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Objective and Subjective Quality Characteristics of Pork *Longissimus* Muscle as a Function of the Ultimate pH

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Abstract

The aim of the present study was to evaluate the variation in ultimate pH of commercial populations of pure-breed (Landrace, Duroc and Yorkshire) pig's *longissimus* muscles and their effect on objective meat quality traits and sensory characteristics. Fifty boars were sampled from 184 pigs, which were reared at three breeding farms and slaughtered at a commercial abattoir. The selection was determined based on ultimate pH, and animals were segregated into three groups: low pH (pH ≤ 5.5, n=13), medium pH (pH 5.5 to 5.6, n=18) and high pH (pH ≥ 5.6, n=16). The breeds had no significant effects; however, pigs with a higher ultimate pH had significantly (p<0.05) higher intramuscular fat content, lower level of polyunsaturated fatty acids, lower level of lipid oxidation and higher eating quality compared to those with lower ultimate pH. As the ultimate pH increased, the relative proportion of C14:0, C16:0 and C18:1 increased while C18:2n6 and C20:4n6 decreased. The present study demonstrates that the economic value of pigs can be characterized by the ultimate pH and/or intramuscular fat content. However, these results do not necessarily indicate that a high ultimate pH directly corresponds to high intramuscular fat content and *vice versa*.

Key words : pig, pH, intramuscular fat content, fatty acid, sensory traits

Introduction

It has been well documented that the rate and extent of pH decline have great effects on meat quality traits including water-holding capacity (Huff-Lonergan and Lonergan, 2005), tenderness (Savell *et al*., 2005), meat color (Holmer *et al*., 2009), and lipid oxidation (Hansen *et al*., 2004). Furthermore, ultimate pH of pork muscle is the most important single attribute influencing both eating quality (Lindahl *et al*., 2006; Huff-Lonergan and Lonergan, 2005) and fatty acid composition in particular genotype of pigs (Lundström *et al*., 1998; Zhang *et al*., 2007).

Huff-Lonergan *et al*. (2002) reported significantly high simple correlation coefficient values between ultimate pH and tenderness, juiciness and flavor of pork *longissimus* muscle. A recent study reported by the same research group (Lonergan *et al*., 2007) demonstrated that ultimate pH between 5.8 and 5.5 had a significant effect on sensory properties of Berkshire, Chester White, Duroc, Hampshire, Landrace, Poland China, Spotted, and Yorkshire barrows and gilts while meats with a greater or lesser ultimate pH had little effect on sensory quality. On the other hand, an early study (Dransfield *et al*., 1985) reported that ultimate pH accounts for 5% of the variation in juiciness scores of pork. The study by Van Oeckel and Warnants (2003) failed to identify a significant difference in sensory characteristics between normal meat and PSE pork *longissimus* meat. Given these findings, ultimate pH

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across most commercial breeds appears to have significant effect on meat quality only when pH of meats ranges within relatively normal values, but not higher or lower. The fact, however, implies that difference in ultimate pH by a decimal unit (e.g., Δ 0.1) can influence eating quality greatly. Studies also showed that ultimate pH as related to genotypes had significant effect on fatty acid composition. Zhang *et al*. (2007) reported that pigs with NN genotype (normal) had more C16:0 and C18:1 and less C18:2 and C20:4 than those with Nn genotype. In addition, RN^{-} carrier gilts (PSE high glycolytic potential line) had the lowest amount of saturated fatty acid and MUFA, but had the highest amount of PUFA (Lundström *et al*., 1998).

In the Korean pig industry where guidelines for pre-, peri-, and post-slaughter procedures are not standardized, there are presumably many extrinsic factors that could affect ultimate pH including feeding scheme, slaughter weight and post-slaughter process (Park *et al*, 2009), as well as genetic factors (Hwang *et al*., 2004). For example, if the glycogen concentration of the muscle tissue is decreased due to feed restriction and stress prior to slaughter, the ultimate pH is higher than 5.5. On the other hand, even if the glycogen content in the muscle tissue is high enough to achieve pH 5.5, the pH does not fall much lower than 5.4 under ordinary slaughter process due to inactivation of glycolytic enzymes under acidic environment (Young *et al*., 2004). However, if pigs are subjected to extreme stressors, the muscle will turn into PSE meat (Park *et al*., 2004).

The present study was designed to evaluate the variation in ultimate pH of commercial population of purebreed (Landrace, Duroc and Yorkshire) pigs' *longissimus* muscles and their effect on objective meat quality traits and sensory characteristics.

