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Characterizing the amount and variability of intramuscular fat deposition throughout pork loins using barrows and gilts from two sire lines

Jack D. Redifer,[†] Jon E. Beever,[†] Chad A. Stahl,[‡] Dustin D. Boler,[†] and Anna C. Dilger[†,1]

[†]Department of Animal Sciences, University of Illinois, Urbana-Champaign, IL 61801, [‡]Choice Genetics, Des Moines, IA 50266

[1]Corresponding author: adilger2@illinois.edu

Abstract

The objective was to determine the amount and variability of intramuscular fat (**IMF**) in a pork loin attributable to anatomical chop location, sex, and sire line. Pigs were sired by commercially available terminal Duroc boars selected for meat quality (**MQ**; $n = 96$) or lean growth (**LG**; $n = 96$) and equally split between barrows and gilts. After slaughter and fabrication, bone-in chops were removed from four locations of each left-side loin (A = 6th rib, B = 10th rib, C = last rib, and D = 4th lumbar vertebrae). An adjacent pair of chops from each location was collected and evaluated for visual color and marbling, subjective firmness, moisture and extractable lipid (IMF) (anterior chop), and Warner–Bratzler shear force (posterior chop). Data were analyzed using the MIXED procedure of SAS as a split-plot design. Homogeneity of variances was tested on raw data using Levene's test of the GLM procedure and found to be heterogeneous. Thus, a two-variance model was fit using the REPEATED statement of the MIXED procedure, grouped by pig. The mivque(0) option of the VARCOMP procedure was used to calculate the proportion of variability that each factor contributed to the total variance. Barrows (3.64%) produced chops with greater ($P < 0.01$) IMF content than gilts (3.20%), and barrows (2.14) had greater ($P < 0.01$) IMF variability than gilts (1.23). Chops from MQ pigs (4.02%) exhibited greater ($P < 0.01$) IMF content than LG (2.82%), and MQ (1.76) had greater IMF variability ($P < 0.01$) than LG pigs (0.97). Chops from locations A (3.80%) and D (3.77%) had greater IMF than B (3.34%; $P < 0.01$), and A, B, and D had greater IMF than C (2.77%; $P < 0.01$). Variances of IMF also differed (A = 1.44, B = 1.59, C = 1.05, and D = 2.18; $P = 0.01$) across chop locations. Of the variability in IMF, 33.0% was attributed to sire line, 10.16% to chop location, and 4.01% to sex, with 52.83% not accounted for by these three factors. Location A chops were the most ($P < 0.01$) tender (2.57 kg) and C chops the least ($P < 0.01$) tender (2.93 kg), while B and D chops were intermediate and not different from each other. No differences in variability ($P = 0.40$) of tenderness were observed among chop locations (A = 0.31, kg B = 0.24 kg, C = 0.24 kg, and D = 0.23 kg). These results demonstrated that variability in tenderness values did not reflect the variability of IMF. In conclusion, chop location, sex, and sire line all contribute to the amount and variability of pork loin marbling.

Key words: chop location, intramuscular fat, marbling, pork, variability

Abbreviations	
HCW	hot carcass weight
IMF	intramuscular fat
IMPS	Institutional Meat Processing Specifications
IQR	interquartile range
LG	lean growth
LMA	loin muscle area
MQ	meat quality
NPPC	National Pork Producers' Council
PA	proximate composition analysis
SID	standardized ileal digestible
WBSF	Warner–Bratzler shear force

Introduction

Retail consumers generally evaluate marbling and color of the pork loin by the observation of individual chops or groups of chops within packages. In contrast, when pork quality is assessed by commercial processors, evaluations are conducted on the ventral surface of a whole boneless loin. General estimations about the amount of marbling of that loin are assigned to the entire loin without regard to any differences that may exist in chop marbling throughout the length of the loin (King et al., 2011). Thus, the sorting criteria assigned to an entire loin based on the appraisal of the ventral surface of the loin or of a single-ribbed (cutting between ribs to expose the *longissimus*) chop face may not be representative of all the chops produced from that loin. This may result in loins classified as "high marbling" at the processing facility not being uniformly highly marbled chops at retail. Additionally, because marbling is one of many traits involved in pork quality, loins with a high degree of marbling in one location may not produce a consistently high-quality eating experience.

In addition to absolute differences in the amount of marbling produced by barrows and gilts or by pigs from two different sire lines, the variability of that marbling differed between sexes and sire lines (Overholt et al., 2016; Arkfeld et al., 2017). There were differences in the amount of marbling in chops from different locations along the loin (Faucitano et al., 2004; Homm et al., 2006). Marbling on the ventral surface of fresh loins correlated ($r = 0.84$) with marbling of a chop collected at the 10th rib (Lowell et al., 2018), but that relationship has not been defined with chops collected at other anatomical locations throughout the loin. Therefore, a critical need exists to characterize the differences in the amount of marbling and the variability of marbling throughout the loin of different types of pigs so that pork processors and retailers can provide consumers with chops that are more uniform at the retail level to provide greater consumer satisfaction. Pork loin color, pH, water-holding capacity, firmness, and many other factors are influential in determining the ultimate pork loin quality (Huff-Lonergan et al., 2002; Boler et al., 2010), but the focus of this work was marbling. The objective of this study was to determine marbling variation along the length of the loin and attribute variation in marbling to known factors. It was hypothesized that marbling would vary between anatomical locations and, similar to previous work, variability in marbling would differ between sexes, sire lines, and anatomical locations.

Materials and Methods

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment.

