16.6	17.0	17.0	16.7	16.8	16.6	16.4	16.3	0.16	16.8	16.6	0.08				
d 5	16.5	17.0	16.9	16.6	16.6	16.6	16.3	16.4	0.16	16.7	16.5	0.08				
d 6	16.3	16.8	16.8	16.5	16.6	16.4	16.3	16.2	0.16	16.6	16.4	0.08				
Overall	16.8	17.1	17.1	16.8	16.9	16.7	16.4	16.4	0.15	16.9	16.6	0.07	---	---	0.001	0.02
ΔE, d 0 to 6[10]	3.0	3.2	3.0	2.8	3.0	3.0	1.5	1.7	0.23	2.9	2.4	0.12	---	---	0.001	0.01

[1]Longissimus muscle chops from barrows (72) and gilts (72) were measured daily for objective lean color analysis (CIE *L**, *a**, and *b**) during 6 d of simulated retail display using a HunterLab Miniscan™ XE Plus spectrophotometer (Model 45/0 LAV, 2.54-cm-diameter aperture, 10° standard observer, Illuminant D65, Hunter Associates Laboratory, Inc., Reston, VA).
[2]Paylean, Elanco, Greenfield, IN.
[3]Nāturxan (astaxanthin from *Xanthophyllomyces dendrorhous*), IGENE Biotechnology, Columbia, MD.
[4]CIE L* = measure of darkness to lightness (black = 0 to white = 100).
[5]Effect of d (linear, $P < 0.01$).
[6]Not significant ($P > 0.10$).
[7]CIE a* = measure of redness (a larger value indicates a more red color).
[8]Effect of d (a* quadratic, $P < 0.001$; b* linear, $P < 0.001$), treatment × d ($P < 0.02$), gender × d ($P < 0.01$).
[9]CIE b* = measure of yellowness (a larger value indicates a more yellow color).
[10]ΔE = total color change, calculated as $\sqrt{((d\ 0\ L^* - d\ 6\ L^*)^2 + (d\ 0\ a^* - d\ 6\ a^*)^2 + (d\ 0\ b^* - d\ 6\ b^*)^2)}$ (Minolta, 1998).

CHAPTER 6 - Meta-analyses describing the variables that influence the backfat, belly fat, and jowl fat iodine values of pork carcasses

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ABSTRACT

Concern for the quality of pork fat has increased in the United States over the last decade, largely because of the increased availability and use of dried distillers grains with solubles (DDGS) in swine diets. The iodine value (IV) of fat is commonly used as an indicator of pork fat quality. To identify the factors associated with carcass fat IV, meta-analyses were conducted to describe the variables that influence the IV of pork fat, and to develop prediction equations to assist nutritionists and producers in producing pork fat with an acceptable IV. Data from 21 experiments were used to develop prediction equations for carcass fat IV of pigs fed a relatively constant dietary iodine value product (IVP) throughout the feeding period, and 6 experiments were used to develop prediction equations for carcass fat IV of pigs fed a dietary IVP reduction strategy before marketing. Backfat, belly fat, and jowl fat IV were all highly correlated amongst the experiments that measured the IV of the multiple fat depots ($r \geq 0.880$; $P < 0.001$). As expected, the dietary concentrations of unsaturated (primarily polyunsaturated) fatty acids were the most important to predict carcass fat IV. However, improved models for predicting the carcass fat IV were achieved by including variables to describe the initial and/or final BW, ADG, and carcass leanness of the pigs. Increased ADG, final BW, BW range over which the diet was fed, and backfat depth resulted in reduced backfat IV ($P < 0.02$). Belly fat IV was also reduced by increasing final BW, BW range over which the diet was fed, and backfat depth ($P < 0.03$). A reduced jowl fat IV was associated with an increase in backfat depth and a lower fat-free lean index (FFLI, $P < 0.02$). Data analyzed to develop equations for predicting carcass fat IV using a dietary IVP reduction strategy indicated that the concentrations of dietary polyunsaturated fatty acids fed in the initial diet were the most important. The concentrations of dietary polyunsaturated fatty acids in the reduced IVP diet fed before marketing were also important for

predicting the IV of carcass fat. However, the IV of backfat was the most amenable to change using an IVP reduction strategy. Feeding the pigs for a longer period and to a heavier final BW resulted in a reduced backfat IV ($P \leq 0.05$). These results indicate that, although primarily determined by dietary factors, understanding the other variables that influence the IV of pork fat is necessary to reduce the likelihood of problems with pork fat quality.

Key words: fat quality, fatty acids, finishing pigs, iodine value

INTRODUCTION

Attention to the quality of pork fat has increased in the United States over the last decade, largely because of the increased availability and use of dried distillers grains with solubles (DDGS) in swine diets. Adding 10% DDGS to traditional, corn-soybean meal-based swine diets may not affect finishing pig performance or carcass characteristics; but increases the concentration of polyunsaturated fatty acids in the diet and the resulting carcass fat. Feeding a diet containing greater than 20% DDGS may result in reduced growth performance, with a further increase in the unsaturation of carcass fat. Feeding up to 30% or more DDGS in the diet may not affect carcass lean characteristics, but results in a greater increase in the unsaturation level of carcass fat and the likelihood for soft bellies (Whitney et al., 2006). Recent economic circumstances have encouraged many pork producers to feed greater concentrations of DDGS when necessary, despite anticipated reductions in growth performance. As a result, some processors have become increasingly involved in the feeding practices employed by pork producers.

Iodine value (IV) is currently utilized as a standard indicator of carcass fat quality in the United States. It provides an overall estimate of the unsaturated fatty acid content (greater IV = greater unsaturated fatty acid concentration), and also serves as an indicator of the fat firmness

(greater IV = softer fat) and risk for rancidity (greater IV = increased risk of rancidity; Hugo & Roodt, 2007). However, carcass fat quality standards can vary considerably. Various thresholds for backfat IV have been described, ranging from 60 (Hugo & Roodt, 2007) to 74 (Boyd et al., 1997). Currently, one processor (Triumph Foods, St. Joseph, MO) in the United States routinely samples carcass jowl fat for IV determination, and they have established a threshold of 73. However, the IV of pork fat differs according to anatomical position, with the IV of jowl fat generally being greater than that of backfat (Barton-Gade, 1984; Benz et al., 2008). Therefore, the IV obtained from sampling a location selected for convenience relative to the IV of the fat depot of interest must be known. Various research performed to evaluate dietary effects on pork fat IV has measured backfat, belly fat, or jowl fat; with a few studies reporting measurements of two or all three of these fat depots.

To assist producers with meeting the standards for fat IV that might be imposed by a processor, Madsen et al. (1992) and Boyd et al. (1997) developed equations to predict backfat IV based on the contribution of dietary fatty acids described in terms of the iodine value product (IVP) of the diet ([IV of the dietary lipids] × [percentage dietary lipid] × 0.10; Christensen, 1962). While useful for understanding the importance of dietary fatty acids relative to carcass fat quality, recent research indicates that the diet IVP alone may not be an accurate predictor of carcass fat IV (Benz et al., 2008). In addition to the diet, other factors associated with growth have been found to influence the composition and quality of fat; such as genetics, backfat depth, age and/or slaughter weight, gender, rearing conditions, environmental temperature, and growth promoters (Hugo & Roodt, 2007).

Recently, economic conditions have encouraged some producers to periodically feed diets with a relatively high IVP early and switch to a lower IVP diet later in an attempt to reduce

the unsaturation of carcass fat. Xu et al. (2010) demonstrated that the belly fat IV was successfully reduced by feeding a diet without DDGS for 9-wk before harvest after feeding either 15% or 30% DDGS for 6-wk. However, Benz et al. (2008) reported that, although jowl and backfat IV were reduced, feeding a corn-soybean meal diet without added fat for 56-d (after feeding 5% soybean oil for 26-d) prior to harvesting was insufficient to reduce the jowl IV below the accepted threshold. Thus, the methods to predict fat quality need to be improved so that swine producers can produce acceptable pork products in an economically sustainable fashion.

Therefore, meta-analyses were conducted to determine 1) the effects of dietary fatty acids (or dietary IVP) and variables associated with growth and carcass characteristics on the backfat, belly fat, and/or jowl fat fatty acids (or IV) and 2) the effects of dietary fatty acid (or IVP) reduction strategies on the backfat, belly fat, and/or jowl fat fatty acids (or IV). The data for the first objective was utilized to develop equations to improve our ability to predict backfat, belly fat, and jowl fat IV. Data for the second objective was utilized to develop equations to improve our ability to use IVP reduction strategies to meet acceptable fat quality standards.

MATERIALS AND METHODS

Selection of data

The data used for the meta-analyses were obtained from numerous sources. A comprehensive search for published data was conducted via the Kansas State University Libraries using the internet and the ISI Web of Knowledge^{SM}/CABI search engine. Additional data were obtained through communication with authors affiliated with a few of the studies. Data from both refereed and non-refereed publications, such as theses, technical memos, and university publications were included.

Selection of data to fulfill the objectives of the meta-analyses was based on a number of criteria. For the data set used to fulfill the objectives of the first meta-analysis, the treatments had to be replicated and each treatment had to consist of a single diet or series of diets to provide a similar diet IVP throughout the feeding period. Replicated treatments were also required for the data to be included for the second meta-analysis of reduction strategies, and data had to originate from experiments consisting of 2 periods using diets with distinct differences in dietary IVP. The control treatments (that consisted of a similar diet IVP throughout the feeding period) utilized in any of the reduction studies were also included in the first meta-analysis.

Treatment diets had to be formulated to meet the nutrient requirements of all the pigs within each experiment. The gender utilized in the experiment had to be specified as barrow, gilt, or mixed (there were no studies that used boars). If barrows and gilt were included in an experiment separately, the interactive means of the response criteria had to be reported to evaluate the influence of gender. Otherwise, the mixed gender means reported for the main effects of dietary treatment were used. Dietary and performance data had to be reported, including the actual diets and data to calculate or estimate the dietary IVP; dietary content of C16:0, C18:0, C16:1, C18:1, C18:2, and C18:3 fatty acids; dietary ME concentration; percentage of the dietary ME from fat; initial BW; ADG; duration of the feeding period; final BW; hot carcass weight; 10^{th}-rib or last-rib backfat depth; fat-free lean index; and backfat, belly fat, and/or jowl fat IV.

