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Impacts of Irradiation Sources on Quality Attributes of Low-salt Sausage during Refrigerated Storage

Dong-Heon Song, Hyun-Wook Kim¹, Ko-Eun Hwang, Yong-Jae Kim, Youn-Kyung Ham, Yun-Sang Choi², Dong-Jin Shin, Tae-Kyung Kim, Jae Hoon Lee, Cheon-Jei Kim*, and Hyun-Dong Paik*

Department of Food Science and Biotechnology of Animal Resources, Konkuk University, Seoul 05029, Korea

¹Department of Animal Science and Biotechnology, Gyeongnam National University of Science and Technology, Jinju 52725, Korea

²Food Processing Research Center, Korean Food Research Institute, Wanju 55365, Korea

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*Corresponding authors

Hyun Dong Paik

Department of Food Science and
Biotechnology of Animal Resources,
Konkuk University, Seoul 05029,
Korea

Tel: +82-2-2049-6011

Fax: +82-2-455-3082

E-mail: hdpaik@konkuk.ac.kr

Cheon Jei Kim

Department of Food Science and
Biotechnology of Animal Resources,
Konkuk University, Seoul 05029,
Korea

Tel: +82-2-450-3676

Fax: +82-2-455-3082

E-mail: kimcj@konkuk.ac.kr

*Cheon-Jei Kim and Hyun-Dong Paik
contributed equally to this work.

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Abstract

This study was performed to investigate the impacts of irradiation sources on quality attributes of low-salt sausage during refrigerated storage. Control sausage was prepared with 1.5% sodium chloride (NaCl), whereas low-salt sausage was formulated with 0.75% NaCl (a 50% reduction; L-control). Sausage samples were vacuum-packaged, and low-sausages were irradiated with gamma-ray, electron-beam and X-ray at 5 kGy, respectively. The samples were stored at 4°C for 28 d to determine changes in quality attributes. The pH of low-salt sausages was unaffected by irradiation at 5 kGy ($p>0.05$). Higher redness values were found at irradiated low-salt sausages compared to control ($p<0.05$). The hardness, gumminess and chewiness of control sausage were higher than those of low-salt sausages ($p<0.05$). However, there were no significant differences in the textural parameters between low-salt sausage treatments. The overall sensory acceptability score of irradiated/low-salt sausages were lower than L-control due to decreased scores for cooked meat flavor but increased radiolytic off-flavor ($p<0.05$). The initial 2-thiobarbituric acid-reactive substances (TBARS) values of irradiated/low-salt sausages were higher than control and L-control ($p<0.05$). However, the TBARS values of irradiated treatments were significantly lower than control at the end of storage. Irradiation could effectively inhibit the microorganism growth (total aerobic bacteria, coliforms, *Enterobacteriaceae*, and *Pseudomonas* spp.) in low-salt sausages ($p<0.05$). Therefore, our findings show that irradiation could be to improve microbial safety of low-salt sausages, and suggest that further studies should be necessary to reducing radiolytic off-flavor of irradiated/low-salt sausages.

Keywords sausage, low-sodium, lipid oxidation, microbial, ionizing source

Introduction

Excessive sodium intake is highly related to the potential risks of cardiovascular diseases, hypertension and stroke in human body (Grossi *et al.*, 2012; Tobin *et al.*, 2013). In this regard, modern consumers have attempted to reduce sodium intake from their daily diet. Processed meat products are regarded as a high-sodium food, since they generally contain 433-1,080 mg of sodium (approximately 1.1-2.7 g of salt) per 100 g of sausage (Desmond, 2006). To meet the consumer's demand on

healthier meat products, thus, the meat industry has been trying to reduce the addition of sodium salts in processed meat products (Ruusunen and Puolanne, 2005).