Experimental design

Pigs (192 total) used for the experiment were sired by commercially available terminal sire Duroc boar lines (Choice Genetics, West Des Moines, IA) from two distinct sire lines selected for either meat quality (**MQ**; $n = 96$) or lean growth (**LG**; $n = 96$). Semen from multiple boars of each sire line was used to breed Camborough (Pig Improvement Company, Hendersonville, TN) sows, and parity was balanced between sire lines. Of the resulting progeny, 48 barrows and 48 gilts were selected from each sire line to fill a 2 × 2 factorial arrangement of treatments (sex × sire line) in a randomized complete block design for the live portion. Block was used to define the farrowing group, with pigs in block 1 ($n = 96$) being 2 wk older than pigs in block 2 ($n = 96$). Pigs within a block were allocated to treatments when they reached approximately 10 wk of age and penned to minimize variation in initial body weight. Once allocated, pigs were moved from the nursery to the grower/finisher facility and began a three-phase, 98-d grow-finish feeding program. Pigs were housed in pens of four pigs of the same sex and sire line. A total of 48 pens of pigs were used for the experiment with 24 pens used in each block.

Pigs were raised at the University of Illinois Swine Research Center. All pigs were fed the same corn–soybean meal-based diet that was formulated to meet or exceed the nutrient requirements for growing-finishing pigs based on the recommendations of the 2012 National Research Council (NRC) of swine. Synthetic lysine was included, and the finishing diet (phase 3) had a calculated standardized ileal digestible (**SID**) lysine value of 0.68%. Day 98 for each block was the end of the feeding portion of the trial. Pigs were weighed, and this was recorded as final trial weight. On day 98, 32 pigs per block were selected and transported to the University of Illinois Meat Science Laboratory (Urbana, IL) for slaughter on day 99. These 32 pigs were selected for tissue collection to fulfill a subsequent experiment. Both sire lines and sexes were represented in this subset of animals. On day 99, all remaining pigs (block 1 = 63 and block 2 = 64) were transported approximately 50 km to a federally inspected commercial abattoir and slaughtered. All pigs were tattooed on the ham with an individual identification number matching their identification tag number prior to transport.

Slaughter, carcass characteristics, and loin collection

Pigs slaughtered at the commercial abattoir were held in lairage (access to water but not feed) for a minimum of 3 h prior to slaughter. Pigs were immobilized via carbon dioxide gas and terminated via exsanguination. A sequential identification number was written on the shoulder of each carcass with a food-safe crayon after evisceration to help align carcass data. Hot carcass weight (**HCW**) was recorded immediately before each carcass entered the blast chiller. After the approximately 90-min blast chill, carcasses were moved to an equilibration cooler where they remained for approximately 20 h until fabrication. Estimates of carcass composition were determined on the left side of each carcass. Midline back fat thickness at the area of the last rib was recorded. Bone-in skinned left-side loins (modified Institutional Meat Processing Specifications [**IMPS**] Item No. 410, skin-on; IMPS, 2014) from the left side were collected, boxed, and promptly transported to the University of Illinois Meat Science Laboratory.

Pigs harvested at the University of Illinois were held in lairage for approximately 16 h prior to slaughter. They were provided access to water but had no access to feed during this time. Pigs were slaughtered under the supervision of the Food Safety and Inspection Service of the U.S. Department of Agriculture (USDA). Pigs were immobilized via head-to-heart electrical stunning and terminated via exsanguination. Carcasses were weighed approximately 30 min postmortem to determine HCW. Carcasses were chilled at 4 °C for a minimum of 20 h. During fabrication on day 1 postmortem, bone-in skin-on left-side loins (IMPS Item No. 410) were collected and tagged with the tattoo identification number from the ham.

Loin quality evaluation

Loins from both the commercial facility and the university meat lab were collected and evaluated simultaneously. On the evening of day 1 postmortem, the tenderloin (IMPS Item No. 415) and sirloin (modified IMPS Item No. 413D, bone-in pork sirloin split at the anatomical landmark of the last sacral vertebrae) were removed from all loins, and then loins were laid out on tables in the cooler, covered, and allowed approximately 12 h to acclimate. At day 2 postmortem, all bone-in loins were sliced into 2.54-cm-thick chops on a band saw. The number of chops produced by each loin was recorded. Chops were collected in anatomical order on a tray and then moved to a separate location where selected chops were identified and tagged. Pairs of chops were collected from four locations throughout the loin (A = 6th rib, B = 10th rib, C = last rib, and D = 4th lumbar; Figure 1). Of each pair, the anterior chop was designated for proximate composition analysis (**PA**), and the posterior chop was assigned to Warner–Bratzler shear force (**WBSF**) determination. The anterior chop from the 10th rib location from each loin was traced on to acetate paper for loin muscle area (**LMA**) determination and those with skin-on (pigs harvested at the university meat science laboratory) were measured for back fat thickness three-quarters of the distance from the dorsal spinal process, perpendicular to the widest point of LMA (Lowe et al., 2011). Chops chosen for WBSF were trimmed of subcutaneous fat leaving the epimysium intact, then vacuum packaged, boxed, aged to 7 d postmortem, and then frozen at less than −29 °C.

Chops chosen for PA were used first to score visual color (National Pork Producers' Council [NPPC], 1999), visual marbling (NPPC, 1999), and subjective firmness (NPPC, 1991). Visual color was scored on a 1 to 6 scale in half units with 1 being the lightest. Visual marbling was scored on a 1 to 10 scale in half units with 1 being the least. Firmness was scored on a 1 to 5 scale in whole units with 1 being the least firm. After receiving a tag, chops were allowed a minimum of 20 min for oxygenation of myoglobin, and then scores were assigned in batches of approximately 40 chops at a time, randomized for anatomical location and pig. After this, PA chops were closely trimmed to remove all peripheral fat and connective tissue, placed into a Whirl-Pak bag (Nasco, Gurnee, IL), and immediately frozen at less than −29 °C.

Proximate composition analysis

Chops frozen for the analysis of moisture and extractable lipid content were allowed to partially thaw at approximately 22 °C with careful attention to prevent the loss of exudate and then homogenized in a Cuisinart food processor (East Windsor, NJ). Duplicate 10 g samples of the homogenate were weighed and placed in an oven for drying at 110 °C for at least 24 h. Dried samples were weighed to determine percent moisture, and duplicate samples averaged. Samples were then placed in extractor columns and washed in a mixture of chloroform and methanol for at least 8 h as described by Novakofski et al. (1989). After extraction, samples were re-dried for at least 24 h and then weighed to determine lipid percentage, and duplicate samples averaged.

