Food Microbiology 46 (2015) 51–57

Contents lists available at ScienceDirect

Food Microbiology

journal homepage: www.elsevier.com/locate/fm

Flexible thin-layer dielectric barrier discharge plasma treatment of pork butt and beef loin: Effects on pathogen inactivation and meat-quality attributes

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ARTICLE INFO

Article history:
Received 25 April 2014
Received in revised form
7 July 2014
Accepted 9 July 2014
Available online 18 July 2014

Keywords:
Thin-layer dielectric barrier discharge plasma
Meat quality
Microbial inactivation
Pork butt
Beef loin

ABSTRACT

The effects of a flexible thin-layer dielectric barrier discharge (DBD) plasma system using a sealed package on microbial inactivation and quality attributes of fresh pork and beef were tested. Following a 10-min treatment, the microbial-load reductions of *Listeria monocytogenes*, *Escherichia coli* O157:H7, and *Salmonella* Typhimurium were 2.04, 2.54, and 2.68 Log CFU/g in pork-butt samples and 1.90, 2.57, and 2.58 Log CFU/g in beef-loin samples, respectively. Colorimetric analysis showed that DBD-plasma treatment did not significantly affect L* values (lightness) of pork and beef samples, but lowered a* values (redness) significantly after 5- and 7.5-min exposures. The plasma treatment significantly influenced lipid oxidation only after a 10-min exposure. The texture of both types of meat was unaffected by plasma treatment. All sensory parameters of treated and non-treated samples were comparable except for taste, which was negatively influenced by the plasma treatment ($P < 0.05$). This thin-layer DBD-plasma system can be applied to inactivate foodborne pathogens. The observed minor deterioration of meat quality might be prevented by the use of hurdle technology.

1. Introduction

Meat and meat products are contaminated by microbes at distinct stages of the production chain, including the preparation, storage, and distribution stages. Thus, the quality of the products deteriorates and potential public-health problems develop unless the products are properly handled and preserved (Jayasena and Jo, 2013). Foodborne diseases are not limited to a particular age group or country and have emerged as a growing economic problem in most countries over the past few decades (Tauxe et al., 2010). In USA, 76 million cases of foodborne diseases are reported to occur annually leading to 325,000 hospitalizations and 5000 deaths (Mead et al., 1999; Tauxe et al., 2010); this results in high medical costs and in productivity losses in the range of US$ 6.6–37.1 billion (Tauxe et al., 2010). Furthermore, in Korea, the number of cases of foodborne diseases in 2010 was twice that in 2003 (Kim et al., 2013). In the case of meat and meat products, contamination by several pathogenic microorganisms (such as *Salmonella* Typhimurium, *Escherichia coli* O157:H7, other enterohemorrhagic *E. coli*, *Campylobacter jejuni*, *Listeria monocytogenes*, and *Clostridium* spp.) can cause severe foodborne diseases in consumers.

Conventional thermal treatments can inactivate foodborne pathogens, but they can have a negative impact on the nutrient value and the sensory qualities of food. Therefore, considerable attention is currently being focused on developing new non-thermal and highly energy-efficient techniques that can be used to effectively reduce microbial contamination in foods (Kim et al., 2014; Toepfl et al., 2006; van Boekel et al., 2010). One such emerging technology that has a high potential for application in the food-processing sector involves the use of plasmas, which are ionized gases in a quasineutral state (Lee et al., 2011). Plasmas generate highly reactive species such as free electrons, ions,

Non-standard abbreviations: DBD, dielectric barrier discharge; APP, atmospheric-pressure plasma.

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http://dx.doi.org/10.1016/j.fm.2014.07.009
0740-0020/

radicals, excited molecules, and UV photons that are widely recognized to exert microbial-inactivation effects (Kaushik et al., 2013; Kim et al., 2014). Given the recent developments in plasma technology, numerous distinct plasma systems have been designed, and, among these, low-temperature atmospheric-pressure plasma (APP) has attracted considerable attention; this is because the generation of non-thermal plasma discharges at atmospheric pressure helps reduce the difficulties and costs associated with the decontamination process (Kim et al., 2011, 2013).

