Korean J. Food Sci. An. Vol. 36, No. 5, pp. 641~649 (2016)

DOI http://dx.doi.org/10.5851/kosfa.2016.36.5.641
ISSN 1225-8563 eISSN 2234-246X

ARTICLE

Meat Quality and Physicochemical Trait Assessments of *Berkshire* and Commercial 3-way Crossbred Pigs

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Abstract

In this study, we compared qualities and physiochemical traits of meat from *Berkshire* (black color) pigs with those of meat from 3-way *Landrace* (white color) × *Yorkshire* (white color) × *Duroc* (red color) crossbred pigs (*LYD*). Meat quality characteristics, including pH, color, drip loss, cooking loss, and free amino acid, fatty acid, vitamin, and mineral contents of *longissimus dorsi* muscles, were compared. Meat from *Berkshire* pigs had deeper meat color (redness), higher pH, and lower drip loss and cooking loss than meat from *LYD* pigs. Moreover, meat from *Berkshire* pigs had higher levels of phosphoserine, aspartic acid, threonine, serine, asparagine, α-aminoadipic acid, valine, methionine, isoleucine, leucine, tyrosine, histidine, tryptophan, and carnosine and lower levels of glutamic acid, glycine, alanine, and ammonia than did meat from *LYD* pigs. The fatty acids oleic acid, docosahexaenoic acid (DHA), and monounsaturated fatty acids (MUFA) were present in significantly higher concentrations in *Berkshire* muscles than they were in *LYD* muscles. Additionally, *Berkshire* muscles were significantly enriched with nucleotide components (inosine), minerals (Mg and K), and antioxidant vitamins such as ascorbic acid (C) in comparison with *LYD* muscles. In conclusion, our results show that in comparison with *LYD* meat, *Berkshire* meat has better meat quality traits and is a superior nutritional source of all essential amino acids, monounsaturated fatty acids, vitamin C, and minerals (Mg and K).

Keywords: meat quality, physicochemical traits, *Berkshire*, *LYD*, pork

Received June 28, 2016; Revised August 31, 2016; Accepted September 4, 2016

Introduction

Pigs have been a prominent domesticated animal source of food for about 9,000 years, and 30-40 domesticated pig species have been bred (Rothschild and Ruvinsky, 2010). Pork remains the most highly consumed meat in the world and contains high quantities of complete proteins, essential nutrients, minerals, vitamins, and fats. South Korea is one of the highest pork-consuming countries in the world (Choe *et al*., 2015), and the pig industry is under corresponding pressure to satisfy consumer demands for high-quality pork products (Oh and See, 2012). Meat quality has become increasingly important economically and is affected by factors such as breed, sex, species, genetic background, nutrition, age, finishing weight, slaughter management, muscle type, and storage time (Gjerlaug-Enger, 2010; Muhlisin *et al*., 2014). Hence, various techniques have been developed to improve pork quality characteristics in sensory panel assessments, and some researchers suggest that breed pig stock strongly influences the quality of meat and success or failure in the pig industry and has a greater effect on eating quality than sex or finish weight (Magowan *et al*., 2011).

Visual assessments of meat quality are based on color, marbling, water-holding capacity (WHC), drip loss, and purge loss. Meat that has an attractive bright red color and low visible fat is appealing for consumers. However, meat quality indicators, such as drip loss, cooking loss, WHC, Warner-Bratzler Shear Force (WBSF), and fatty acid composition, vary between pig breeds. Specifically, *Landrace* pigs have higher scores for flavor and taste and lower drip loss than *Pietrain* pigs (Magowan *et al*., 2011).

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Moreover, cross breeds of *Duroc* × *Landrace* and *Large White* × *Landrace* (*LYD*) pigs produced meat with lower cooking loss and drip loss, leading to higher quality than that from purebred *Landrace* pigs (Poldvere *et al*., 2015). Intense meat color and lower drip loss were also observed in *Duroc* pigs when compared to those in *Yorkshire* and *LYD* pigs (Choi *et al*., 2014; Li *et al*., 2013). In addition, Suzuki *et al*. (2003) showed that variations in fatty acid composition affect meat quality, and fatty acid contents were higher in *Duroc* pigs than they were in *Berkshire* pigs, thus *Duroc* producing greater meat quality than *Berkshire*. However, coat hair color (black, white, red, white spots in black, black spots in white, and black spots in red coats) was not significantly associated with meat quality (Choi *et al*., 2014). *Berkshire* pigs have black glossy hair color, short necks, and erect ears, whereas *LYD* pigs have white coats. Although *LYD* pigs and are mainly used for commercial pork production (Nelson and Robison, 1976), differences in meat quality traits between *Berkshire* and *LYD* pigs (Suzuki *et al*., 2003) remain poorly characterized. In the present study, we evaluated differences in meat quality parameters, nucleotide related compounds, vitamins, minerals, free amino acids, and fatty acid composition, and compared these between the pig genotypes *Berkshire* and *LYD*.