Warner–Bratzler shear force

Chops designated for WBSF were removed from frozen storage and allowed to thaw for at least 24 h at approximately 4 °C prior to analysis. Shear force was performed on all chops from an individual pig on the same day to eliminate variation in instrumental tenderness due to shear day. Chops were individually weighed and then cooked on a Farberware Open Hearth grill (model 455N, Walter Kidde, Bronx, NY). Chops were cooked on one side to an internal temperature of 31 °C, then flipped and cooked until they reached an internal temperature of 63 °C, at which point they were removed. While cooking, the internal temperature was monitored using copper constantan thermocouples (Type T, Omega Engineering, Stamford, CT) placed in the geometric center of each chop and connected to a digital scanning thermometer (model 92000-00, Barnant Co., Barrington, IL). Chops were allowed to cool and then weighed again to determine percent cook loss. A target of five 1.25 cm-diameter cores (some location A chops were too small in diameter to collect five cores) was removed from each chop parallel to the orientation of the muscle fibers and sheared using a Texture Analyzer TA.HD Plus (Texture Technologies Corp., Scarsdale, NY/Stable Microsystems, Godalming, UK) with a blade speed of 3.33 mm/s and a load cell capacity of 100 kg. The shear force values for all cores from a single chop were averaged, and the average was reported in kilograms of force as WBSF.

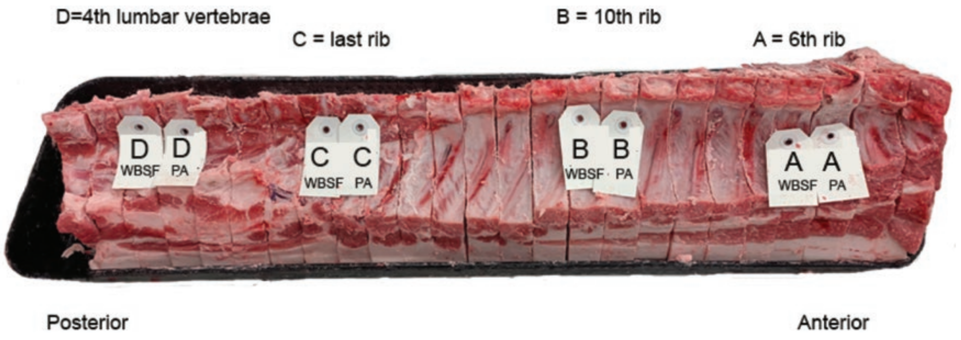

Figure 1. Illustration of chops selected for MQ measurements. Locations included at the 6th rib (A), at the 10th rib (B), at the last rib (C), and at the 4th lumbar vertebrae (D). At each location, two chops were collected with the more posterior chop used for WBSF analysis and the more anterior chop used for PA. Labels on this loin have been edited to replace handwritten identifiers with typed labels.

Statistical analysis

This experiment was designed as a 2 × 2 × 4 factorial arrangement of treatments in a split-plot design. Given that random effects such as blocks or slaughter facility cannot be included in a split-plot analysis, the effects of block and facility and interactions of these factors with selected quality traits were determined using the MIXED procedure of SAS 9.4 (SAS Inst. Inc., Cary, NC). Block did not affect any quality trait and did not interact with other fixed effects. Slaughter facility did not affect intramuscular fat (**IMF**), color, or marbling but did affect ($P < 0.05$) WBSF and cook loss. WBSF was increased approximately 0.3 kg and cook loss increased 2 percentage units in one facility compared with the other. However, the effect of facility did not interact with any other fixed effect in the experiment. As treatments were equally distributed between facilities and the facility did not interact with other fixed factors in the model, the lack of facility as a random effect in the split-plot model did not alter interpretations.

Data were analyzed using the MIXED procedure of SAS 9.4 as a three-way ANOVA in a 2 × 2 × 4 factorial arrangement of treatments in a split-plot design. Pig served as the experimental unit. Fixed effects in this model were sex, sire line, and chop location. The whole-plot factors were sex (barrow or gilt) and sire line (MQ or LG), and the split-plot factor was chop location (A, B, C, and D). The whole-plot factors of sex, sire line, and the interaction between sex and sire line were tested with the error term of pig × sex × sire line. The split-plot factor of chop location and all interactions with chop location were tested with the pooled error term of pig × sex × sire line × chop location. Homogeneity of variance of the residuals was tested using Levene's test of the GLM procedure, which revealed that the variance of residuals of several dependent variables was unequal. Variances were considered different at $P \leq 0.05$. Therefore, a two-variance model was fit for each dependent variable using the REPEATED statement of the MIXED procedure, grouped by pig similar to previous studies (Overholt et al., 2016; Arkfeld et al., 2017). Statistical differences were considered significant at $P \leq 0.05$. Mean, sample variance, and coefficient of variation (**CV**) of variables were calculated using the MEANS procedure.

The variability of traits is illustrated by box and whisker plots. The bottom line of the box indicates quartile 1 (Q1; 25th percentile); the middle line is the median (50th percentile); and the top line represents quartile 3 (Q3; 75th percentile). The interquartile range (**IQR**) was calculated as Q3 − Q1. An upper fence was calculated as Q3 + (1.5 × IQR) and a lower fence was calculated as Q1 − (1.5 × IQR). Whiskers represent the maximum and minimum observations of data within the respective fences that are not outliers. Any observation greater than the upper fence or less than the lower fence was considered an outlier. Although outliers were factored into variance calculations, they are not graphically illustrated on box and whisker plots for clarity purposes. The P-values displayed on the box plots represent differences in variance determined by Levene's test. Therefore, a P-value of <0.05 indicates that variances were different between treatments. However, variances were not separated statistically for the four chop locations. CV has been included as an additional measure of variability that takes into account the magnitude of differences in means.

