

Pork Quality Traits According to Postmortem pH and Temperature in Berkshire

Tae Wan Kim, Chul Wook Kim, Mi Ra Yang, Gun Ryoung No, Sam Woong Kim*, and Il-Suk Kim*
*Swine Science and Technology Center, Gyeongnam National University of Science & Technology,
Jinju 52725, Korea*

Abstract

This study was performed to investigate the role of pH and temperature postmortem, and to demonstrate the importance of these factors in determining meat quality. Postmortem pH_{45min} (pH at 45 min postmortem or initial pH) via analysis of Pearson's correlation showed high positive correlation with pH change pH_{c24} (pH change from pH_{45min} to pH_{24h} postmortem). However, postmortem pH after 24 h (pH_{24h} or ultimate pH) had a high negative correlation with pH change, pH_{c24}, CIE L*, and protein content. Initial temperature postmortem (T_{1h}) was positively associated with a change in temperature from 45 min to 24 h postmortem (T_{c24}) and cooking loss, but negatively correlated with water holding capacity. Temperature at 24 h postmortem (T_{24h}) was negatively associated with T_{c24}. Collectively, these results indicate that higher initial pH was associated with higher pH_{c24}, T_{1h}, and T_{c24}. However, higher initial pH was associated with a reduction in carcass weight, backfat thickness, CIE a* and b*, water holding capacity, collagen and fat content, drip loss, and cooking loss as well as decreased shear force. In contrast, CIE a* and b*, drip loss, cooking loss, and shear force in higher ultimate pH was showed by a similar pattern to higher initial pH, whereas pH_{c24}, carcass weight, backfat thickness, water holding capacity, fat content, moisture content, protein content, T_{1h}, T_{24h}, and T_{c24} were exhibited by completely differential patterns ($p < 0.05$). Therefore, we suggest that initial pH, ultimate pH, and temperatures postmortem are important factors in determining the meat quality of pork.

Keywords: meat quality trait, Berkshire, pH_{45min}, pH_{24h}, pH change, temperature change

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Introduction

Consumption of meat has significantly increased due to the rise in income levels in developing countries. Specifically, pork consumption accounts for more than half of the meat consumption in many countries. In addition, consumers who prefer pork are changing their focus from pork quantity to quality. Thus, factors involved in improving meat quality will become increasingly important. Factors involved in pork quality include pH, color, tenderness, water holding capacity, and chemical composition. All of these factors are influenced by breed and heredity as well as processes involved in breeding, slaughter-

ing, meat processing, and storage (Pearce *et al.*, 2011; Tomovic *et al.*, 2014; Xu *et al.*, 2012). Since there is a direct connection between meat quality and consumer preference, which influences producers' economic gain, it is beneficial to produce high quality pork at lower cost (AMSA, 2012; Lindahl *et al.*, 2001).

Although several studies have noted the importance of pork quality (Gonzalez *et al.*, 2014; Miar *et al.*, 2014; Turyk *et al.*, 2014), the complexity resulting from the number of factors involved in quality has made it difficult to study. In other words, to date, there is no one-size-fits-all methodology to achieve high-quality pork that can be applied to the pork industry. Instead, meat quality is described by the sum of all meat quality characteristics, which are typically adjusted by the effects of muscle pH (Pearce *et al.*, 2011). The classification of pork quality is performed through visual observation by an expert who assesses the appearance, color, and postmortem ultimate pH (Prieto, 2007).

The muscle in a live pig maintains a neutral pH of 7.0 to 7.2. As the muscle is processed to meat, the processing methods result in incomplete oxidation because of the lack

†To whom correspondence should be addressed.