Material and Methods

Animals and sampling

A total of 30 pigs were maintained under identical conditions, and included 1) 15 *Berkshire* breed pigs with an average age of 185 ± 10 d and 2) 15 three-way crossbred (*Landrace* × *Yorkshire* × *Duroc; LYD*) pigs with an average age of 175 ± 5 d. Pigs were fed commercial feed according to the regimens of Purina Ltd. Pigs were conventionally slaughtered at the marketing weight of 115 ± 7 kg, and the *longissimus dorsi* muscles were excised at 24 h post-mortem. Meat quality traits were analyzed immediately thereafter, and the remaining samples were separated into 2 parts and were powdered using liquid nitrogen for analyses of nucleotides and free amino-acids, and freeze dried for fatty acids, vitamins, and minerals. All samples were stored at -70°C until further analysis.

Meat quality

The pH values of *longissimus dorsi* muscles were recorded 24 h post-mortem using a portable pH meter (Horiba 6252-10D, USA) held directly in the muscle. Three color (L*, a*, b*) coordinate measurements were performed at three different locations on bloomed cut surfaces of meat sample blocks using D65 illuminant and 10° observations via a film lid using a Konica Minolta spectrophotometer (CM-2500d; UK). Color was expressed according to the Commission International de l'Eclairage (CIE) system and was reported as CIE L* (lightness), a* (redness), and b* (yellowness). We assessed water holding capacity (WHC) according to drip loss, filter paper fluid uptake, and cooking loss as described by Zhuang *et al*. (2012). Drip loss was measured using the gravimetric method described by Honikel (1998). Briefly, samples (20 × 20 × 20 mm) were trimmed and weighed before placement in an inflated plastic bag and were then hung for 48 h at 4°C. Subsequently, samples were weighed and drip loss was calculated as percentage change in hanging weight. Filter paper fluid uptake was measured as described by Kauffman *et al*. (1986). Initially, meat samples were exposed to air for 15 min and a filter paper of known weight was placed in contact with the meat sample for 2 s. Water contents were then determined according to weight changes of the filter paper from before to after contact with the meat. Cooking loss was determined as described by Honikel (1998). Samples (20 × 20 × 10 mm) were weighed and placed in a plastic bag in an 80°C water bath until the internal temperature reached 75°C. Subsequently, samples were cooled and weighed again and percentage change in weight was recorded as cooking loss. To determine Warner-Bratzler shear force (WBSF), three representative 1.27 cm diameter cores were taken parallel to the muscle fiber from approximately 300-g meat sample steaks after cooling. Shear force values were then determined using a Warner-Bratzler shear attachment with an Instron universal testing machine (Model 3342; Instron Corporation, USA) at a load cell of 50 kg and a crosshead speed of 200 mm/min. Core samples were sheared once across the center of the core perpendicular to the muscle fiber. Shear force values were calculated as the mean of the maximum forces required to shear each set of core samples and were expressed as kg of force (kgf).

Measurements of nucleotides and their degradation products

Inosine, adenosine monophosphate (AMP), guanosine monophosphate (GMP), and adenosine diphosphate (ADP) nucleotide contents were determined using High-performance liquid chromatography (HPLC). Briefly, 0.3-g meat samples were frozen and ground in liquid nitrogen using a mortar and pestle, and tissue powders were then incubated in 5 mL of ice cold 0.5 M perchloric acid for 15 min. Extracts were centrifuged at 9,200×g for 5 min at 4°C, and 2.1 M $KHCO_3$ was added to 1 mL aliquots of supernatant and incubated for 10 min on ice, followed by centrifugation at 9,200×g for 5 min at 4°C. Supernatants were collected and filtered through 0.45-μm syringe filters and were analyzed using a Shiseido Nanospace SI-2 (Shiseido Co., Ltd. Japan) HPLC instrument. Samples in HPLC vials (5 μL) were placed into an auto-sampler and passed through a Cadenza CD-C18 (4.6 × 250 mm, 3 μm column; Imtakt Corp., USA) column at 40°C and were eluted with mobile phase A comprising 1% phosphoric acid (H_3PO_4) and 5% tert-butyl ammonium hydroxide in water and then mobile phase B comprising 1% phosphoric acid (H_3PO_4) and 5% tert-butyl ammonium hydroxide in methanol.