The mivque(0) option of PROC VARCOMP was used to estimate the proportion of variance each fixed effect (sex, sire line, chop location, and slaughter facility) contributed to the total variance. Variation that could not be attributed to one of these variables was attributed to biological differences between pigs and other variation not accounted for by sex, sire line, or chop anatomical location (error). Computed negative estimates were treated as contributing zero variation to the population. Due to the nature of the statistical analysis used, variation percentages should total to 100%.

Results

Carcass characteristics

Main effects on carcass characteristics are presented in Table 1. Differing numbers of observations reflect the two locations in which these pigs were slaughtered. No significant sex by sire line interactions existed for these carcass characteristics. Barrows were 5.50 kg heavier ($P < 0.01$) and had 7.44 kg greater HCW ($P < 0.01$) compared with gilts. Barrows were fatter than gilts both at the 10th rib (3.17 vs. 2.39 cm; $P < 0.01$) and the last rib (3.39 vs. 2.96 cm; $P < 0.01$) but had similar ($P = 0.37$) LMA. Barrows produced loins with approximately 0.6 greater ($P < 0.01$) chops per loin. MQ pigs were 9.95 kg heavier ($P < 0.01$) and had 2.92 kg greater HCW ($P < 0.05$) compared with LG pigs. Carcasses from MQ pigs were 0.59 cm fatter at the 10th rib ($P < 0.01$) than LG pigs, with 5.16 cm^2 less LMA ($P < 0.01$) and had approximately 0.5 greater ($P < 0.05$) chops per loin.

Loin quality evaluation

Effects of sex, sire line, and chop location on chop quality are presented in Table 2. No sex by location or three-way interactions were significant ($P > 0.05$) for any of the observed parameters. Visual color score demonstrated an interaction of sire line and sex ($P = 0.05$). Color scores of MQ barrows (4.26) were not different than MQ gilts (4.21), but LG gilts (4.30) were darker than LG barrows (4.20). Color score also demonstrated an interaction of sire line and chop ($P = 0.02$). No sire line difference existed within any location except for D, where LG pigs scored 0.11 units darker than MQ pigs. No differences in visual color ($P = 0.39$) or subjective firmness ($P = 0.13$) existed between sexes. Also, no differences in visual color ($P = 0.78$) or subjective firmness ($P = 0.13$) were observed between sire lines. Within loin, visual color scores differed ($P < 0.01$) with A chops scoring the darkest (4.46) and location B chops the lightest (4.06) of all locations. Chops C (4.23) and D (4.22) were intermediate to A and B and not different from each other. Subjective firmness scores increased from anterior to posterior (A = 2.06, B = 2.21, C = 2.85, and D = 3.22; $P < 0.01$), with means differing from each other.

Visual marbling score exhibited an interaction of sire line and sex ($P = 0.04$). Marbling scores of MQ barrows (3.40) were greater than MQ gilts (3.16), but there was no difference between sexes found within LG pigs (barrows 2.84 and gilts 2.88). Marbling score also demonstrated an interaction of sire line and chop location ($P = 0.04$). Chops from MQ pigs scored greater at every location, but the difference between sire lines was less at the A location than the other three locations. No sex difference existed for marbling score ($P = 0.14$). Chops from MQ pigs (3.28) had a greater ($P < 0.01$) visual marbling score than LG (2.86). Differences in visual marbling existed among all chops ($P < 0.01$) with location D chops (3.50) being greater than C chops (3.11), which were greater than B chops (2.92) which all scored greater for marbling than A chops (2.76).

There was an interaction in extractable lipid (IMF) between sire line and chop location ($P < 0.01$). A difference of 1.69 percentage units of IMF can be observed at the D chop location

Table 1. Main effects of sire line and sex on carcass characteristics and chop number per loin

		Sex		Sire line[1]			P-value		
Item	Total observations	Barrows	Gilts	MQ	LG	SEM[2]	Sex	Sire Line	Sire Line × Sex
Final trial weight, kg	191	131.72	126.22	133.94	123.99	1.36	<0.01	<0.01	0.40
HCW, kg	188	102.30	94.86	100.04	97.12	0.87	<0.01	0.02	0.43
LMA (10th rib), cm^2	189	47.00	47.67	44.75	49.91	0.59	0.37	<0.01	0.66
Back fat[3] (10th rib), cm	64	3.17	2.39	3.07	2.48	0.12	<0.01	<0.01	0.35
Back fat[3] (last rib), cm	126	3.39	2.96	3.27	3.08	0.16	<0.01	0.12	0.80
Chop count[4]	190	23.92	23.37	23.89	23.40	0.11	<0.01	<0.01	0.46

[1] Pigs were sired by boars selected for either MQ or LG.

[2] Standard error of least squares means.

[3] Backfat measurements were taken at 10th rib (off-midline) and at the last rib (midline).

[4] Number of chops (2.54 cm) cut from whole bone-in loins.