Materials and Methods

Animals, experimental design and sampling

Fifty boars (Landrace 17, Duroc 17 and Yorkshire 16) were selected from 184 pigs reared at three breeding farms and slaughtered at a commercial abattoir. Average live weight of the selected pigs were 100±12 kg. All animals were fasted overnight and transported for 1 h to a commercial abattoir with minimal handling and transit stress. A lairage period of 6 h was followed and similar slaughter procedures were applied for all the pigs. All carcasses were hanged, chilled for 24 h and subsequently graded. A day after slaughter, *m. longissimus thoracis et lumborum* (LTL) were taken from the right side of the carcasses. The sample selection was determined on the basis of pH of the *longissimus* muscle on the 10^{th} rib of the right carcass at 24 h postmortem. All samples were frozen at -20°C and transported to the Meat Science laboratory at CBNU, South Korea.

The frozen whole loin samples were cut into sub-sample sizes starting from the cranial end of the LTL (Fig. 1) depending on the type of analysis in the following order: pH, sensory evaluation, intramuscular crude fat content, fatty acid composition, thiobarbituric acid reactive substance (TBARS), color, cooking loss, Warner Bratzler shear force (WBSF), moisture content, and protein solubility. Considering the number of population and range of pH, pigs were segregated into three groups: low pH (pH ≤5.5, n=13), medium pH (pH 5.5 to 5.6, n=18) and high pH (pH≥5.6, n=16). Sub-samples were vacuum-packed in oxygen impermeable polyethylene bags and stored at -

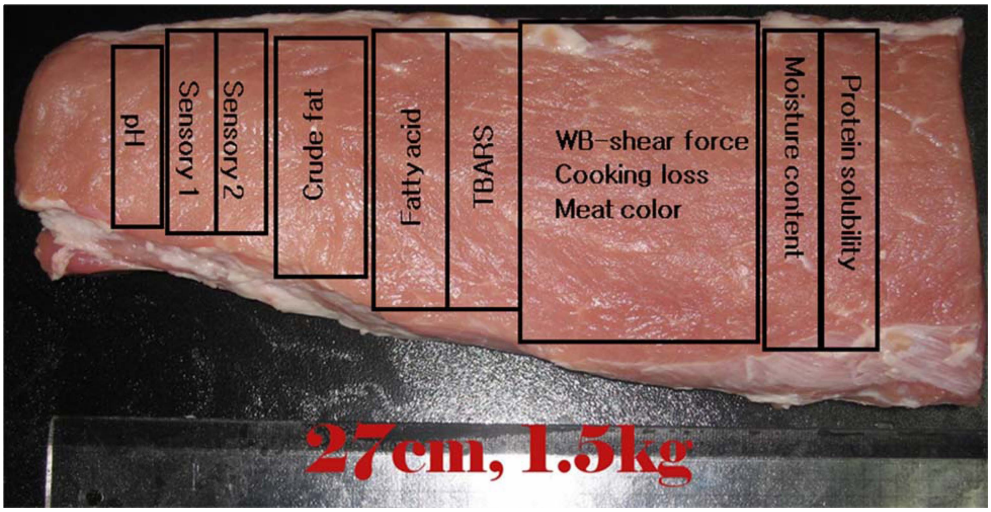

Fig. 1. Photograph of pig *longissimus* muscle and portion of sampling.

20°C until analysis.

Objective meat quality traits

The pH was determined in duplicates following the procedure of Bendall (1973) using a portable pH meter (Orion Model 301, USA). 5 mM iodoacetate-KCl solution at a volume of 10 times the weight of the meat sample was added to 1 to 2 g of finely cut sample contained in a 50 mL conical tube. The mixture was homogenized twice for 30 s at 11, 000 rpm with 15 s break using the Ultra-Turrax T25B (IKA Works (Asia) Sdn, Bhd, Malaysia). The pH was measured at 25°C with an Orion 3 Star (Thermo Electron Corp., USA) pH meter.

