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Flexible thin-layer plasma inactivation of bacteria and mold survival in beef jerky packaging and its effects on the meat's physicochemical properties

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ABSTRACT

The aims of the present study were to examine the use of a flexible thin-layer plasma system in inactivating bacteria and mold on beef jerky in a commercial package and to evaluate the physicochemical changes of the jerky. After plasma treatment for 10 min, *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Salmonella* Typhimurium, and *Aspergillus flavus* populations on the beef jerky were reduced by approximately 2 to 3 Log CFU/g. No significant changes in metmyoglobin content, shear force, and myofibrillar fragmentation index were found in the plasma-treated beef jerky. On the other hand, the peroxide content and L^* value were decreased whereas the a^* and ΔE value were increased in the plasma-treated sample. Sensory evaluation indicated negative effects of plasma treatment on flavor, off-odor, and overall acceptability of the beef jerky. In conclusion, the flexible thin-layer plasma system could be employed as a means for decontamination of beef jerky, with slight changes to the physicochemical quality of the product.

1. Introduction

Jerky, a ready-to-eat meat product, is a snack food in high demand owing to its flavorful taste, nutritional value, and storage stability without refrigeration (Kim, Lee, Choi, & Kim, 2014). In general, jerkies are made by curing the meats with nitrite, which controls bacterial growth, especially *Clostridium botulinum*, and drying for an extended period of time (Sofos, Busta, & Allen, 1979).

Despite of the nitrite and low water activity, however, over 250 cases of foodborne diseases were epidemiologically related with jerky consumption from 1966 to 2003. These accidents were linked to *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Staphylococcus aureus*, and several types of *Salmonella* (Dierschke, Ingham, & Ingham, 2010; Kim, Lee, Choi, & Kim, 2014). Moreover, spoilage of jerky occurs easily as a result of fungal growth (Clavero, 2010). Therefore, it is necessary to find a safe, efficient, and cost-effective system for the microbial decontamination of jerky.

Plasma devices operated under atmospheric pressure at room temperature have attracted a great deal of attention as a non-thermal technology (Misra, Keener, Bourke, Mosnier, & Cullen, 2014a). These devices, called atmospheric pressure plasma (APP) or cold plasma, have many advantageous features: (i) bactericidal and virucidal effects; (ii) inexpensive facilities and operation costs; (iii) ease of use; and (ix) high concentrations of energetic particles such as reactive oxygen species (ROS), reactive nitrogen species (RNS), other reactive species, electrons, ions, and UV photons (Heuer et al., 2015; Jayasena et al., 2015). Many previous research studies have reported the antimicrobial effect of APP on foods (Kim et al., 2011; Suhem, Matan, Nisoa, & Matan, 2013; Yong et al., 2014).

In the food industry, both economical cost and product safety are the most important issues (Antle, 2000). To adopt the APP system in this industry, the operating cost of the process gas has to be considered. An ideal gas for operating APP would be ambient air (Misra et al., 2014a). In addition, cross-contamination is a serious problem in the field (Wilks, Michels, & Keevil, 2006). Foods treated with some APP systems can be exposed to the risk of cross-contamination from other contaminated foods, food handlers, or equipment during the post production process (Wilks et al., 2006). Therefore, a few studies have attempted APP generation using ambient air in packages or containers. Misra et al. (2014b) reported that aerobic mesophilic bacteria, yeasts, and molds of strawberries were reduced by 2 Log CFU after in-package APP treatment with ambient air for 5 min and storage for 24 h. Using a sealed type of flexible thin-layer plasma and encapsulated plasma for 10 min, the numbers of *L. monocytogenes* on cheese and milk were reduced to 2.4 and 2.1 Log CFU/g, respectively (Kim et al., 2015; Yong et al., 2015).

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However, so far, only a limited number of studies have dealt with a processed meat product by applying a sealed-type APP system using ambient air, which is worth studying for industrial utilization. In addition, there is very limited information available on the quality of the processed meat products like jerky including lipid oxidation, color, and textural properties after application of APP. Therefore, the present study used a flexible thin-layer plasma system inside a commercial food package and investigated its inactivation of different bacteria and molds on the beef jerky. Changes in the physicochemical quality of the beef jerky were also evaluated.