Sodium chloride (NaCl) is commonly added to processed meat products with multiple purposes, leading to desirable quality attributes of final products (Desmond, 2006; Grossi *et al.*, 2012; Tobin *et al.*, 2013). In particular, a direct reduction in NaCl (less 0.75 g per 100 g) could result in considerable quality defects on technological (emulsion stability, protein solubility, cooking yield), textural, sensory, and microbial properties of emulsion sausage (Desmond, 2006; Song *et al.*, 2014). Recent studies have reported that the technological and textural properties of low-salt emulsion sausage could be improved through the addition of functional ingredients such as hydrocolloids and non-meat proteins (García-García and Totosaus, 2008; Grossi *et al.*, 2012). However, Desmond (2006) indicated that additional preservative methods should be necessary to guarantee the microbial safety of low-salt processed meat products during further storage, thereby controlling the growth of food spoilage and/or food-borne bacteria.

Food irradiation technology has been practically used as an effective preservative method to not only reduce initial microbial contamination, but also delay microorganism growth during storage in meat products (Kim *et al.*, 2012; Park *et al.*, 2010; Roberts, 2014). According to Shin *et al.* (2014), irradiation dose over 4 kGy could be effective in controlling total aerobic bacteria in emulsion sausage. Thus, it would be reasonable to anticipate that irradiation technology contributes to ensure microbial safety of low-salt emulsion sausage. In practice, previous studies have revealed that irradiation technology could improve microbial property of several low-salt foods, without any adverse impacts on quality characteristics (Byun *et al.*, 2000; Lee *et al.*, 2002; Park *et al.*, 2002). However, the effect of irradiation on microbial property in low-salt emulsion sausage has not been fully investigated.

Codex Alimentarius Commission (CODEX), World Health Organization (WHO), and Food and Agriculture Organization (FAO) have approved gamma-rays, electron-beams, and X-rays as sources for food irradiation (CODEX, 2003; Grégoire *et al.*, 2003). Gamma-rays are electromagnetic waves emitted from radioactive isotopes such as cobalt-60 or cesium-137 that have strong penetration (Shin *et al.*, 2014). Electron-beams are mechanically generated by electron accelerator and directly irradiate products, it has advantages of control convenience and

favorable perception consumer acceptance, but weak penetration power compared to gamma-ray (Grégoire *et al.*, 2003; Ham, 2017). Electron accelerators can be transform from the electron beam mode to the X-ray mode, thereby providing a wide range of dose rates (Miller, 2003). X-rays are produced by bremsstrahlung effect when high-energy electrons strike target material and indirectly irradiate products (Ham, 2017; Miller, 2003). It has advantages which are better power utilization, reduced treatment time, improved dose uniformity and strong penetration (Grégoire *et al.*, 2003). However, the major limitation of X-ray irradiation is high cost and low energy efficiency compared to gamma or electron beam irradiation (Ham, 2017). In this regard, the percentage of their use is approximately 80% for gamma rays, and 20% for electron beams and X-rays (Go, 2016). A recent study has indicated that three irradiation sources (gamma-ray, electron-beam, and X-ray) led to different efficacies on microbial properties as well as color characteristic and lipid oxidation stability (Ham *et al.*, 2017).

Therefore, the objective of this study was to evaluate the irradiation efficacies of three irradiation sources, gamma-ray (γ -ray), electron-beam (E-beam) and X-ray, on physico-chemical, textural, sensory, and microbial properties of low-salt emulsion sausage during 28 d of refrigerated storage.

Materials and Methods

Emulsion sausage processing

Fresh pork ham (*M. biceps femoris*, *M. semitendinosus*, and *M. semimembranosus*) and pork back fat at 48 h post-mortem were purchased from a local market. All subcutaneous fat and visible connective tissues were removed from the pork ham muscle. The pork ham and pork back fat were ground using a meat grinder (Optimo MEW 619, Mado, Germany) equipped with an 8-mm plate. Five different groups of emulsion sausages were prepared as follows. The Control group was prepared with 1.5% salt, whereas four low-salt groups, to reduce salt addition by 50% were individually formulated with 0.75% salt. Pork meat, with the targeted amount of NaCl (1.5 or 0.75%), 0.012% sodium nitrite and 0.3% sodium tripolyphosphate were homogenized and ground for 1 min 30 s in a silent cutter (MSK 760-II, Mado, Germany). Then, ice and pork back fat were added and mixed for additional 2 min 30 s. Finally, the meat batter was homogenized with spices (0.05%, ascorbic acid, 0.5% spice, 2% isolated soy protein, 0.5% sugar, 0.1% pepper, 0.3% onion powder, 0.2%