The dielectric barrier discharge (DBD) plasma system, which is commonly considered the most widely used APP system (Lee et al., 2012), generates plasma between two electrodes that are covered with dielectric layers (Moreau et al., 2008). Sun et al. (2007) reported that as compared to the APP-jet and microwave-discharge methods, DBD-plasma system is considerably simpler but more effective in eliminating pathogens; the authors further stated that DBD plasma was discharged more stably and at a higher power level compared to the plasma generated using the other methods. The plasma technique has recently been tested on various animal-derived foods and products such as pork (Fröhling et al., 2012; Kim et al., 2013), chicken (Lee et al., 2011), cheese (Lee et al., 2012; Song et al., 2009), ham (Lee et al., 2011; Song et al., 2009), beef jerky (Kim et al., 2014), and bacon (Kim et al., 2011) by using distinct types of plasma devices, in particular DBD plasma. These studies indicated that plasma technology could be potentially applied to inactivate foodborne pathogens in the aforementioned foods. Furthermore, plasma devices that can generate APP in sealed packages are required, particularly for use in food-safety applications (Song et al., 2012). However, very few studies that describe plasma devices that can be used for large-area and uniform treatments have been published. Song et al. (2012) recently developed a cold atmospheric-plasma setup in a sealed package and demonstrated that this system could be used to inactivate *Candida albicans* coated on a thick glass plate; however, this device has not been tested on food products. Furthermore, many of the aforementioned studies have not evaluated the influence (s) of DBD-plasma treatment on various aspects of meat quality, such as texture and sensory attributes.

The main objectives of this study were to develop a flexible thin-layer DBD-plasma system for generating APP in a sealed food package and to examine the ability of the plasma system to inactivate common foodborne pathogens inoculated into pork-butt and beef-loin samples. Moreover, we compared the quality attributes of the DBD-plasma–treated pork and beef at various plasma-exposure times with the corresponding attributes of untreated samples.

2. Materials and methods

2.1. Sample preparation and sterilization

Pork butt and beef loin were purchased from a local market in Daejeon, Korea and each meat type was subdivided into two parts. One part from each meat type was used for the inoculation test before which slices (25 × 25 × 7 mm) of the meat samples were vacuum-packaged and sterilized by irradiation (35 kGy) in a linear electron-beam RF accelerator (2.5 MeV, 40 kW; EB Tech, Daejeon, Korea). The other part from each meat type was directly treated with DBD plasma and utilized to measure the physicochemical properties.

2.2. Microorganisms and inoculation

E. coli O157:H7 (KCCM 40406), *S.* Typhimurium (KCTC 1925), and *L. monocytogenes* (KCTC 3569) were cultivated respectively in tryptic soy broth, nutrient broth, and tryptic soy broth containing 0.6% yeast extract (Difco Laboratories, Detroit, Michigan, USA) at 37 °C for 48 h. The cultures were then centrifuged at 2090 × *g* for 15 min at 4 °C in a refrigerated centrifuge (UNION 32R, Hanil Science Industrial Co. Ltd., Korea). The pellets obtained were washed twice with sterile saline solution (0.85%) and then suspended in sterile saline solution to a final concentration of approximately 10^8–10^9 CFU/mL. The sterilized pork-butt and beef-loin samples were removed from the packages and separately inoculated with the test-culture suspensions (100 μL). After spreading, the meat samples were maintained for 10 min at room temperature (approximately 22 °C) under sterile conditions to enable the microorganisms to attach to the samples.

2.3. Treatment with flexible thin-layer DBD plasma

A flexible food-package system designed for generating DBD plasma within the food package was prepared by using the conductive layer of a commercial, zippered food package (129 × 199 mm) as the powered electrode (Fig. 1). A 0.28 mm-thick polytetrafluoroethylene (PTFE; 100 × 100 mm) sheet and a patterned conductive sheet (70 × 70 mm) were installed inside the package (Fig. 1). A bipolar square-waveform voltage at 15 kHz was applied to the outer electrode while the inner patterned electrode was grounded. The plasma was generated at the surface of the inner electrode at 100-W peak power and 2-W average power. The carrier gas used was atmospheric gas containing nitrogen and oxygen.

