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ARTICLE

Application of an Electric Field Refrigeration System on Pork Loin during Dry Aging

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Abstract This study aimed to investigate the effect of an electric field refrigeration (EFR) on the quality characteristics of pork loin including dry aging loss, pH, water holding capacity (WHC), cooking loss, color, shear force, thiobarbituric acid reactive substances (TBARS), and microbial growth during dry aging (0, 1, 2, 3, 4, 7, and 9 wk) in comparison with a commercial refrigerator (CR). Total plate counts (TPC) of the CR group approached 8.07 Log CFU/g at 2 wk of dry aging, thus indicating meat spoilage. Cooking loss, lightness, and shear force of EFR were significantly decreased ($p<0.05$) at subsequent aging weeks in both the EFR and CR. Aging loss, TPC, TBARS levels increased at subsequent aging weeks; however, pH values were not influenced by aging. At the same aging weeks (1 or 2 wk), the EFR group displayed significantly lower values ($p<0.05$) of aging loss, pH, TPC, and TBARS levels than the CR group. No significant differences in WHC, cooking loss, and shear force was observed until 2 wk of aging between the EFR and CR groups. The present results show that application of the EFR system improves the tenderness, color, and lipid oxidation stability of pork loin and extends its shelf life in comparison with a commercial refrigeration.

Keywords dry aging, pork loin, electric field refrigeration, quality properties

Introduction

Electric field freezing has been recently carried out to minimize quality loss in frozen meat (Park and Kim, 2018). In electric field freezing, a supercooled state is maintained through the generation of a continuous electric field within a freezer to vibrate water molecules and prevent ice crystallization (Park and Kim, 2018). Since this method simultaneously freezes the interior and exterior portion of food products, changes in the water molecules are minimized during freezing and thawing, thus reducing quality deterioration of meat products (Iwasaka et al., 2011; Xanthakis et al., 2013); this method has been evaluated using various types of foods products (Jalte et al., 2009; Lee et al., 2017; Xanthakis et al., 2013).

However, most studies are limited to electric field freezing, and studies are required to focus on electric field refrigeration (EFR) systems, capable of storing meat for long

periods while maintaining a supercooled state (–3°C to –1°C).

Recently, consumers have displayed increasing interest in aged meat (Boleman et al., 1997). In general, there are two methods of meat aging: wet aging and dry aging. Both methods retain a more tender texture of meat because during meat aging, the proteins in myofibrils are proteolyzed by proteases in the meat (Wicklund et al., 2005). Among production methods for aged meat, consumers have expressed strong interest in dry-aged meat because of its unique flavor (Choe et al., 2018). During dry aging, meat is aged for a long period at a constant temperature and the surface of the meat is exposed, leading to hardening and microbial growth; hence, the meat is subjected to trimming, wherein the surface is cut away (Perry, 2012). Furthermore, the proteins and lipids constituting the meat continuously become rancid; therefore, for beef sirloin, the aging period is typically set to 28–35 d at 4°C (Perry, 2012). Hence, commercial dry aging of meat is limited to 6 weeks or longer owing to concerns regarding food safety.

Therefore, the present study aimed to evaluate the suitability of an EFR system for dry aging of pork. To this end, we used EFR for long-term (1, 2, 3, 4, 5, 6, and 9 wk) dry aging of pork loin at –1°C, simultaneously suppressing changes in water molecules and microbial growth, observed the changes in product quality during aging, and compared the results with pork loin dry-aged commercially for the same duration at 4°C.

Materials and Methods

Preparation of dry-aged pork loin

In total, 6 pork loins (M. *longissimus thoracis et lumborum,* 3 days postmortem) were obtained from three carcass and each loin was cut into four sections (500 g each). Each three loin cuts were used for dry aging either commercial refrigerator (CR; air velocity, 5±3 m/s; temperature, 4°C; CA-H17DZ, LG, Seoul, Korea) or EFR system (air velocity, 5±2 m/s; temperature, –1°C; ARD-090RM-F, Mars, Fukushima, Japan) at different aging durations of 0 (fresh meat), 1, 2, 3, 4, 5, 6, and 9 wk. Samples of commercially dry-aged pork loin were contaminated after 3 wk; hence, samples dry-aged for up to 2 wk were used for comparison. After aging, the sample surfaces were cut and thermally processed in a 70°C chamber (10.10ESI/SK, Alto Shaam Co, WI, USA) for 120 min, followed by cooling at 10°C for 30 min.

Each treatment of samples were sampling three times for 290–500 g, respectively.