Interpretation of the data

The IVP of every treatment diet was calculated as [IV of the dietary lipids] × [percentage dietary lipid] × 0.10, even when already reported, to ensure a uniform interpretation of dietary IVP across experiments. The IV of the lipid fraction of the dietary ingredients was calculated

with the AOCS (1998) equation (IV = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723) using either the published fatty acid values for added fat sources (NRC, 1998) or the analyzed profiles of the diet or diet components when reported. When analyzed values for the fat or fatty acid content were not provided for corn and soybean-based ingredients, the fatty acid profiles were calculated by using the NRC (1998) values for their fat content and the fatty acid profiles from corn oil and soybean oil (Table 6-1). This provided a greater value for the C18:2 of corn and soybean meal than that listed in the NRC (1998) table for the chemical composition of ingredients, and a greater estimate than the calculated values reported by authors using the NRC (1998) ingredient values. However, this method was used in order to estimate the relative amounts of the other important fatty acids found in corn and soybean-based ingredients that are not listed in the NRC (1998). This resulted in an estimated IVP for corn and soybean meal of 48.7 and 37.8, respectively, very similar to the values found in the National Swine Nutrition Guide (2010) of 48.8 and 39.0. When necessary, the values required for estimating the fatty acid contents of barley-, wheat-, and sorghum-based ingredients were obtained from the USDA National Nutrient Database for Standard Reference, Release 22 (2009).

The ME content of every diet was determined by using the ingredient ME values provided in the NRC (1998). However, for corn-based DDGS, an ME value of 3,420 kcal/kg was used to account for quality changes that have occurred with more recently designed ethanol plants (Pedersen et al., 2007). Although some authors reported an estimate of dietary ME concentration using different ingredient values, the above values were applied to standardize the data. When the ME value for an ingredient was not listed in the NRC (1998), the reported energy content of the diet and/or ingredient was used. Energy values that were reported in terms of DE

or NE were converted to an ME basis using the equations of Noblet and Perez (1993) and Noblet et al. (1994), respectively, when necessary. For the only study (Bee et al., 2002) that implemented limit-feeding, the dietary ME values were adjusted using the equation of Noblet and Shi (1993). Finally, an estimate of the percentage of the ME that originated from fat was determined for every diet.

For treatments applied over more than one dietary phase to achieve a desired IVP or dietary fatty acid treatment, the mean IVP, mean content of fatty acids, mean ME density, and the mean percentage of dietary ME from fat of the diets were used to describe the treatment applied.

All of the studies used for the analyses reported the overall growth performance and some also reported the performance by period. Originally, the goal was to utilize the ADG for each period of the IVP reduction studies, but not enough data were provided across the studies to include this in the analyses. Most of the IVP reduction studies reported both the length of the feeding periods and the BW at which the change in dietary IVP was initiated. However, a few provided only the days or the BW at which the change in diet strategy occurred. To retain these treatments in the analysis of IVP reduction strategies, the other reported criteria (such as overall ADG and period days or interim BW) were used to calculate a value for the missing variable of interest (period days or interim BW).

Backfat depth and carcass lean were selected to be variables of interest for the analyses. Either the 10^{th}-rib or last-rib backfat depth was used as the measure of backfat depth, depending on the measure provided by the experiment. However, a consistent method of reporting lean percentage estimates across the studies was lacking. Therefore, the fat-free lean index (FFLI; National Pork Producers Council, 2000) was applied across all the treatments using the reported

variables necessary to calculate it, regardless of whether it was already reported by the authors. Some authors reported the FFLI using hot carcass weight (HCW) as a covariate, resulting in slight differences from our recalculation. Slight differences might also be expected with the interpretation and conversion of metric to English units for the FFLI calculations. However, the relative differences in FFLI among the treatments already reported remained the same. When the ending live BW and backfat measurements were reported without a HCW (Boyd et al., 1997), an estimate of the HCW was calculated assuming a dressing percentage of 75%. This resulted in estimates of FFLI with relatively similar differences between the treatments as the determination of lean percentage that was reported.

A few published studies reported the actual dissected lean percentage or overall chemical composition of the carcasses, but did not provide a backfat measurement or the means to calculate the FFLI. These studies were excluded from the modeling analyses because they were unable to contribute to the determination of backfat depth or FFLI as factors in the fatty acid composition of backfat, belly fat, or jowl fat.

The analyzed fatty acid composition of backfat, belly fat, and/or jowl fat were used to calculate their IV with the AOCS (1998) equation (IV = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723) when the IV was not already reported using this equation.

Overall, 21 experiments were used to develop models for predicting the backfat, belly fat, or jowl fat IV of pigs fed a relatively constant IVP throughout the feeding period (Table 6-2). Sixteen of these experiments provided 95 observations for backfat IV, 10 experiments provided 49 observations for belly fat IV, and 12 experiments provided 58 observations for jowl fat IV. Five of the experiments provided 22 observations to describe the relationship of belly fat and

jowl fat IV, 8 experiments provided 37 observations to describe the relationship of backfat and jowl fat IV, and 9 experiments provided 46 observations to describe the relationship of belly fat and backfat IV.

For the analysis of IVP reduction strategies, 6 experiments were used for modeling the backfat, belly fat, or jowl fat IV (Table 6-3). Four of the experiments provided 33 observations for backfat IV, 3 experiments provided 21 observations for belly fat IV, and 3 experiments provided 23 observations for jowl fat IV. Six observations from 1 experiment were used to describe the relationship of belly fat and jowl fat IV, 15 observations from 2 experiments were used to describe the relationship of backfat and jowl fat IV, and 12 observations from 2 experiments were used to describe the relationship of belly fat and backfat IV.

Statistical analyses

Each dietary IVP treatment strategy applied within each study was considered the experimental unit (or observation) for modeling the effects of diet, duration, growth, and carcass fat/lean characteristics on backfat, belly fat, and jowl fat IV. The specific variables of interest included in the data were the experiment, genetic line, gender, dietary treatment IVP, grain source(s), protein source(s), added fat source(s), average caloric density (ME, kcal/kg), average C16:0 (%), average C18:0 (%), average C16:1+C18:1 (%), average C18:2 (%), average C18:3 (%), diet ME from fat (%), initial BW (kg), total duration (d), ADG (kg), ending BW (kg), BW range (ending BW – initial BW, kg), HCW (kg), backfat depth (mm), FFLI, and backfat IV, belly fat IV, and/or jowl fat IV.

Although the genetic line was recorded and included in the data set, it was not included in the analyses. The growth and lean characteristics of pigs are primarily a function of genotype, and the continuous variables describing these characteristics (ADG, initial and ending BW,

backfat depth, and FFLI) were determined to be the most important, descriptive, and relevant for these analyses. All of the genotypes included could be described as domesticated, modern, lean-genotype pigs.

Similarly, the primary grain sources, protein sources, and added fat sources were not included in the analysis. The existing research indicates a positive, linear relationship between the dietary polyunsaturated fatty acid concentration with that of carcass lipids; regardless of the source. The fatty acid profiles, fat content, and ME concentrations of the various ingredients and diets accounted for the differences necessary to characterize the effects of the ingredients on the carcass fat IV. Growth rate and fat deposition are largely a function of the genetics, feed intake, and the dietary nutrient and energy content. Therefore, growth rate and the diet characteristics of interest; such as fat content, the content of the individual fatty acids, dietary IVP, and energy density; were variables included in the analyses.

Most of the experiments (17) applied the dietary treatments to pigs of mixed gender, while some (7) used only barrows or gilts. Few experiments (2) applied the treatments to both genders and reported the gender × treatment interactive means. Dummy variables can be used in regression to distinguish between the qualitative characteristics of populations (SAS Institute, Inc., 2010). Therefore, dummy variables were used to evaluate the effect of gender on backfat, belly fat, and jowl fat IV across the studies.

For the meta-analysis of IVP reduction strategies, the same dietary variables of interest were used for the diet fed during the period of reduced IVP. The total duration of the feeding period was also divided into the number of pre-reduction and actual reduction days. Interim BW was also included for the reduction analysis, and the BW range over which the pre-reduction and actual reduction periods occurred were included. An additional variable was created for the IVP

reduction analyses by multiplying the dietary IVP fed during the reduction period by the number of days of the reduction period. This was necessary to describe the combined effect of the reduced IVP and duration that it was fed. All other variables remained the same as the previous meta-analysis of pigs fed a constant IVP throughout the feeding period.

The data for both meta-analyses were analyzed using the correlation, general linear models, and regression procedures of the SAS Institute, Inc. (2010). The correlation procedure was used to indicate the significance of the relationship of each independent variable to the backfat IV, belly fat IV, and jowl fat IV; and to identify the significance of the relationship of IV among the 3 fat depots. The general linear models procedure was used to test the variables for significant interactions, and the regression procedure was used to develop prediction equations for backfat, belly fat, and jowl fat IV using a stepwise approach. The models were first developed without using the dummy variables for gender. Intercept adjusted collinearity diagnostics (using the SAS syntax = COLLINOINT) and variance inflation factor (SAS syntax = VIF) were used to assist with the identification of variables with collinearity. Pairwise collinearity of variables was indicated by a condition index of ≥ 30 or a variance inflation of ≥ 10. When 2 variables were found to be collinear, the variable that provided the greatest R^2 was kept in the model, and the other variable was excluded. Additionally, plots of the residuals were examined to identify influential observations. No observations were identified and removed for introducing bias into the models. Lastly, the dummy variables were tested with the final models to evaluate the influence of gender on backfat IV, belly fat IV, and jowl fat IV. Overall, correlations, interactions, variables, and models were considered significant at $P < 0.05$.

RESULTS

Meta-analyses of experiments with treatments consisting of a continuous IVP throughout the feeding period

Correlations

Backfat, belly fat, and jowl fat IV were all highly correlated ($r \geq 0.887$; $P < 0.0001$) to each other (Table 6-4).

Dietary characteristics had the highest correlations with the carcass backfat, belly fat, and jowl fat IV. For backfat IV, the total dietary concentration of C18:2 and C18:3 had the highest correlation ($r = 0.782$; $P < 0.0001$); followed by the diet IVP ($r = 0.765$; $P < 0.0001$), dietary concentration of C18:2 ($r = 0.689$; $P < 0.0001$), total dietary concentration of the unsaturated fatty acids C16:1, C18:1, C18:2, and C18:3 ($r = 0.618$; $P < 0.0001$), percentage of the diet ME from fat ($r = 0.506$; $P < 0.0001$), and dietary concentration of C18:3 ($r = 0.418$; $P < 0.0001$). For belly fat IV, the diet IVP had the highest correlation ($r = 0.882$; $P < 0.0001$); followed by the total dietary concentration of C18:2 and C18:3 ($r = 0.881$; $P < 0.0001$), total dietary concentration of the unsaturated fatty acids C16:1, C18:1, C18:2, and C18:3 ($r = 0.776$; $P < 0.0001$), dietary concentration of C18:3 ($r = 0.635$; $P < 0.0001$), percentage of the diet ME from fat ($r = 0.629$; $P < 0.0001$), dietary concentration of C18:2 ($r = 0.608$; $P < 0.0001$), total dietary concentration of C16:1 and C18:1 ($r = 0.335$; $P < 0.02$), and the ME density of the diet ($r = 0.324$; $P < 0.03$). For jowl fat IV, the dietary concentration of C18:2 had the highest correlation ($r = 0.759$; $P < 0.0001$), followed by the total dietary concentration of C18:2 and C18:3 ($r = 0.754$; $P < 0.0001$), diet IVP ($r = 0.671$; $P < 0.0001$), total dietary concentration of the unsaturated fatty acids C16:1, C18:1, C18:2, and C18:3 ($r = 0.536$; $P < 0.0001$), percentage of

the diet ME from fat (r = 0.346; P < 0.01), dietary concentration of C18:3 (r = 0.298; P < 0.03), and total dietary concentration of C16:1 and C18:1 (r = 0.256; P = 0.05).