*Corresponding authors: Sam Woong Kim, Swine Science and Technology Center, Gyeongnam National University of Science & Technology, Jinju 52725, Korea. Tel: +82-55-751-3288, Fax: +82-55-751-3280, E-mail: swkim@gntech.ac.kr
Il-Suk Kim, Swine Science and Technology Center, Gyeongnam National University of Science & Technology, Jinju 52725, Korea. Tel: +82-55-751-3288, Fax: +82-55-751-3280, E-mail: iskim@gntech.ac.kr

of oxygen supply, and as a result, there is an accumulation of lactic acid in the muscle tissues (Pearce *et al.*, 2011). The accumulation of lactic acid results in acidification and a decrease in pH throughout this tissue. The rate at which the postmortem pH declines is an important determinant of meat color and water holding capacity (Tomovic *et al.*, 2014). Furthermore, water holding capacity determines both drip loss in raw pork and cooking loss during cooking procedures (Pearce *et al.*, 2011). PIC (2003) suggested that the preferred ranges for initial and ultimate pH were 6.3-6.7 and 5.7-6.1, respectively. Postmortem pH is generally measured within one hour of slaughter (initial pH or pH_{45min}) or at 24 h (ultimate pH or pH_{24h}). However, several studies have focused on differences in meat quality as it relates to pH changes in postmortem examinations of pork (Kauffman *et al.*, 1992; Lee *et al.*, 2000; Warner, 1994).

In this study, we examined the relationship between the initial and ultimate pH as well as the rate of pH change and how these factors affect Berkshire's meat quality postmortem. Furthermore, we examined *longissimus dorsi* muscles' postmortem temperature and change in temperature and the effect on meat quality characteristics. To do this, we considered three pH ranges from our data on pH_{45min} and pH_{24h} postmortem and examined the meat quality characteristics at each of these ranges.

Materials and Methods

Animals and tissue preparation

For this study, 391 6-mon-old Berkshire pigs (110±10 kg) were used (Cheonryeong-Pork Genetics, Korea). Pigs were fed for 6 mon by conventional diets in accordance with the Guide for the Care and Use of Laboratory Animals (Gyeongnam National University of Science and Technology Animal Care Committee). Pigs were stunned with electrical tongs (Stun-Tong EP, Germany, FREUND UK) after 12 h of feed restriction. The stunned pigs were exsanguinated while suspended. Carcasses were then placed in a dehairer at 62°C for 5 min, and remaining hair was removed using a knife and flame. Carcasses were eviscerated and split before being placed in a chiller set at 2-4°C for 12 h. After chilling, the *longissimus dorsi* muscle from each pig were collected, transferred into a refrigerated condition in a laboratory, and then examined for meat quality traits.

Analysis of meat quality characteristics

After the pigs were sacrificed, the carcasses were washed

with water and then weighed. Postmortem temperature of the *longissimus dorsi* muscle was measured at 1 and 24 h by a deep carcass thermometer (Delta Track Flash Link electronic logger, Model 20209, USA). To evaluate postmortem pH_{45min} and pH_{24h}, 10 g of samples were homogenized in 100 mL of distilled water for 30 s at 7,000 rpm with a homogenizer (Nihonseiki, Japan). The pH value of the homogenized sample was determined using a pH meter (Mteeler Delta 340, Mettler-tolede, Ltd., UK).

Backfat thickness was measured based on the backfat of the 10th rib region positioned at three-quarters distance along the *longissimus dorsi* muscle toward the belly. The meat color was recorded after 30 min blooming at 1°C using a Minolta Chromameter (CR400, Minolta, Japan). A light source of illuminant C (2° observer) was standardized to a standard white plate (L*+=97.83, a*=-0.43, b*+=1.98).