garlic powder, and 0.1% ginger powder) for 3 min. The temperature of the meat batter was maintained below 10°C throughout batter preparation. The meat batter was stuffed into collagen casings (#240; NIPPI Inc., Japan; approximate diameter, 25 mm) using a stuffer (Vacuum stuffer Konti A50, Frey, Germany). The raw sausages were heated to 75±1°C (core temperature) for 30 min in a smoke chamber (1900 EL-C-Q, Kerres, Germany). After cooking, the cooked sausages were cooled, vacuum-packaged, and stored in a 4°C refrigerator for one day until the irradiation process. A total of three different batches were prepared on different days.

Irradiation procedure

The vacuum-packaged emulsion sausages (approximately 25-mm thickness) were irradiated at 5 kGy using three different ionizing sources under the an ambient temperature of 22±2°C. Gamma-ray irradiation was conducted in a cobalt-60 irradiator (100 kCi, AECL, IR-79, MDS Nordion Inc., Canada) at the Korea Atomic Energy Research Institute (Korea) with a source strength of approximately 11.1 PBq, at a dose rate of 10 kGy/h. X-ray and E-beam irradiation were performed using an ELV-4 electron-beam accelerator (10 MeV) and X-ray linear accelerator (7.5 MeV), respectively, at EB-Tech Co. (Korea). X-ray and E-beam irradiation were performed with a beam current of 1 mA and dose rate of 5 kGy/h and 2.9 kGy/s, respectively. For dosimetry of samples, alanine dosimeters (5 mm diameter; Bruker Instruments, Germany) were attached to two different positions (top and bottom) of the samples. The absorbed dose was measured with an electron paramagnetic resonance analyzer in accordance with international standards (ISO/ASTM 51607, 2004). The dose uniformity ratios (min/max ratios) of all irradiation sources were less than 1.2 and the actual dose was within ±5% of the target dose. After irradiation, the irradiated samples were stored at 4±1°C for 28 d and weekly analyzed.

pH values

The pH values of samples were measured in a homogenate prepared with 5 g of sample and distilled water (20 mL) using an electric pH meter (Model 340, Mettler-Toledo GmbH, Switzerland). All determinations were performed in triplicate.

Color measurements

The color of each sample was determined using a col-

orimeter (Minolta Chroma meter CR-210, Minolta Ltd., Osaka, Japan; illuminate C, calibrated with a white plate, L* = +97.83, a* = -0.43, b* = +1.98) from cross-sections selected from five random locations on cross-section of each sample. Lightness (CIE L* - value), redness (CIE a* - value), and yellowness (CIE b* - value) values were recorded.

2-Thiobarbituric acid-reactive substances (TBARS)

Lipid oxidation was assessed in triplicate by the 2-thiobarbituric acid (TBA) method by Hwang *et al.* (2015). TBARS values of sausage samples were calculated using a standard curve (8-50 nmol) of 1,1,3,3-tetraethoxy propane (TEP) and expressed as mg malondialdehyde per kg sample (mg MDA/kg sample).

Texture profile analysis (TPA)

The texture profile analysis (TPA) of low-salt sausages were measured using a texture analyzer (TA-XT2i, Stable Micro System Ltd., UK). The sausages samples (20 mm in height) were taken from the central portion of each sample. The conditions of texture analysis were as follows: pre- and post-test speed 2.0 mm/s and 5.0 mm/s, head speed 2.0 mm/s, maximum load 2 kg, distance 8.0 mm, force 5 g. The calculation of texture values was obtained by graphing a curve using time and force plots.