Assessment of dry aging loss

Dry aging loss was calculated using pre- and post-aging weights.

$$\text{Dry aging loss (\%)} = \frac{\text{Post-aging weight (g)}}{\text{Pre-aging weight (g)}} \times 100$$

Assessment of pH

For measuring pH, each 5 g sample was placed in a conical tube along with 20 mL distilled water. After sample preparation, the sample was homogenized using a ultra-turrax homogenizer (HMZ-20DN, Poolim Tech, Seoul, Korea) at 10,000 rpm for 1 min. The pH of prepared mixture was measured using a pH meter (Model S220, Mettler-Toledo, Schwerzenbach, Switzerland).

Assessment of water holding capacity (WHC)

The water holding capacity (WHC) of samples was measured using the filter paper press method (Grau and Hamm, 1953) with slight modification. After dry aging, the dried surfaced were trimmed off and each 300 mg sample was placed in a filter-press device and compressed for 3 min. The WHC calculated using the following methods by measuring the meat area and the total area.

$$\text{WHC } (\%) = \frac{\text{Meat area } (\text{mm}^2)}{\text{Total area } (\text{mm}^2)} \times 100$$

Assessment of cooking loss

Uncooked samples (weighed before cooking) were heat-processed in a chamber (70℃ for 120 min), such that the core temperature approached 70±1℃. After cooling at 10℃ for 1 h, cooked samples were weighed (after cooking) and percentage cooking loss was determined using the following formula.

$$\text{Cooking loss } (\%) = \frac{\text{Weight before cooking} - \text{weight after cooking (g)}}{\text{Weight before cooking (g)}} \times 100$$

Assessment of sample color

The inner surface of the samples before and after heating was assessed using a colorimeter (CR-10, Minolta, Tokyo, Japan) for CIE L* (lightness), CIE a* (redness), and CIE b* (yellowness). A white standard plate with a CIE L* of +97.83, CIE a* of –0.43, and CIE b* of +1.98 was used for reference.

Assessment of shear force

The shear force of each sample was assessed by cutting samples into 1.1×1.1×1.1 cm^3 blocks and analyzed using a V-blade attached to a Texture Analyzer (test speed, 5.0 mm/s; maximum load, 2 kg; head speed, 2.0 mm/s; distance, 8.0 mm; force, 5 g; TA 1, Ametek, FL, USA). Six blocks per each sample were analyzed for shear force. Measured values are expressed in Newton (N).

Assessment of thiobarbituric acid reactive substances (TBARS) levels

Thiobarbituric acid reactive substances (TBARS) levels in samples were measured using the method of Tarladgis et al. (1960). Upon the formation of malondialdehyde and 2-thiobarbituric acid resulting from lipid peroxidation, and the absorbance of samples was measured at 538 nm, using a spectrophotometer (Optizen 2120UV, MECASYS, Daejeon, Korea). The TBARS value was expressed as mg malondialdehyde/kg sample.

Assessment of total plate count (TPC)

Microbial growth during aging was evaluated via a total viable count. Ninety milliliters of a peptone solution was added into 10 g samples and homogenized using a bag mixer, and serially diluted samples were plated onto Difco plate count agar, followed by incubation at 36℃ for 24 h. Total plate counts (TPC) was determined from the mean of three assessments and

expressed as Log CFU/g values.

Statistical analysis

All results were analyzed in triplicate. Analysis of variance were performed on all variables measured using the General Linear Model (GLM) procedure of the SAS software program (SAS version 9.3 for window; SAS Institute Inc., NC, USA), ANOVA and Duncan's multiple range test with $p<0.05$ indicating statistical significance, and the results are presented as mean±SD values.

Results and Discussion

Assessment of aging loss

Aging loss in pork loin increased with an increase in the duration of aging (Table 1). On using the EFR system, aging loss increased significantly with an increase in aging duration ($p<0.05$), and dry aging using a CR system also showed a significant increase in aging loss at wk 2 in comparison with week 1 ($p<0.05$). On comparing the EFR and CR systems, no significant difference was observed after 1 wk of dry aging; however, aging loss was significantly lower in the EFR group after 2 wk ($p<0.05$), concurrent with Kim et al. (2016), wherein beef sirloin aging at a low temperature (1°C) showed lesser initial aging loss and drip loss than beef aged at a high temperature owing to increased moisture loss via evaporation at higher temperatures (3°C). The EFR technique used herein aimed to suppress ice crystallization during cooling through vibration of water molecules (Choi et al., 2015), thus preventing freezing at lower temperatures in comparison with commercial dry aging conditions.