The pork-butt and beef-loin samples inoculated with *E. coli* O157:H7, *S.* Typhimurium, and *L. monocytogenes* and the non-inoculated samples were treated with the thin-layer DBD plasma for 0, 2.5, 5, 7.5, or 10 min. Each sample was placed inside the food package containing the DBD-plasma system; the package was then sealed using the zipper to confine the reactive chemical species generated during plasma treatment. Immediately after DBD-plasma treatment, respective samples were used for microbial analysis and instrumental color measurement. The other samples were stored under commercial storage conditions at 4 °C until the next day for the analysis of other physicochemical properties and sensory parameters.

2.4. Visible emission spectrum and determination of ozone levels

The visible emission spectrum of the plasma discharge was obtained using a spectrometer (MAYA2000 Pro, Ocean Optics, Inc., FL, USA) equipped with the relevant optical setup. The levels of ozone produced during DBD-plasma generation were measured using a UV ozone photometer (UV–H; Aeroqual Ltd., Auckland, New Zealand).

2.5. Microbial analysis

DBD-plasma–treated pork and beef samples (5 g each) were blended with 45 mL of sterile saline (0.85%) by using a Bag Mixer®

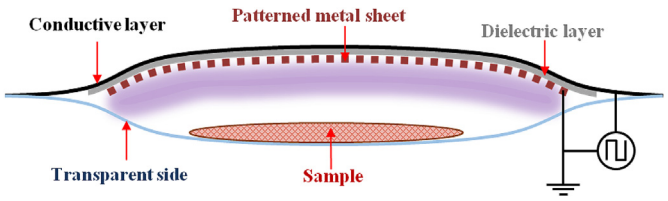

Fig. 1. Schematic diagram of the experimental setup used for generating flexible thin-layer dielectric barrier discharge plasma.

400 (Interscience, Saint Nom, France). Subsequently, the samples were serially diluted using sterile saline solution. The media used to enumerate *E. coli* O157:H7, *S.* Typhimurium, and *L. monocytogenes* were tryptic soy agar, nutrient agar, and tryptic soy agar containing 0.6% yeast extract (Difco), respectively. We spread 100 μL of each dilution on plates containing the appropriate medium; this was performed in triplicate. The plates were incubated at 37 °C for 48 h; the colonies were counted after the incubation period.

2.6. Physicochemical properties

2.6.1. Instrumental color measurement

We measured the surface-color values (International Commission on Illumination (CIE) L*, a*, and b* values representing lightness, redness, and yellowness, respectively) of the plasma-treated pork-butt and beef-loin samples by using a colorimeter (Spectrophotometer, CM-3500d, Konica Minolta Sensing, Inc., Osaka, Japan). The instrument was calibrated using a standard black-and-white plate before analysis. The color values were monitored by using a computerized system under the control of Spectra Magic software (Konica Minolta Sensing, Inc.).

2.6.2. Measurement of 2-thiobarbituric acid reactive substances (TBARS)

Each sample (3 g) was homogenized (Ika Laboratory Equipment, Korea) with 9 mL of distilled water and 50 μL BHT (7.2% in ethanol) and then centrifuged at 1130 × *g* for 20 s. The homogenate (1 mL) was transferred to a 15-mL test tube and mixed with 2 mL of a solution of thiobarbituric acid (20 mmol/L)/trichloroacetic acid (15%). Next, the test tubes were heated in a water bath at 90 °C for 30 min, cooled, and centrifuged (Hanil Science Industrial Co. Ltd.) at 2090 × *g* for 10 min. The absorbance of the supernatant was measured at 532 nm using a spectrophotometer (DU 530; Beckman Instruments Inc., USA). The TBARS value (mg malondialdehyde/kg sample) was calculated using a standard curve.

2.6.3. Texture analysis

Pork and beef patties (diameter: 4 cm; thickness: 2 cm; weight: 20 g) were separately prepared using minced plasma-treated meat samples and cooked to an internal temperature of 75 °C. The centers of the cooked meat samples were compressed twice to 75% of their original height using a texture analyzer (TA-XT Plus, Stable Micro Systems Ltd., Surrey, UK) attached with a compression platen (75 mm in diameter) at a test speed of 2.00 mm/s and a trigger force of 0.005 kg. Texture analysis was performed using the Exponent Lite Texture Analysis software (Stable Micro System Ltd.), and the values obtained for hardness, springiness, cohesiveness, gumminess, and chewiness were recorded. Three replicate samples were used for each treatment.