Microbial analyses

The bacterial count in each sample was determined after 0, 7, 14, 21, and 28 d of refrigerated storage, using 3 M-Petrifilm for aerobic count plates, *E. coli*/coliforms and *Enterobacteriaceae* (AOAC International, 2005; Silbernagel and Lindberg, 2003). The *Pseudomonas* spp. were determined using *Pseudomonas* agar base with Cetrimide-Fucidin-Cephaloridine selective supplement (Oxoid), incubated at 30°C for 48 h (Georgantelis *et al.*, 2007).

Sensory evaluation

The sensory evaluations were performed by nine trained sensory panelists (25-31 years old) from the Department of Food Sciences and Biotechnology of Animal Resources at Konkuk University. The selection of trained panelists was performed according to sensory evaluation procedures (Lawless and Heymann, 2010). Sausage sample were evaluated in terms of the intensity of cured/cooked color, the intensity of cooked meat flavor, the intensity of radiolytic off-flavor, juiciness, tenderness, and overall acceptability. The emulsion sausage samples were reheated until the core temperature reached 40°C, cut into 1-cm-thickness

slice, and served randomly to the panelists. Each sample was coded with a randomly selected 3-digit number. Sensory evaluations were performed under fluorescent lighting. Panelists were instructed to cleanse their palates with water before tasting the next samples. The cured/cooked color (1 = weak cured/cooked pink-reddish color, 9 = strong cured/cooked pink-reddish color), cooked meat flavor intensity (1 = extremely weak, 9 = extremely strong), radiolytic off-flavor (1 = extremely strong, 9 = extremely weak), tenderness (1 = extremely tough, 9 = extremely tender), juiciness (1 = extremely dry, 9 = extremely juicy), and overall acceptability (1 = extremely rejective, 9 = extremely acceptable) of the cooked samples were evaluated using a 9-point descriptive scale. This analysis was conducted using the hedonic test described by Bergara-Almeida *et al.* (2002).

Statistical analysis

The experimental design of this study was a completely randomized block design with three different batches. Statistical analysis and comparisons among means were carried out using the statistical package SPSS 18.0 (SPSS Inc., USA). All data were analyzed by ANOVA to test the effects of two fixed factors: storage periods and irradiation type. The Duncan's multiple range test was applied for comparisons of means; differences were considered significant at $p < 0.05$.

Results and Discussion

pH and color characteristics

Change in the pH value of irradiated/low-salt sausages during refrigerated storage is shown in Table 1. The initial pH of emulsion sausages was not affected by NaCl level and irradiation source ($p > 0.05$). Similar to our result, Hwang *et al.* (2015) reported that the pH value of chicken sausages irradiated at 0, 2.5 and 5 kGy was not different. In addition, Kim *et al.* (2012) also revealed that gamma-ray irradiation within 4 kGy had no impact on the pH values of fermented pork sausage. In this current study, the change in pH value during refrigerated storage was observed at only control, in which the pH increased from 6.25 to 6.36 ($p < 0.05$). However, the pH value of low-salt sausages was not changed during refrigerated storage, regardless of irradiation ($p > 0.05$). Thus, our finding indicates that irradiation had little to no impacts on change in pH value of emulsion sausage during refrigerated storage.

CIE L*-value (lightness) of control sausage was significantly higher than that of low-salt sausages during overall

storage period. Among low-salt sausage treatments, there was no significant difference in lightness between L-control and irradiated/low-salt sausages. Similarly, Shin *et al.* (2014) reported that X-ray or E-beam irradiation did not influence the lightness of emulsion sausage. Park *et al.* (2010) also reported that the lightness of beef sausage patties was not changed by gamma and E-beam irradiation, regardless of irradiation doses within 0-20 kGy.

