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 physicochemical traits of meat from Berkshire (black color) pigs with those 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-amino adipic 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

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 Ruvsinsky, 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 (Gjerlau-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).
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 Robinson, 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 crossbreed (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
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Extracts were centrifuged at 9,200 × g for 5 min at 4°C, and 2.1 M KHCO₃ 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; Intakt Corp., USA) column at 40°C and were eluted with mobile phase A comprising 1% phosphoric acid (H₃PO₄) and 5% tert-butyl ammonium hydroxide in water and then mobile phase B comprising 1% phosphoric acid (H₃PO₄) 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 ratio 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 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.

| 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.
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.

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, a-aminoacidic 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)
Data are presented as means±SE. Values in rows differ significantly between the groups.

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

| Amino Acid       | Berkshire (n=15) | LYD (n=15) |
|------------------|-----------------|------------|
| Phosphoserine    | 0.28±0.01       | 0.24±0.01  |
| Taurine          | 9.74±0.29       | 10.29±0.42 |
| Aspartic Acid    | 4.46±0.11       | 1.59±0.17  |
| Threonine        | 3.36±0.06       | 3.05±0.09  |
| Serine           | 3.84±0.12       | 3.34±0.15  |
| Asparagine       | 4.68±0.18       | 3.81±0.57  |
| Glutamic Acid    | 9.74±0.50       | 13.91±0.71 |
| α-Aminoacidipic  | 1.61±0.16       | 0.77±0.26  |
| Glycine          | 15.28±0.23      | 17.85±0.32 |
| Alanine          | 12.86±0.28      | 16.64±0.48 |
| Citrulline       | 0.97±0.08       | 1.11±0.10  |
| Valine           | 3.01±0.06       | 2.09±0.08  |
| Cystine          | 0.09±0.01       | 0.1±0.01   |
| Methionine       | 1.75±0.05       | 1.35±0.07  |
| Isoleucine       | 1.76±0.04       | 1.11±0.06  |
| Leucine          | 4.42±0.11       | 2.90±0.15  |
| Tyrosine         | 2.66±0.06       | 1.78±0.09  |
| Phenylalanine    | 2.48±0.07       | 1.92±0.10  |
| 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       | 0.96±0.04  |
| 3-Methylhistidine| 0.10±0.04       | 0.09±0.01  |
| Tryptophan       | 6.37±0.25       | 4.41±0.35  |
| Carnosine        | 0.51±0.05       | 0.29±0.08  |
| Ornithine        | 0.17±0.02       | 0.55±0.030 |
| Lysine           | 1.56±0.03       | 1.67±0.04  |
| Ammonia          | 6.91±0.35       | 7.95±0.49  |
| 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).

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

| Fatty Acid | 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       | 15.21±1.01 |
| C18:1n9c   | 43.74±1.51       | 38.06±2.09 |
| 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        | 0.06±0.01  |
| SFA        | 39.59±2.09       | 46.69±2.90 |
| MUFA       | 46.76±2.05       | 38.67±2.85 |
| 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

| Vitamin      | Berkshire (n=15) | LYD (n=15) |
|--------------|-----------------|------------|
| 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±0.0001    | 0.006±0.0001 |
| Ascorbic acid (C) | 0.17±0.01       | 0.07±0.03  |

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     | 179.99±5.30 |
| Mg                  | 102.92±1.12     | 92.96±1.56  |
| K                   | 1702.84±30.78   | 1573.88±42.80 |
| Ca                  | 1.50±0.02       | 1.53±0.03  |
| Mn                  | 0.03±0.001      | 0.03±0.001 |
| Fe                  | 2.68±0.15       | 2.99±0.21  |
| Cu                  | 0.36±0.01       | 0.48±0.02  |
| Zn                  | 6.71±0.62       | 11.55±0.86  |
| P                   | 0.10±0.01       | 0.14±0.01  |

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 (Mallin 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 LDD 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 MUFA (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 MUFA or PUFA 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 scavenge 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.

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