2.7. Sensory evaluation

DBD-plasma–treated and untreated samples were cut into sections (20 × 30 × 7 mm) and cooked on a preheated clam-type electric grill featuring double heating surfaces (1400 W, Nova EMG-533, Evergreen Enterprise, Korea). The internal temperature was monitored using a digital thermometer (YF-160A Type-K; YFE, Hsinchu City, Taiwan) that was placed in the center of the meat samples; the samples were removed from the grill after they reached an internal temperature of 72 °C. For evaluation, these samples were placed into randomly coded white dishes and served together with drinking water. Seven semi-trained panelists evaluated the cooked samples for appearance, color, taste, off-flavor, and overall acceptability by using a 9-point hedonic scale (from extremely dislike = 1 to extremely like = 9). Each panelist who participated in the sensory evaluation had at least 1-year experience in analyzing meat quality.

2.8. Statistical analysis

The experimental data were subjected to a one-way analysis of variance (ANOVA) for a completely randomized design using the procedure of General Linear Model, and significant differences between mean values were determined by using the Student-Newman-Keul's multiple-range test in SAS Release 9.2. (SAS Institute Inc., Cary, NC, USA) at a significance level of $P < 0.05$. All experimental procedures were conducted in triplicate, and data are reported as means ± standard error of the mean.

3. Results and discussion

3.1. Visible emission spectrum and ozone level during plasma generation

The emission spectrum of the discharge is shown in Fig. 2. When the locations of peaks were examined, the following nitrogen and oxygen molecular spectra were observed in the emission spectrum because of the ambient air used in the plasma system: $NO_\gamma(A^2\Sigma^+ - X^2\Pi)$, N_2 ($C^3\Pi_u - B^3\Pi_g$, second positive system), and $N_2^+(B^3\Pi_g - A^3\Sigma_u^+$, first negative system). The newly developed plasma setup might also generate hydroxyl radicals, although these radicals were not detected in the emission spectrum because they are short lived (Shimmura et al., 1999).

The ozone photometer used in this study can detect a maximum of 200 ppm of ozone. Because the amount of ozone produced exceeded 200 ppm, the exact level could not be measured, but the observations confirmed that the new plasma device produced ozone at a level of >200 ppm. Therefore, the generated reactive species such as ozone, hydroxyl radicals, and NOγ could serve as effective sterilization agents in addition to UV radiation at a wavelength ranging from 200 to 300 nm (Kim et al., 2013; Mastanaiah et al., 2013).

3.2. Inactivation of foodborne pathogens

The newly developed flexible thin-layer DBD-plasma setup generated plasma that was visually almost uniform within the

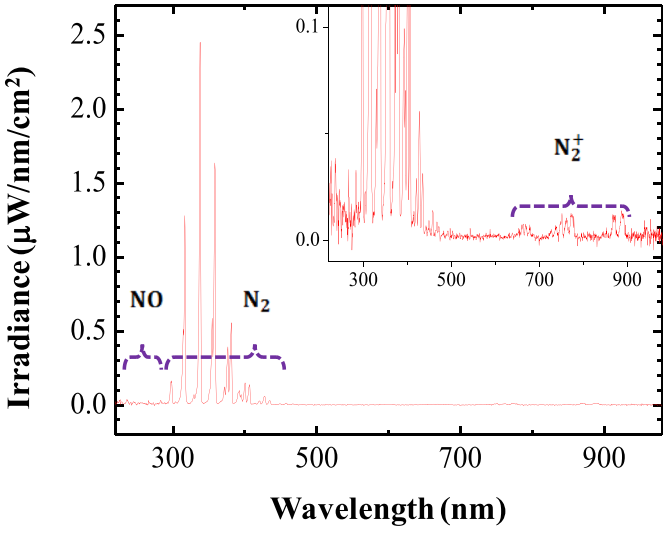

Fig. 2. Emission spectrum of the flexible thin-layer DBD plasma. NO, N_2, and N_2^+ molecular spectra generated because of the ambient air are observed.