The water holding capacity was determined according to a previously described procedure (Kristensen and Purslow, 2001). Longissimus muscle samples (0.5±0.05 g) from each line were placed in centrifugation tube with filter units, heated for 20 min at 80°C, and then cooled for 10 min. Samples were centrifuged at 2,000 g for 10 min at 4°C and WHC was calculated as the change of sample weight. To evaluate drip loss, a slice of 2-cm thickness (weight 100±5 g) separated from the *longissimus dorsi* muscle was placed into a polypropylene bag (Dongbang Co., Korea), packaged by vacuum, and then stored for 24 h at 4°C. Drip loss was calculated by the difference in weight among samples. A slice of 3-cm thickness (weight 100±5 g) separated from the *longissimus dorsi* muscle for measurement of cooking loss was put into polypropylene bag (Dongbang Co., Korea), cooked for 40 min at 70°C in a water bath, and then cooled to room temperature (Cho *et al.*, 2015). Cooking loss was calculated by the difference in weight of the samples before and after boiling.

To evaluate shear force, a 3-cm-thick slice (weight 100±5 g) separated from the *longissimus dorsi* muscle was placed into a polypropylene bag, then cooked for 40 min at 70°C in a water bath, and then cooled for 30 min. The treated samples were separated into 1 × 2 × 1 cm³ (width × length × height) pieces. Maximum weight was measured utilizing a Shearing, Cutting Test on a Rheo meter (Model Compac-100, Sun Scientific Co., Japan) under the following operational conditions: table speed of 110 mm/sec, graph interval of 20 msec, and load cell (max) of 10 kg using the R.D.S (Rheology Data System) ver 2.01.

Analysis of chemical composition

The moisture, crude protein, and crude fat contents of the

longissimus dorsi muscle samples taken at 24 h post-slaughter were determined according to the methods of the Association of Official Agricultural Chemists (AOAC, 2000). Collagen content was measured as follows: 4 g of sample was put into triangular flask, 30 mL of sulfuric acid solution was added, and then sample was heated in a dry oven at 105°C for 16 h. Oxidant solution and color reagent were mixed, and then absorbance was measured by a spectrophotometer (Optizen-3220UV, Mecasys, Korea) at 558 nm. Collagen content (g/100 g) was calculated using a regression equation. A standard curve was obtained by absorbance measurements from a known working standard solution.

Data classification

The preferred ranges for initial and ultimate pHs were 6.3 to 6.7 and 5.7 to 6.1, respectively (PIC, 2003). Therefore, in this study, pH values were divided into three ranges as follows.

- pH value of *longissimus dorsi* muscle postmortem at 45 min: <6.3, 6.3-6.7, and >6.7
- pH value of *longissimus dorsi* muscle postmortem at 24 h: <5.7, 5.7-6.1, and >6.1

Statistical analysis

Descriptive statistics for the carcass and meat quality

traits were examined depending on the sex of the pig. Pearson's correlation coefficients were calculated between pH values (initial and ultimate values, and the rate of change between these values) and between postmortem temperatures (T_{1h} and T_{24h} values, and the rate of change between these values) and meat quality characteristics. Differences in meat quality at the three pH ranges (<6.3, 6. -6.7, and >6.7 for pH_{45min} , <5.7, 5.7-6.1, and >6.1 for pH_{24h}) were analyzed using analysis of variance (ANOVA). All variances in the model were considered fixed effects except residual effects, and the model was considered to be independent and normally distributed. As a post hoc test, Duncan's multiple range tests (MRT) were employed to verify significant differences ($p < 0.05$) in pH values and meat quality traits. All values are reported as mean with standard deviation (SD). All analyses were performed using the SAS statistical software package (version 9.1, SAS Inst., Inc., USA), with significance set at $p < 0.05$.

Results

Effect of postmortem pH and temperature on meat quality characteristics

To analyze the roles of temperature and pH changes post-mortem, we examined the relationship between these fac-