As expected, growth and/or carcass variables were also found to be significantly correlated with backfat, belly fat, and jowl fat IV. For backfat IV, the ending BW had the highest negative correlation (r = -0.318; P < 0.01); followed by the weight range fed (r = -0.257; P < 0.02), backfat depth (r = -0.245; P < 0.02), and ADG (r = -0.242; P < 0.02). For belly fat IV, the ending BW and backfat depth had the highest negative correlation (r = -0.395; P < 0.01), followed by the weight range fed (r = -0.317; P < 0.03), with trends ($P \leq 0.06$) for a negative correlation for days fed (r = -0.271) and a positive correlation for FFLI (r = 0.272). Jowl IV was negatively correlated with backfat depth (r = -0.365; P < 0.01) and positively correlated with FFLI (r = 0.315; P < 0.02).

Prediction equations

The regression analyses of dietary and growth characteristics resulted in equations to predict backfat, belly fat, and jowl fat IV (Table 6-5). Equations using a single predictor demonstrated the primary influence of dietary unsaturated fatty acids on the IV of pork fat. However, improved equations were obtained by including multiple variables to describe the diet, animals, and growth.

The prediction equation for backfat IV was improved considerably by including multiple variables to characterize the diet, as well as to describe the growth and rate at which it occurred. Using the dietary concentration of C18:2 + C18:3 (*Adjusted* R^2 = 0.61) and/or backfat depth (*Adjusted* R^2 = 0.64) resulted in improvements over using the diet IVP alone (*Adjusted* R^2 = 0.58). Further improvements were obtained by adding the dietary C18:2 with or without C18:2 + C18:3 concentrations to an equation with the diet IVP, and replacing backfat depth with ADG

and initial BW (*Adjusted* R^2 = 0.79). The equation that included the diet IVP, percentage dietary C18:2, percentage total dietary C18:2 + C18:3, initial BW, and ADG resulted in the greatest R^2 (*Adjusted* R^2 = 0.80). The precision with which this equation was able to predict the IV when compared to the actual data is depicted in Figure 6-1.

The prediction equation for belly fat IV was improved by including multiple variables to characterize the diet and growth. Adding the dietary percentage of ME from fat as an adjustment to the dietary IVP (*Adjusted* R^2 = 0.80) and/or variables to describe the weight during which the diet was fed and the ending backfat depth resulted in greater precision. The equation that included the diet IVP, percentage of ME from fat, BW range, ending BW, and backfat depth resulted in the greatest R^2 (*Adjusted* R^2 = 0.89, Figure 6-2).

The prediction equation for jowl fat IV was improved by including more than one dietary variable and an estimate of carcass lean. Beginning with the simple equation using dietary IVP (*Adjusted* R^2 = 0.44), replacing it with the dietary concentration of C18:2 or adding the estimated FFLI (*Adjusted* R^2 = 0.57) resulted in increased precision. Further precision was obtained by adding back the diet IVP and the percentage of ME from fat, and using either the backfat depth (*Adjusted* R^2 = 0.71) or estimated FFLI. The equation that included the diet IVP, percentage of C18:2, percentage of ME from fat, and estimated FFLI resulted in the greatest R^2 (*Adjusted* R^2 = 0.73, Figure 6-3).

Meta-analyses of experiments evaluating dietary IVP reduction strategies

Correlations

Backfat, belly fat, and jowl fat IV were all highly correlated ($r \geq 0.880$; $P < 0.001$) to each other (Table 6-6).

As in the previous meta-analysis, dietary characteristics had the highest correlations with the carcass backfat, belly fat, and jowl fat IV. Various measures of the fatty acids in the initial dietary treatment had the highest correlations with the backfat IV, primarily the percentage of C18:2 (r = 0.819; P < 0.0001), C18:3 (r = 0.764; P < 0.0001), total C18:2 + C18:3 (r = 0.826; P < 0.0001), total unsaturated fatty acids (r = 0.755; P < 0.0001), and the diet IVP (r = 0.815; P < 0.0001). The same dietary characteristics of the IVP reduction treatment were also correlated ($r \geq$ 0.564; P < 0.0001) with the backfat IV, as well as the ME density ($r \geq 0.605$; P < 0.001) and percentage of ME from fat ($r \geq 0.402$; P < 0.03) for both the initial and reduction period diets. For belly fat IV, the initial dietary percentage of total C16:1 + C18:1 (r = 0.655; P < 0.01), C18:2 (r = 0.817; P < 0.0001), total C18:2 + C18:3 (r = 0.836; P < 0.0001), total unsaturated fatty acids (r = 0.907; P < 0.0001), and the diet IVP (r = 0.915; P < 0.0001) were all highly correlated. The same dietary characteristics of the IVP reduction treatment were also correlated ($r \geq 0.635$; P < 0.01) with the belly fat IV, as well as the ME density ($r \geq 0.586$; P < 0.01) and percentage of ME from fat ($r \geq 0.523$; P < 0.02) for both the initial and reduction period diets. For jowl fat IV, the percentage of C18:2 (r = 0.901; P < 0.0001), total C18:2 + C18:3 (r = 0.878; P < 0.0001), total unsaturated fatty acids (r = 0.675; P < 0.01), and the IVP (r = 0.785; P < 0.0001) of the initial diet had the highest correlations. The dietary percentage of C18:2 and total C18:2 + C18:3 of the IVP reduction treatment were also correlated ($r \geq 0.464$; P < 0.03) with the jowl fat IV, as well as the percentage of ME from fat (r = 0.511; P < 0.02) in the initial diet.

Other variables were also found to be correlated with the backfat and belly fat IV. The total length of the feeding period was negatively correlated with the backfat IV (r = -0.581; P < 0.001) and belly fat IV (r = -0.518; P < 0.02), and the number of days that the initial diet was fed was negatively correlated with the backfat IV (r = -0.494; P < 0.01). Additionally, the initial BW

(r = 0.627; P < 0.0001), overall BW range (r = -0.594; P < 0.001), reduction period diet IVP × actual reduction period days (r = 0.522; P < 0.01), BW at the initiation of the reduction period (r = -0.353; P < 0.05), and final BW (r = -0.340; P = 0.05) were correlated with the backfat IV. As in the previous meta-analysis, backfat depth was negatively correlated (r = -0.629; P < 0.01) with the belly fat IV. Jowl IV was not correlated with the growth and carcass variables.

Prediction equations

Regression analyses of the dietary characteristics; growth, carcass, and BW data; along with feeding durations resulted in equations to predict backfat, belly fat, and jowl fat IV (Table 6-7). Although the meta-analysis of diet IVP reduction treatments was performed primarily with data not included in the previous meta-analysis, the prediction equations resulting in the greatest precision for determining the backfat, belly fat, and jowl fat IV used the same dietary variables. Similar to the previous meta-analysis, the equations with a single predictor demonstrated the primary influence of dietary unsaturated fatty acids on the IV of pork fat. However, the best single predictors were derived from the unsaturated fatty acid characteristics of the initial diet rather than the final diet.

Improved equations for backfat IV were obtained by using either the IVP, concentration of C18:2, or concentration of C18:2 + C18:3 of the initial diet and the BW at the initiation of IVP reduction, reduction period diet IVP × actual reduction period days, and/or the final BW rather than the IVP of the initial diet alone. The equation that included the IVP of the initial diet, the BW at the initiation of IVP reduction, the reduction period diet IVP × actual reduction period days, and the final BW resulted in the greatest R^2 (*Adjusted* R^2 = 0.90). The precision with which this equation was able to predict the IV when compared to the actual data is depicted in Figure 6-4.

Similar to the previous meta-analysis, the prediction equation for belly fat IV included the IVP of the initial diet. The precision of the equation was improved by also including the reduction period diet IVP × actual reduction period days (*Adjusted* R^2 = 0.90, Figure 6-5).

The concentration of C18:2 in the initial diet was an important dietary variable for predicting the jowl fat IV. The prediction equation was improved by including the number of days that the initial diet was fed (*Adjusted* R^2 = 0.87, Figure 6-6).

DISCUSSION

It is well established that the fatty acid composition of pig adipose tissue can be manipulated by changing the amounts and proportions of fatty acids in the diet (Wood et al., 2003). This is also evident in the meta-analyses. The equations with a single predictor, similar to the equation developed by Boyd et al. (1997), demonstrate the primary influence of the dietary unsaturated fatty acid concentration on the IV of pork fat. Brooks (1971), Gläser et al. (2002), and Miller et al. (1990) demonstrated the influence of both dietary mono- and polyunsaturated fatty acids on their concentrations in pork adipose tissue. Eastwood et al. (2009), Kouba et al. (2003), Madsen et al. (1992), Nguyen et al. (2003), and Warnants et al. (1996) also reported the positive linear relationship between the dietary and adipose tissue contents of polyunsaturated fatty acids. The diet IVP and fat IV describe the combined characteristics of the mono- and polyunsaturated fatty acid content of a particular fat. Therefore, it is not surprising that the diet IVP is a common predictor of IV across many of the prediction equations in the analyses.

Although the data from Boyd et al. (1997) was included in the meta-analyses for backfat and belly fat IV, the R^2 of the equations using a single measure of the dietary unsaturated fatty acid concentration as a predictor was considerably less than that reported by Madsen et al. (1992) and Boyd et al. (1997). The equation of Madsen et al. (IV = 47.1 + 0.14 × IVP/day, R^2 = 0.86)

was derived from Danish experiments using individually-housed pigs limit-fed a dietary IVP within the range of 37 to 88 (IVP/day of 42 to 190) from 20 kg BW until harvest at 90 kg BW. The equation of Boyd et al. (IV = 52.4 + 0.32 × IVP, R^2 = 0.99) was derived from a single controlled experiment, with an IVP in the range of 44 to 90 for pigs fed *ad libitum* from 43 kg BW until harvest at 118 kg BW. In the current meta-analyses, the simple equations for predicting backfat IV using the diet IVP were derived from multiple studies. The equation (backfat IV = 57.89 + 0.18 × IVP, R^2 = 0.58) from the meta-analysis of feeding a continuous IVP included data with an initial BW range of 22 kg to 91 kg, a final BW range of 44 kg to 138 kg, and a diet IVP range of 5 to 187. The equation (backfat IV = 54.20 + 0.23 × IVP of the initial diet, R^2 = 0.66) from the meta-analysis of IVP reduction strategies included data with an initial BW range of 39 kg to 62 kg, a final BW range of 103 kg to 133 kg, and a diet IVP range of 43 to 111. Nguyen et al. (2003) demonstrated that the variation in the fatty acid composition of pork adipose tissue is increased when data from various experiments are pooled, resulting in weaker correlations than those obtained in an individual experiment. The increased variation results from differences in the conditions across the experiments. In the present analyses, accounting for some of these differences resulted in improved equations for predicting backfat, belly fat, and jowl fat IV.