flexible food package (figure not shown). Table 1 presents the inactivation effect of the flexible thin-layer DBD plasma against *L. monocytogenes*, *E. coli* O157:H7, and *S.* Typhimurium inoculated on pork-butt and beef-loin samples. The plasma treatment exerted potent bactericidal effects on *L. monocytogenes*, *E. coli* O157:H7, and *S.* Typhimurium, irrespective of the meat type: the populations of all three pathogens on pork-butt and beef-loin samples decreased with increasing treatment time ($P < 0.05$). In this regards, the reductions of the pathogens tested in this study as a result of a 10-min DBD-plasma treatment ranged from 1.90 to 2.68 Log CFU/g.

Kim et al. (2013) have recently investigated plasma-induced inactivation of microorganisms inoculated onto pork loins. They demonstrated that populations of *E. coli* and *L. monocytogenes* inoculated onto pork loin were significantly decreased ($P < 0.05$) following treatment with DBD plasma generated using a 3-kV, 30-kHz bipolar square wave; log-reductions in *E. coli* and *L. monocytogenes* counts increased from 0.5 to 0.55 Log CFU/g and from 0.43 to 0.59 Log CFU/g with increases of plasma-exposure time from 5 min to 10 min, respectively.

The bactericidal effect of the thin-layer DBD-plasma device can be attributed to specific types of reactive species generated by DBD plasma, including ozone, hydroxyl radicals, and NOγ (Kim et al., 2013; Mastanaiah et al., 2013; Yun et al., 2010). These highly reactive species play a critical role in the inactivation of microorganisms because they can overcome natural defense mechanisms and thereby cause damage to cell membranes, nucleic acids, proteins, and lipids (Ma et al., 2008; Montie et al., 2000; Song et al., 2009). Sun et al. (2007) demonstrated that low-temperature plasma induced using DBD destroyed the outer membrane of bacteria.

3.3. Physicochemical properties

3.3.1. Surface-color values

When purchasing meat, consumers use meat color as an indicator of the freshness and the quality of meat (Joo and Kim, 2011). More importantly, this appearance of meat affects consumers' meat-purchasing decision more than any other trait related to meat quality (Mancini and Hunt, 2005). Thus, the changes in the surface-color values of the pork-butt and beef-loin samples treated for various times with the flexible thin-layer DBD plasma were measured (Table 2). The results showed that after DBD-plasma treatment, L* values of pork and beef samples and the b* value of pork samples were not significantly different from those of the untreated samples ($P > 0.05$). Similarly, Fröhling et al. (2012) determined that the L* value of porcine longissimus dorsi muscle was not strongly affected by indirect plasma treatment. By contrast, L* values of pork loin decreased substantially following treatment with DBD plasma in a recent study by Kim et al. (2013). However, this reduction was only detected when the plasma was produced using helium gas but not using a mixture of helium and oxygen gases. Hence, the effect of DBD plasma produced using the mixture of helium and oxygen gases on L* value of pork loin was similar to the results of the present study in which atmospheric air was used as the gas.

Table 2
Surface-color values of pork-butt and beef-loin samples after treatments with flexible thin-layer dielectric barrier discharge plasma for different times.

Time of treatment (min)	Pork butt			Beef loin		
	L*	a*	b*	L*	a*	b*
0	45.42	8.17^{A}	14.45	27.35	13.86^{A}	13.00^{B}
2.5	44.90	7.69^{A}	15.39	28.54	12.92^{AB}	13.80^{AB}
5	47.12	5.42^{B}	13.85	27.53	11.82^{AB}	13.47^{AB}
7.5	47.06	5.07^{B}	13.70	30.77	9.78^{BC}	14.63^{AB}
10	48.26	4.85^{B}	13.34	32.85	6.79^{C}	16.28^{A}
SEM[a]	2.31	0.74	1.04	1.91	1.12	0.93

$^{A-C}$Distinct letters within the same column indicate significant differences ($P < 0.05$).
[a] Standard error of the mean ($n = 15$).