2. Materials and methods

2.1. Study design and sample preparation

Commercial beef jerky (Kojubu Co., Ltd., Suwon, Korea) were purchased from a local market and cut into 40 × 40 mm pieces (totally 216 samples, each sample was approximately 6 g). Then, the samples were divided into two groups. The study design was shown in Fig. 1. For inoculation test, one group of samples (48 pieces) was irradiated on both sides in a linear electron-beam RF accelerator (2.5 MeV, beam power 40 kW; EB-Tech., Daejeon, Korea). To achieve complete sterilization of the samples, a radiation dose of 35 kGy was employed. The sterilized samples were inoculated with prepared inocula and then antimicrobial effect of flexible thin-layer plasma was investigated. The other group of sample was not sterilized and used for the analysis of physicochemical quality traits after the plasma treatment.

2.2. Inoculation test

2.2.1. Preparation of inocula

L. monocytogenes (KCTC 3569), *E. coli* O157:H7 (ATCC 43894), and *Salmonella* Typhimurium (KCTC 1925) were cultivated in tryptic soy broth containing 0.6% yeast extract (Difco Laboratories, Detroit, MI, USA), tryptic soy broth (Difco), and nutrient broth (Difco), respectively, at 37 °C for 48 h. The cultures were centrifuged (2419 ×*g* for 15 min) using a refrigerated centrifuge (Union 32R; Hanil BioMed Inc., Incheon, Korea). Then, the resulting pellets were washed twice with sterile saline solution and further processed by following the method of Kim et al. (2011). *Aspergillus flavus* (KCTC6905) was obtained from mycelia grown on potato dextrose agar (PDA; Difco) acidified with 10% citric acid. Spores were collected by flooding the surface of the PDA with a sterile saline solution containing Tween 80 (0.1%, v/v). After counting the spores using a hemocytometer (Paul Marienfeld GmbH & Co. KG, Lauda-Königshofen, Germany), the suspension was standardized to a concentration of 10^7 spore/mL by dilution with sterile saline. The viability of each strain in each suspension was checked using quantitative colony counts, and the final concentrations were approximately 10^7–10^8 CFU/mL.

2.2.2. Inoculation and microbial analysis

The prepared beef jerky (6 g) was inoculated with each different microbial solution (100 μL) separately. To enable the microorganisms to attach to the meat, all samples were placed on a clean bench and air dried for 15 min at room temperature. Then, beef jerky was exposed to plasma except for control sample (plasma treatment time for 0 min). Both plasma-treated and non-treated whole beef jerkies (6 g) were blended separately with sterile saline solution (54 mL) in a stomacher bag. A serial dilution using sterile saline is followed. The media used for *L. monocytogenes*, *E. coli* O157:H7, *S.* Typhimurium, and *A. flavus* were tryptic soy agar containing 0.6% yeast extract (Difco), tryptic soy agar (Difco), nutrient agar (Difco), and PDA (Difco), respectively. Each microbial dilution (100 μL) was spread on the appropriate medium. The agar plates for the three bacteria were incubated at 37 °C for 48 h, whereas the PDA plates were incubated at 25 °C for 5 days. Once the colonies had been counted, the results were expressed as log colony-forming units per gram (log CFU/g). The decimal reduction time (*D* value) was calculated as the negative reciprocal slope of the log (N_0/N) versus time curve (N_0 = initial CFU, N = CFU after exposure to plasma).