Table 1. Pearson's correlation coefficients between meat quality traits and postmortem pH values (n=391)

	pH_{45min}	pH_{24h}	pH_{c24}
pH_{45min} ¹⁾	1.0000		
pH_{24h}	0.0949	1.0000	
pH_{c24}	0.7949*	-0.5286*	1.0000
Carcass weight (kg)	-0.1444* ⁵⁾	0.1074*	-0.1886*
Backfat thickness (mm)	-0.1158*	0.2155*	-0.2301*
CIE L* ²⁾	-0.0558	-0.5553*	0.2908*
CIE a*	-0.2263*	-0.2387*	-0.0475
CIE b*	-0.4102*	-0.4561*	-0.0718
Water holding capacity	-0.2175*	0.1682*	-0.2880*
Collagen content (%)	-0.1382*	-0.0171	-0.1075*
Fat content (%)	-0.1105*	0.2260*	-0.2320*
Moisture content (%)	0.0889	0.1599*	-0.0216
Protein content (%)	-0.0066	-0.5266*	0.3153*
Drip loss (%)	-0.1628*	-0.4038*	0.1072*
Cooking loss (%)	-0.1637*	-0.2009*	-0.0171
Shear force (kg)	-0.3801*	-0.2626*	-0.1641*
T_{1h} (°C) ³⁾	0.2253*	0.0841	0.1409*
T_{24h} (°C)	0.1808*	-0.2550*	0.3095*
T_{c24} (°C) ⁴⁾	0.0667	0.2229*	-0.0789

¹⁾ pH_{45min} , pH_{24h} , and pH_{c24} are initial pH, ultimate pH, and difference between initial and ultimate pH, respectively.

²⁾CIE L*, a*, and b* represent the meat lightness, redness and yellowness, respectively.

³⁾ T_{1h} and T_{24h} indicate temperatures measured at 1 h and 24 h postmortem, respectively.

⁴⁾ T_{c24} is the changed value of temperature between T_{1h} and T_{24h} postmortem.

⁵⁾Superscript asterisk indicates significant correlations between the variables ($p < 0.05$).

tors and meat quality characteristics in postmortem pork. The results from our analysis indicated that postmortem $\text{pH}_{45\text{min}}$ was positively correlated with pH_{c24} , T_{1h} , and T_{24h} (Table 1). However, postmortem $\text{pH}_{45\text{min}}$ showed a negative correlation with carcass weight, backfat thickness, redness, yellowness, water holding capacity, collagen and fat contents, drip loss, cooking loss, and shear force. In contrast, we observed positive correlations of pH_{24h} with carcass weight, backfat thickness, water holding capacity, fat and moisture content, and temperature change. Postmortem pH_{24h} was a negatively correlated with pH_{c24} , lightness, redness, yellowness, protein content, drip loss, cooking loss, shear force, and T_{24h} . Postmortem pH_{c24} was positively correlated with lightness, protein content, drip loss, T_{1h} and T_{24h} , but negatively correlated with carcass weight, backfat thickness, water holding capacity, collagen and fat contents, and shear force ($p < 0.05$).

The postmortem temperature was associated with various meat quality characteristics (Table 2). Initial temperature showed a positive correlation with the ultimate temperature change (T_{c24}), redness, and fat content as well as drip and cooking loss, whereas T_{1h} showed a negative correlation with yellowness, water holding capacity, and protein content. The ultimate temperature (T_{24h}) postmortem was positively associated with lightness, moisture content, protein content, and drip loss, but it was negatively associated with temperature changes (T_{c24}), backfat thickness, redness, and water holding capacity as well as collagen and fat content. T_{c24} was positively correlated

with redness, fat content, and cooking loss, but negatively associated with yellowness, and water holding capacity as well as moisture and protein content ($p < 0.05$).

Meat quality characteristics within different pH ranges

To analyze meat quality characteristics based on initial pH, initial $\text{pH}_{45\text{min}}$ was divided into three ranges (Table 3). When higher initial pH and temperature postmortem were evaluated, we observed greater values of pH_{c24} . With $\text{pH}_{45\text{min}} > 6.7$ ($p < 0.05$), we observed a high postmortem temperature compared with temperatures in the other pH ranges (Table 3 and Fig. 1A). Furthermore, for T_{c24} with $\text{pH}_{45\text{min}} > 6.7$, there was a greater changes in temperature and pH ($p < 0.05$). However, the meat at a $\text{pH}_{45\text{min}} > 6.7$ was observed by the normal maintenance of ultimate pH, CIE L^* , and drip loss. Otherwise, the meat maintained higher lightness and protein content, but lower yellowness, water holding capacity, fat content, and shear force than those of the other ranges at $p < 0.05$ (Table 3).