WBSF, cooking loss and meat color were determined on the same sample block which was thawed overnight at 2° to 4°C in a chiller. Approximately 300 g block sample (approximately 5×6×7 cm, 6-7°C) was placed in plastic bag and cooked in a pre-heated 70°C water bath for 1 h when core meat temperature reached 70°C. Cooked samples were immediately cooled in an 18°C running water for 30 min and weighed. WBSF values were measured in an Instron Universal Testing Machine (Model 3342, Instron Corporation, USA) on six pieces core samples with 0.5 inch diameter using a crosshead speed of 400 mm/min and a 40 kgf load cell. The weights of the meat before and after cooking were recorded and the cooking loss was reported as weight loss expressed as percentage of the weight of sample before cooking. Objective meat color was evaluated with Konica Minolta Spectrophotometer CM-2500d with an 8 mm measuring port, D 65 illuminant and 10° observer. Three measurements were taken on the cut surface of the meat that has been bloomed for 30 min. Hunter L, a, b values were recorded. The data presented are means of three measurements.

TBARS was assessed following the procedure of Buege and Aust (1978). A 2.5 g meat sample with 7.5 mL distilled water, 25 μL saturated butylated hydroxyanisole (BHA) solution and 10 mL thiobarbituric acid/ trichloroacetic acid (TBA/TCA) solution was homogenized at 11,000 rpm for 15 s using an Ultra Turrax T25 (IKA Works (Asia) Sdn., Bhd., Malaysia). The volume of the homogenate was adjusted to 30 mL with a TBA/TCA solution and was immediately placed in ice. The tube containing the homogenate was immersed in a 90°C water bath for 15 min. Thereafter, it was placed in ice to cool for 20 min. Centrifugation at 3,000 rpm (SUPRA 21K, Hanil Science Industrial Co., Korea) for 10 min followed. About 1 to 1.5 mL supernatant was taken and the absorbance was measured at 531 nm in Ultrospec 2000 spectrophotometer (Pharmacia Biotech, Cambridge, England). The TBARS value was calculated by multiplying the absorbance reading by 5.88. TBARS was expressed as mg malonaldehyde/kg meat sample.

Sarcoplasmic protein solubility measurements were carried out following the method of Warner *et al*. (1997). One gram muscle tissue sample was placed in a 50 mL conical tube and 10 mL of ice-cold 0.025 M potassium phosphate buffer (pH 7.2) was added. It was homogenized thrice, each with 4 s burst and 10 s break in between, with an UltraTurrax T25B (IKA Works (Asia) Sdn, Bhd, Malaysia) at 11,000 rpm. After keeping overnight in ice, samples were centrifuged at 1500 xg at 4°C for 20 min. About 1 mL supernatant was taken and protein concentration was determined and expressed as mg/g tissue. The moisture content was measured in duplicates in an HR73 halogen moisture analyzer (Mettler-Toledo GmbH, Switzerland) set at 105°C. A 2.5 g minced meat sample was used for each measurement. Crude fat determination followed the Soxhlet method with petroleum ether as the extracting solvent (AMPC Meat and Livestock Australia). Five g of finely minced sample was placed in an extraction thimble, dried to constant weight at 102°C for 5 h, cooled and placed in a Soxhlet extractor. Extraction was done with petroleum ether for 6 h. Petroleum ether was evaporated at the end of extraction then the flask containing the fat extract was kept for 1 h in the drying oven set at 102°C. The crude fat content of the lean sample was reported as the amount of extracted fat expressed as the percentage of the weight of the fresh sample.

Fatty acid analysis and extraction

Direct transesterification of fatty acid followed the procedure developed by Rule (1997). Thin slices of meat sample were freeze-dried for 48 h and pulverized. Five hundred mg of dried pork muscle was placed into a 20 mL headspace vial with silicone-lined cap. This was done in duplicates. Into each vial, 2 mL of 14% boron-trifluoride in methanol (BDH, BDH Lab. Supplies, Poole, England) and 2 mL of methanol were added. The tube was sealed with a scrimp cap before it was placed in a heating block set at 80°C. The tube was maintained at 80°C and vortex-mixed every 5 min for 2 h. Cooling of the tubes soon followed and thereafter, 3 mL distilled water and 3 mL hexane were added. The tubes were capped and vortex-mixed for 15. Centrifugation at 1000 g force for 5 min was done to accelerate phase separation. One mL of the upper hexane phase was transferred to

GLC auto-sampler vials and was sealed. The extract was stored at -20°C as gas chromatography was not done immediately.