2.3. Treatment with flexible thin-layer plasma

The plasma apparatus applied was a dielectric barrier discharge and is illustrated in Fig. 2. To construct the flexible thin-layer plasma system, a polytetrafluoroethylene sheet (100 × 100 mm) and a patterned conductive sheet (70 × 70 mm) were installed inside the commercial, zippered food package (129 × 199 mm). The package was sealed using the zipper once the sample had been placed inside. Thereafter, a bipolar square-waveform voltage at 15 kHz was applied to the conductive layer (outer electrode) of the food package while the patterned conductive sheet (inner electrode) was grounded. The plasma was generated as a base for material treatment (Yong et al., 2015). Ambient air was used as the carrier gas, and the plasma treatment times were for 0

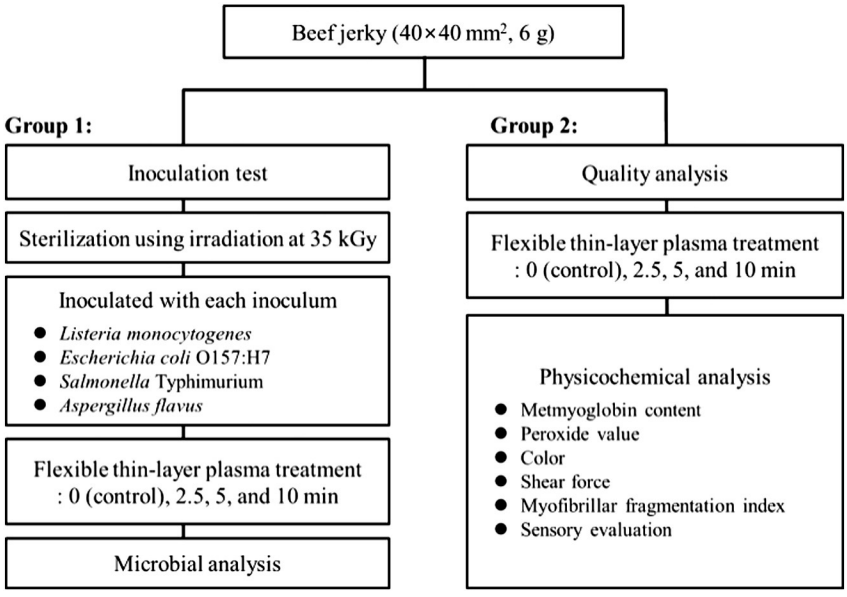

Fig. 1. Diagram illustrating the experimental procedure of the present study.

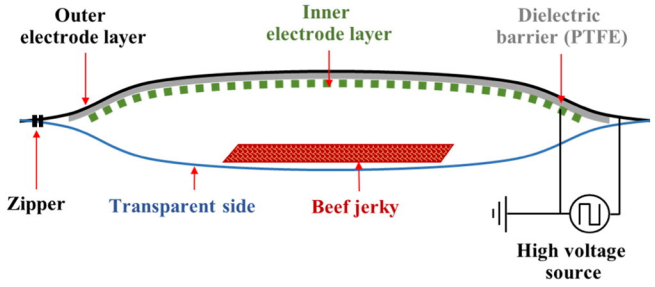

Fig. 2. Experimental setup for the flexible thin-layer plasma treatment of beef jerky. PTFE, polytetrafluoroethylene sheet.

(control), 2.5, 5, and 10 min. The sample temperature before and after treatment of plasma were 25 °C and 28 °C, respectively.

2.4. Physicochemical properties

2.4.1. Metmyoglobin content measurements

The metmyoglobin concentration in the beef jerky was determined using a modification of the procedures of Krzywicki (1979). Samples were blended with 5 volumes of 0.04 M phosphate buffer (pH 6.8) using a homogenizer (T10 basic; Ika Works, Staufen, Germany). After standing at 4 °C for 24 h, the mixtures were centrifuged at 566 ×*g* for 30 min (Union 32R) and the supernatant was filtered with filter paper (Whatman No. 1; Whatman PLC., Maidstone, UK). The absorbance of the filtrate was measured at 525, 572, and 700 nm using a spectrophotometer (X-ma 3100; Human Co. Ltd., Seoul, Korea). The metmyoglobin contents were calculated as follows (Han et al., 2011):

$$\text{Metmyoglobin (\%)} = [1.395 - (A_{572} - A_{700})/(A_{572} - A_{700})] \times 100$$

where A_λ is the absorbance value at λ nm.