In contrast to L* and b* values, a* values of both pork and beef samples were affected by the DBD-plasma treatment; a* values decreased when the exposure time was increased ($P < 0.05$). However, the effect on pork and beef samples was prominent only when the samples were treated with plasma for at least 5 and 7.5 min, respectively ($P < 0.05$). In a previous study, a* values measured for porcine longissimus dorsi muscle samples exposed to indirect plasma treatment were markedly lower than those measured for untreated porcine longissimus dorsi muscle samples (Fröhling et al., 2012), which is consistent with the results of the present study. Furthermore, only beef samples that were treated for 10 min with DBD plasma exhibited a significantly higher b* value than those of untreated samples ($P < 0.05$). Kim et al. (2013) have shown that b* value of pork loin samples treated with DBD plasma was not significantly different from that of the untreated samples and it is similar to the results of the present study.

The low a* and high b* values measured for meat samples treated with DBD plasma could be attributed to the formation of metmyoglobin during plasma treatment. Fröhling et al. (2012) explained that hydrogen peroxide is generated during the treatment of meat with plasma; this was because hydrogen peroxide was previously detected in liquids treated with indirect plasma (Oehmigen et al., 2011). Thus, the greenish color of plasma-treated meat could increase because of the reaction between the generated hydrogen peroxide and myoglobin. Furthermore, metmyoglobin, whose high concentrations might increase the b* value of meat (Brewer, 2004), is formed as a result of the oxidation of deoxymyoglobin or oxymyoglobin (Mancini and Hunt, 2005). Increasing plasma-exposure times might accelerate the aforementioned oxidation process due to the formation of radicals and thereby increase the concentration of metmyoglobin (Fröhling et al., 2012).

Table 1
Counts of pathogens (Log CFU/g) inoculated on pork-butt and beef-loin samples after treatments with flexible thin-layer dielectric barrier discharge plasma for different times.

Time of treatment (min)	Pork butt			Beef loin		
	Listeria Monocytogenes	*Escherichia coli*	*Salmonella* Typhimurium	*Listeria monocytogenes*	*Escherichia coli*	*Salmonella* Typhimurium
0	5.90^{A}	5.95^{A}	5.49^{A}	5.91^{A}	5.87^{A}	5.51^{A}
2.5	5.52^{B}	5.44^{B}	5.18^{B}	5.24^{B}	5.07^{B}	5.11^{B}
5	4.69^{C}	4.81^{C}	4.58^{C}	4.74^{C}	4.77^{C}	4.64^{C}
7.5	4.17^{D}	4.05^{D}	3.16^{D}	4.27^{D}	4.08^{D}	3.13^{D}
10	3.86^{E}	3.41^{E}	2.81^{E}	4.01^{E}	3.30^{E}	2.93^{E}
SEM[a]	0.07	0.09	0.09	0.05	0.04	0.07

$^{A-E}$Distinct letters within the same column indicate significant differences ($P < 0.05$).
[a] Standard error of the mean ($n = 15$).