Table 2. Main effects of sex, sire line, and chop location on the quality parameters of loins

	Sex		Sire line[2]			Chop location[3,6]					P-value[8]				
Item	Barrows	Gilts	MQ	LG	SEM[4]	A	B	C	D	SEM[5]	Sex	Sire Line	Location	Sire Line × Sex	Sire Line × Location
Color score[1]	4.22	4.26	4.24	4.25	0.03	4.46^{c}	4.06^{a}	4.23^{b}	4.22^{b}	0.03	0.39	0.78	<0.01	0.05	0.02
Marbling score[1]	3.12	3.02	3.28	2.86	0.05	2.76^{a}	2.92^{b}	3.11^{c}	3.50^{d}	0.04	0.14	<0.01	<0.01	0.04	0.04
Firmness score[1]	2.62	2.56	2.62	2.56	0.03	2.06^{a}	2.21^{b}	2.85^{c}	3.22^{d}	0.03	0.13	0.13	<0.01	0.90	0.80
Extractable lipid, %	3.64	3.20	4.02	2.81	0.10	3.80^{c}	3.34^{b}	2.77^{a}	3.77^{c}	0.08	<0.01	<0.01	<0.01	0.10	<0.01
Moisture, %	73.68	74.06	73.40	74.33	0.07	73.92^{b}	73.93^{b}	74.12^{c}	73.49^{a}	0.06	<0.01	<0.01	<0.01	0.59	<0.01
WBSF[7], kg	2.73	2.79	2.67	2.85	0.04	2.56^{a}	2.79^{b}	2.93^{c}	2.75^{b}	0.04	0.18	<0.01	<0.01	0.83	0.25
Cook loss, %	17.17	17.19	16.97	17.40	0.20	15.33^{a}	16.66^{b}	18.01^{c}	18.74^{d}	0.24	0.94	0.13	<0.01	0.69	0.02

[1] NPPC subjective scoring system for color (NPPC, 1999), marbling (NPPC, 1999), and firmness (NPPC, 1991). Visual color was scored on a 1 to 6 scale in half units with 1 being the lightest. Visual marbling was scored on a 1 to 10 scale in half units with 1 being the least. Firmness was scored on a 1 to 5 scale in whole units with 1 being the least firm.

[2] Pigs were sired by boars selected for either MQ or LG.

[3] Chops were collected from four locations: A = 6th rib, B = 10th rib, C = last rib, and D = 4th lumbar vertebrae.

[4] Standard error of least squares means (whole plot).

[5] Standard error of least squares means (split plot).

[6] Within location effect, means without a common superscript letter differ ($P < 0.05$).

[7] WBSF determination on chops cooked to 63 °C.

[8] No significant ($P \geq 0.05$) Sex by Location or three-way interactions existed.

between MQ and LG pigs, while the other three locations were in similar proportions within the sire line. Moisture percentage exhibited an interaction of sire line and chop location ($P < 0.01$). There is a greater difference between MQ and LG pigs at the D chop location than at any of the other chop locations. Barrows (3.64%) produced chops with greater ($P < 0.01$) IMF than gilts (3.20%) regardless of sire lines. Chops from barrows (73.68%) contained less moisture ($P < 0.01$) than chops from gilts (74.06%). Chops from MQ pigs (4.02%) exhibited greater ($P < 0.01$) IMF than chops from LG pigs (2.82%). Chops from MQ pigs (73.40%) contained a lower ($P < 0.01$) moisture content than chops from LG pigs (74.33%). Differences in IMF by chop location existed ($P < 0.01$), with chops from locations A (3.80%) and D (3.77%) greater than B chops (3.34%), and all three locations greater than C chops (2.77%). Mean differences for moisture content also existed across chop locations ($P < 0.01$).

Variability of IMF percentage

Chops from barrows were more variable in IMF content (s^2: 2.14 vs. 1.23; $P < 0.01$; CV: 40.32 vs. 34.61) than gilts (Figure 2A). Chop IMF from MQ pigs had a greater variance than LG (1.76 vs. 0.97; $P < 0.01$), but with the other measure of variability, the treatments were reversed (CV: 33.06 vs. 35.00, respectively; Figure 2B). Variance of IMF also differed (A = 1.44, B = 1.59, C = 1.05, and D = 2.18; $P < 0.05$) across chop locations (Figure 2C). The CV of chops B and C was similar, but within the two locations with the greatest means, A chops are the least variable, while D chops remain the most variable in both CV and variance. It is common for greater means to have increased variance, but CV accounts for differences in the magnitudes of means. The total variance of the IMF was 2.19. Of this, 33% was attributed to variation in sire line, 10% to chop location, 4% to sex, and 0% to facility, with 53% unaccounted for by factors in this model (Figure 3A).

WBSF and cooking loss

Cooking loss exhibited an interaction of sire line and location ($P = 0.02$). No sire line difference existed within any chop location except for D, where chops from LG pigs had 1.20 percentage units greater cooking loss. Chops from barrows and gilts did not differ in shear force ($P = 0.18$) or in cooking loss ($P = 0.94$). Chops from MQ pigs (2.66 kg) were more tender ($P < 0.01$) than LG chops (2.85 kg). Cooking loss did not differ between sire lines ($P = 0.13$). Shear force differed by location ($P < 0.01$) as location A chops were the most tender (2.57 kg) and C chops the least tender (2.93 kg), with D and B chops intermediate (2.75 and 2.79 kg, respectively). Differences existed among all chops in cooking loss ($P < 0.01$) with location A chops (15.33%) having the least and D chops (18.74%) with the greatest cooking loss, while B and C were intermediate (16.65% and 18.01%, respectively). Variance of WBSF did not differ ($P = 0.31$) between sexes (Figure 4A). No differences in variance of WBSF ($P = 0.11$) were observed between sire lines (Figure 4B). No differences in the variability ($P = 0.40$) of WBSF were observed between chop locations (A = 0.31, B = 0.24, C = 0.24, and D = 0.23; Figure 4C). The total variance of WBSF was 0.30. If this, 6% was attributed to sire line, 8% to chop location, <1% to sex, and 10% to facility with 77% unaccounted for by factors in this model (Figure 3B).