2.4.2. Peroxide value

Peroxide value was measured by following the method of Jung et al. (2015a). Lipid extraction was first conducted with Folch's solution (chloroform:methanol = 2:1). Then, the lipid sample was treated with 35 mL of solvent mixture (acetic acid:chloroform = 3:2) and 0.5 mL of saturated potassium iodide solution. The mixture was kept in the dark for 5 min, after which 75 mL of distilled water was added. Then, 2.5 mL of starch solution (1%, w/v) was added as an indicator. The peroxide value (POV) was determined by titrating the iodine liberated from potassium iodide with a standardized sodium thiosulfate solution (0.005 N). The POV was calculated with the following equation (Jung et al., 2015a):

$$\text{POV (meq/kg)} = [(V_1 - V_0) \times F \times 0.01]/\text{SW} \times 100$$

where V_1 is the titration volume (mL) of 0.005 N $Na_2S_2O_3$ on the samples, V_0 is the titration volume (mL) of 0.005 N $Na_2S_2O_3$ on the blank, F is the factor of the 0.005 N $Na_2S_2O_3$ solution, and SW is the sample weight (g).

2.4.3. Color measurement

The Hunter color, L^* (whiteness or brightness/darkness), a^* (redness/greenness), and b^* (yellowness/blueness) values were determined using a spectrophotometer with the illuminant D_{65} (CM 3500d; Konica Minolta Censing Inc., Osaka, Japan) which was calibrated against a black and a white reference plate. Measurements were taken to the surface of beef jerky with 8 mm diameter of aperture area. Then, the total color difference ($\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$), hue ($H = \tan^{-1} b/a$), and chroma ($C = \sqrt{a^2 + b^2}$) were calculated from the L^*, a^*, and b^* values. The Browning index (BI) was calculated using the following:

$$\text{BI} = [100(x - 0.31)]/0.172$$
$$x = (a + 1.75\,L)/(5.645\,L + a - 3.012b)$$

2.4.4. Shear force and myofibrillar fragmentation index measurements

After plasma treatment, each beef jerky samples were cut into two pieces (20 × 40 mm). Using these pieces, two technical replicates, repeated measurements of the same sample, were used to test [4 treatments × 3 independent repetitions (average of 2 technical replicates)]. Shear force (N) value was measured using a Warner–Bratzler blade attachment on a texture analyzer (CT3 10 K; Brookfield Engineering Laboratories, Middleboro, MA, USA), with a maximum cell load of 10 kg, target load of 10 g, target value of 25 mm, and target speed of 2.0 mm/s. Cross-sections of the samples were placed midway to the blade.

To measure the myofibrils, jerky samples (4 g) were homogenized with 40 mL of MFI buffer (20 mM K_3PO_4, 100 mM KCl, 1 mM EDTA, 1 mM $MgCl_2$, and 1 mM NaN_3) at pH 7.0. An aliquot of the myofibril suspension was diluted with the MFI buffer to 0.5 mg/mL protein concentration. Then, the absorbance of this suspension was measured at 540 nm using a spectrophotometer (X-ma 3100). MFI values were recorded as absorbance units per 0.5 mg/mL myofibril protein concentration multiplied by 200.

2.4.5. Sensory evaluation

Sensory analysis of color, flavor, taste, tenderness, off-odor, and overall acceptability was appreciation by 10 panels each of whom had at least 1 year of previous experience in sensory evaluation testing. The sensory evaluation was run three times independently as a replication. The attributes color, flavor, taste, tenderness, off-odor, and overall acceptability were assessed. A 9-point hedonic scale, where 9 indicates "extremely like" and 1 indicates "extremely dislike," was employed for evaluating all the qualities, except off-odor. Off-odor was assessed as follows: 9, very strong; and 1, no off-odor. A sensory evaluation of the beef jerky was conducted with an individual trial.

2.5. Statistical analysis

Statistical analysis was performed by one-way analysis of variance, and significant differences between mean values were identified using Duncan's multiple comparison tests in the SAS software (SAS, Release 9.4; SAS Institute Inc., Cary, NC, USA) with a significance level of $P < 0.05$. In sensory test, the trials and panelists as random terms were statistically checked, but no effects were found. Thus they were excluded from the model. Results are reported as least square mean values and standard error of the least square means (SEM) in the Tables. In the Figs. 3 and 4, error bars indicate the standard deviation obtained from a total of three analyses.