The activity of stearoyl-CoA-desaturase in backfat (which generates monounsaturated fatty acids from saturated fatty acids) is decreased when the dietary content of C18:2 and C18:3 is increased (Guillevic et al., 2009; Kloareg et al., 2007). This may explain the improved models for predicting the backfat IV in both the continuous feeding and withdrawal meta-analyses with the inclusion of dietary C18:2 and C18:3. The effect of the dietary fatty acid profile on belly fat IV was sufficiently characterized by the diet IVP in the prediction equations of both meta-analyses. However, for jowl fat IV, the diet C18:2 was also important to improve the prediction

equations in both meta-analyses. The differences in the significance of dietary C18:2 for predicting the IV of the 3 fat depots may be due to anatomical differences in the activity of stearoyl-CoA-desaturase enzyme. The activity of this enzyme has been found to be greater in subcutaneous adipose tissue, and its effects may not be as significant in the adipose tissue of the belly. Belly fat has been described as an intermediate adipose tissue, with characteristics similar to both subcutaneous and intermuscular adipose tissues (Monziols et al., 2007).

Other variables are known to influence the amount, composition, and quality of pork fat. Several excellent reviews have been published that describe some of these variables. Wood et al. (2008) described the relationships of backfat thickness, gender, and the age, BW, or maturity of growing pigs with fat composition. Younger, lighter, and leaner pigs were found to have lower concentrations of C18:0 and C18:1 and greater concentrations of C18:2 in their subcutaneous adipose tissue; and this is also the case when intact males and gilts are compared to castrates. Fat quality defects are more common in pigs from very lean strains that are slaughtered at lower weights with thinner backfat (Hugo & Roodt, 2007). The genetic influence on the fatty acid composition of adipose tissue in swine has been described by several authors (Gläser et al., 2002; Kloareg et al., 2007; Monziols et al., 2007; Pascual et al., 2007; Villegas et al., 1973; Wood et al., 2003), but the differences observed between genotypes are likely attributable to their differences in leanness and subcutaneous fat depth (Hugo & Roodt, 2007). Gender differences in fat composition are also a function of the differences in subcutaneous fat depth and leanness, and differences found between intact males and females with the same backfat thickness indicate that the adipose tissue of intact males may be less mature than that of castrates and females (Wood et al., 2008). None of the data included in the meta-analyses was derived from feeding intact males, and the dummy variables to describe the gender as either barrow, gilt, and mixed did not improve

the precision of any of the models. The current analyses support the conclusion that the backfat depth or lean characteristics account for much of the differences observed between genotypes and genders, and that backfat depth is negatively correlated with the IV of carcass fat.

Increasing the age, BW, or relative maturity will result in improved fat quality, or reduced carcass fat IV. Growth rate is a function of genotype and gender, but is also influenced by environmental conditions or the presence of stressors. Restricted growth results in animals with a lighter BW and lower relative maturity. Several studies have reported increased unsaturated fatty acids (primarily C18:2) in carcass fat when energy intake (relative to that required for maximum growth) and growth rate were reduced. When pigs were limit-fed a diet without added fat and housed under 2 different temperature regimes, Mac Grath et al. (1968) reported that pigs exposed to temperatures of 0 to 5 $^{\circ}$C grew slower and had a greater backfat IV compared to those at temperatures of 25 to 30 $^{\circ}$C. However, Lizardo et al. (2002) reported slower growth and increased unsaturation of adipose tissue for pigs fed *ad libitum* and housed at 29 $^{\circ}$C compared to 22 $^{\circ}$C; and White et al. (2008) reported slower growth and an increase in backfat IV and belly fat IV for pigs housed at 32.2 $^{\circ}$C and 0.66 m^2/pig of spatial allocation when compared to 23.9 $^{\circ}$C or 0.93 m^2/pig. Rinaldo and Mourot (2001) also reported a reduced backfat depth with a greater unsaturation for pigs fed in a cool- or warm-season tropical climate (averaged 24.8 and 27.9 $^{\circ}$C, respectively) compared to a controlled indoor climate (20 $^{\circ}$C). Bee et al. (2002) demonstrated that restricted energy and growth was associated with a reduction in the activity of lipogenic enzymes, resulting in a greater concentration of polyunsaturated fatty acids in backfat. Our analyses provide further evidence for the relationship of BW with backfat and belly fat IV, and the negative relationship of ADG or feeding duration with backfat IV.

Relatively few experiments have evaluated the effects of reducing the major dietary sources of unsaturated fatty acids for a period prior to slaughter on carcass fatty acids. Six experiments were used in our meta-analyses of IVP reduction treatments. Thirty of the 50 observations represented IVP reduction treatments, or dietary strategies to reduce the effects of the initial diet that was fed on fat IV. The other 20 observations were the control treatments applied in these experiments, and were also used in the first meta-analyses of various levels of diet IVP fed throughout the feeding period. Nevertheless, the same characteristics of the initial diet were important for modeling the backfat IV, belly fat IV, and jowl fat IV in both sets of data.

An important finding was that the characteristics of the initial diet were most important for predicting the fat IV of pigs fed IVP reduction treatments. Jaturasitha et al. (2009) also showed that the early deposition of fatty acids obtained from feeding a diet with tuna oil to 60 kg BW was largely maintained at a slaughter BW of 90 kg. The activity of lipogenic enzymes involved in the *de novo* synthesis of adipose tissue is reduced with increasing levels of dietary fatty acids (Allee et al., 1971). However, data to describe the changes in activity of these enzymes after a reduction of dietary fatty acids for growing-finishing pigs could not be found. In the existing data, although not measured directly, it would appear that the changes in lipogenic enzyme activity are not easily reversed in growing-finishing pigs.

Backfat IV may be the most amenable to change using an IVP reduction strategy; and this may be accomplished by initiating the strategy at a lighter BW and/or feeding to a heavier final BW. This is not surprising, as the relative growth of backfat increases during the growth period, whereas the relative growth of belly fat and jowl fat tend to decrease (Landgraf et al., 2006). Jowl fat IV appears to be the most difficult to modify using an IVP reduction strategy,

and nutritionists and producers may be limited in their selection of ingredients when IV testing standards are based on a measurement of jowl fat.

Other factors not included in these analyses have been shown to affect the fatty acid content of pork fat, but the data are limited. When 10 ppm of ractopamine HCl was fed for 28 days (Carr et al., 2005) and 35 days (Apple et al., 2008) prior to slaughter the backfat depth was reduced and the IV of backfat increased approximately 0.07 points per day that ractopamine was fed. Weber et al. (2006) also reported a small increase in the fat IV of pigs fed 10 ppm ractopamine HCl for 28 days. The IV of the inner and outer backfat increased about 0.08 points per day, but the IV of belly fat increased only 0.04 points per day. However, Duttlinger et al. (2008) did not observe differences in backfat, belly fat, or jowl fat IV when 7.5 ppm of ractopamine HCl was fed for 28 days.

Weber et al. (2006) also reported a reduction in fat IV from feeding 0.6% conjugated linoleic acid (CLA) for 56 days. White et al. (2009) reported a reduction in the IV of the outer and middle backfat layers and belly fat when 0.6% CLA was added to diets containing up to 40% DDGS. They reported that feeding 0.6% CLA during the last 10 days prior to slaughter successfully minimized the effects of feeding 20% DDGS for the last 30 days.

The demand for lean pork, coupled with the increased utilization of DDGS as a feed ingredient for swine, has stimulated greater interest in understanding the factors that influence pork fat quality. The meta-analyses described here provide for a greater understanding of the factors that are known to influence pork fat quality. Furthermore, the relationships described in the prediction equations obtained should prove to be useful for producing pork with acceptable fat quality.

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Table 6-1. Crude fat, fatty acid, IV, and IVP values used for some of the ingredients when analyzed values were not provided.

		Individual fatty acids of interest, % of fat									
	Crude Fat, %	C16:0	C18:0	C16:1	C18:1	C18:2	C18:3	C20:1	C22:1	IV of fat[1]	IVP
Barley	1.9	21.8	0.9	0.3	12.8	53.0	5.8	0.0	0.0	118.4	22.5
Corn	3.9	10.9	1.8	0.0	24.2	59.0	0.7	0.0	0.0	124.8	48.7
Corn DDGS[2]	10.7	10.9	1.8	0.0	24.2	59.0	0.7	0.0	0.0	124.8	133.6
Sorghum	2.9	14.4	1.2	1.0	34.2	46.3	2.3	0.0	0.0	116.6	33.8
Sorghum DDGS	7.3	14.4	1.2	1.0	34.2	46.3	2.3	0.0	0.0	116.6	85.1
Soybean meal, 47.5% CP[3]	3.0	10.3	3.8	0.2	22.8	51.0	6.8	0.0	0.0	125.9	37.8
Wheat, hard red winter	2.0	15.2	0.8	0.5	12.5	39.0	1.8	0.0	0.0	83.3	16.7

[1] IV = iodine value (IV = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; AOCS, 1998); and IVP = iodine value product (IVP = [iodine value of the dietary lipids] × [percentage dietary lipid] × 0.10; Christensen, 1962).
[2] DDGS = dried distillers grains with solubles.
[3] CP = crude protein.

Table 6-2. Characteristics of the experiments used in the meta-analysis of treatments formulated to a similar dietary IVP throughout the feeding period to identify variables related to backfat, belly fat, or jowl fat IV.