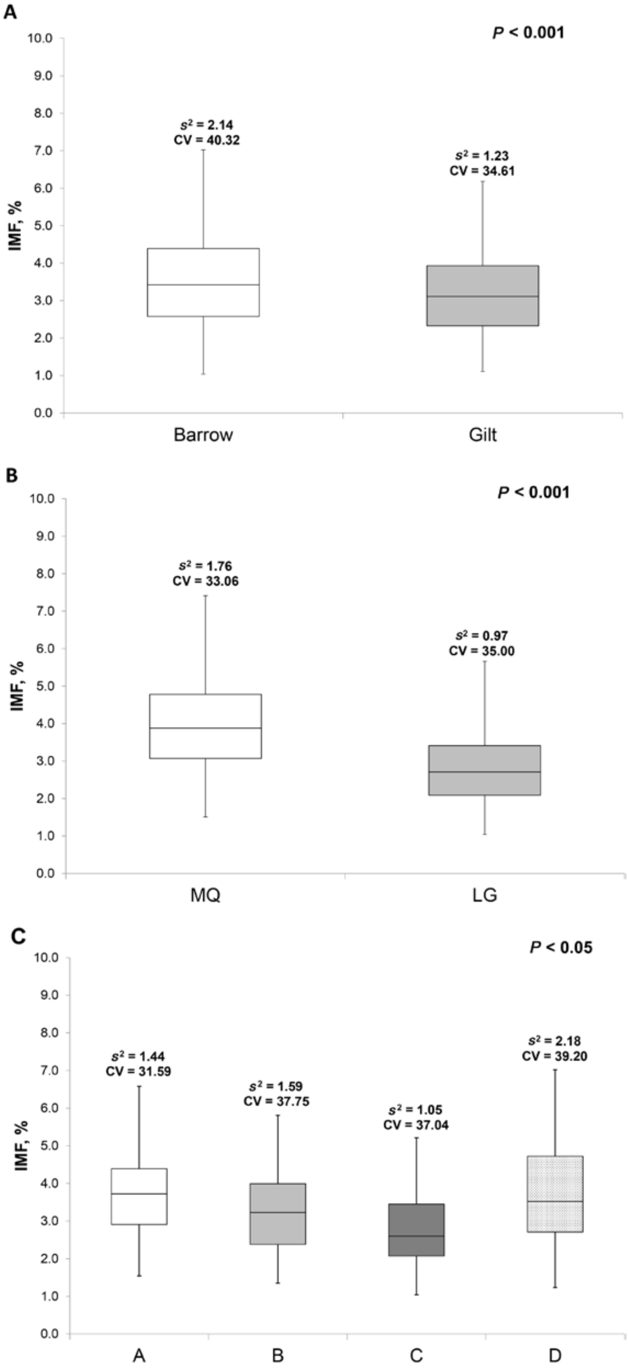

Figure 2. Variability of IMF percentage by (A) sex, (B) sire line, and (C) chop location. Chops were collected from four locations: A = 6th rib, B = 10th rib, C = last rib, and D = 4th lumbar vertebrae. Pigs were sired by boars selected for either MQ or LG. The P-value of each panel indicates the probability that variances are unequal between groups.

Discussion

Variation in quality exists in the pork industry (Arkfeld et al., 2017), and management of this variability is a vital step to add value to pork products. The opportunity to choose among displayed packages is important to shoppers (Aberle et al., 2012), and consumers can have different perspectives of the ideal characteristics of a pork chop (Brewer et al., 2001; Cannata et al., 2010; Murphy et al., 2015), so rather than attempting to eliminate all variation in quality, that variability should instead be characterized in an effort to leverage those differences for a positive benefit. Variability within a package is selected against

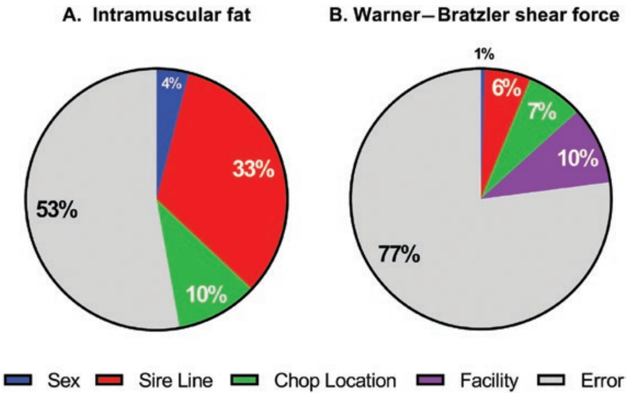

Figure 3. Percent of total variance attributed to sex, sire line, chop location, and slaughter facility for (A) IMF percentage (s^2 = 2.19) and (B) WBSF (s^2 = 0.30). Variance that cannot be attributed to these factors is termed "error."

by consumers, while variation within a retail case allows consumers to choose the product that they prefer.

Differences in composition and IMF means between sex and sire lines in the present study were aligned with previous literature (Martel et al., 1988; Ellis et al., 1996; Lee et al., 2013). In agreement with Overholt et al. (2016) and Arkfeld et al. (2017) who reported differing variability due to sex and sire line, the present study confirmed that IMF in barrows is greater and more variable than gilts, and that MQ pigs have greater IMF and are more variable in that IMF than LG pigs. Sire lines used in this study were not replicates of those used in the previously mentioned literature, but in both cases, pigs were sired by boars selectively bred for either improved meat quality or increased lean gain.

In the current study, IMF content is increased at both the anterior and posterior chop locations, with an intermediate IMF content at the area of the 10th rib and the least amount at the area of the last rib. This phenomenon was demonstrated repeatedly across all examined treatment groups (Figure 5). This is similar to the results reported by Faucitano et al. (2004) who reported the greatest IMF values in the middle thoracic (6th rib) and the caudal lumbar (4th lumbar) portions of pork loin, and the least amount located where the thoracic region meets the lumbar region (last rib), with the area between the 10th and 12th ribs best representing the average of the whole loin. Similarly, Homm et al. (2006) reported that posterior chops were the most marbled and tender in 8-rib boneless loins, and the posterior and anterior ends of 11-rib boneless loins had increased marbling content with the least amount in the middle. Those chops were collected from boneless loins. Therefore, exact comparisons cannot be made with rib locations from the current study. However, posterior and middle chops from Homm et al. (2006) should align with D and C chops (respectively) in the current data.