Measurements of free amino acid contents

Free amino acid contents were determined using an amino acid auto-analyzer (S4300 amino acid analyzer, Sycam, Germany) with an S7130 auto-sampler (Sycam) and an S2100 solvent delivery system (Sycam). In these analyses, 1 g of freeze dried sample was microwaved in 20 mL of 75% ethanol for 15 min. The extract was then filtered using a glass filter with a vacuum pump and 20 mL of 75% ethanol was added and the sample was microwaved again for 15 min. After filtration into a round flask, the ethanol was evaporated to dryness at 45°C and the sample was lysed in dilution buffer and filtered using syringe filters. The sample was then injected into an auto-amino acid analyzer S7130 auto-sampler with a S2100 solvent delivery system (Sycam, Germany) and eluted through a cation separation column (LCA K06/NA; 4.6 × 250 mm) using mobile phase and ninhydrin flows of 0.45 and 0.4 mL/min respectively.

Measurements of fatty acids

Fatty acid contents were determined using gas chromatography (GC). In these analyses, 0.5 g of powdered fat samples was added to glass tubes containing 2 mL of boron-trifluoride and 2 mL of methanol. Teflon-lined caps were then placed on tubes to prevent evaporation, and the mixtures were incubated at 80°C for 2 h with vortexing after 10 min and then every 5 min thereafter. Samples were immediately cooled to room temperature and 3 mL of distilled water and 3 mL of hexane were added, and the samples were vortexed for 15 s followed by centrifugation at 2,000 rpm for 5 min. The supernatants were collected and transferred to GC vials and analyzed using a Shimadzu GC-2014 instrument (Shimadzu Co., USA) with a FAME-WAX column (30 m × 0.32 mm i. d., 0.25 μm; column temperature, 250°C). Nitrogen/air was used as a carrier gas at 53.8 mL/min (split ration 30:1). The GC start temperature was 150°C and was increased to 250°C with a 3-min equilibration time.

Measurements of vitamin contents

Vitamin contents were measured using liquid chromatography mass spectrometry (LC/MS/MS). Briefly, 10 mg of freeze-dried meat powder samples were sonicated in 100 μL of distilled water, and 900 μL of methanol was added and the samples were vortexed. Mixtures were then sonicated and centrifuged, and the supernatants were analyzed using a UPLC system (Waters Xevo TQ-S, Waters Corporation, USA) with a Waters ACQUITY UPLC ®BEH C18 (2.1 × 100 mm, 1.7 μm) column. Water soluble vitamins were eluted using 0.1% formic acid in distilled water (buffer A) and 0.1% formic acid in acetonitrile (ACN; buffer B). Fat soluble vitamins were eluted in 0.1% formic acid in distilled water (buffer A) and 0.1% formic acid in methanol/ACN (40/60, v/v; buffer B). Water soluble vitamins were eluted with a gradient of 0% buffer B (0-0.5 min), 0% buffer B linear gradient (0.5-4.5 min), 100% buffer B (4.5-5 min), 100% buffer B linear gradient (5-6 min), and 0% buffer B (6-10 min). Fat soluble vitamins were gradient eluted as follows: 100% buffer B (0-0.5 min), 100% buffer B linear gradient (0.5-4.0 min), 50% buffer B (4.0-4.5 min), 50% buffer B linear gradient (4.5-6.0 min), and 100% buffer B (6.0-10.0 min). Results from multiple reaction monitoring (MRM) of water/fat soluble vitamins are presented in Table 1.