Gas chromatograph Agilent Technologies 6890N Network GC System equipped with Agilent Technologies 7683B Series Injector and Agilent Technologies 5973 Network Mass Selective Detector was used to separate and identify the fatty acid components of the samples. GC separation of components was carried out on a fused silica capillary column (30m x 0.25mm x 0.25 μm film thickness, Supelcowax 10) at a split ratio of 100:1. Helium was used as the carrier gas. The inlet temperature was 250°C and the oven temperature program used was as follows: 50°C for 1 min, raised to 200°C at the rate of 25°C per min, further increased to 230°C at 3°C per min. The temperature was held at 230°C for 15 min. Detector temperature was 280°C. Total running time was 35 min. Individual fatty acids were expressed as percentage of the total fatty acids detected as fatty acid methyl esters.

Sensory Evaluation

The sensory evaluation was done following the protocols reported by Hwang *et al*. (2008). Given the experimental design for sensory evaluation, only 48 pigs out of 50 pigs used in the current study were assessed. Each pig was tested by 6 panels allocated in randomized block arrangement. Consumer panels consisted of 48 non-trained male and female university students. A total of 288 sensory samples were randomly allocated in 12 sets of four sessions; each session had 12 panelists and each panelist evaluated 6 samples.

The vacuum-packed and frozen sensory sample blocks were cut in frozen state. Approximately ten to twelve thin slices (30 mm×30 mm×4 mm) were sliced parallel to fiber direction across the sample block and strips were immediately placed in the freezer. 6 strips for each sample were finally chosen and placed in the labeled plastic sample bag depending on the designed session, panel and testing order. Samples were again vacuum-packed and immediately placed in the freezer set at -20°C until use.

Samples allotted for evaluation were thawed for 30 min before the scheduled sensory session. The vacuum-packed meats were opened only when the samples are about to be cooked. Cooking was done on open tin-coated grill (surface temperature: 250-260°C). Two sets of grill were used where each grill was set to cook 6 strips of samples. The twelve cooked samples were immediately dispensed on individual plates and served to the panelists. A 100 mm unstructured line scale with verbal anchors based on quantitative descriptive analysis was used, where the left anchor represented scoring of either tough, dry, extremely dislike the flavor or sample is extremely unacceptable. After evaluating each sample, the panelists were asked to refresh their mouth with the provided distilled drinking water and salt-free crackers.

Statistical Analysis

The data was analyzed using a general linear model (SAS Institute, Cary, NC, 2007). A preliminarily analysis was conducted to examine breed, farm and their interactions with ultimate pH. When ultimate pH was included in the model as a covariate, the effects of breed and farm on meat quality traits showed no significance. Although these effects were not statistically significant the terms were retained in the final model to adjust these factors. Least square means were examined with pair difference test, and simple correlation coefficient between the quality traits of the pooled data were calculated using the Pearson procedure (SAS Institute, Cary, NC, 2007).

Results and Discussion

Objective meat quality

Results showed that pH values ranged from 5.38 to 5.81 with three distinctive pH groups. Preliminary analysis applying a mixed model with ultimate pH as a covariate showed that pH had significant effects on most meat quality traits. However, given that the values of the ultimate pH were clustered within three distinctive groups, the pigs were segregated into groups and used that groups as a fixed effect on the analysis of variance (Table 1).

Least square means for the groups were 5.44, 5.54 and 5.67 for lower (pH≤5.5, n=13), middle (pH 5.5 to 5.6, n=18) and higher (pH≥5.6, n=16) groups, respectively. To minimize variations in the rate and extent of pH decline as affected by pre- and post-slaughter procedures (Park *et al*., 2007; Park *et al*., 2004), feed restriction, lairage, and chilling regimes were standardized. Earlier study revealed a significant breed effect of Korean native black pig on pH decline (Hwang *et al*., 2004). However, the breeds (i.e., Landrace, Duroc and Yorkshire) used in the present study showed a limited effects on pH decline. Nevertheless, these factors were retained in the final models as fixed effects because, for the current population, breeds had a limited effect on meat quality traits, we reckon that the breed effects are confounded. The pH results indicated a considerable variation in ultimate pH of commercial boars

and its significant effects on objective and subjective meat quality traits. As earlier noted, it is well known that the rate and extent of pH decline have great effects on meat quality traits including water-holding capacity (Huff-Lonergan and Lonergan, 2005), meat color (Holmer *et al*., 2009) and lipid oxidation (Hansen *et al*., 2004). In particular, ultimate pH greatly influences sensory attributes such as tenderness and juiciness for meats with pH between 5.8 and 5.5 (Lonergan *et al*., 2007). Considering the report of Lonergan *et al*. (2007) and the pH groups used in the present study, significant difference in carcass traits and eating quality between the pH groups was rather expected. However, it should be noted that in the present study, a difference of approximately one decimal point in pH values between groups (i.e., 5.44, 5.54 and 5.67 for low, medium and high, respectively) had significant (p<0.05) effects on intramuscular fat content, cooking loss and WB-shear force (Table 1).