Assessment of pH, water holding capacity (WHC), and cooking loss

The pH of dry-aged pork loin ranged pH 5.67–5.83, depending on the aging conditions and duration (Table 2). During EFR aging, aging at 3 and 4 wk showed significantly higher pH values than the other groups ($p<0.05$), and the pH was the highest at 2 and 5 wk, followed by 6, 9, and 0 wk ($p<0.05$). Upon CR aging, aging at 2 wk displayed a significantly higher pH than that at 0 and 1 wk ($p<0.05$). On comparing EFR and CR systems, the pH was significantly higher during CR aging at 1 and 2 wk of aging ($p<0.05$). Our results are in contrast with those of Brewer and Novakofski (2008), in that no pH changes were observed with upon aging of beef. However, Juarez et al. (2009) assessed pork loin aging and reported that the pH was lower after 7 d of aging in comparison with that at 2 d; however, the pH was higher after 14 d than after 2 d, concurrent with our results.

Table 1. Aging loss of pork loin with different dry aging methods and periods

Trait	Dry aging method	Dry aging time (weeks)						
		1	2	3	4	5	6	9
Aging loss (%)	EFR	12.74±4.28^{E}	14.63±1.92^{Eb}	22.41±1.17^{D}	33.34±0.21^{C}	34.69±1.73^{C}	39.34±0.43^{B}	47.24±1.01^{A}
	CR	11.11±0.08^{B}	19.36±0.01^{Aa}					

All values are mean±SD.
$^{A–E}$ Means on the same row with different numbers are significantly different ($p<0.05$).
^{a,b} Means on the same column with different numbers are significantly different ($p<0.05$).
EFR, electric field refrigeration; CR, commercial refrigeration.

Table 2. pH, water holding capacity (WHC), and cooking loss in pork loin with different dry-aging methods and periods

Trait	Dry aging methods	Dry aging time (weeks)							
		0	1	2	3	4	5	6	9
pH	EFR	5.67±0.03^{B}	5.54±0.01^{Db}	5.68±0.02^{Bb}	5.76±0.02^{A}	5.75±0.01^{A}	5.67±0.03^{B}	5.62±0.02^{C}	5.61±0.05^{C}
	CR	5.67±0.03^{B}	5.66±0.07^{Ba}	5.83±0.01^{Aa}					
WHC (%)	EFR	42.81±1.95^{C}	69.28±17.10^{B}	35.62±2.27^{C}	41.63±7.33^{C}	66.59±4.87^{B}	75.52±2.45^{B}	90.01±0.93^{A}	92.39±5.62^{A}
	CR	42.81±1.95^{B}	69.63±2.77^{A}	36.25±2.84^{C}					
Cooking loss (%)	EFR	32.75±1.76^{A}	24.32±3.95^{BC}	21.06±3.29^{BCD}	26.42±3.55^{B}	24.17±0.67^{BC}	18.54±3.15^{CD}	18.84±0.27^{CD}	16.97±1.30^{D}
	CR	32.75±1.76^{A}	27.67±0.92^{B}	25.93±0.75^{B}					

All values are mean±SD.
$^{A–D}$ Means on the same row with different numbers are significantly different ($p<0.05$).
^{a,b} Means on the same column with different numbers are significantly different ($p<0.05$).
EFR, electric field refrigeration; CR, commercial refrigeration.

As aging progresses, the Z lines of the muscle fibers in meat are cleaved during aging, thus improving water retention by increasing the surface area for water retention in the muscle fibers (Ellis et al., 1998). Upon long-term dry aging of pork loin, a persistent increase in WHC was observed at a longer duration of aging since the stabilization of water evaporation owing to surface drying (2 wk) (Table 2). Excluding the 1 wk aging group, the EFR aging group displayed a significant increase in WHC with a longer duration of aging ($p<0.05$), and the CR aging group also displayed a significantly lower WHC at wk 0 than at 2 wk ($p<0.05$). On comparing the EFR and CR systems, no significant difference was observed after either 1 or 2 wk of aging. The EFR system provides additional energy in the form of an electromagnetic field to facilitate the vibration of water molecules in the food and suppress ice crystal formation, maintaining a supercooled state at –3°C to –1°C. On thawing the supercooled material, its stability was retained with few changes in moisture levels (Pruppacher, 1973). This explains why the EFR aging group displayed an increase in WHC with a longer duration of aging. Similarly, another study reported that aging of pork increases WHC (Ellis et al., 1998). Choi et al. (2015) compared WHC between different cooling methods for meat, reporting that EFR resulted in a higher WHC than CR. The sudden increase in the WHC of the 1 wk samples in comparison with non-aged samples probably resulted from rapid evaporation of water upon initiation of dry aging. After 3 wk, the samples showed a significant increase in WHC with a longer aging duration, indicating the stabilization of water evaporation owing to dry aging.