Table 1. MRM conditions of LC/MS/MS analyses of vitamins

Compound	Pol.	Parent ion	Daughter ion	Frag	CID
Riboflavin (B2)	ESI+	377.1	244	110	25
Vitamin B6-B	ESI+	169	152.0	70	10
Vitamin B6-C	ESI+	170	151.9	50	10
Ascorbic acid (C)	ESI+	176.9	140.8	50	5
Retinol (A)	API+	285.24	105.05	4	34

MRM, multiple reaction monitoring; Pol., polarity; CID, collision induced dissociation; ESI, electrospray ionization; API, atmospheric pressure ionization.

Table 2. Meat quality of *longissimus dorsi* muscles from *Berkshire* and crossbred (*LYD*) pigs

	Berkshire (n=15)	*LYD* (n=15)
pH (24 h)	5.74±0.04[a]	5.59±0.06[b]
Color		
CIE L* (Lightness)	49.86±0.56[b]	54.93±0.91[a]
CIE a* (Redness)	15.78±0.24[a]	14.27±0.39[b]
CIE b* (Yellowness)	4.32±0.21[b]	5.43±0.35[a]
Filter paper fluid uptake (mg)	71.82±4.47[a]	53.06±7.27[b]
Drip loss (%)	2.08±0.39	3.40±0.64
Cooking loss (%)	12.04±0.62[b]	20.03±1.01[a]
Shearing force (N)	2.47±0.15	2.54±0.25
NPPC color	3.47±0.11[a]	2.91±0.19[b]
NPPC marbling	1.93±0.16	2.08±0.25

LYD, Landrace × Yorkshire × Duroc.
Data are presented as means±SE. Values in rows differ significantly (p<0.05).

Measurements of mineral contents

Mineral contents were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) and phosphate contents were analyzed using an assay kit (DIPI-500, BioAssay systems, USA) according to the manufacturer's protocol. Prior to use of ICP-MS and phosphate assay kits, 0.05-g samples were incubated with 600 μL of 70% nitric acid in conical tubes for 2 d, and were then incubated at 80°C for 5 h. Samples were then adjusted to 10 ml using distilled water and were serially diluted from 10 to 10,000 times with 2% nitric acid prior to analysis. The minerals Na, Mg, K, Ca, Fe, Cu, and Zn were measured using ICP-MS (Agilent 7500a, USA) with the following parameters: RF power, 1250 W; outer gas flow rate, 15 L/min; intermediate gas flow rate, 0.9 L/min; nebulizer gas flow rate, 0.7 L/min; carrier gas flow rate, 0.4 L/min; sampling depth, 7.0 mm; nickel sampler/skimmer orifices with diameter of 1.0 mm/0.4 mm; dwell time, 30 ms; sample volume, 3-5 μL.

Statistical analysis

Statistical analyses were performed using SAS software (Version 9.0, USA). Data are presented as means ± standard errors of the mean (SE). Differences were identified using t-tests and were considered significant when p<0.05.

Results

Meat quality parameters

Differences in the meat quality traits of pH, color (L*, a*, b*), WHC, cooking loss, drip loss, WBSF, and marbling scores between *Berkshire* and *LYD* pigs are summarized in Table 2. Muscles from *LYD* pigs had significantly lower color a*, pH, filter paper fluid uptake, and National Pork Producers Council (NPPC) color, and had significantly higher cooking loss than meat from *Berkshire* pigs. No significant differences in drip loss, WBSF, or NPPC marbling were identified between groups.

Table 3. Nucleic acid-related compounds (ppm) in *longissimus dorsi* muscles from *Berkshire* and *LYD* pigs

	Berkshire (n=15)	*LYD* (n=15)
Inosine	40.23±2.73[a]	27.54±4.73[b]
AMP	0.94±0.30	-
GMP	-	0.24±0.22
ADP	28.80±1.19	25.27±1.68

LYD, Landrace × Yorkshire × Duroc.
Data are presented as means±SE. Values in rows differ significantly (p<0.05).

Nucleotides and their degradation products

Nucleic acid related compounds from porcine *longissimus dorsi* muscles of experimental animals are listed in Table 3. Inosine and AMP concentrations were significantly higher in meat from *Berkshire* pigs than in meat from *LYD* pigs, whereas GMP concentrations were significantly lower, and ADP concentrations did not differ between the two groups.