The most noticeable result was the significant (p<0.05) linear increase in intramuscular fat content from lower to higher pH group. This relationship was evidenced by a simple correlation coefficient value of 0.57 (p<0.001, Table 4). Based on published literatures, it was not easy to understand the current relationship. Lonergan *et al*. (2007) reported that pH classification had very little effect on lipid content although pork in the intermediate pH class (pH 5.5-5.8) had significantly higher lipid content than the greater pH class (pH≥5.95). In addition, intramuscular fat content did not differ between normal and PSE meat (Van Oeckel and Warnants, 2003), Similarly, crossbred pigs (Duroc × Landrace, Tia Meslan × Landrace) with various intramuscular fat levels in *longissimus* muscle showed an identical ultimate pH (Fernandez *et al*., 1999).

In general, intramuscular fat content of pig's meat is affected by genetics, nutrition and environmental factors (Shi-Zeng and Su-Mei, 2009). The results of the present study differed with previous studies (Lonergan *et al*., 2007; Van Oeckel and Warnants, 2003 and Fernandez *et al*., 1999). These likely indicate that intrinsic and/or extrinsic factors related to intramuscular fat content are linked to ultimate pH. In fact, numerous reports showed that NN genotype pig had greater lipid content than Nn pigs (Zhang *et al*., 2007; Maddock *et al*., 2002) or than nn genotype (Piedrafita *et al*., 2001). Because the halothane carrier pigs (Nn and nn) are prone to low pH, higher lipid content can be obtained from NN (normal) genotype pig.

The benefit of high pH pork was evidenced in the stability of unsaturated fatty acids. Meat of the low pH group had a significantly higher TBARS value than meat of the medium pH and high pH groups. The results imply that lipid stability tended to decrease with decreasing pH of pork and that more lipid oxidation occurs at a lower ultimate pH (lower than 5.5). An early study (Yasosky *et al*., 1984) reported a critical ultimate pH value of 6.1 or higher for maximum inhibition of lipid oxidation. Similarly, Juncher *et al*. (2001) suggested a threshold value of approximately ultimate pH 5.8 until which lipid oxidation continuously occurs. A higher risk of fat oxidation for meat with lower pH was also observed in frozen samples. Hansen *et al*. (2004) reported that lipid oxidation developed more significantly in pork with low ultimate pH. Although pH range in each pH groups in the current study differed from the pH threshold for the minimum

Table 1. Objective quality traits of pork *M. longissimus thoracis et lumborum* as a function of ultimate pH levels

Parameters	pH Level[1]			Average standard error	F value
	Low pH (n=13)	Medium pH (n=18)	High pH (n=16)		
pH	5.44[c]	5.54[b]	5.67[a]	0.01	99.53***
Moisture, %	72.22[a]	72.06[a]	71.38[b]	0.28	2.50*
Intramuscular Fat, %	1.67[c]	2.77[b]	3.67[a]	0.33	8.08***
Hunter L	59.00	59.47	58.16	1.01	0.45
Hunter a	4.57	4.67	4.69	0.42	0.02
Hunter b	15.50[ab]	16.35[a]	15.35[b]	0.34	2.59*
Cooking loss, %	21.65[a]	20.86[a]	19.37[b]	0.60	3.46*
Warner Bratzler Shear Force, N	23.25[a]	21.68[ab]	18.74[b]	0.15	2.32*
Soluble Sarcoplasmic protein, mg/g	35.33	36.16	34.78	0.07	1.18
TBARS, mg MA/kg meat	0.32[a]	0.26[b]	0.24[b]	0.02	2.84*
df[2]					2/44

[1]Low pH, pH ≤ 5.5; Medium pH, pH 5.5 to 5.6; High pH, pH>5.6.
[2]Numerator/Denominator degree of freedom.
*p≤0.05, **p≤0.01, ***p≤0.001.
[abc] Means in the same row with different superscripts differed significantly (p<0.05).