Cooking loss decreased with an increase in the aging duration (Table 2). For EFR-aged pork loin, cooking loss was significantly decreased with an increase in the aging duration ($p<0.05$) because WHC increased with a longer aging duration, resulting in a lower rate of water dissociation during cooking. Even in the CR aging group, cooking loss was significantly lower after both 1 and 2 wk of aging than at 0 wk ($p<0.05$). On comparing EFR and CR systems, no significant differences were observed after either 1 or 2 wk. Concurrently, Ellis et al. (1998) reported that cooking loss decreased with an increase in the aging duration of pork loin, and Kim et al. (2016) reported that during beef sirloin aging, aging at a high temperature resulted in lesser cooking loss than aging at a low temperature.

Color

Meat blooms during aging (Lindahl et al., 2006), thus resulting in color changes. In our study, pork loin displayed a specific color depending on the duration of dry aging; however, the change in color (L*, a*, and b*) occurred more quickly in the CR

aging group and relatively slower in the EFR aging group (Table 3). Lightness (L*) in the EFR aging group was highest at 0 wk and lowest at 9 wk ($p<0.05$), even in the CR aging group, lightness was significantly higher for non-aged meat at 0 wk than at 1 and 2 wk ($p<0.05$). Thus, lightness measurements indicated that the meat becomes darker as with aging beyond a certain point. Choe and Kim (2017) reported that the lightness of dry-aged beef sirloin was lower than that of non-aged sirloin owing to a reduction in water content during dry aging, resulting in a relative increase in myoglobin levels, which determines the color of meat. Redness (a*) and yellowness (b*) in the EFR aging group were significantly higher at 2–4 wk ($p<0.05$) but decreased after 5 wk ($p<0.05$). In the CR aging group, redness and yellowness were significantly higher at 1 wk than at 0 wk ($p<0.05$) but decreased significantly again at 2 wk ($p<0.05$). Redness and yellowness of meat were significantly lower in the EFR group than in the CR group after 1 wk of aging ($p<0.05$) but significantly lower in the CR group after 2 wk ($p<0.05$). Li et al. (2009) and Marino et al. (2014) assessed meat aged for 14–21 d and reported that redness and yellowness increased with an increase in the aging duration; thus, while color changes may slightly differ depending on the aging method and conditions, the color of meat generally changes to bright red with aging, and herein, the color of meat changed to dark brown upon aging.

Assessment of shear force

One very important aspect of quality changes in aged meat is the change in shearing force owing to the cleavage of Z lines in the muscle fibers (Dashdorj et al., 2016). Concurrently, we observed a reduction in the shearing force in pork loin after a certain duration of aging (Table 4). The EFR aging group showed no significant changes in shear force at 0–4 wk; however, the shearing force decreased significantly after 5 wk ($p<0.05$). The CR aging group did not show any significant changes in shearing force during aging. On comparing the EFR and CR systems, no significant differences in shearing force were observed in accordance with the aging conditions. As known well, shearing force decreases with an increased aging duration of meat aging, which results in a more tender texture on instrumental and sensorial evaluation (Choe and Kim, 2017; Juarez et al., 2009; Li et al., 2009; Tornberg et al., 1994) because after death, the protease calpain is produced in meat, which degrades sarcomere components including actin and troponin, resulting in reduced hardness and shearing force (Onopiuk et al., 2017).

Assessment of total plate count (TPC)

TPC increased significantly with an increase in the duration of aging ($p<0.05$); however, the rate of TPC increase differed

Table 3. Instrumental color of pork loin with different dry aging methods and periods

Trait	Dry aging methods	Dry aging time (weeks)							
		0	1	2	3	4	5	6	9
L*	EFR	53.35±0.21^{A}	52.18±0.18^{ABCa}	52.70±1.63^{ABa}	50.82±2.24^{BC}	48.04±2.79^{D}	52.30±2.19^{ABC}	50.30±1.06^{C}	45.04±0.44^{E}
	CR	53.35±0.21^{A}	48.54±1.14^{Bb}	46.36±1.67^{Cb}					
a*	EFR	5.27±0.14^{D}	8.32±0.08^{Cb}	14.58±2.06^{Aa}	12.26±1.50^{B}	11.12±2.40^{B}	5.26±0.86^{D}	5.76±1.59^{D}	6.68±0.16^{CD}
	CR	5.27±0.14^{B}	10.30±0.76^{Aa}	5.66±0.87^{Bb}					
b*	EFR	9.23±0.16^{C}	9.72±0.25^{Cb}	15.04±2.14^{Aa}	13.78±1.24^{AB}	12.80±2.90^{B}	8.28±0.79^{CD}	8.00±1.46^{CD}	6.40±0.23^{D}
	CR	9.23±0.16^{B}	11.28±0.48^{Aa}	8.50±2.50^{Bb}					

All values are mean±SD.
$^{A–E}$ Means on the same row with different numbers are significantly different ($p<0.05$).
^{a,b} Means on the same column with different numbers are significantly different ($p<0.05$).
L*, lightness; a*, redness; b*, yellowness; EFR, electric field refrigeration; CR, commercial refrigeration.