Free amino acids

Analyses of free amino acids levels (Table 4) showed higher phosphoserine, aspartic acid, threonine, serine, asparagine, α-aminoadipic acid, valine, methionine, isoleucine, leucine, tyrosine, phenylalanine, histidine, tryptophan, and carnosine levels in *Berkshire* than in *LYD* meats. However, muscles from *LYD* animals had higher levels of glutamic acid, glycine, alanine, ornithine, and ammonia than those from *Berkshire* pigs. No significant differences in taurine, citrulline, cysteine, β-alanine, r-aminobutyric acid, 3-methylhistidine, lysine, or arginine levels were identified between *Berkshire* and *LYD* pigs. These amino acids are associated with flavor development in taste tests. Taken together, these amino acid analyses indicate that muscles from *Berkshire* are highly enriched in all essential amino acids, suggesting that *Berkshire* meats have higher nutritional value than *LYD* meats.

Fatty acid composition

Analyses of fatty acid levels in porcine *longissimus dorsi* muscles from *Berkshire* and *LYD* pigs (Table 5)

Table 4. Free amino acid composition (% of total free amino acids) of *longissimus dorsi* muscles from *Berkshire* and *LYD* pigs

	Berkshire (n=15)	*LYD* (n=15)
Phosphoserine	0.28±0.01[a]	0.24±0.01[b]
Taurine	9.74±0.29	10.29±0.42
Aspartic Acid	4.46±0.11[a]	1.59±0.17[b]
Threonine	3.36±0.06[a]	3.05±0.09[b]
Serine	3.84±0.12[a]	3.34±0.15[b]
Asparagine	4.68±0.18[a]	3.81±0.57[b]
Glutamic Acid	9.74±0.50[b]	13.91±0.71[a]
α-Aminoadipic	1.61±0.16[a]	0.77±0.26[b]
Glycine	15.28±0.23[b]	17.85±0.32[a]
Alanine	12.86±0.28[b]	16.64±0.40[a]
Citrulline	0.97±0.08	1.11±0.10
Valine	3.01±0.06[a]	2.09±0.08[b]
Cystine	0.09±0.01	0.1±0.01
Methionine	1.75±0.05[a]	1.35±0.07[b]
Isoleucine	1.76±0.04[a]	1.11±0.06[b]
Leucine	4.42±0.11[a]	2.90±0.15[b]
Tyrosine	2.66±0.06[a]	1.78±0.09[b]
Phenylalanine	2.48±0.07[a]	1.92±0.10[b]
β-Alanine	0.17±0.01	0.15±0.01
r-Aminobutyric	0.18±0.01	0.17±0.01
Histidine	1.19±0.03[a]	0.96±0.04[b]
3-Methylhistidine	0.10±0.004	0.09±0.01
Tryptophan	6.37±0.25[a]	4.41±0.35[b]
Carnosine	0.51±0.05[a]	0.29±0.08[b]
Ornithine	0.17±0.02[b]	0.55±0.030[a]
Lysine	1.56±0.03	1.67±0.04
Ammonia	6.61±0.35[b]	7.95±0.49[a]
Arginine	0.94±0.03	0.99±0.04

LYD, Landrace × Yorkshire × Duroc.
Data are presented as means±SE. Values in rows differ significantly (p<0.05).

showed significantly greater oleic acid (C18:1n9c), docosahexaenoic acid (C22:6n3), and MUFA contents in *Berkshire* than in *LYD* meats, although significantly lower levels of stearic acid (C18:0) were observed. No significant differences in saturated fatty acid (SFA), polyunsaturated fatty acid (PUFA), or unsaturated fatty acid (UFA) levels were identified between the groups.

Vitamins and minerals

Concentrations of the water soluble vitamin ascorbic acid were significantly higher in *Berkshire* than in *LYD* meats (Table 6). However, riboflavin, vitamin B6, and retinol levels did not differ significantly between the pig groups. Mineral analyses in porcine *longissimus dorsi* muscles (Table 7) showed significantly higher Mg and K levels in muscles from *Berkshire* than in those from *LYD*

Table 5. Fatty acid compositions (% of total fatty acids) of *longissimus dorsi* muscles from *Berkshire* and *LYD* pigs