Table 2. Consumer sensory characteristics of *M. longissimus thoracis et lumborum* (% of total fatty acids) as a function of ultimate pH levels

Parameters[2]	pH Level[1]			Average standard error	F value
	Low pH (n=13)	Medium pH (n=18)	High pH (n=16)		
Tenderness	50.24[b]	58.79[a]	61.36[a]	2.64	4.20*
Juiciness	51.92[b]	62.44[a]	61.01[a]	2.73	3.86*
Flavor	56.73[b]	61.42[ab]	63.48[a]	1.98	2.66*
Overall acceptability	50.64[b]	59.01[a]	61.70[a]	2.70	3.95*
df[3]					2/41

[1]Low pH, pH≤5.5; Medium pH, pH 5.5 to 5.6; High pH, pH>5.6.
[2]Tenderness, 0(not tender) to 100 (very tender); Juiciness, 0 (not juicy) to 100 (very juicy); Flavor, 0 (dislike extremely) to 100 (like extremely); Overall acceptability, 0 (dislike extremely) to 100 (like extremely).
[3]df: Numerator/Denominator degree of freedom.
*p<0.05, **p<0.01, ***p<0.001.
[abc]Means in the same row with different superscripts differed significantly (p<0.05).

oxidation of fatty acids, limited oxidation of meat with high pH was evident.

Although the simple correlation coefficient between pH and TBARS was not significant (p>0.05) (Table 4), the small difference in pH between the three groups showed a significant difference in TBARS measurement. Given that the samples were vacuum packed and not chiller-aged, the result in part (if not) can be attributed to differences in the fatty acid composition of pork in the three pH groups. Fatty acid composition showed that polyunsaturated fatty acid contents decreased as the ultimate pH of pork increased (Table 3), thus there were likely less substrate for lipid oxidation resulting in lower TBARS value. A further discussion is in the following section.

WB-shear force indicated that toughness was significantly (p<0.05) reduced for the higher pH meat (Table 1).

Table 3. Fatty acid composition of *M. longissimus thoracis et lumborum* (% of total fatty acids) as a function of ultimate pH levels

Parameters	pH level[1]			Average standard error	F value
	Low pH (n=13)	Medium pH (n=18)	High pH (n=16)		
C14:0	1.35[b]	1.53[ab]	1.66[a]	0.10	2.40*
C16:0	23.34[b]	23.73[ab]	24.60[a]	0.38	2.81*
C16:1	2.70	2.90	2.89	0.26	0.19
C18:0	13.36	14.21	14.11	0.64	0.49
C18:1	37.47[b]	39.29[ab]	41.61[a]	1.20	2.80*
C18:2n6	16.73[a]	14.19[ab]	11.61[b]	1.20	4.21**
C20:4n6	4.79[a]	3.66[ab]	2.86[b]	0.50	3.40**
df[2]					2/44

[1]Low pH, pH≤5.5; Medium pH, pH 5.5 to 5.6; High pH, pH>5.6.
[2]Numerator/Denominator degree of freedom.
*p≤0.05, **p≤0.01, ***p≤0.001
[abc] Means in the same row with different superscripts differed significantly (p<0.05).

The underlying mechanism(s) is not clear as differences in both physical and biological status of meat samples between the pH groups were not determined. However, this is likely partly related to the greater amount of intramuscular fat content for the higher pH group. Thompson (2002) discussed that the major function of intramuscular fat in the textural property of meat includes reduced number of muscle fiber within a certain dimension. In other words, the muscle tissue with higher fat content has a lower resistance to shearing force because of the dilution

Table 4. Simple correlation coefficient (r) between pH and the objective and subjective quality traits of pork *M. longissimus thoracis et lumborum*

Parameter	Correlation coefficient
Moisture	-0.333*
Intramuscular fat	0.569***
Hunter L*	0.013
Hunter a*	-0.038
Hunter b*	-0.085
Cooking loss	-0.343*
Warner Bratzler shear force	-0.328*
Soluble sarcoplasmic protein	-0.013
TBARS	-0.256
C14:0	0.365***
C16:0	0.294*
C16:1n7	0.121
C18:0	0.073
C18:1	0.334*
C18:2n6	-0.401**
C20:4n6	-0.348*
Tenderness	0.392**
Juiciness	0.286*
Flavor	0.320*
Overall Acceptability	0.417**
Rating	0.390**

*p<0.05, **p<0.01, ***p<0.001.