At initial storage time (0 d), control sausage exhibited significantly lower redness than irradiated/low-salt sausages. Among low-salt sausages, irradiation tended to decrease redness, in which low-salt sausage irradiated E-beam showed significantly lower redness than L-control sausage. At 28 d of storage period, the redness of low-salt sausage irradiated with E-beam was lower compared to L-control sausage, but higher than control sausage ($p < 0.05$). At during storage period, the redness values of low-salt sausage irradiated with γ -ray and X-ray was similarly to L-control sausage. In relation to this observation, Ham *et al.* (2017) reported that irradiation up to 10 kGy decreased the redness of emulsion sausage, and they postulated that it might be related to the decomposition of nitrosyl hemochrome.

The initial yellowness of L-control sausage was slightly higher than that of low-salt sausages irradiated with E-beam or X-ray ($p < 0.05$). As storage period increased, the yellowness of all sausage treatments increased ($p < 0.05$). At final storage time (28 d), there was no significant difference in yellowness between sausage treatments. Thus, the results of this current study indicate that γ -ray, E-beam and X-ray irradiation at 5 kGy had little impacts on color characteristics of low-salt sausages during 28 d of refrigerated storage, however, the redness of irradiated/low-salt sausages higher values than control sausage.

Textural properties

Change in textural properties of irradiated/low-salt sausages during refrigerated storage is shown in Table 2. At 0 d, low-salt sausages exhibited significantly lower initial hardness, gumminess and chewiness than control sausage. The textural properties of emulsion sausage are associated with salt-soluble protein extraction, which greatly affects water and fat binding capacities, gel-formation, and viscosity (Lee *et al.*, 1998; Ruusunen and Puolanne, 2005). In general, an increase in NaCl concentration could contribute to increase hardness of emulsion sausage (Tobin *et al.*, 2013). Thus, the decreased hardness, gumminess and chewiness of low-salt sausages was likely due to a dec-

Table 1. Changes in pH value and color characteristics of irradiated/low-salt sausage during refrigerated storage

Storage (d)	Control (1.5% NaCl)	Low-salt sausages ¹⁾ (0.75% NaCl)				SEM ²⁾
		L-control	γ-ray	E-beam	X-ray	
pH						
0	6.25 ^a	6.27	6.29	6.32	6.30	0.013
7	6.32 ^{ab}	6.34	6.34	6.34	6.34	0.012
14	6.32 ^{ab}	6.29	6.29	6.30	6.30	0.015
21	6.31 ^{ab}	6.26	6.26	6.29	6.30	0.012
28	6.36 ^b	6.32	6.29	6.30	6.30	0.013
SEM	0.014	0.014	0.013	0.012	0.012	
CIE L*-value (lightness)						
0	75.45 ^{Bc}	73.59 ^{Ab}	73.78 ^{Abc}	73.74 ^{Abc}	73.39 ^{Ab}	0.371
7	75.50 ^{Bc}	74.12 ^{Ab}	74.28 ^{Ac}	74.18 ^{Ac}	74.13 ^{Ab}	0.266
14	74.43 ^{Cb}	73.63 ^{ABb}	73.81 ^{ABbc}	73.28 ^{Ab}	74.19 ^{BCb}	0.203
21	75.34 ^{Bc}	73.83 ^{Ab}	73.27 ^{Ab}	73.58 ^{Abc}	73.88 ^{Ab}	0.357
28	72.88 ^{Ba}	71.82 ^{ABa}	71.49 ^{Aa}	72.14 ^{ABa}	71.38 ^{Aa}	0.270
SEM	0.499	0.407	0.487	0.344	0.523	
CIE a*-value (redness)						
0	7.95 ^A	9.35 ^{Cb}	9.04 ^{BCb}	8.98 ^{Bab}	9.32 ^{BCc}	0.255
7	7.56 ^A	8.81 ^{Ba}	8.48 ^{Ba}	8.72 ^{Ba}	8.96 ^{Bbc}	0.249
14	7.79 ^A	9.15 ^{Cab}	8.80 ^{Cab}	8.87 ^{Cab}	8.42 ^{Ba}	0.236
21	8.12 ^A	8.90 ^{Bab}	8.95 ^{Bb}	9.09 ^{Bb}	9.19 ^{Bc}	0.189
28	8.10 ^A	9.25 ^{Dab}	8.98 ^{Cb}	8.69 ^{Ba}	8.75 ^{Bab}	0.190
SEM	0.106	0.102	0.100	0.076	0.160	
CIE b*-values (yellowness)						
0	12.60 ^{ABab}	12.97 ^B	12.53 ^{ABa}	12.33 ^{Aa}	12.40 ^{Aa}	0.112
7	12.75 ^{ab}	13.19	12.84 ^a	12.98 ^{bc}	12.88 ^b	0.076
14	13.41 ^{bc}	13.05	12.81 ^a	13.20 ^{bc}	13.25 ^b	0.101
21	13.27 ^{Bc}	13.24 ^B	12.91 ^{Aab}	12.74 ^{Aab}	12.82 ^{Ab}	0.109
28	13.42 ^c	13.45	13.38 ^b	13.37 ^c	13.25 ^b	0.035
SEM	0.172	0.084	0.138	0.183	0.158	