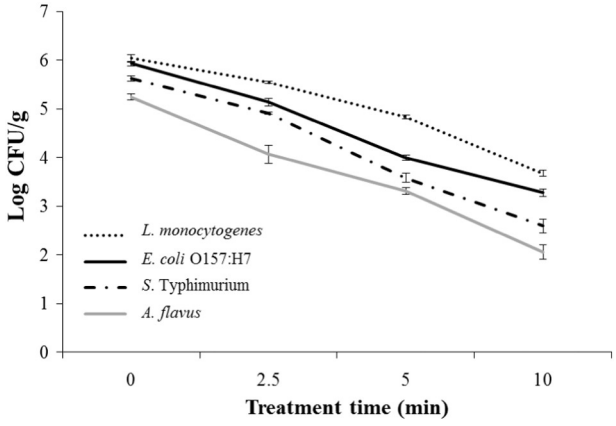

Fig. 3. Inactivation effect of flexible thin-layer plasma against the growth of different bacteria and mold inoculated onto beef jerky.

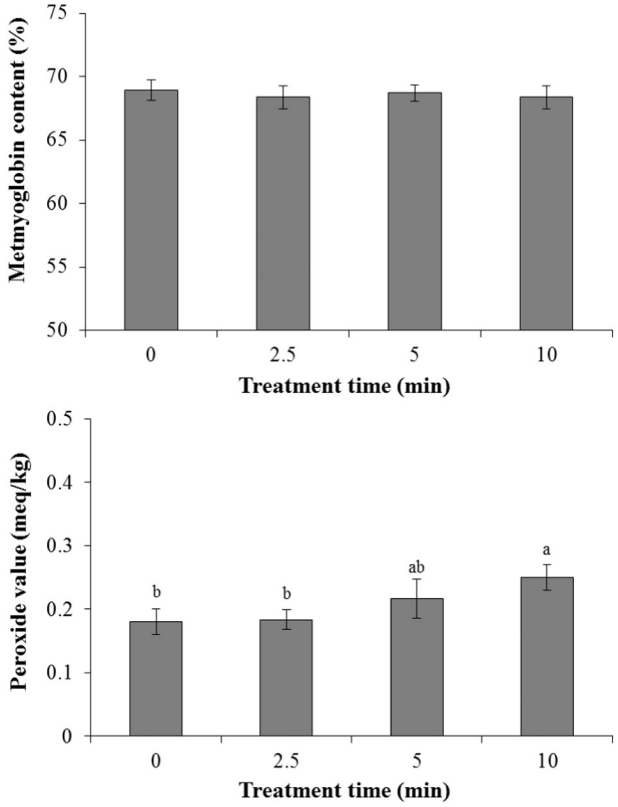

Fig. 4. Metmyoglobin content and average peroxide value measured in control and flexible thin-layer plasma-treated beef jerky samples. [a–b]Bars with different letters are significantly different per Duncan's multiple comparison test ($P < 0.05$).