of fibrous protein by soft fat (Shi-Zheng and Su-Mei, 2009). Furthermore, the accumulation of fat in the perimysial connective tissues forces the muscle bundles apart thus opening up the muscle structure (Wood *et al*., 1999). In addition, less cooking loss for the high pH group can be related to a tender texture of cooked sample. In pig studies within a similar fat content group, Van Laack *et al*. (2001) pointed out that the relationship of ultimate pH with tenderness is dependent on genetics. It was observed that in meat from Hampshire pigs, WB-shear force increased linearly as ultimate pH increased, whereas in Duroc and Berkshire pork, WB-shear force decreased as ultimate pH increased. WB-shear values in the current study are all negatively correlated with tenderness (r=-0.478), juiciness (r=-0.164), flavor (r=-0.119) and overall acceptability (r=-0.150). It should be emphasized that the current result again demonstrated that WB-shear force largely reflects tenderness and approximately 50% variation in sensory tenderness, but not in other sensory traits such as juiciness and flavor.

The pork in the high pH group had significantly ($p<$ 0.05) smaller cooking losses than the low and medium pH groups. The cooking loss for medium pH was lower but not significantly different from meat with low pH. These confirm previous findings that water binding ability of muscle proteins are reduced with decreasing pH, resulting in increased cooking loss (Aaslyng *et al*., 2003). The pH affects the distance between the myofilaments and distribution of water due to its effect on electrostatic repulsion (Aaslyng *et al*., 2003; Mortensen *et al*., 2006; Bertram *et al*., 2002). It was modeled that fiber and fiber bundles shrink when their constituent myofibrils shrink thus giving rise to extracellular compartments around fibers and fiber bundles in which meat juice accumulates. Furthermore, lateral shrinkage of the filament lattice is brought about by a pH-fall closer to the isoelectric point, rigor contraction and myosin denaturation (Offer and Knight, 1988; Offer and Cousins, 1992). The results of this study demonstrated the importance of muscle pH for water holding capacity and consequently cooking loss.

On the other hand, less cooking loss for the higher pH group was less likely related to protein denaturation because sarcoplasmic protein solubility did not differ between the three pH groups. An early study (Joo *et al*., 1999) reported that sarcoplasmic protein solubility increases for pig *longissimus* muscle with a higher ultimate pH. In a similar notion, Channon *et al*. (2000) observed that solubility of sarcoplasmic, myofibrilllar and total protein was significantly influenced by halothane genotype, with halothane carrier pigs exhibiting lower sarcoplasmic, myofibrillar and total protein solubility compared with homozygous normal pigs. Early postmortem events including rate and extent of pH decline, proteolysis and even protein oxidation are keys in influencing the ability of meat to retain moisture (Huff-Lonergan and Lonergan, 2005). In addition, a number of studies have shown that a fast rate of pH decline with a slow decline in temperature results in protein denaturation and thereby causing a decrease in protein solubility (Rees *et al*., 2003). The rate and extent of pH and temperature decline were not determined, but current result implies that pH/temperature window during rigor development was not great enough to be reflected in the measurement of sarcoplasmic protein solubility. This is more likely because pre-, peri-, and post-slaughter procedures were standardized in the present study.

Hunter L and a values were similar in all pH groups. Although Hunter b was significantly higher in the medium pH than the high pH group, numerical difference was very limited. Lower muscle pH is believed to increase free water at the cell surface resulting in an increased reflectance giving the meat a lighter appearance (Pearson and Dutson, 1985; Rees *et al*., 2003). Lindahl *et al*. (2006) observed that the combination of high temperature and low pH early postmortem increased lightness and yellowness, which is ascribed to inactivation of oxygen-consuming enzymes and protein denaturation. Ashmore *et al*. (1972) explained that the higher a and b values at low pH is due to the inactivation of mitochondria that leads to the inhibition of oxygen consumption. More oxygen is available for oxygenation of myoglobin thus the meat has a deeper layer of oxymyoglobin. Nevertheless, an identical color dimension between the pH groups indicated these differences do not influence objective meat color.