Table 4. **Shear force of pork loin with different dry aging methods and periods**

Trait	Dry aging method	Dry aging time (weeks)							
		0	1	2	3	4	5	6	9
Shear force (N)	EFR	27.45±4.51^{A}	31.44±2.39^{A}	29.06±5.80^{A}	27.83±2.44^{A}	27.35±3.48^{A}	22.62±4.15^{B}	18.54±1.35^{C}	14.82±0.40^{C}
	CR	27.45±4.51	31.81±2.04	29.43±2.73					

All values are mean±SD.
$^{A–C}$ Means on the same row with different numbers are significantly different ($p<0.05$).
EFR, electric field refrigeration; CR, commercial refrigeration.

greatly depending on aging conditions (Table 5). On comparing the EFR and CR systems, TPC was significantly higher in the CR aging group at 1 and 2 wk ($p<0.05$). When TPC values approached 7 Log CFU/g, meat was considered rotten (Lambert et al., 1991), and that at 2 wk in the CR aging group and wk 9 in the EFR aging group were 8.07 Log CFU/g and 7.43 Log CFU/g, respectively. Thus, in terms of microbial growth, compared to dry aging with a CR system at 4°C, the EFR system at –1°C controls microbial stability and enables prolonged dry aging.

Assessment of thiobarbituric acid reactive substances (TBARS) levels

Fat rancidity is a critical aspect of evaluating the hygienic safety of meat, and high fat rancidity results in lipid peroxidation and a warmed-over flavor, thus decreasing the value of the meat as a food product (Ladikos and Lougovois, 1990). In the present study, similar to TPC, rancidity increased significantly in pork loin samples at longer aging durations ($p<0.05$; Table 4), and for the same aging duration, EFR aging displayed significantly lower rancidity levels than CR aging ($p<0.05$). Temperature is a very important factor for the hygienic safety of meat products during storage; maintenance of a low storage temperature can extend the shelf life of food products (Genigeorgis, 1985). Thus, while CR aging occurs at 4°C, EFR aging at –1°C potentially provides greater hygienic safety.

Conclusion

The present results show that EFR dry aging of pork loin resulted in greater hygienic safety and facilitated long-term (3–6 wk) dry aging, resulting in pork loin with excellent dry aging characteristics. Future studies are required to further assess EFR systems for other species and cuts to expand the scope of this method.

Table 5. **Total plate count (TPC) and thiobarbituric acid reactive substances (TBARS) levels of pork loin with different dry aging methods and periods**

Trait	Dry aging methods	Dry aging time (weeks)							
		0	1	2	3	4	5	6	9
TPC (Log CFU/g)	EFR[1)]	2.20±0.13^{D}	2.54±0.16^{Db}	2.64±0.16^{Db}	5.58±0.60^{C}	5.59±0.53^{C}	5.66±0.59^{C}	6.52±0.88^{B}	7.43±0.11^{A}
	CR[2)]	2.20±0.13^{C}	5.45±0.23^{Ba}	8.07±0.40^{Aa}					
TBARS (mg MDA/kg meat)	EFR	0.29±0.02^{F}	0.28±0.01^{Fb}	0.34±0.02^{Eb}	0.43±0.02^{D}	0.44±0.01^{D}	0.55±0.02^{C}	0.62±0.02^{B}	0.95±0.03^{A}
	CR	0.29±0.02^{C}	0.32±0.01^{Ba}	0.47±0.01^{Aa}					

All values are mean±SD.
$^{A–F}$ Means on the same row with different numbers are significantly different ($p<0.05$).
^{a,b} Means on the same column with different numbers are significantly different ($p<0.05$).
EFR, electric field refrigeration; CR, commercial refrigeration.

Conflict of Interest

The authors declare no potential conflict of interest.

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Author Contributions

Conceptualization: Kim HY. Data curation: Kim HY, Choe J. Formal analysis: Park SY. Validation: Park SY, Choe J. Writing - original draft: Park SY. Writing - review & editing: Park SY, Kim HY, Choe J.

Ethics Approval

This article does not require IRB/IACUC approval because there are no human and animal participants.

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