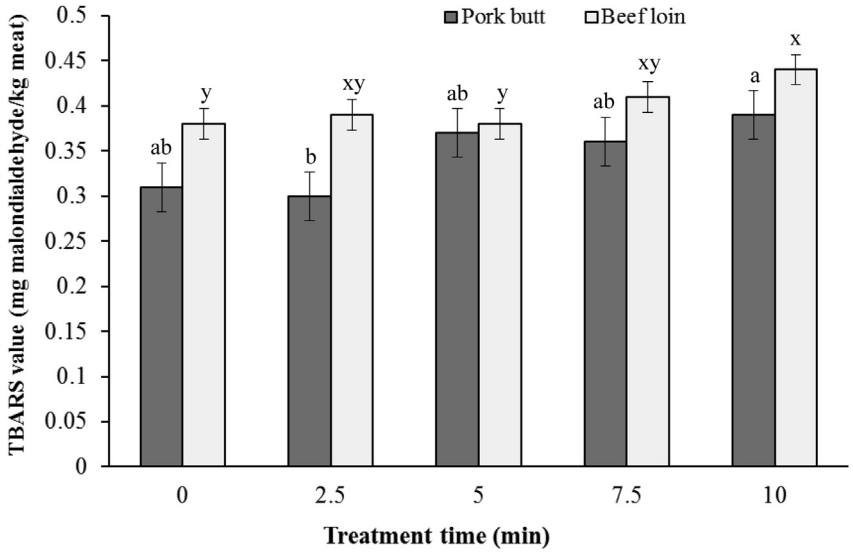

Fig. 3. 2-Thiobarbituric acid reactive-substance values (mg malondialdehyde/kg meat) of pork-butt and beef-loin samples treated with flexible thin-layer dielectric barrier discharge plasma. Vertical bars represent the standard error of the mean ($n = 15$). Means indicated by distinct letters within each meat type differ significantly ($P < 0.05$).

3.3.2. TBARS values

To investigate the effect of the flexible thin-layer DBD-plasma exposure on the lipid oxidation of meat samples, TBARS values of the samples were measured. The TBARS values of DBD-plasma-treated pork and beef samples increased slightly when the treatment time was increased (Fig. 3). However, compared with the lipid oxidation in untreated and other treated samples after one day of treatment, the lipid oxidation in meat samples was significantly affected ($P < 0.05$) by DBD-plasma treatment only after exposure to the plasma for 10 min. Furthermore, the TBARS values of beef-loin samples were slightly higher than those of pork-butt samples. This might be attributed to the variations in fat content and fatty-acid composition of the two meat types. By contrast, the TBARS value of APP-treated bacon was lower than that of untreated bacon at Day 0, but these values increased after 7 days of storage (Kim et al., 2011). The observed increase in TBARS values of plasma-treated samples can be attributed to free radicals—the precursors of lipid hydroperoxides produced during plasma treatment—that trigger lipid oxidation (Kim et al., 2013). Consequently, lipid-oxidation byproducts such as hexanal and malondialdehyde are produced (Liu et al., 2008). The current data suggest that the flexible thin-layer DBD-plasma treatment minimally affected lipid oxidation in pork butt and beef loin up to a treatment time of 7.5 min when measured one day after plasma treatment. However, further investigations are needed to find out the effect of newly developed DBD-plasma system on lipid oxidation of meat samples with the medium-term and long-term storage period.

3.3.3. Texture profile

Table 3 presents the effect of flexible thin-layer DBD plasma on the texture parameters of pork-butt and beef-loin samples as a function of increasing treatment time. The results indicate that no texture parameter was affected ($P > 0.05$) by the DBD-plasma treatment, irrespective of the meat type: springiness and cohesiveness values of pork and beef samples were constant even when treatment time was increased ($P > 0.05$), but the hardness, gumminess, and chewiness values of both meat samples fluctuated, though not significantly, when the treatment time was increased ($P > 0.05$). Kim et al. (2013) recently demonstrated that textures were not different ($P > 0.05$) between controls and DBD-plasma-treated samples in sensory evaluations of pork loin. Thus, the flexible thin-layer DBD-plasma treatment used in this study could serve as a non-destructive plasma treatment in terms of meat texture. However, the current results should be further confirmed in future investigations.

3.4. Sensory evaluation

Sensory evaluation was conducted on pork-butt and beef-loin samples treated with the flexible thin-layer DBD plasma (Table 4).

Table 3
Texture-profile analysis of pork-butt and beef-loin samples after treatments with flexible thin-layer dielectric barrier discharge plasma for different times.

Meat	Time of treatment (min)	Hardness (kg)	Springiness (mm)	Cohesiveness (%)	Gumminess (kg)	Chewiness (kg)
Pork butt	0	6.17	0.72	0.57	3.68	2.69
	2.5	3.80	0.75	0.56	2.14	1.54
	5	8.13	0.78	0.61	4.83	3.49
	7.5	4.67	0.74	0.58	2.69	2.14
	10	9.66	0.78	0.58	5.53	4.12
	SEM[a]	2.94	0.06	0.02	1.69	1.12
Beef loin	0	6.18	0.72	0.55	3.24	1.72
	2.5	5.64	0.76	0.60	5.06	2.25
	5	6.66	0.74	0.56	2.95	1.03
	7.5	5.46	0.77	0.59	3.43	2.24
	10	7.69	0.75	0.56	6.09	1.81
	SEM[a]	1.79	0.04	0.03	1.07	0.49

[a] Standard error of the mean ($n = 15$).