Sensory characteristics and fatty acid composition

Meat in the low pH group showed inferior eating quality than the other groups for all aspects determined (i.e, tenderness, juiciness, flavor, and overall acceptability, Table 2). As pointed out earlier, the higher eating quality coincided with higher lipid content and lower cooking loss. The positive effect of intramuscular fat content on eating quality has been obvious, but the magnitude of its effects on individual sensory characteristics (i.e, tenderness, flavor and juiciness) has been controversial. Shi-Zheng and Su-Mei (2009) reported that intramuscular fat content below the optimum range of 2.5-3% diminishes

eating quality whereas a higher fat content does not further improve sensory quality. Other researches, however, have demonstrated that a higher fat content improved more the eating quality (Eikelenboom and Hoving-Bolink, 1994; Goodwin and Burroughs, 1995). Eating quality is not determined by a single parameter, but is confounded by numerous factors including fat content and water holding capacity. Taking only lipid content and ultimate pH, the current consumer panel indicated that intramuscular fat content of 2.8 and 3.7 did not differ while 1.7% had inferior quality. In addition, meats from medium and high pH groups were similar. This may indicate that a larger difference in pH and lipid content was required to distinguish flavor difference.

There were significant positive correlations between intramuscular fat content and tenderness (r=0.431), juiciness (r=0.267), flavor (r=0.380) and overall acceptability (r=0.383). The tendency of the relationships between ultimate pH and sensory traits were also observed (Table 4). This re-confirmed the importance of lipid content and ultimate pH on sensory quality and was consistent with the previous study of Eikelenboom *et al*. (1996) who reported a 33% correlation between juiciness and lipid fat content. More recently, Lonergan *et al*. (2007) reported that pork belonging to high pH classes (pH≥5.80 to 5.95 and pH≥5.95) had higher juiciness and tenderness scores than the low pH class (pH<5.50).

With the increase in ultimate pH, initial examination showed a clear tendency that the relative proportions of C14:0, C16:0 and C18:1 increased whereas C18:2n6 and C20:4n6 decreased, although significant differences were observed only between low and high pH groups for five fatty acids. We are unaware of available literature reporting relationship between pH and fatty acid composition, but a number of genetic studies showed that pigs susceptible to low ultimate pH showed a similar proportion of fatty acid composition with our current data. Zhang *et al*. (2007) reported that pigs with NN genotype (normal) had more C16:0 and C18:1 and less C18:2 and C20:4 than Nn pigs. Furthermore, RN^- carrier gilts had the lowest amount of saturated fatty acid and MUFA, but had the highest amount of PUFA (Lundström *et al*., 1998). It has been well known that meat from RN^- pigs has characteristically high glycolytic potential and consequently low ultimate pH.

As earlier discussed, the breed effect on lipid content and fatty acid composition was examined during the preliminary analysis, but no statistically significant effects were noted. On the other hand, it was observed that a higher level of polyunsaturated fatty acid was related to low pH group while a lower level of other fatty acids was related to high pH group which, relates to low and high intramuscular fat groups, respectively. Wood and Enser (1997) have reported that there is a strong correlation between the amount of fat and the concentration of polyunsaturated fatty acids. Linoleic acid (C18:2) is mainly derived from feeds and are readily incorporated into adipose tissues of pigs. The proportion of C18:2 and its derivative C20:4 declines while the proportion of synthesized fatty acids increases as fat deposition proceeds thus a dilution effect is created (Wood and Enser, 1997; Wood *et al*., 2008). Similarly Lonergan *et al*. (2007) reported the simple correlation coefficients between intramuscular fat content and C14:0 (r=0.63), C16:0 (r=0.44), C16:1 (r =0.41) and C18:1 (r=0.52), C18:2 (r=-0.59) and C20:4 (r =-0.55). The results of the study showed that higher pH pigs contained less level of polyunsaturated fatty acid. However, the underlying mechanism(s) for this relationship is not clear.

In the case of flavor, it is particularly noted that consumers preferably marked greater scores for higher pH group, although statistical difference was observed only between low and high groups. This implies that high levels of polyunsaturated fatty acids for pigs with low fat content result in unfavorable flavor and that concurred with high level of TBARS.

Implications

Pigs with higher ultimate pH resulted in higher intramuscular fat content, lower level of unsaturated fatty acids, lower level of lipid oxidation and higher eating quality compared to those with lower ultimate pH. Some carcass traits and sensory characteristics did not differ between the low and medium pH groups, and between the medium and high pH groups, but the high pH group showed overall superior carcass and eating qualities and fat stability than the low pH group. The result of the present study implies that higher economic value of pigs can be characterized by a high ultimate pH and/or high intramuscular fat content. For the current population, breeds had a limited effects on meat quality traits, but the results are likely confounded by breed effects, On the other hand, it does not follow that high ultimate pH results in high intramuscular fat content and *vice versa*. Furthermore, pH threshold between groups was experimental comparisons and does not reflect pH window for meat quality.

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