Experiment Author(s)	# of dietary treatments included	Gender	Range of diet IVP[1]	Range of diet 18:2, %	Range of diet ME from fat, %	Duration, d	Initial BW, kg	Final BW(s), kg	Range of ADG, kg	Range of backfat depth, mm	Range of FFLI[2]	Range of backfat IV	Range of belly fat IV	Range of jowl fat IV
Apple et al., 2009	4	Mixed	36.4 – 102.5	1.90 – 4.43	9.29 – 22.53	98	28	113	0.82 – 0.84	21 - 24	48.9 – 50.0	65.3 – 82.6	---	---
	4	Mixed	35.8 – 101.9	1.94 – 4.43	9.19 – 22.46	77	28	92	0.79 – 0.83	17 - 19	49.7 – 50.4	65.2 – 85.7	---	---
	4	Mixed	34.8 – 100.9	1.94 – 4.43	9.19 – 22.46	49	28	68	0.77 – 0.81	11 - 13	50.1 – 50.4	67.9 – 83.9	---	---
	4	Mixed	34.8 – 100.9	1.94 – 4.43	9.19 – 22.46	21	28	44	0.73 – 0.78	7	50.4	70.5 – 85.2	---	---
Averette Gatlin et al., 2002	7	Barrows	45.7 – 88.1	2.12 – 3.71	9.22 – 19.55	42	80	118 – 126	0.90 – 1.10	23 – 27	45.8 – 48.3	69.9 – 73.3	---	---
Averette Gatlin et al., 2003	4 (PIC[3])	Mixed	52.5 – 84.2	2.02 – 3.47	19.34	52	79 - 81	134 - 138	1.07 – 1.09	26 - 27	46.7 – 47.5	66.5 – 74.5	67.4 – 73.4	---
	4 (NPD[4])	Mixed	52.5 – 84.2	2.02 – 3.47	19.34	52	73 - 74	128 - 129	1.00 – 1.07	22 - 26	47.1 – 49.2	67.2 – 72.8	67.4 – 74.4	---

Table 6-2. (continued)

Experiment Author(s)	# of dietary treatments included	Gender	Range of diet IVP	Range of diet 18:2, %	Range of diet ME from fat, %	Duration, d	Initial BW, kg	Final BW(s), kg	Range of ADG, kg	Range of backfat depth, mm	Range of FFLI	Range of backfat IV	Range of belly fat IV	Range of jowl fat IV
Benz et al., 2008	6	Barrows	45.4 – 66.2	2.10 – 2.58	9.18 – 17.05	83	48	117 - 130	0.83 – 0.99	20 - 21	49.8 – 50.3	59.9 – 70.8	---	64.6 – 72.3
Benz et al., 2008	6	Mixed	36.5 – 70.7	1.45 – 1.96	7.93 – 18.38	83	54	128 - 138	0.89 – 1.01	17 – 21	50.7 – 53.0	61.0 – 67.2	---	66.2 – 72.2
Benz et al., 2008	5	Mixed	78.5 – 93.8	2.66 – 3.39	21.10 – 23.91	78	50	116 - 118	0.88 – 0.92	18 - 19	51.5 – 52.0	68.3 – 72.8	70.2 – 74.5	70.7 – 73.8
Bergstrom et al., 2009	1	Barrows (dry[5])	60.0	2.94	12.58	99	35	125	0.89	18	51.9	---	---	72.0
	1	Barrows (wet-dry[6])	60.0	2.94	12.58	99	35	131	0.96	21	50.1	---	---	70.3
	1	Gilts (dry)	60.0	2.94	12.58	99	35	120	0.86	15	54.3	---	---	75.0
	1	Gilts (wet-dry)	60.0	2.94	12.58	99	35	128	0.94	18	52.4	---	---	73.8
Boyd et al., 1997	5	Mixed	43.8 – 85.4	1.30 – 3.70	18.41-21.03	90	43	118	0.81 – 0.85	20 - 22	48.9 – 50.4	66.4 – 77.8	58.3 – 77.5	---
Duran-Montgé, 2008	7	Gilts	5.0 – 187.2	0.14 – 7.33	0.80 – 32.92	50	62	97 - 104	0.93 – 1.10	15 - 19	51.1 – 53.5	53.0 – 89.7	60.9 – 91.7	---

Table 6-2. (continued)

Experiment Author(s)	# of dietary treatments included	Gender	Range of diet IVP	Range of diet 18:2, %	Range of diet ME from fat, %	Duration, d	Initial BW, kg	Final BW(s), kg	Range of ADG, kg	Range of backfat depth, mm	Range of FFLI	Range of backfat IV	Range of belly fat IV	Range of jowl fat IV
Duttlinger et al., 2008	6	Barrows	55.9 – 77.3	2.26 – 3.23	15.39 – 18.70	97	31	123 - 124	0.96 – 0.97	19 - 20	51.0 – 51.5	63.5 – 73.1	65.5 – 73.6	68.6 – 74.1
Duttlinger et al., 2008	4	Mixed	38.3 – 43.2	1.96 – 2.14	9.05 – 9.26	28	94	116 - 120	0.88 – 1.01	17 - 18	52.0 – 52.8	67.8 – 69.0	68.6 - 70	68.9 – 70.7
Feoli et al., 2007	4	Mixed	41.0 – 78.0	2.08 – 3.73	9.11 – 17.07	72	64	128 - 132	0.89 – 0.94	16	53.0 – 53.3	---	---	69.3 – 80.2
Feoli et al., 2008	4	Barrows	43.1 – 87.1	2.13 – 3.85	9.26 – 28.13	69	64	125 - 135	0.89 – 1.03	18 - 19	51.0 – 51.6	---	---	67.9 – 73.2
Feoli et al., 2008	4	Barrows	43.1 – 81.1	2.13 – 3.38	9.26 – 28.73	67	68	120 - 125	0.77 – 0.82	16 - 18	52.2 – 53.0	---	---	66.6 – 71.7
Feoli et al., 2008	5	Mixed	42.5 – 80.5	2.12 – 3.86	9.22 – 16.00	65	64	115 - 124	0.86 – 0.97	15 - 17	52.9 – 53.7	---	---	70.3 – 80.4
Jacela et al., 2009	5	Mixed	41.5 – 76.0	2.09 – 2.71	9.22 – 26.88	99	65	116 - 121	0.87 – 0.91	16 - 17	52.8 – 53.4	68.4 – 73.5	67.1 – 73.7	67.5 – 73.3
Jacela et al., 2009	2	Mixed	57.9 – 85.8	2.37 – 3.63	15.34 – 20.29	89	39	119 - 121	0.91 – 0.93	17 - 18	52.1 – 52.5	66.9 – 74.2	67.8 – 75.4	68.6 – 74.7
Xu et al., 2010	4	Mixed	42.8 – 71.1	2.12 – 3.40	9.24 – 14.49	101	22	129 - 130	0.91 – 0.92	27 - 29	49.9 – 50.6	58.4 – 72.4	61.5 – 72.3	---
Xu et al., 2010	3	Mixed	42.5 – 70.8	2.13 – 3.27	9.22 – 14.47	105	30	121 - 125	0.87 – 0.92	27 - 28	50.4 – 51.1	---	58.8 – 71.2	---

[1] IVP = iodine value product (IVP = [iodine value of the dietary lipids] × [percentage dietary lipid] × 0.10; Christensen, 1962); and IV = iodine value (IV = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; AOCS, 1998).
[2] FFLI = fat-free lean index.
[3] PIC = PIC genetic source.
[4] NPD = NPD genetic source.
[5] *ad libitum* fed using a dry feeder.
[6] *ad libitum* fed using a wet-dry feeder.

Table 6-3. Characteristics of the experiments used to identify variables related to backfat, belly fat, or jowl fat IV in the meta-analysis of IVP reduction strategies.

Experiment Author(s)	# of IVP levels fed[1]	Gender	Initial period diet IVP	Initial period 18:2, %	Initial BW, kg	Initial period, d	Reduction period IVP	Reduction period 18:2, %	BW at initiation of IVP reduction, kg	IVP reduction period, d	Final BW, kg	Back-fat IV	Belly fat IV	Jowl fat IV
Averette	1	Gilt	111.1	4.73	62	49	---	---	---	---	105	81.7	---	---
Gatlin et						63	---	---	---	---	114	86.1	---	---
al., 2002						77	---	---	---	---	125	84.2	---	---
	3	Gilt	111.1	4.73	62	21	44.6	2.02	80	28	103	82.3	---	---
	reduction									42	114	76.2	---	---
	levels									56	129	72.6	---	---
							65.9	2.87	80	28	103	81.6	---	---
										42	115	78.4	---	---
										56	128	76.7	---	---
							88.9	3.83	80	28	108	79.3	---	---
										42	117	83.6	---	---
										56	128	80.8	---	---
Benz et al.,	3	Mixed	45.4	2.10	44	82	---	---	---	---	125	63.3	---	67.1
2008			72.5	2.59	44	82	---	---	---	---	129	68.8	---	71.5
			109.6	4.69	44	82	---	---	---	---	132	84.3	---	82.0
	1	Mixed	72.1	2.57	44	26	45.8	2.13	71	56	128	64.8	---	68.8
	reduction					54	45.8	2.13	101	28	128	67.7	---	70.3
	level					68	45.8	2.13	118	14	129	68.0	---	70.2
			109.2	4.67	44	26	45.8	2.13	71	56	128	67.6	---	73.3
						54	45.8	2.13	102	28	128	77.2	---	79.1
						68	45.8	2.13	120	14	133	81.2	---	80.9

Table 6-3. (continued)

Experiment Author(s)	# of IVP levels fed	Gender	Initial period diet IVP	Initial period 18:2, %	Initial BW, kg	Initial period, d	Reduction period IVP	Reduction period 18:2, %	BW at initiation of IVP reduction, kg	IVP reduction period, d	Final BW, kg	Back-fat IV	Belly fat IV	Jowl fat IV
Bergstrom	2	Barrows	60.0	2.94	35	99	---	---	103	---	125	---	---	72.0
et al., 2009		(dry[2])	96.3	4.60	35	78	58.9	2.91	100	21	122	---	---	81.0
	2	Barrows	60.0	2.94	35	99	---	---	109	---	131	---	---	70.3
		(wet-dry[3])	96.3	4.60	35	78	58.9	2.91	103	21	128	---	---	79.3
	2	Gilts	60.0	2.94	35	99	---	---	99	---	120	---	---	75.0
		(dry)	96.3	4.60	35	78	58.9	2.91	97	21	120	---	---	82.9
	2	Gilts	60.0	2.94	35	99	---	---	107	---	128	---	---	73.8
		(wet-dry)	96.3	4.60	35	78	58.9	2.91	103	21	126	---	---	81.4
Boyd et al.,	5	Mixed	43.8	1.30	43	90	---	---	---	---	118	66.4	58.3	---
1997			50.8	1.70	43	90	---	---	---	---	118	68.3	62.2	---
			58.6	2.10	43	90	---	---	---	---	118	70.3	66.4	---
			66.8	2.50	43	90	---	---	---	---	118	72.0	68.6	---
			85.4	3.70	43	90	---	---	---	---	118	77.8	77.5	---
	1 reduction level	Mixed	85.4	3.70	43	55	54.7	1.90	90	35	118	76.0	72.2	---
Jacela et	2	Mixed	57.9	2.37	39	89	---	---	---	---	119	66.9	67.8	68.6
al., 2009			85.8	3.63	39	89	---	---	---	---	121	74.2	75.4	74.7
	2 reduction levels	Mixed	85.9	3.64	39	48	57.4	2.36	81	41	121	73.2	73.5	72.6
							71.6	3.00	81	41	119	73.1	74.2	74.2
						69	57.4	2.36	100	20	121	72.8	73.9	73.3
							71.6	3.00	99	20	119	74.9	75.9	74.6