The pork was also assessed according to three pH ranges for the ultimate pH postmortem (Table 4). When the ultimate pH was high, the $\text{pH}_{45\text{min}}$ was also high, whereas pH_{c24} was low (Fig. 1B). In addition, the higher the ultimate pH was, the greater was the magnitude of temperature change (Table 4 and Fig. 1B). Water holding capacity, fat content, and moisture content were higher in samples in the ultimate pH range of $\text{pH}_{24h} > 6.1$, whereas meat colors, protein content, drip loss, cooking loss, and shear

Table 2. Pearson's correlation coefficients between meat quality traits and temperature changes postmortem (n=391)

	T_{1h}	T_{24h}	T_{c24}
T_{1h} (°C) ¹⁾	1.0000		
T_{24h} (°C)	-0.0011	1.0000	
T_{c24} (°C) ²⁾	0.7893 ^{*4)}	-0.6149*	1.0000
Carcass weight (kg)	-0.0813	-0.0211	-0.0511
Backfat thickness (mm)	-0.0392	-0.1939*	0.0881
CIE L^* ³⁾	0.0300	0.1185*	-0.0491
CIE a^*	0.1096*	-0.2475*	0.2384*
CIE b^*	-0.3568*	-0.0673	-0.2401*
Water holding capacity	-0.5977*	-0.1357*	-0.3881*
Collagen content (%)	-0.0750	-0.1363*	0.0246
Fat content (%)	0.1068*	-0.3003*	0.2686*
Moisture content (%)	-0.0408	0.1694*	-0.1362*
Protein content (%)	-0.2950*	0.3117*	-0.4240*
Drip loss (%)	0.1770*	0.1070*	0.0739
Cooking loss (%)	0.5222*	-0.0504	0.4428*
Shear force (kg)	0.0569	-0.0554	0.0789

¹⁾ T_{1h} and T_{24h} indicate temperatures measured at 1 h and 24 h postmortem, respectively.

²⁾ T_{c24} is the changed value of temperature between T_{1h} and T_{24h} postmortem.

³⁾CIE L^* , a^* , and b^* represent the meat lightness, redness and yellowness, respectively.

⁴⁾Superscript asterisk indicates significant correlations between the variables ($p < 0.05$).

Table 3. Comparison of carcass, meat quality traits, and temperature according to 45min postmortem pH categories in Berkshire pork