Beyond simple mean differences in IMF by location, the present study demonstrates significant differences in the variability of that level of IMF between locations. In addition to the sex and sire line variability discussed above, the location within a loin from which a chop is selected adds more variability. The most posterior chops have relatively similar IMF content compared with other chops but have the greatest amount of variability in that marbling. With these data, it is evident that combining factors to increase the average marbling of a population of pigs will increase the variability as well. A chop selected from the posterior end of the loin of a barrow from a meat quality sire line within the present population has a mean of 4.97% and an s^2 of 2.60 for IMF. Chops from location A had the same amount of IMF as those posterior chops from location D; however, A chops were less variable in relation to that increased IMF, exhibiting the second-lowest s^2 and the lowest CV of all four locations (Figure 2C).

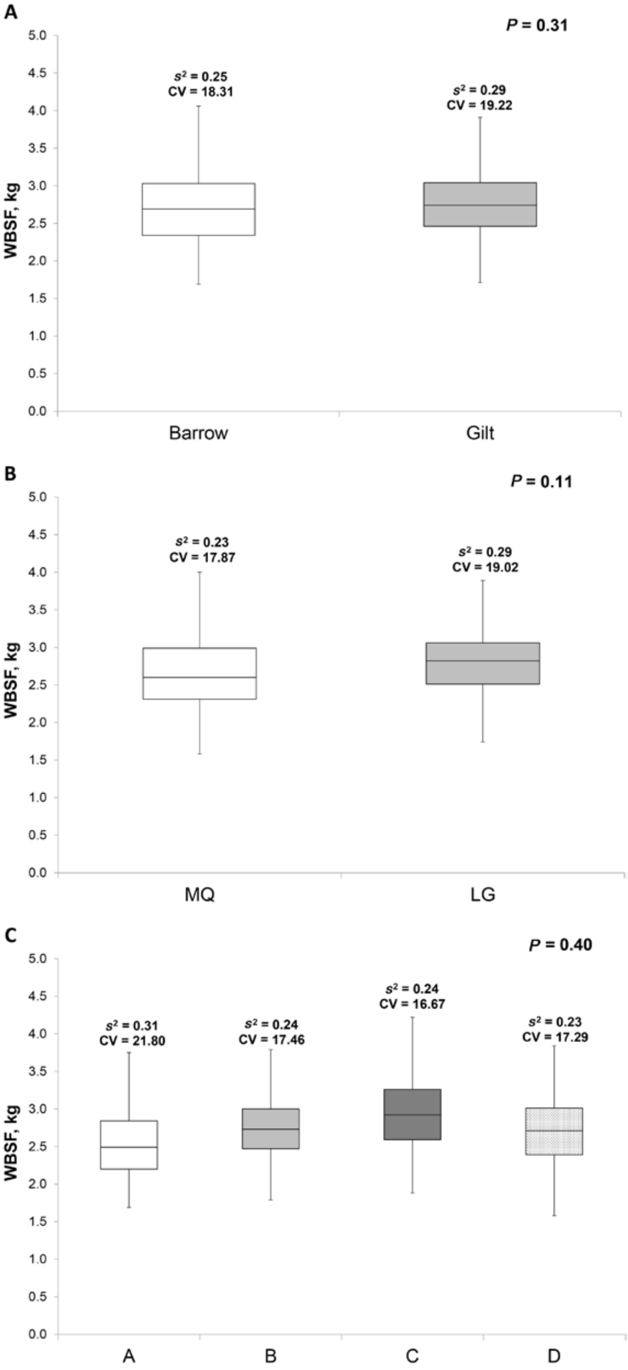

Figure 4. Variability of WBSF by (A) sex, (B) sire line, and (C) chop location. Chops were collected from four locations: A = 6th rib, B = 10th rib, C = last rib, and D = 4th lumbar vertebrae. Pigs were sired by boars selected for either MQ or LG.

MQ differences stemming from changes in anatomical location within a loin are an additional variable to be aware of in decision-making. A stark difference may be realized between a pair of chops selected from the fourth lumbar vertebrae and a pair of chops selected just anterior to that at the area of the

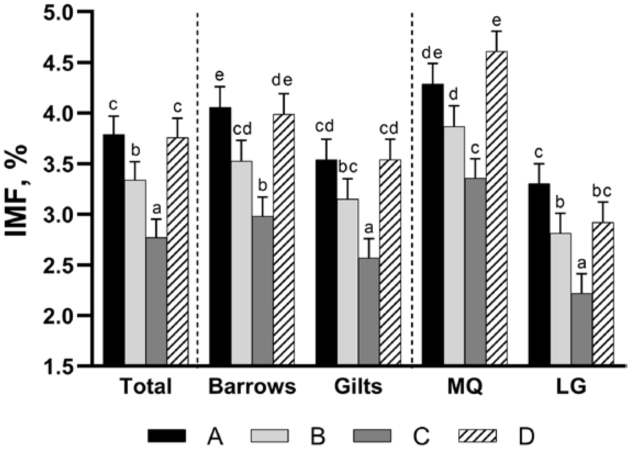

Figure 5. IMF percentage by treatment group. Chops were collected from four locations: A = 6th rib, B = 10th rib, C = last rib, and D = 4th lumbar vertebrae. Pigs were sired by boars selected for either MQ or LG. Means within a comparison (total, sex, and sire line) that do not share a common superscript are different ($P < 0.05$).