Table 6-3. (continued)

Experiment Author(s)	# of IVP levels fed	Gender	Initial period diet IVP	Initial period 18:2, %	Initial BW, kg	Initial period, d	Reduction period IVP	Reduction period 18:2, %	BW at initiation of IVP reduction, kg	IVP reduction period, d	Final BW, kg	Back-fat IV	Belly fat IV	Jowl fat IV
Xu et al.,	3	Mixed	42.5	2.13	30	105	---	---	---	---	125	---	58.8	---
2010			56.6	2.69	30	105	---	---	---	---	125	---	67.3	---
			70.8	3.27	30	105	---	---	---	---	121	---	71.2	---
	1	Mixed	56.1	2.68	30	42	44.2	2.16	60	63	121	---	62.7	---
	reduction					63	44.2	2.16	78	42	126	---	64.1	---
	level					84	44.2	2.16	103	21	123	---	64.4	---
			70.3	3.26	30	42	44.2	2.16	61	63	124	---	62.7	---
						63	44.2	2.16	78	42	122	---	64.5	---
						84	44.2	2.16	100	21	124	---	68.2	---

[1] IVP = iodine value product (IVP = [iodine value of the dietary lipids] × [percentage dietary lipid] × 0.10; Christensen, 1962); and IV = iodine value (IV = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; AOCS, 1998).
[2] *ad libitum* fed using a dry feeder.
[3] *ad libitum* fed using a wet-dry feeder.

Table 6-4. Correlation coefficients of variables with backfat, belly fat, or jowl fat IV in the meta-analysis of treatments formulated to a similar dietary IVP throughout the feeding period.

Independent Variable[1]	Backfat IV, n = 95	Belly fat IV, n = 49	Jowl fat IV, n = 58
Diet IVP	0.765 (P < 0.0001)	0.882 (P < 0.0001)	0.671 (P < 0.0001)
Diet C16:0, %	0.048 (P = 0.65)	0.182 (P = 0.21)	0.135 (P = 0.31)
Diet C18:0, %	-0.097 (P = 0.35)	0.005 (P = 0.98)	-0.003 (P = 0.98)
Total diet C16:1+C18:1, %	0.168 (P = 0.10)	0.335 (P < 0.02)	0.256 (P = 0.05)
Diet C18:2, %	0.689 (P < 0.0001)	0.608 (P < 0.0001)	0.759 (P < 0.0001)
Diet C18:3, %	0.418 (P < 0.0001)	0.635 (P < 0.0001)	0.298 (P < 0.03)
Total of C18:2+C18:3, %	0.782 (P < 0.0001)	0.881 (P < 0.0001)	0.754 (P < 0.0001)
Total UFA[2], %	0.618 (P < 0.0001)	0.776 (P < 0.0001)	0.536 (P < 0.0001)
ADG, kg	- 0.242 (P < 0.02)	0.171 (P = 0.24)	-0.061 (P = 0.65)
Days fed	-0.082 (P = 0.43)	-0.271 (P = 0.06)	-0.033 (P = 0.81)
ME density of diet, kcal/kg	0.016 (P = 0.88)	0.324 (P < 0.03)	0.144 (P = 0.28)
Diet ME from fat, %	0.506 (P < 0.0001)	0.629 (P < 0.0001)	0.346 (P < 0.01)
Initial BW, kg	-0.027 (P = 0.79)	0.180 (P = 0.22)	-0.054 (P = 0.68)
Final BW, kg	-0.318 (P < 0.01)	-0.395 (P < 0.01)	-0.148 (P = 0.27)
Weight range fed, kg	-0.257 (P < 0.02)	-0.317 (P < 0.03)	< -0.001 (P = 1.00)
Backfat depth, mm	-0.245 (P < 0.02)	-0.395 (P < 0.01)	-0.365 (P < 0.01)
FFLI[3]	0.005 (P < 0.96)	0.272 (P < 0.06)	0.315 (P < 0.02)
Backfat IV	---	0.907 (n = 46, P < 0.0001)	0.922 (n = 37, P < 0.0001)
Belly fat IV	0.907 (n = 46, P < 0.0001)	---	0.887 (n = 22, P < 0.0001)
Jowl IV	0.922 (n = 37, P < 0.0001)	0.887 (n = 22, P < 0.0001)	---

[1] IVP = iodine value product (IVP = [iodine value of the dietary lipids] × [percentage dietary lipid] × 0.10; Christensen, 1962); and IV = iodine value (IV = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; AOCS, 1998).
[2] UFA = unsaturated fatty acids (C16:1 + C18:1 + C18:2 + C18:3).
[3] FFLI = fat-free lean index.

Table 6-5. Regression models to describe the relationship of growth and diet variables (from treatments formulated to a similar dietary IVP throughout the feeding period) with backfat, belly fat, and jowl fat IV.

Dependent variable	Models[1]	C.V.	R^2	Adjusted R^2
Backfat IV	= 76.58 + 0.08*diet IVP + 1.82*diet C18:2 (%) + 2.00*[diet C18:2 (%) + diet C18:3(%)] + 0.10*initial BW (kg) – 29.30*ADG (kg)	4.20	0.81	0.80
	= 75.28 + 0.13*diet IVP + 3.04*diet C18:2 (%) + 0.10*initial BW (kg) – 28.54*ADG (kg)	4.31	0.80	0.79
	= 77.76 + 0.06*diet IVP + 3.64*[diet C18:2 (%) + diet C18:3(%)] + 0.09* initial BW (kg) – 28.86*ADG (kg)	4.34	0.80	0.79
	= 75.63 + 0.12*diet IVP + 2.85*diet C18:2 (%) – 0.07*BW range (kg) – 18.06*ADG (kg)	4.44	0.79	0.78
	= 79.44 + 5.00*[diet C18:2 (%) + diet C18:3(%)] + 0.09*initial BW (kg) – 30.05*ADG (kg)	4.51	0.78	0.77
	= 75.38 + 4.80*[diet C18:2 (%) + diet C18:3(%)] – 19.78*ADG (kg)	5.05	0.72	0.71
	= 75.71 + 0.19*diet IVP + 0.08*initial BW (kg) – 24.58*ADG (kg)	5.25	0.70	0.69
	= 72.18 + 0.18*diet IVP – 15.71*ADG (kg)	5.61	0.65	0.65
	= 63.53 + 4.51*[diet C18:2 (%) + diet C18:3(%)] – 0.28*BF depth (mm)	5.65	0.65	0.64
	= 63.09 + 0.18*diet IVP – 0.25*BF depth (mm)	5.91	0.61	0.61
	= 57.82 + 4.59*[diet C18:2 (%) + diet C18:3(%)]	5.91	0.61	0.61
	= 57.89 + 0.18*diet IVP	6.11	0.58	0.58
Belly fat IV	= 50.36 + 0.23*diet IVP – 0.33*diet ME from fat (%) – 0.05*BW range (kg) + 0.18*final BW (kg) – 0.45*BF depth (mm)	2.78	0.90	0.89
	= 63.06 + 0.22*diet IVP – 0.33*diet ME from fat (%) + 0.05*initial BW (kg) – 0.22*BF depth (mm)	3.08	0.87	0.86
	= 57.10 + 0.22*diet IVP – 0.29*diet ME from fat (%) + 0.06*initial BW (kg)	3.27	0.85	0.84
	= 56.06 + 0.16*diet IVP + 0.05*initial BW (kg)	3.67	0.81	0.80
	= 60.11 + 0.21*diet IVP – 0.25*diet ME from fat (%)	3.70	0.81	0.80
	= 63.93 + 0.15*diet IVP – 0.22*BF depth (mm)	3.80	0.80	0.79
	= 58.85 + 0.16*diet IVP	3.96	0.78	0.77

Table 6-5. (continued)

Dependent variable	Models	C.V.	R^2	Adjusted R^2
Jowl fat IV	= 2.70 + 0.18*diet IVP + 2.15*diet C18:2 (%) – 0.33*diet ME from fat (%) + 1.10*estimated FFLI	2.71	0.75	0.73
	= 72.57 + 0.17*diet IVP + 2.01*diet C18:2 (%) – 0.32*diet ME from fat (%) – 0.69*BF depth (mm)	2.78	0.73	0.71
	= -9.82 + 0.26*diet IVP – 0.37*diet ME from fat (%) + 1.36*estimated FFLI	2.90	0.70	0.69
	= 20.65 + 4.12*diet C18:2 (%) + 0.76*estimated FFLI	3.23	0.62	0.61
	= 59.93 + 4.89*diet C18:2 (%) – 0.12*diet ME from fat (%)	3.35	0.60	0.58
	= -5.32 + 0.16*diet IVP + 1.28*estimated FFLI	3.38	0.59	0.57
	= 59.74 + 4.28*diet C18:2 (%)	3.40	0.58	0.57
	= 61.95 + 0.15*diet IVP	3.88	0.45	0.44

[1] IVP = iodine value product (IVP = [iodine value of the dietary lipids] × [percentage dietary lipid] × 0.10; Christensen, 1962); and IV = iodine value (IV = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; AOCS, 1998).

Table 6-6. Correlation coefficients of variables with backfat, belly fat, or jowl fat IV in the meta-analysis of IVP reduction strategies.