pH _{45min} ranges	<6.3 (n=211)	6.3-6.7 (n=134)	>6.7 (n=46)
Carcass weight (kg)	85.98±5.50 ^{ab5)}	84.31±5.17 ^b	83.74±4.73 ^b
Backfat thickness (mm)	24.94±5.10 ^a	23.35±4.93 ^b	24.09±3.29 ^{ab}
pH _{45min} ¹⁾	6.10±0.16 ^c	6.44±0.10 ^b	6.84±0.12 ^a
pH _{24h}	5.84±0.19 ^b	5.89±0.24 ^a	5.86±0.18 ^b
pH _{c24}	0.26±0.24 ^c	0.55±0.25 ^b	0.99±0.23 ^a
CIE L* ²⁾	48.60±2.89 ^{ab}	48.09±2.84 ^b	49.15±2.55 ^a
CIE a*	6.32±1.06 ^a	5.87±0.91 ^b	6.11±1.05 ^{ab}
CIE b*	3.35±0.97 ^a	2.98±1.20 ^b	2.05±0.67 ^c
Water holding capacity	59.31±2.49 ^a	59.24±2.75 ^a	56.24±1.24 ^b
Collagen content (%)	0.90±0.14 ^a	0.89±0.12 ^a	0.84±0.12 ^b
Fat content (%)	2.90±1.25 ^a	2.75±1.10 ^{ab}	2.52±0.82 ^b
Moisture content (%)	75.45±0.92	75.62±0.78	75.55±0.61
Protein content (%)	23.88±0.79 ^{ab}	23.84±0.77 ^b	24.05±0.63 ^a
Drip loss (%)	4.32±1.66 ^a	3.76±1.68 ^b	4.06±1.68 ^{ab}
Cooking loss (%)	27.63±4.23	26.70±4.30	26.54±2.50
Shear force (kg)	2.92±0.62 ^a	2.64±0.55 ^b	2.38±0.50 ^c
T _{1h} (°C) ³⁾	36.40±4.17 ^b	36.95±4.46 ^b	40.38±1.00 ^a
T _{24h} (°C)	5.02±3.05 ^b	6.30±3.76 ^a	5.85±2.23 ^{ab}
T _{c24} (°C) ⁴⁾	31.38±5.50 ^b	30.65±5.53 ^b	34.52±2.11 ^a

¹⁾pH_{45min}, pH_{24h}, and pH_{c24} are initial pH, ultimate pH, and difference between initial and ultimate pH, respectively.

²⁾CIE L*, a*, and b* represent the meat lightness, redness and yellowness, respectively.

³⁾T_{1h} and T_{24h} indicate temperatures measured at 1 h and 24 h postmortem, respectively.

⁴⁾T_{c24} is the changed value of temperature between T_{1h} and T_{24h} postmortem.

⁵⁾Significant differences between the variables are indicated with different superscript lowercase letters according to Duncan's test ($p < 0.05$).

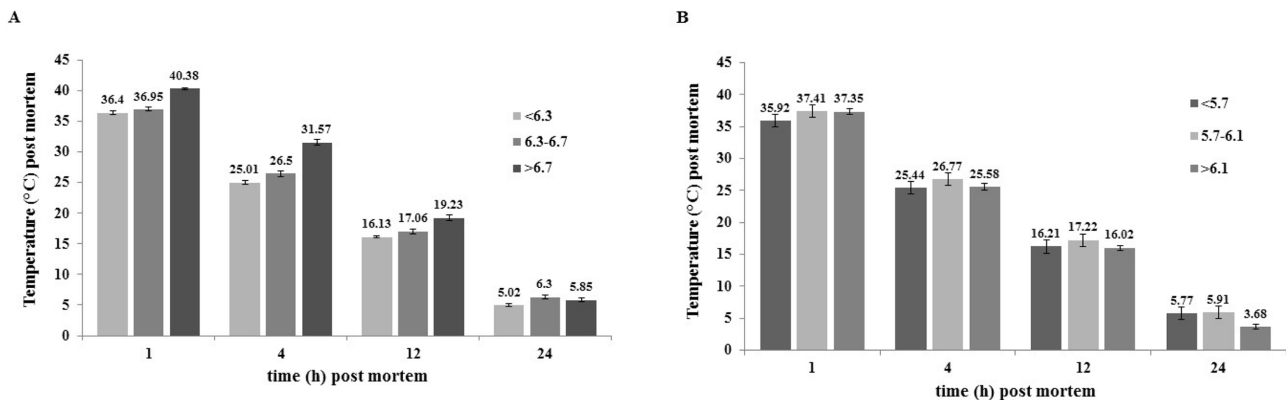


Fig. 1. Changes of temperature values in the different ranges of postmortem pH_{45min} (A) and pH_{24h} (B). Each temperature change depending on time postmortem was drawn by a bar graph. X- and Y-axes indicate temperature and time postmortem, respectively.

force were reduced in these samples ($p < 0.05$). Specifically, drip loss was lowest at a pH_{24h} >6.1 and the highest at a pH_{24h} <5.7 ($p < 0.05$), suggesting a loss in meat juiciness with a change in the ultimate pH. At the intermediate ranges for ultimate pH (5.7 pH 6.1), a preferred range among consumers, we observed the highest T_{1h} and T_{24h}, but T_{c24} had the intermediated change at this pH range.