	Berkshire (n=15)	*LYD* (n=15)
C12:0	0.15±0.04	0.11±0.05
C14:0	2.35±0.61	1.76±0.85
C16:0	26.87±1.36	29.61±1.85
C16:1	6.25±1.48	3.14±2.02
C18:0	11.97±0.76[b]	15.21±1.01[a]
C18:1n9c	43.74±1.51[a]	38.06±2.09[b]
C18:2n6c	12.88±0.53	12.69±0.75
C18:3n6	0.13±0.02	0.10±0.03
C18:3n3	1.06±0.56	0.47±0.75
C20:5n3	0.07±1.22	2.34±1.46
C22:6n3	0.08±0.01[a]	0.06±0.01[b]
SFA	39.59±2.09	46.69±2.90
MUFA	46.76±2.05[a]	38.67±2.85[b]
PUFA	13.63±1.05	14.64±1.46
UFA	60.39±2.08	53.31±2.90

LYD, Landrace × Yorkshire × Duroc; SFA, saturated fatty acid; MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid; UFA, unsaturated fatty acid.
Data are presented as means±SE. Values in rows differ significantly (p<0.05).

Table 6. Vitamins in *longissimus dorsi* muscles from *Berkshire* and *LYD* pigs

	Berkshire (n=15)	*LYD* (n=15)
Soluble vitamin (mg/100 g)		
Riboflavin (B2)	0.14±0.01	0.18±0.02
Vitamin B6-B	0.002±0.0002	0.002±0.0002
Vitamin B6-C	0.006±0.001	0.006±0.001
Ascorbic acid (C)	0.17±.0.01[a]	0.07±0.03[b]
Fat soluble vitamin (mg/100 g)		
Retinol (A)	0.29±0.02	0.37±0.03

LYD, Landrace × Yorkshire × Duroc.
Data are presented as means±SE. Values in rows differ significantly (p<0.05).

Table 7. Inorganic substances (mg/100 g) in *longissimus dorsi* muscles from *Berkshire* and *LYD* pigs

Inorganic substance	*Berkshire* (n=15)	*LYD* (n=15)
Na	148.04±3.81[b]	179.99±5.30[a]
Mg	102.92±1.12[a]	92.96±1.56[b]
K	1702.84±30.78[a]	1573.88±42.80[b]
Ca	1.50±0.02	1.53±0.03
Mn	0.03±0.001	0.03±.001
Fe	2.68±0.15	2.99±0.21
Cu	0.36±0.01[b]	0.48±0.02[a]
Zn	6.71±0.62[b]	11.55±0.86[a]
P	0.10±0.01[b]	0.14±0.01[a]

LYD, Landrace × Yorkshire × Duroc.
Data are presented as means±SE. Values in rows differ significantly (p<0.05).

animals. However, Na, Cu, Zn, and P levels were significantly higher in muscles from *LYD* pigs than in those from *Berkshire* pigs, and Ca, Mn, and Fe levels did not differ significantly between the groups.

Discussion

Meat quality parameters

The present comparisons of meat qualities between *Berkshire* and *LYD* pigs showed profound differences in pH, color, filter paper fluid uptake, drip loss, cooking loss, and shearing force. Similarly, breed played a crucial role in meat quality in previous comparisons, and *Duroc* pigs had better meat quality in terms of color, higher pH, more marbling, and less drip loss than *Yorkshire* and *Landrace* pigs (Mandell *et al*., 2006). In agreement, muscles from *Duroc* pigs reportedly had more color, were more palatable, and had greater tenderness and flavor than those from *Landrace* and *Large White* pigs and the cross of these two breeds (Jeremiah *et al*., 1999). Moreover, Channon *et al*. (2004) suggested that meat from *Duroc* pigs had lower drip loss, shear force, and hardness than meat from *Large White* pigs and cross breeds of *Duroc* and *Large White* pigs. However, a contradictory study demonstrated that meat from *Duroc* pigs was tougher, and was less acceptable than meat from *Landrace* pigs (Cameron *et al*., 1999). Muscles from *Berkshire* pigs reportedly had lower drip loss, cooking loss, and higher intramuscular fat and fatty acid contents than *Duroc* meat, indicating higher eating quality (Suzuki *et al*., 2003). However, in our study, higher pH (5.74) and lower drip loss, cooking loss, and shear force were observed in *longissimus dorsi* muscles from *Berkshire* pigs than in those from *LYD* pigs. Taken together, the present data demonstrate that *Berkshire* muscles have overall better meat quality than *LYD* muscles. In accordance, Kim *et al*. (2013) showed that meat from *Duroc* had the highest qualities, with lower drip loss, cooking loss, and shear force, and higher pH, tenderness, juiciness, and flavor than meat from *LYD* muscles. Moreover, higher pH was previously associated with color, drip loss (higher water holding and water binding capacity), and firmness (Warner, 1994). Additionally, muscles with lower drip loss reportedly have reduced lactate production and glycolytic substrates, leading to rapid ATP depletion (Maltin *et al*., 2003; Nitipongsuwan and Mekchay, 2015). Hence, because lower pH was previously associated with increased drip loss and decreased ADP synthesis (van Laack *et al*., 2001), the higher pH of *Berkshire* muscles may decrease drip loss and increase ADP concentrations.