Independent Variable[1]	Backfat IV, n = 33	Belly fat IV, n = 21	Jowl fat IV, n = 23
Initial diet IVP	0.815 (P < 0.0001)	0.915 (P < 0.0001)	0.785 (P < 0.0001)
Reduction period diet IVP	0.661 (P < 0.0001)	0.818 (P < 0.0001)	0.300 (P = 0.17)
Initial diet C16:0, %	-0.416 (P < 0.02)	0.468 (P < 0.04)	-0.305 (P = 0.16)
Reduction period diet C16:0, %	0.304 (P = 0.09)	0.414 (P = 0.06)	-0.130 (P = 0.55)
Initial diet C18:0, %	-0.642 (P < 0.0001)	0.253 (P = 0.27)	-0.459 (P < 0.03)
Reduction period diet C18:0, %	0.252 (P = 0.16)	0.300 (P = 0.19)	-0.198 (P = 0.37)
Initial diet C16:1+C18:1, %	-0.231 (P = 0.20)	0.655 (P < 0.01)	-0.126 (P = 0.57)
Reduction period diet C16:1+C18:1, %	0.035 (P = 0.85)	0.635 (P < 0.01)	-0.088 (P = 0.69)
Initial diet C18:2, %	0.819 (P < 0.0001)	0.817 (P < 0.0001)	0.901 (P < 0.0001)
Reduction period diet C18:2, %	0.711 (P < 0.0001)	0.755 (P < 0.0001)	0.468 (P < 0.03)
Initial diet C18:3, %	0.764 (P < 0.0001)	0.338 (P = 0.13)	0.367 (P = 0.09)
Reduction period diet C18:3, %	0.680 (P < 0.0001)	0.328 (P = 0.15)	0.332 (P = 0.12)
Initial diet C18:2+C18:3, %	0.826 (P < 0.0001)	0.836 (P < 0.0001)	0.878 (P < 0.0001)
Reduction period diet C18:2+C18:3, %	0.716 (P < 0.0001)	0.763 (P < 0.0001)	0.464 (P < 0.03)
Initial diet UFA[2], %	0.755 (P < 0.0001)	0.907 (P < 0.0001)	0.675 (P < 0.01)
Reduction period diet UFA, %	0.564 (P < 0.001)	0.862 (P < 0.0001)	0.204 (P = 0.35)
Overall ADG, kg	-0.217 (P = 0.23)	-0.018 (P = 0.94)	-0.143 (P = 0.52)
ME density of initial diet, kcal/kg	0.605 (P < 0.001)	0.626 (P < 0.01)	-0.048 (P = 0.83)
ME density of reduced IVP diet, kcal/kg	0.647 (P < 0.0001)	0.586 (P < 0.01)	0.070 (P = 0.75)
Initial diet ME from fat, %	0.402 (P < 0.03)	0.523 (P < 0.02)	0.511 (P < 0.02)
Reduction period diet ME from fat, %	0.633 (P < 0.0001)	0.729 (P < 0.01)	0.111 (P = 0.61)
Total days	-0.581 (P < 0.001)	-0.518 (P < 0.02)	0.313 (P = 0.15)
Days initial diet fed	-0.494 (P < 0.01)	-0.119 (P = 0.61)	0.091 (P = 0.68)
Days reduction period diet fed	0.300 (P = 0.09)	-0.072 (P = 0.76)	0.022 (P = 0.92)
Initial BW, kg	0.627 (P < 0.0001)	0.373 (P = 0.10)	-0.282 (P = 0.19)
BW at initiation of IVP reduction, kg	-0.353 (P < 0.05)	0.052 (P = 0.82)	-0.037 (P = 0.87)
Final BW, kg	-0.340 (P = 0.05)	-0.388 (P = 0.08)	0.043 (P = 0.85)
Backfat depth, mm	0.067 (P = 0.71)	-0.629 (P < 0.01)	-0.202 (P = 0.35)
FFLI[3]	-0.075 (P = 0.68)	0.410 (P = 0.06)	0.200 (P = 0.36)
Overall weight range, kg	-0.594 (P < 0.001)	-0.388 (P = 0.08)	0.290 (P = 0.18)
Weight range for reduction period, kg	0.228 (P = 0.20)	-0.098 (P = 0.67)	0.049 (P = 0.82)
Reduction period IVP*reduction days	0.522 (P < 0.01)	0.075 (P = 0.75)	0.071 (P = 0.75)
Backfat IV	---	0.880 (n = 12, P < 0.001)	0.963 (n = 15, P < 0.0001)
Belly fat IV	0.880 (n = 12, P < 0.001)	---	0.987 (n = 6, P < 0.001)
Jowl IV	0.963 (n = 15, P < 0.0001)	0.987 (n = 6, P < 0.001)	---

[1] IVP = iodine value product (IVP = [iodine value of the dietary lipids] × [percentage dietary lipid] × 0.10; Christensen, 1962); and IV = iodine value (IV = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; AOCS, 1998).
[2] UFA = unsaturated fatty acids (C16:1 + C18:1 + C18:2 + C18:3).
[3] FFLI = fat-free lean index.

Table 6-7. Regression models to describe the relationship of variables involved in IVP reduction strategies with backfat, belly fat, and jowl fat IV.

Dependent variable	Model[1]	C.V.	R^2	Adjusted R^2
Backfat IV	= 63.57 + 0.25*initial diet IVP + 0.28*BW at initiation of IVP reduction (kg) + 0.003*(reduction period diet IVP*reduction days) – 0.36*final BW (kg)	2.75	0.91	0.90
	= 67.66 + 0.28*initial diet IVP + 0.12*BW at initiation of IVP reduction (kg) – 0.25*final BW (kg)	4.04	0.80	0.77
	= 71.49 + 4.94*[initial diet C18:2 (%) + initial diet C18:3(%)] + 0.11*BW at initiation of IVP reduction (kg) – 0.22*final BW (kg)	4.10	0.79	0.77
	= 38.74 + 4.51*[initial diet C18:2 (%) + initial diet C18:3(%)] + 0.16*BW at initiation of IVP reduction (kg) + 0.001*(reduction period diet IVP*reduction days)	4.38	0.76	0.74
	= 33.14 + 0.25*initial diet IVP + 0.17*BW at initiation of IVP reduction (kg) + 0.001*(reduction period diet IVP*reduction days)	4.48	0.75	0.72
	= 78.53 + 3.97*[initial diet C18:2 (%) + initial diet C18:3(%)] – 0.16*final BW (kg)	4.62	0.72	0.71
	= 47.86 + 4.88*[initial diet C18:2 (%) + initial diet C18:3(%)] + 0.08*BW at initiation of IVP reduction (kg)	4.66	0.71	0.70
	= 76.67 + 0.22*initial diet IVP – 0.18*final BW (kg)	4.70	0.71	0.70
	= 41.85 + 0.28*initial diet IVP + 0.08*BW at initiation of IVP reduction (kg)	4.76	0.71	0.69
	= 47.05 + 5.51*initial diet C18:2 (%) + 0.07*BW at initiation of IVP reduction (kg)	4.77	0.71	0.69
	= 58.19 + 4.15*[initial diet C18:2 (%) + initial diet C18:3(%)]	4.87	0.68	0.67
	= 57.38 + 4.69*initial diet C18:2 (%)	4.96	0.67	0.66
	= 54.20 + 0.23*initial diet IVP	5.01	0.66	0.65
Belly fat IV	= 43.31 + 0.39*initial diet IVP – 0.001*(reduction period diet IVP*reduction days)	2.65	0.91	0.90
	= 44.49 + 0.35*initial diet IVP	3.47	0.84	0.83
Jowl fat IV	= 52.43 + 4.99*initial diet C18:2 (%) + 0.06*days fed the initial diet	2.26	0.89	0.87
	= 57.89 + 4.71*initial diet C18:2 (%)	2.83	0.81	0.80
	= 58.69 + 0.19*initial diet IVP	4.04	0.62	0.60

[1] IVP = iodine value product (IVP = [iodine value of the dietary lipids] × [percentage dietary lipid] × 0.10; Christensen, 1962); and IV = iodine value (IV = [C16:1] × 0.95 + [C18:1] × 0.86 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C22:1] × 0.723; AOCS, 1998).

Figure 6-1. Predicted vs. actual backfat IV using the model [Y = 76.58 + 0.08*diet IVP + 1.82*diet C18:2 (%) + 2.00*[diet C18:2 (%) + diet C18:3(%)] + 0.10*initial BW (kg) – 29.30*ADG (kg)] and data from the meta-analysis of treatments formulated to similar dietary IVP throughout the feeding period.

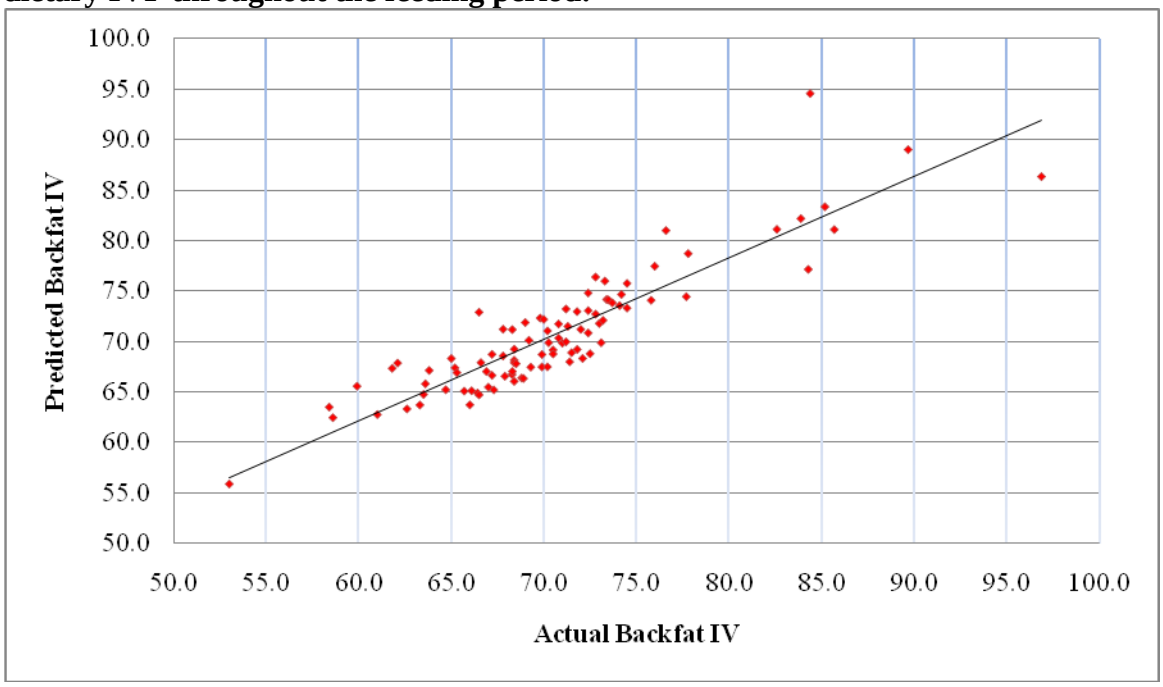

Figure 6-2. Predicted vs. actual belly fat IV using the model [Y = 50.36 + 0.23*diet IVP – 0.33*diet ME from fat (%) – 0.05*BW range (kg) + 0.18*final BW (kg) – 0.45*BF depth (mm)] and data from the meta-analysis of treatments formulated to similar dietary IVP throughout the feeding period.