3. Results and discussion

3.1. Inactivation of foodborne pathogens

The flexible thin-layer plasma treatment exerted potent inactivation effects on all the bacteria and mold tested (Fig. 3). The populations of all inocula on beef jerky decreased with increasing treatment time ($P < 0.05$). The numbers of *L. monocytogenes*, *E. coli* O157:H7, *S.* Typhimurium, and *A. flavus* in control samples were 6.04, 5.93, 5.62, and 5.24 Log CFU/g, respectively, which reduced to 3.68, 3.28, 2.59, and 2.06 Log CFU/g after exposure of the plasma for 10 min. The time needed to reduce the *L. monocytogenes*, *E. coli* O157:H7, and *S.* Typhimurium populations by 90% (*D* value) was 4.14, 3.74, and 3.22 min, respectively (data not shown). The energy species produced by plasma can access and directly attack the microbial cell wall. Damage of the cell wall structures as a result of APP treatment has been reported in both *Bacillus cereus* vegetative cells and spores, and in *E. coli* (Joshi et al., 2011; Kim, Lee, & Min, 2014). Thus, different cell wall structures show different sensitivity to plasma. In general, gram-positive bacteria had a higher *D* value than gram-negative bacteria, suggesting that peptidoglycan works as a physical shield against plasma (Yong et al., 2015). Suhem et al. (2013) reported that unlike APP treatment of prokaryotic cells (e.g., bacteria) where the effective exposure time is in the order of seconds, the inhibition of eukaryotic cells (e.g., fungi) required a longer plasma treatment time in the order of several minutes. In the present study, however, the *D* value of *A. flavus* (a mold) was 3.24 and similar to that of bacteria (data not shown).

The inactivation effect of in-package APP was similar on the background aerobic mesophilic bacteria, yeast, and mold of strawberry (Misra et al., 2014b). In contrast, Lee, Paek, Ju, and Lee (2006) showed that the *D* values at the initial concentrations were 18 s for *E. coli*, 19 s for *S. aureus*, 1 min 45 s for *Saccharomyces cerevisiae*, and 14 min for *Bacillus subtilis* spores. Ohkawa et al. (2006) reported that the necessary plasma treatment time was only 1 min for the biological indicators *Salmonella* Enteritidis, *E. coli*, and *Candida albicans*, and 5 min for *S. aureus*. The longest treatment time ever needed was 20 min to sterilize the spore-forming bacteria *Geobacillus stearothermophilus* and *Bacillus atrophaeus*.

Operated with ambient air, APP generates RNS such as nitric oxide (NO) and nitrogen dioxide (NO_2), and ROS like ozone (O_3), superoxide anion (O_2^-), and hydroxyl radicals (Jayasena et al., 2015). There is strong evidence from previous research into physiological exposures that the ROS formed by APP would cause cell death. Energetic reactive species generated from APP can induce DNA damage and mitochondria dysfunction to mediate cell apoptosis (Kim, Kim, Kim, & Lee, 2010). Similarly, reactive species that result from APP cause membrane potential decrease, membrane lipid peroxidation, and breaches in the membrane integrity of *E. coli* (Joshi et al., 2011). These findings indicate that APP sufficiently leads to oxidative DNA damage and eventual cellular death.

3.2. Metmyoglobin content and peroxide value

Myoglobin is a metalloprotein composed of globin and heme prosthetic groups containing iron. When myoglobin is oxidized, metmyoglobin is produced along with superoxide ($\bullet O{=}O^-$), which can be dismutated to O_2 and H_2O_2. The secondary products, including superoxide and H_2O_2, are strong oxidants that can oxidize other biomolecules (Faustman, Liebler, McClure, & Sun, 1999). A number of studies have revealed that the formation of metmyoglobin is a catalyst of lipid oxidation (Baron & Andersen, 2002).

Fröhling et al. (2012) suggested that the radicals formed by the APP may lead to a production of metmyoglobin, resulting in higher b^* values of raw pork. On the other hand, no significant differences were found in metmyoglobin content and lipid oxidation value when raw pork was treated with low-pressure plasma (Ulbin-Figlewicz & Jarmoluk, 2015). In the present study, the metmyoglobin content (%) of beef jerky was unchanged but the POV was significantly increased by the 10 min of thin-layer plasma treatment (Fig. 4). Because peroxides are commonly formed as the primary products during lipid oxidation, the POV in pork jerky can be used as a lipid oxidation value (El-Alim, Lugasi, Hóvári, & Dworschák, 1999).

Even though myoglobin oxidation is excluded, lipid oxidation might be initiated by radicals or other agents (UV, ionizing radiation, or heat) (Faustman et al., 1999). APP treatment of packages caused lipid oxidation in bresaola compared with control samples (Rød, Hansen, Leipold, & Knøchel, 2012). Flexible thin-layer plasma treatment also caused lipid oxidation of raw pork and beef after only a 10 min exposure (Jayasena et al., 2015). Generally, conditions of increased plasma power, treatment time, and storage will result in lipid oxidation. The different lipid oxidation results with APP treatment might be explained by the variations in fat content and fatty acid composition of the meat products being tested (Kim et al., 2011).