¹⁾Low-salt sausages were non-irradiated (L-control) or irradiated with gamma-ray (γ-ray), electron-beam (E-beam), X-ray at 5 kGy, respectively.

²⁾SEM: the standard error of the means (n=3).

^{A-C}Means with different letters within the same row were significantly different (p<0.05).

^{a-c}Means with different letters within the same column were significantly different (p<0.05).

rease in salt-soluble protein solubility with reduced level of NaCl. At 28 d of storage time, although the hardness of low-salt sausages irradiated with E-beam or X-ray was lower than that of L-control sausage (p<0.05), there was no significant differences in gumminess and chewiness between low-salt sausage treatments. In addition, all sausage treatments showed similar springiness and cohesiveness at each storage time (p>0.05). As similar observations, previous studies have reported that irradiation dose or irradiation source had no impacts on textural properties of processed meat products (Gámez *et al.*, 2011; Ham *et al.*, 2017; Park *et al.*, 2010). Thus, our findings also show that the addition level of NaCl could be more critical factor affecting initial textural properties of emulsion sausage, such as hardness, gumminess and chewiness, rather than the application of irradiation and/or irradiation sources.

Sensory properties

Change in sensory properties of irradiated/low-salt sausages during refrigerated storage is shown in Table 3. During 28 d of refrigerated storage, all sausage treatments exhibited similar cured/cooked color intensity at each storage time (p>0.05). In terms of flavor parameters, the intensity of cooked meat flavor of low-salt sausages was lower than that of control during overall storage period (p<0.05). Previously, Gillette (1985) reported that NaCl added to meat products plays an important role in forming saltiness, mouthfeel, balance, and sweetness, while it could contribute to decrease off-flavor odors. Thus, it has been suggested that major limitation of low-salt meat products is the declines of perceived saltiness and the intensity of flavor (Desmond, 2006; Ruusunen and Puolanne, 2005). In this current study, low-salt sausage irra-

Table 2. Changes in textural properties of irradiated/low-salt sausage during refrigerated storage