Table 4
Sensory evaluation of pork-butt and beef-loin samples after treatments with flexible thin-layer dielectric barrier discharge plasma for different times.

Meat type	Time of treatment (min)	Appearance	Color	Taste	Off-flavor	Overall acceptability
Pork butt	0	4.94	5.06	5.10^{A}	1.22	4.88
	2.5	5.09	4.97	5.12^{A}	1.41	5.28
	5	5.16	5.12	4.47^{B}	1.31	5.12
	7.5	4.81	4.91	4.84^{AB}	1.25	4.84
	10	4.81	4.75	4.53^{B}	1.31	4.88
	SEM[a]	0.17	0.17	0.18	0.16	0.28
Beef loin	0	5.12	5.16	5.22^{A}	1.12	5.25
	2.5	5.19	4.97	5.06^{AB}	1.09	4.78
	5	5.09	4.94	5.16^{A}	1.12	5.12
	7.5	4.81	5.25	4.75^{AB}	1.34	4.81
	10	5.09	4.94	4.62^{B}	1.38	4.91
	SEM[a]	0.18	0.16	0.17	0.11	0.17

[A-B]Distinct letters in the same column within the same meat type indicate significant differences ($P < 0.05$).
[a] Standard error of the mean ($n = 35$).

None of the plasma treatments affected the appearance, color, off-flavor, and overall acceptability of the pork and beef samples ($P > 0.05$). This finding has a controversy with the instrumental color data shown in Table 2. By contrast, the preference for taste was significantly influenced by the DBD-plasma treatment of both meat samples: the sensory score for taste was significantly lower when pork-butt samples were treated with DBD plasma for 5 and 10 min than with other treatments including no treatment (control), whereas this sensory score measured for beef loin was negatively affected only by the 10-min treatment ($P < 0.05$). Sensory-evaluation data on plasma-treated meat and meat products are scarce. DBD-plasma treatment substantially lowered the scores measured for appearance, color, odor, and overall acceptability of raw pork loin (Kim et al., 2013). However, no marked differences in any of these parameters were detected between plasma-treated and untreated pork loin after cooking (Kim et al., 2013).

Free radicals generated during plasma treatment trigger lipid and/or protein oxidation and generate secondary oxidation products such as alkanes, alkenes, aldehydes, alcohols, ketones, and acids (Kim et al., 2013). These molecules produce fishy, metallic, rancid, and oxidized flavors (Kochhar, 1996). Thus, low taste scores might have been obtained because of the high fat content in pork butt and beef loin that led to increased production of lipid-oxidation byproducts during plasma treatment (Lee et al., 2012). However, panelists did not record any significant difference for off-flavor scores between the plasma-treated and untreated samples. Therefore, the deterioration of taste in flexible thin-layer DBD–treated meat should be considered and minimized. Adding natural antioxidants to meat and meat products can serve as a possible strategy to minimize lipid oxidation (Jayasena and Jo, 2014) and thereby improve the sensory quality of DBD-treated meat and meat products.

4. Conclusions

Findings of the present study suggest that the microbial safety of raw pork butt and beef loin can be enhanced using the newly developed flexible thin-layer DBD–plasma system. Out of the tested conditions in this study, DBD-plasma treatment for 10 min might be the optimum treatment because under this treatment condition, the bactericidal effect on *L. monocytogenes*, *E. coli* O157:H7, and *S.* Typhimurium was the highest, and the physicochemical and sensory attributes of the meat samples were similar to those of samples treated for 7.5 min. However, this plasma device must be improved to increase pathogen-inactivation efficiency and minimize the adverse effects on physicochemical and sensory qualities of meat.

Acknowledgments

This work was conducted with the support of the R&D Program (Plasma Farming) of the National Fusion Research Institute of Korea (Project No. EN1425-1), which is funded by the Government.

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