Free amino acids and nucleotides

Lysine, isoleucine, leucine, phenylalanine, valine, histidine, threonine, and methionine are essential amino acids, whereas serine, aspartic acid, arginine, tyrosine, glutamic acid, glycine and alanine are non-essential amino acids. In a previous study, Lim *et al*. (2013) reported that meat from *Yorkshire* × *Berkshire* pigs had higher alanine, glutamic acid, leucine, lysine, methionine, phenylalanine, glycine, histidine, isoleucine, serine, threonine, tyrosine, valine, and proline levels than meat from *Yorkshire* × *Landrace* and *Yorkshire* × *Chester* pigs. Moreover, muscles from *Yorkshire* × *Berkshire* contained lower percentages of arginine and tyrosine. In the present study, amino acid levels were higher in *Berkshire* than in *LYD* meats, and *Berkshire* meat was enriched in all essential free amino acids, which are of great importance to eating quality and have numerous health benefits for consumers.

Glutamic acid, phenylalanine, tyrosine, AMP, IMP, and GMP contribute to meat flavor perceptions and together comprise the umami taste (Kuchiba-Manabe *et al*., 1991; Lioe *et al*., 2005; Wood *et al*., 2004). Remarkably, IMP indirectly contributes to meat flavor through the breakdown of inosine to form hypoxanthine, and with free amino acids such as arginine, phenylalanine, valine, leucine, isoleucine, methionine, and histidine, contributes to a bitter taste (Tikk *et al*., 2006). In contrast, glycine, alanine, lysine, and proline contribute sweet flavors, and other amino acids produce sour or salty tastes (Zhu and Hu, 1993). The present comparisons with *LYD* meats showed that *Berkshire* meats have higher inosine, histidine, leucine, valine, isoleucine, phenylalanine, and tyrosine levels, but lower methionine levels, likely contributing a comparatively bitter taste. Amino acid accumulations in meats were previously associated with decreased WHC (Cornet and Bousset, 1999). However, due to their specific flavors, free amino acids play important roles in the nutrition and eating values of meats (Nishimura and Kato, 1988).

Fatty acid composition

It is widely accepted that the content of MUFA and PUFA are significantly affected by diet, sex, age, and genotype. Accordingly, Suzuki *et al*. (2003) reported that muscles from *Berkshire* and *LDB* had higher levels of saturated fatty acids such as palmitic acid (C16:0) and stearic acid (C18:0), and lower levels of unsaturated fatty acids such as oleic acid (C18:1), linoleic acid (C18:2), and linolenic acids (C18:3) than those in *Duroc* and *LDD* pigs. Moreover, the pig breed *Iberian* had higher C18:0 and SFA levels and lower C16:1, C18:2, C18:3, and PUFA levels than *Landrace* × *Large White* pigs (Barea *et al*., 2013). Additionally, C18:1n9, C18:1n7, C18:2n6, C18:3, PUFA, and MUFA levels were significantly greater in *Yorkshire* × *Berkshire* pigs, followed by those in *Yorkshire* × *Landrace* and then *Yorkshire* × *Chester* pigs (Lim *et al*., 2013). Choi *et al*. (2014) showed that *longissimus muscles* from *Duroc* pigs contained higher palmitic acid (C16:0) and SFA levels than those in *LYD* pigs, but similar eicosenoic acid (C20:1) and USFA levels. We also observed greater oleic acid, docosahexaenoic acid, and MUFA levels in *Berkshire* pigs than in *LYD* pigs, but no significant differences in SFA, PUFA, or UFA levels. SFA concentrations were positively correlated with intramuscular fat (IMF) contents, which were negatively correlated with PUFA concentrations. Accordingly, variations in fatty acid profiles between pig genotypes may reflect differing IMF and fatty acid synthesis (Ramirez and Cava, 2007). Moreover, variations in IMF contents influence tenderness, juiciness, fatty acid profiles, and flavor in pork (Wood *et al*., 1999), and fatty acid profiles generally vary between pig muscles. For example, pork belly contains higher concentrations of fatty acids, especially MUFAs (47%), SFAs (36%), and PUFAs (16%) (Lambe *et al*., 2004). Certain specific dietary fatty acids have been associated with coronary heart disease (CHD) as causative and protective factors (Flock *et al*., 2013). Specifically, replacement of SFAs with MUFAs or PUFAs reduces the risk of CHD. In this study, *Berkshire* meat had higher MUFA contents, potentially leading to positive effects on heart disease risk. Therefore, proportions of fatty acids influence digestibility, nutrition value, and flavor.