Storage (d)	Control (1.5% NaCl)	Low-salt sausages ¹⁾ (0.75% NaCl)				SEM ²⁾
		L-control	γ -ray	E-beam	X-ray	
Hardness (g)						
0	369.77 ^{Ba3)}	291.19 ^{Aa}	302.56 ^{Aa}	287.82 ^{Aa}	294.56 ^{Aa}	6.176
7	449.59 ^{Bbc}	340.96 ^{Ab}	348.98 ^{Ab}	347.69 ^{Ac}	353.62 ^{Ab}	7.852
14	432.78 ^{Cb}	325.89 ^{ABb}	339.26 ^{Ba}	316.26 ^{Ab}	332.08 ^{ABb}	7.105
21	455.52 ^{Cbc}	385.09 ^{Bc}	362.68 ^{Ac}	361.08 ^{Ac}	355.31 ^{Ab}	6.233
28	478.26 ^{Cc}	389.13 ^{BCc}	367.77 ^{ABc}	358.28 ^{Ac}	348.86 ^{Ab}	7.760
SEM	6.961	6.662	5.205	5.421	4.729	
Springiness						
0	0.94	0.93	0.93 ^{ab}	0.93 ^{ab}	0.93	0.003
7	0.95	0.94	0.93 ^{ab}	0.95 ^b	0.94	0.002
14	0.94	0.94	0.95 ^b	0.94 ^b	0.94	0.002
21	0.94	0.93	0.94 ^{ab}	0.94 ^{ab}	0.93	0.002
28	0.94	0.93	0.93 ^a	0.92 ^a	0.94	0.003
SEM	0.002	0.003	0.003	0.003	0.002	
Cohesiveness						
0	0.44 ^a	0.44 ^a	0.45 ^a	0.45 ^a	0.44 ^a	0.002
7	0.46 ^{ab}	0.48 ^b	0.47 ^b	0.46 ^{bc}	0.46 ^b	0.005
14	0.45 ^{Aab}	0.48 ^{Bb}	0.47 ^{Bb}	0.45 ^{Aab}	0.44 ^{Aa}	0.003
21	0.45 ^{Aab}	0.46 ^{Aab}	0.47 ^{Bab}	0.48 ^{Bc}	0.47 ^{Bb}	0.003
28	0.47 ^b	0.46 ^{bc}	0.45 ^{ab}	0.46 ^{bc}	0.47 ^b	0.004
SEM	0.005	0.004	0.003	0.003	0.004	
Gumminess (g)						
0	161.75 ^{Ba}	127.42 ^{Aa}	134.68 ^{Aa}	128.04 ^{Aa}	129.54 ^{Aa}	2.540
7	209.19 ^{Bbc}	162.00 ^{Ab}	163.52 ^{Ab}	160.81 ^{Ac}	163.71 ^{Ac}	3.983
14	194.48 ^{Cb}	156.14 ^{Bb}	159.30 ^{Bb}	142.34 ^{Ab}	145.74 ^{Ab}	3.195
21	205.10 ^{Bb}	175.67 ^{Ac}	169.00 ^{Bb}	171.80 ^{Ac}	167.39 ^{Ac}	2.564
28	225.76 ^{Bc}	180.69 ^{Ac}	167.34 ^{Ab}	165.63 ^{Ac}	164.99 ^{Ac}	4.191
SEM	4.331	3.215	2.758	3.051	2.652	
Chewiness (g)						
0	152.21 ^{Ba}	118.28 ^{Aa}	125.84 ^{Aa}	119.07 ^{Aa}	120.54 ^{Aa}	2.458
7	197.79 ^{Bbc}	151.72 ^{Ab}	152.73 ^{Ab}	152.01 ^{Ac}	153.98 ^{Ac}	3.780
14	183.76 ^{Cb}	147.43 ^{Bb}	150.71 ^{Bb}	134.15 ^{Ab}	136.64 ^{Ab}	3.132
21	192.67 ^{Bbc}	163.70 ^{Ac}	158.50 ^{Ab}	160.91 ^{Ac}	156.32 ^{Ac}	2.428
28	211.49 ^{Bc}	167.76 ^{Ac}	154.99 ^{Ab}	153.14 ^{Ac}	154.82 ^{Ac}	4.034
SEM	4.084	2.984	2.606	2.913	2.515	

¹⁾Low-salt sausages were non-irradiated (L-control) or irradiated with gamma-ray (γ -ray), electron-beam (E-beam), X-ray at 5 kGy, respectively.

²⁾SEM: the standard error of the means ($n=3$).

^{A-C}Means that different letters within the same row were significantly different ($p<0.05$).