3.3. Surface color

Color is important among the several food quality attributes, because it determines consumer acceptance of the food at the time of purchase (Nam & Ahn, 2002). The surface color of plasma-treated jerky is presented in Table 1. With increasing plasma exposure time, the L^* value and hue angle decreased whereas the a^*, ΔE value and chroma increased ($P < 0.05$). No significant changes in b^* value and BI were observed among the samples. According to these results, the surface color of the beef jerky became not brown but more clearly dark-red with plasma treatment.

Several previous studies have applied APP to processed meat products. Rød et al. (2012) use APP inside a polyethylene bag containing 70% argon and 30% oxygen gas. Accordingly, the a^* value of the plasma-treated bresaola was comparable to that of the plasma-untreated sample. Moreover, no significant changes were found in the L^*, a^*, and

Table 1
Effect of flexible thin-layer plasma treatment on color parameter values of beef jerky.

Color parameter values	Treatment time (min)				SEM
	0	2.5	5	10	
L^*	29.28[a]	29.39[a]	27.80[b]	27.48[b]	0.418
a^*	5.24[b]	6.19[a]	7.05[a]	6.92[a]	0.262
b^*	5.70	6.05	5.38	5.22	0.284
ΔE	-[b]	1.55[a]	2.63[a]	2.60[a]	0.385
Hue	47.41[a]	44.32[a]	37.36[b]	36.97[b]	2.026
Chroma	7.76[b]	8.67[a]	8.87[a]	8.67[a]	0.252
Browning index	33.93	37.60	38.90	38.37	1.579

SEM, standard error of the mean ($n = 12$). [a–b]Different letters within a column indicate significant difference per Duncan's multiple comparison test ($P < 0.05$).

b^* values of beef jerky treated with radio-frequency APP using argon gas (Kim, Lee, Choi, & Kim, 2014). On the other hand, Kim et al. (2011) showed decreased L^* values and increased a^* values in APP-treated bacon, similar to the results of the present study.

When APP is generated inside polymeric food packaging materials, including polypropylene and polyethylene terephthalate, organic bonds (i.e., C—H, C—C, C—C, C—O, and C—N) are broken. As such, the organic substances can react with oxygen species (O^-, O^+, O_2, or O_3) to form carbon dioxide or carbon monoxide (Pankaj et al., 2014). If the carbon monoxide combines with myoglobin in meat products, carboxymyoglobin (CO-Mb) can be formed (Nam & Ahn, 2002). Many ligands (O_2, CN, NO, CO, and N_3) can bind to the heme iron in myoglobin, where different binding ligands produce different colors. In the case of CO-Mb, it appears as a bright red color that increases the a^* value (Nam & Ahn, 2002).

Using thin-layer plasma in ambient air, nitrogen and oxygen molecular spectra were observed in the emission spectrum (Jayasena et al., 2015). This result points to the fact that the plasma system is a source of ROS and RNS, including NO. The combination of NO with myoglobin or metmyoglobin produces nitrosomyoglobin (NO-Mb, bright-red color) or nitrosometmyoglobin (NO-MMb, dark-red color), respectively. Both NO-Mb and NO-MMb can increase the a^* value of meat. Previously, APP-treated water was used as a nitrite source for meat curing, and through its increased color developing capacity, it resulted in an increase of the a^* value in meat batter and emulsion-type sausage (Jung et al., 2015a, 2015b).

It is assumed that the formation of NO-MMb will give beef jerky a dark-red color after plasma treatment. However, this is not conclusive because no changes were found in the metmyoglobin content with use of the same plasma (Fig. 4). Further in-depth study is needed to elucidate the mechanism of meat product discoloration by APP.