Vitamins and minerals

Pork is an excellent source of vitamin B and trace elements, and can provide the recommended daily doses for healthy metabolism. However, vitamin and mineral contents of pig meats vary widely with species, age, and diet, and environmental conditions such as temperature, humidity, management, and stress. Accordingly, Tian *et al*. (2001) showed that vitamin C concentrations were increased from 6 to 13 wk of age, and were significantly decreased two months later. During stress periods, vitamin C plays important roles as an antioxidant that scavenges free radicals by transferring electrons during oxidation to dehydroascorbic acid, which is unreactive in animals. The present data show that ascorbic acid levels were significantly higher in *Berkshire* than in *LYD* meats, and may play important antioxidant roles that facilitate digestion, nerve and muscle stimulation, and the formation of red blood cells.

Animal age and diet can alter incorporation of the bone mineral elements Ca and P in pigs. In particular, Armocida *et al*. (2001) showed that Ca levels were higher in 21 wk old pigs than in 6 and 13 wk old pigs, whereas P levels were greater at 6 and 13 wk of age. Moreover, dietary supplementation with montmorillonite led to decreased K, P, Mg, Fe, and Mn contents in *Duroc* × *Large White* × *Landrace* pigs (Duan *et al*., 2013). Meat products contain energetic minerals that are essential for various biochemical functions in organisms (Bilandzic *et al*., 2012; Horita *et al*., 2011), and low dietary access to mineral elements leads to various human disorders (Melo *et al*., 2008). In particular, dietary Se, Mg, and K are required for physical functions and these minerals participate in oxidation reduction reactions (Choi *et al*., 2009). Muscles from two way cross breed of *Yorkshire* × *Large white* pigs (Y×LW) had higher Mg, Fe, and Zn contents than those from *Large white*, and Kanengoni *et al*. (2014) reported that C and P levels were higher in *Large white* × *Landrace* pigs than in *South African* Windsnyer-type indigenous pigs. Moreover, these authors suggested that increased mineral availability improves the digestibility of meats. Mg and K are critical intracellular cations, and deficiencies can cause various disorders, including hypokalemia, neurological complications, muscle weakness, twitches, irritability, and low blood pressure (Huang *et al*., 2007). In the present accurate determinations of these elements, Mg and K contents were higher in *Berkshire* meats than in *LYD* meats.

Conclusion

Meat quality characteristics such as meat color (CIE L* and b*) and pH were significantly higher in *Berkshire* pigs, whereas drip loss and shear force were significantly lower than those in *LYD* meats. In addition, meat from *Berkshire* pigs contained significantly higher levels of all essential free amino acids, MUFA, docosahexaenoic acid, ascorbic acid, Mg, and K than *LYD* meats and had higher levels of inosine. These data indicate that pig genotype strongly influences meat quality and amino acid and fatty acid composition. Taken together, the present data suggest that meat from *Berkshire* pigs has highly desirable characteristics for consumers, and its nutrients may play essential roles in human health.

Acknowledgements

This research was supported by the Korea Institute of

Planning and Evaluation for Technology in Food, Agriculture, Forestry, and Fisheries (IPET) through the Agri-Bioindustry Technology Development Program funded by the Ministry of Agriculture, Food, and Rural Affairs (114073-3). We thank to Mr. Yun-Jo Chung and Mis. Su-Jin Bang, Center for University Research Facility (CURF) at Chonbuk National University.

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