Discussion

The change in initial temperature postmortem is an important factor in the meat industry (Rybarczyk *et al.*, 2015; Salmi *et al.*, 2012). There is a high possibility that an initial low pH and a high temperature are likely responsible for heat shortening (Hamoen *et al.*, 2013; Thompson, 2002). A lower pH owing to lactic acid causes an increased

Table 4. Comparison of carcass, meat quality traits, and temperature according to 24h postmortem pH categories in Berkshire pork

pH _{24h} ranges	<5.7 (n=90)	5.7-6.1 (n=245)	>6.1 (n=56)
Carcass weight (kg)	84.86±4.97	85.03±5.32	86.09±6.17
Backfat thickness (mm)	23.02±4.87 ^{c5)}	24.35±4.91 ^b	26.09±4.42 ^a
pH _{45min} ¹⁾	6.26±0.26 ^b	6.30±0.31 ^b	6.36±0.24 ^a
pH _{24h}	5.62±0.06 ^c	5.85±0.11 ^b	6.23±0.13 ^a
pH _{c24}	0.64±0.26 ^a	0.45±0.33 ^b	0.12±0.27 ^c
CIE L* ²⁾	50.12±2.35 ^a	48.52±2.59 ^b	45.74±2.60 ^c
CIE a*	6.47±1.04 ^a	6.12±1.01 ^b	5.71±0.92 ^c
CIE b*	3.87±1.06 ^a	2.95±1.00 ^b	2.32±0.80 ^c
Water holding capacity	58.71±2.50 ^b	58.71±2.62 ^b	60.16±2.77 ^a
Collagen content (%)	0.89±0.13	0.89±0.13	0.88±0.13
Fat content (%)	2.57±1.02 ^b	2.76±1.18 ^b	3.39±1.09 ^a
Moisture content (%)	75.30±0.79 ^b	75.56±0.84 ^a	75.69±0.87 ^a
Protein content (%)	24.37±0.65 ^a	23.87±0.70 ^b	23.16±0.58 ^c
Drip loss (%)	4.72±1.96 ^a	4.17±1.50 ^b	2.81±1.24 ^c
Cooking loss (%)	27.28±4.91 ^a	27.60±3.73 ^a	25.21±3.77 ^b
Shear force (kg)	2.86±0.58 ^a	2.81±0.62 ^a	2.37±0.51 ^b
T _{1h} (°C) ³⁾	35.92±4.88 ^b	37.41±4.07 ^a	37.35±3.38 ^a
T _{24h} (°C)	5.77±2.41 ^a	5.91±3.59 ^a	3.68±2.37 ^b
T _{c24} (°C) ⁴⁾	30.15±5.92 ^b	31.50±5.27 ^b	33.67±3.90 ^a

¹⁾pH_{45min}, pH_{24h}, and pH_{c24} are initial pH, ultimate pH, and difference between initial and ultimate pH, respectively.

²⁾CIE L*, a*, and b* represent the meat lightness, redness and yellowness, respectively.

³⁾T_{1h} and T_{24h} indicate temperatures measured at 1 h and 24 h postmortem, respectively.

⁴⁾T_{c24} is the changed value of temperature between T_{1h} and T_{24h} postmortem.