3.4. Shear force and myofibrillar fragmentation index

In jerky products, texture is one of the most important sensory attributes to consumers and can be used to assess quality. MFI is a measure of the average length of myofibrils, where the shorter the myofibril fragmentations are the greater is the tenderness (Taylor, Geesink, Thompson, Koohmaraie, & Goll, 1995). MFI also used to evaluate the textural properties in jerky (Han et al., 2011; Jang et al., 2015). In the present study, there is no difference found in MFI and shear force between plasma-treated beef jerky and untreated control (Table 2).

Texture properties in meat products are also affected by lipid oxidation (Baron & Andersen, 2002). Despite that the plasma caused lipid oxidation of raw pork and beef, no changes in texture parameters were found, including hardness, springiness, cohesiveness, gumminess, and chewiness (Jayasena et al., 2015). Kim et al. (2014a, 2014b) also found that plasma treatment did not affect the shear force of beef jerky, which is in agreement with our present results.

3.5. Sensory evaluation

Our results indicated that the color, taste, and tenderness of the beef jerky were not affected by the flexible thin-layer plasma (Table 3). However, plasma treatment over 10 min resulted in the slight change of the flavor, off-odor, and overall acceptability of the beef jerky with statistical significance. Flavor is the combination of basic tastes and odors derived from volatile substances present in the food product. The chemical composition of fresh meat provides the precursor compounds for development of aromas and flavors, desirable or undesirable (Brewer, 2009).

There are several causes of off-odor or different flavor. One is sulfur-containing volatiles, including dimethyl disulfide, methyl mercaptan, and hydrogen sulfide, which are generated by the breakdown of sulfur-containing compounds by radical species (•H, •OH, or H_3O^-). Dimethyl trisulfide is one of the most potent off-odor compounds, contributing fishy and putrid odors, followed by bis(methylthio)methane (Ahn et al., 2016; Brewer, 2009). Another cause is lipid oxidation, which is responsible for rancid odors and flavors, and some are very reactive. Additionally, the oxidation of unsaturated fatty acids in phospholipids and triacylglycerols also contributes to off-flavors (Brewer, 2009).

Irradiation also generates high-energy species ($^1O_2$, •OOH, •OH •OOR, and ROOH) and causes off-odor in meat and meat products (Ahn et al., 2016). Brewer (2009) reported that irradiation-associated odors can be reduced by applying modified-atmosphere packaging, temperature reduction prior to irradiation, and addition of antioxidants. Thus, it should be possible to reduce plasma-generated off-odors; such a method should be found for further implementation to industry.

4. Conclusion

Flexible thin-layer plasma treatment using ambient air reduced the number of bacteria and mold in packaged beef jerky. Although no changes were found in the metmyoglobin content, shear force, and

Table 2
Effect of flexible thin-layer plasma treatment on the shear force and myofibrillar fragmentation index (MFI) of beef jerky.

Physicochemical properties	Treatment time (min)				SEM
	0	2.5	5	10	
Shear force (N)	68.65	73.51	72.13	73.42	3.749
MFI	6.43	6.58	6.47	6.65	0.247

SEM, standard error of the mean ($n = 12$).

Table 3
Effect of flexible thin-layer plasma treatment on the sensory property of beef jerky.

Sensory parameters	Treatment time (min)				SEM
	0	2.5	5	10	
Color	5.95	5.75	5.62	5.58	0.301
Flavor	5.50[a]	5.45[a]	4.33[ab]	3.53[b]	0.444
Taste	5.31	4.98	4.95	4.91	0.415
Tenderness	4.25	4.08	4.45	4.38	0.487
Off-odor	0.90[b]	1.00[b]	1.47[b]	2.28[a]	0.264
Overall acceptability	5.48[a]	5.25[a]	5.09[a]	3.48[b]	0.411

SEM, standard error of the mean ($n = 40$). [a–b]Different letters within a row indicate significant difference per Duncan's multiple comparison test ($P < 0.05$).

MFI of plasma-treated samples, differences were observed in some sensory parameters, including off-odor. The undesirable sensory changes can be minimized by presently available methods, while the effectiveness of this technology for food safety and shelf-life extension may be rapidly developed for the food industry.

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