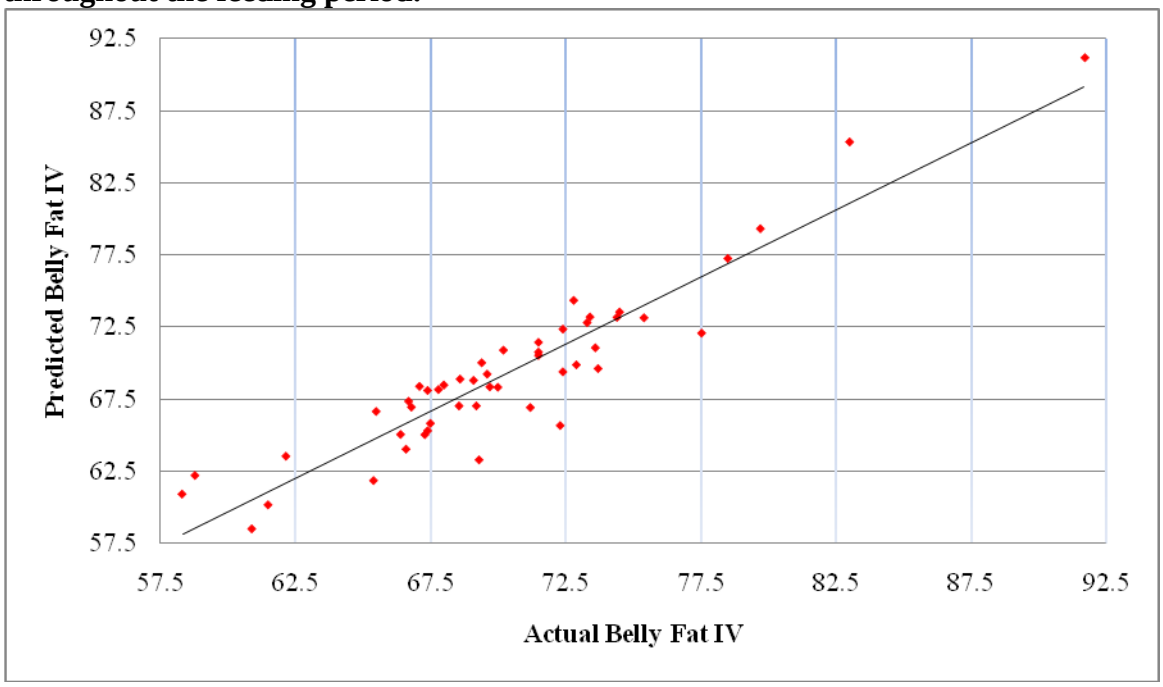

Figure 6-3. Predicted vs. actual jowl fat IV using the model [Y = 2.70 + 0.18*diet IVP + 2.15*diet C18:2 (%) – 0.33*diet ME from fat (%) + 1.10*estimated FFLI] and data from the meta-analysis of treatments formulated to similar dietary IVP throughout the feeding period.

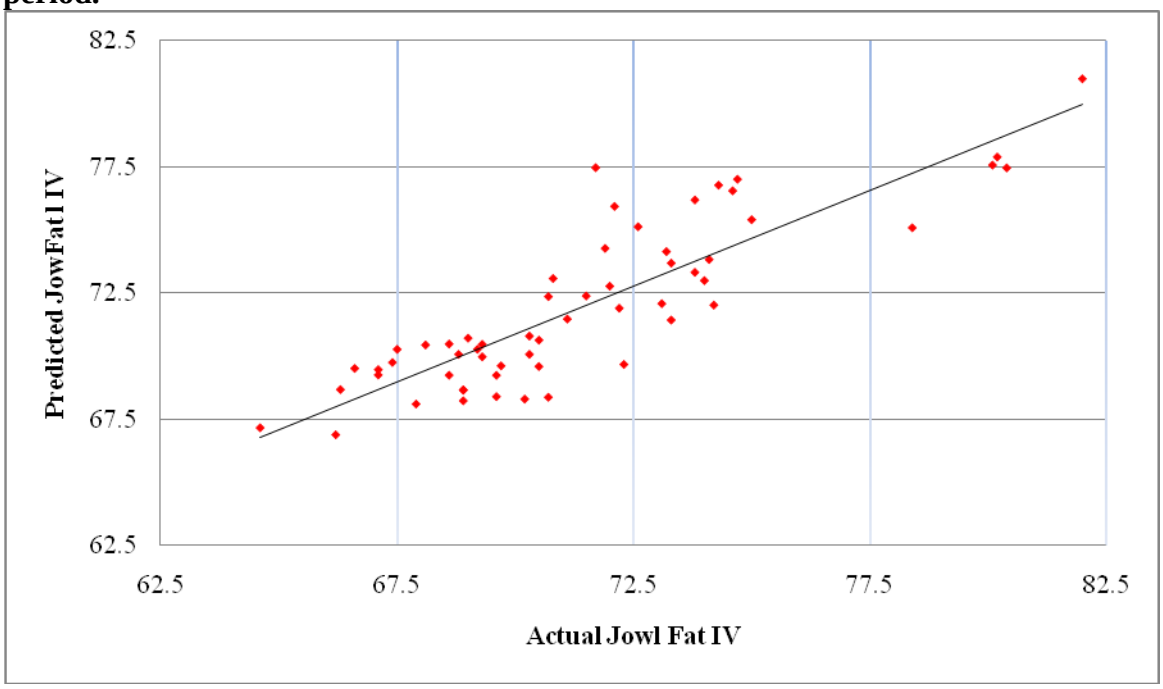

Figure 6-4. Predicted vs. actual backfat IV using the model [Y = 63.57 + 0.25*initial diet IVP + 0.28*BW at initiation of IVP reduction (kg) + 0.003*(reduction period diet IVP*reduction days) – 0.36*final BW] and data from the meta-analysis of IVP reduction strategies.

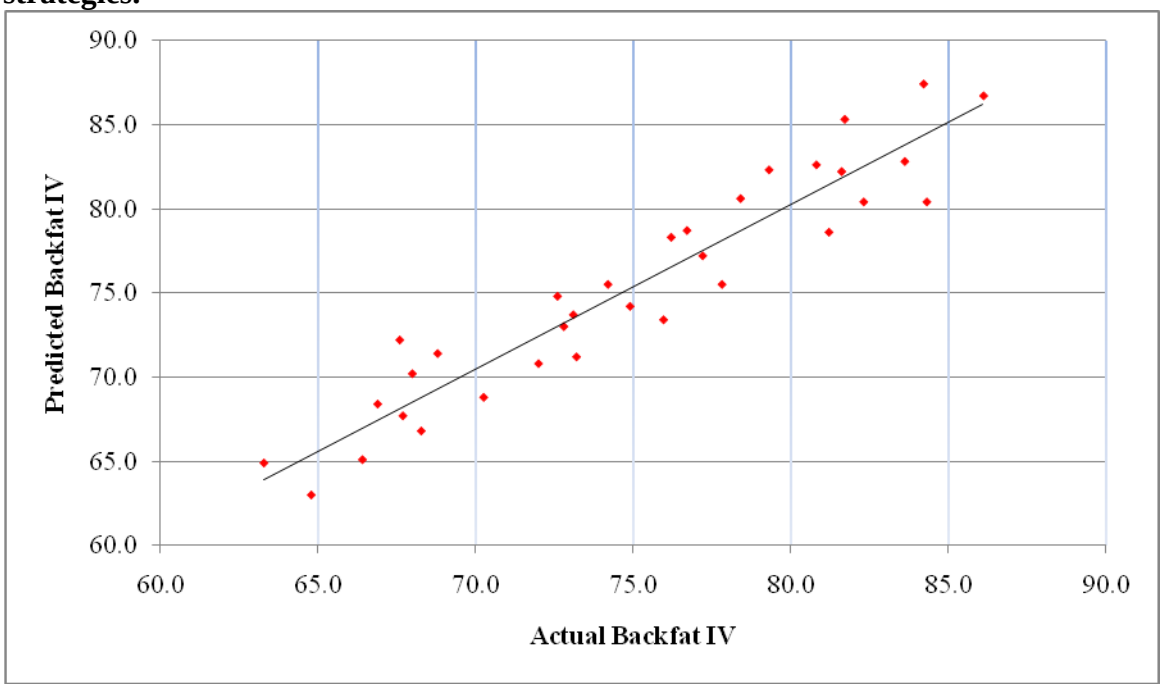

Figure 6-5. Predicted vs. actual belly fat IV using the model [Y = 43.31 + 0.39*initial diet IVP – 0.001*(reduction period diet IVP*reduction days)] and data from the meta-analysis of IVP reduction strategies.

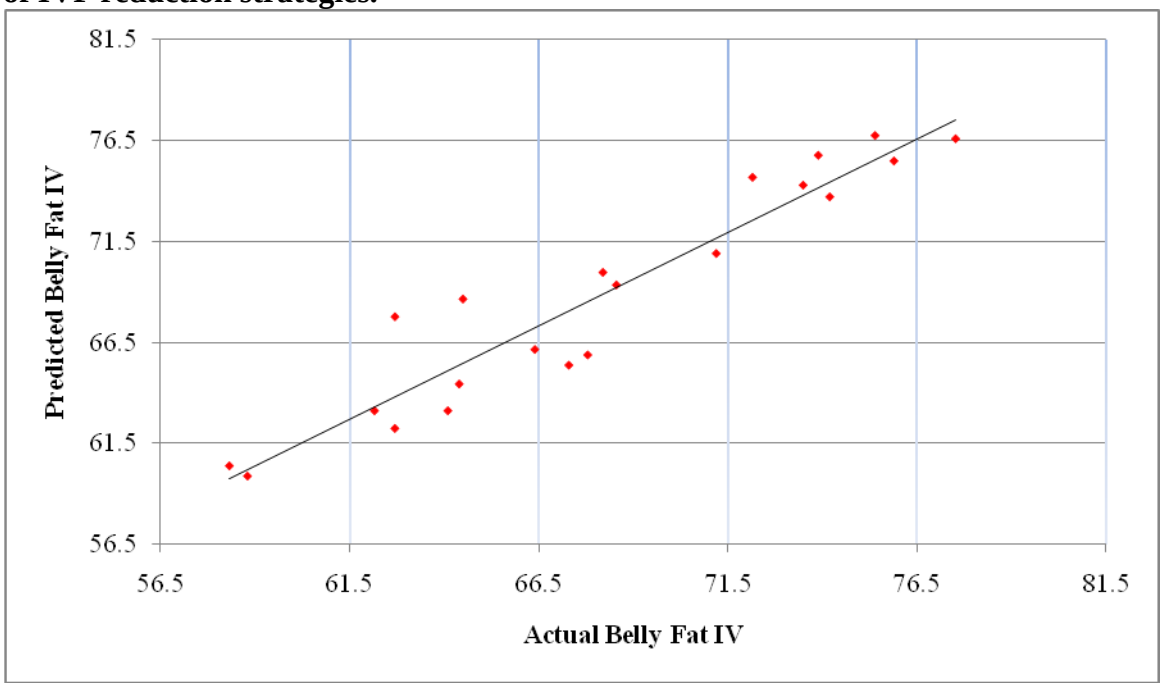

Figure 6-6. Predicted vs. actual jowl fat IV using the model [Y = 52.43 + 4.99*initial diet C18:2 (%) + 0.06*days fed the initial diet] and data from the meta-analysis of IVP reduction strategies.