⁵⁾Significant differences between the phenotype classes are indicated with different superscript lowercase letters according to Duncan's test ($p < 0.05$).

protein denaturation within the meat, resulting in high drip loss and low water holding capacity (Vermeulen *et al.*, 2015). Interestingly, water holding capacity in this study was negatively correlated with initial pH and pH change, but positively associated with ultimate pH (Table 1). Furthermore, postmortem pH_{24h} is negative correlations with drip loss or lightness (Chmiel *et al.*, 2014; Kapper, 2012). Since lower postmortem pH results in the higher meat color values of more damaged meat, postmortem pH in this study was also negatively associated with meat colors (Table 1). Otherwise, a higher protein content results in meat of a lower pH_{24h} value (Kuo and Chu, 2003; van de Perre *et al.*, 2010). Postmortem pH_{24h} value in this study also exhibited high negative correlation with protein content (Table 1).

Initial high temperature and low pH postmortem are known to induce PSE (pale, soft, and exudative) meat (Tomovic *et al.*, 2013; Traore *et al.*, 2012). However, in the case of a loss of glycogen due to long-term stress, the pork is unable to produce lactic acid and instead demonstrates characteristics termed DFD (dark, firm, and dry) which maintain a high ultimate pH (Dokmanovic *et al.*, 2014). The higher rigor temperature causes the more drip loss, but less water holding capacity (Bekhit *et al.*, 2007).

Although the pH_{45min} > 6.7 in this study maintained the highest temperature, relative higher drip loss, and the lowest water holding capacity (Table 2 and 3), the meat is included in normal meat range. Therefore, we suggest that the meat causes more water loss owing to lower protein solubilities from high initial temperature. Otherwise, although meat at a pH_{45min} > 6.7 had high initial temperature (Fig. 1), the meat had lower backfat thickness and fat content than the meats observed at a pH_{45min} < 6.3, and higher protein content than at pH_{45min} < 6.3, which were associated with rapid temperature decline and with the more heat generation, respectively. Collectively these data suggest that the meat showing pH_{45min} > 6.7 did not display DFD owing to decrease in the balanced temperature but maintained as normal meat. In the intermediate range for initial pH (6.3 pH 6.7), a range is preferred by consumers (Kauffman *et al.*, 1992; Lee *et al.*, 2000; Warner, 1994), the highest value of T_{24h} was observed when compared with temperatures measured at all other ranges. However, T_{c24} at 6.3 pH 6.7 was the lowest value when compared with the T_{c24} at the other pH ranges (Table 3).

The ultimate pH is linearly related with water holding capacity or drip loss (Josell *et al.*, 2003), but not related with temperature (Hamoen *et al.*, 2013). For the ultimate

pH>6.0 the drip loss is constant and minimal, but the meat is cold shortened and tough (Fernandez *et al.*, 1994). Although the meat at pH_{24h}>6.1 maintained the lowest drip loss and shear force (Table 4 and Fig. 1B), the meat maintained RFN (reddish pink, firm, non exudative) meat via lightness and drip loss references (Dokmanovic *et al.*, 2014). It is assumed that the meat maintains normal state owing to the balanced component contents between lower protein and fat contents and higher glycogen contents, which are associated with the increased and decreased water holding capacities, or the decreased and increased heat production, respectively. In general, since intramuscular fat is associated with juiciness and flavor (Warner *et al.*, 2010), we suggest that fat content are also involved in meat quality via regulation of water holding capacity or drip loss.

The higher values of lightness, redness, and yellowness are caused by higher content of oxymyoglobin, which this pattern appears well in PSE meat than RFN meat (Karamucki *et al.*, 2013). The pH_{24h}<5.7 in this study was observed by the highest color values, but included in normal meat range. Therefore, it is suggested that the meat suffers more damage than those of the others, but do not progresses to PSE. In summary, these findings suggest that the initial and ultimate pH values as well as the temperature all play critical roles in determining and maintaining pork quality.

Conclusions

The initial temperature postmortem was positively associated with T_{c24}, but the ultimate T_{24h} was negatively associated with T_{c24}. Higher initial pH resulted in higher pH_{c24}, T_{1h}, and T_{c24}. By contrast, higher ultimate pH resulted in higher pH_{45min} and T_{c24}, but lower pH_{c24}.

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