last rib. Two locations are typically just three or four chops apart on a sliced boneless loin contrast each other with the greatest and least total amount and variability of IMF observed out of all locations sampled in the current work. From this evidence, it could be suggested that when chops are sliced consecutively from a boneless loin, they will not have the same composition. If packaged together for consumer display, this may appear as an inconsistent product. Additionally, chop selection, specifically in regard to the location within the loin, is of vital importance and should be strategically considered and reported to ensure efficacy and repeatability of research experiments. Rincker et al. (2008) reported that IMF had little influence on the eating quality of pork chops; however, in that study, a chop taken adjacent to the 10th rib face was used for the determination of extractable lipid and that value was assigned to the entire loin, while the chops given to trained panelists for the evaluation came from a location 3 to 5 chops posterior to the chop that was extracted. This places the chops that were actually eaten in the area of the last rib, which this study, along with many others (Carpenter et al., 1961; Van Oeckel et al., 2003; Faucitano et al., 2004; Homm et al., 2006), deem to have the poorest quality of the entire loin. Inconsistencies in the effect of IMF on eating quality have been previously credited to genetics, processing conditions, degree of doneness, and other factors (Koohmaraie et al., 2002; Wilson et al., 2017), but with current knowledge, it can be assumed that differences in the amount and variability of IMF between different regions of the loin could have been another factor that affected those outcomes. However, many other factors such as color, pH, firmness, and water-holding capacity also can affect the pork quality (van der Wal et al., 1997; Arkfeld et al., 2015; Richardson et al., 2018).

Visual marbling score did not align with extractable lipid in the present study. Specifically, chops from location A exhibited the greatest lipid content in chemical determination yet scored the lowest for visual marbling. A similar discrepancy was also reported by Homm et al. (2006) who reported extractable lipid peaking on both ends of the loin while visual marbling increased from anterior to posterior. Pigs have a varying number of ribs and the Homm study used both 8- and 11-rib boneless loins, so anterior chops from that study may not replicate location A chops from the current study. The inconsistency in marbling quantification found in both studies is potentially due to the appearance of the graded surface of chops from various locations in the loin differing greatly. Location A chops typically had a smaller diameter and had other muscles exposed on the cut surface, which could have ultimately led to misestimates of true *longissimus* marbling in subjective scoring. It is also known that chop color can affect visual marbling scores and vice versa. In retail, chops used for center cut boneless loin chop packages (IMPS Item No. 1414) could exclude the most anterior chop from the present study, depending on the number of ribs the pig has and whether an 8-rib (IMPS Item No. 412) or 11-rib (IMPS Item No. 412C) boneless pork loin is being fabricated, so nonconforming chops from location A may not adversely affect consumer's visual acceptance of center cut boneless pork chops. In this study, subjective color and firmness scores also exhibited significant differences due to the location of where they were removed from the loin. There were clear differences in chop shape among the various locations selected, and although not characterized in this study, it is yet another factor that could come into play as having adverse effects on chop uniformity. Lowe et al. (2011) reported that, when fabricated from a bone-in loin primal, anterior portions of the loin muscle measured the widest and had the largest LMA, but more anterior chops had greater depth-to-width ratios indicating a rounder shape. Commercially relevant and timely analysis by pork processors and consumers of the marbling, color, and overall appearance of pork products will determine sorting and selection in retail applications.

Almost half of the variability in IMF was explained by the three factors in the model, with the greatest of those attributed to variability from sire line. As was expected, the difference in the two Duroc sire lines selected played a role in variability. For IMF, sire line accounted for 33% of the total variation similar to the 39% of total variation in marbling attributed to "production focus" in a previous study (Arkfeld et al., 2017). However, in that previous study, production focus encompassed not only different sire lines but also different diets and production systems. After accounting for sire line, sex, and chop location effects, data in the present study indicate that 53% of variance in IMF was not accounted for by the model. Therefore, identification of other factors that may contribute to variance in IMF is warranted. In contrast, the factors in the model explained only 14% of variability in WBSF similar to the 11% of slice shear force variation attributed to production focus in Arkfeld et al. (2017). Similar to previous reports, sex accounts for a smaller degree of variation in tenderness than marbling. The current data reported mean differences as well as differences in variability of IMF within each of the annotated groups. There were mean differences for WBSF within the groups; however, no differences in variability existed within any of the groups used in this study. Many other factors are evidently responsible for variation in chop tenderness as the lack of variation in IMF did not lead to a lack of variation in WBSF.

Conclusions

Results from this study confirm the hypothesis that differing variability does exist in pork loin IMF and can be attributed to sex, sire line, and chop location. Furthermore, the results of prior studies identifying that marbling varies along the length of the pork loin is confirmed. These findings have relevance to those in the pork supply chain attempting to target a particular amount of marbling to reach a desired product brand specification. As expected, barrows from genetic lines selected for MQ provided the best chance to meet this goal because of their increased IMF content. However, these animals also have the most variability of IMF and different locations within their loin will fluctuate in IMF content. Therefore, pigs with the best chance of reaching the highest mark for meat quality, specifically marbling, also bring about a greater likelihood of missing that target. It should be noted, however, that they will still meet high standards for meat quality more consistently than pigs with less IMF, the LG pigs in this study. Whether results would be similar for other sire lines, for example, those not based on the Duroc breed, is unknown. For the pork processor, as loins approach high-quality product line qualifications based on visual appraisal of the ventral surface, the likelihood of making inaccurate predictions about the quality of individual chops derived from those loins also increases. The current study confirms that the 10th rib is indeed intermediate in terms of IMF and, therefore, the best representative of the average of the entire loin, but it is clear that the composite is not representative of every individual part. If changes were made to the standard location for quality measurements, it should be noted that using a different chop face would greatly skew quality measurements in favor of the producer (moving anterior) or the packer (moving posterior; ribbing at last rib). Possibly the biggest implication is on retail selection for packaging, now knowing that a continuous selection of loin chops from a single loin may not lay out next to each other and appear congruent. Thought should be given to whether a group of chops from the same anatomical location on multiple loins or chops from multiple locations on the same loin are actually perceived better by consumers. While it is unclear what the ideal chop is or which combination of quality traits provides the best eating experience, different consumers seem to have different perspectives regarding their ideal chop. Thus, to maximize consumer satisfaction, presenting uniform chops taken from similar anatomical locations of different loins may be beneficial.

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Conflicts of interest statement

The authors have no conflicts of interest to report.

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