^{a-c}Means that different letters within the same column were significantly different ($p<0.05$).

diated with γ -ray had a significantly lower cooked meat flavor score than L-control. In addition, irradiated/low-salt sausages showed a significantly higher radiolytic off-flavor scores than L-control, regardless of irradiation source. According to Ahn *et al.* (2000), radiolytic off-odor in irradiated pork could be due to the formation of volatile sulfur compounds, especially 2,3-dimethyl disulfide, derived from sulfur-containing amino acids. The tenderness and juiciness of emulsion sausages were greatly affected by the addition level of NaCl during overall storage period ($p<0.05$), rather than the application of irradiation

and/or irradiation sources. These results could be due to the reduced addition of NaCl, as mentioned in the instrumental texture above. As expected, the reduced addition of NaCl decreased salty intensity of emulsion sausage ($p<0.05$). However, the salty intensity score of low-salt sausages was similar, regardless of irradiation source ($p>0.05$). The result of overall acceptability showed a significantly decreased score in irradiated/low-salt sausages compared to control sausage and even L-control sausage, resulting from the decreased intensity of cooked meat flavor, tenderness, juiciness and radiolytic off-flavor.

Table 3. Changes in sensory properties of irradiated/low-salt sausage during refrigerated storage

Storage (d)	Control (1.5% NaCl)	Low-salt sausages ¹⁾ (0.75% NaCl)				SEM ²⁾
		L-control	γ-ray	E-beam	X-ray	
Cured/cooked color						
0	7.89 ^{ab3)}	7.68 ^b	7.61 ^{ab}	7.64 ^b	7.46	0.079
7	7.93 ^b	7.57 ^{ab}	7.68 ^b	7.46 ^{ab}	7.57	0.077
14	7.79 ^{ab}	7.71 ^b	7.75 ^b	7.61 ^b	7.50	0.076
21	7.36 ^a	7.21 ^{ab}	7.39 ^{ab}	7.04 ^a	7.29	0.073
28	7.36 ^a	7.07 ^a	7.18 ^a	7.11 ^a	7.07	0.075
SEM	0.081	0.087	0.068	0.073	0.078	
Cooked meat flavor						
0	7.36 ^C	6.64 ^B	6.04 ^A	6.43 ^{AB}	6.54 ^{AB}	0.089
7	7.11 ^C	6.86 ^{BC}	6.21 ^A	6.36 ^{AB}	6.29 ^A	0.085
14	7.46 ^C	6.64 ^B	5.86 ^A	6.14 ^{AB}	6.21 ^{AB}	0.090
21	7.11 ^C	6.50 ^B	5.86 ^A	6.14 ^{AB}	6.21 ^{AB}	0.079
28	7.32 ^C	6.64 ^B	5.93 ^A	6.21 ^{AB}	6.14 ^A	0.083
SEM	0.066	0.067	0.094	0.075	0.082	
Radiolytic off-flavor						
0	2.00 ^A	2.50 ^A	3.64 ^{Ca}	3.54 ^{Ba}	3.21 ^{Ba}	0.116
7	2.21 ^A	2.32 ^{AB}	3.93 ^{Dab}	3.36 ^{BCa}	3.82 ^{CDab}	0.122
14	2.29 ^A	3.04 ^A	4.50 ^{Bb}	3.50 ^{BCa}	4.04 ^{Bb}	0.137
21	2.21 ^A	2.86 ^{AB}	4.21 ^{Bab}	3.79 ^{Bab}	4.18 ^{Bb}	0.130
28	2.04 ^A	2.79 ^B	4.14 ^{Cab}	4.29 ^{Cb}	4.07 ^{Cb}	0.119
SEM	0.095	0.1118	0.111	0.105	0.117	
Tenderness						
0	7.68 ^B	6.89 ^A	6.68 ^A	6.50 ^A	6.79 ^{Ab}	0.106
7	7.46 ^B	6.46 ^A	6.46 ^A	6.36 ^A	6.54 ^{Aab}	0.088
14	7.25 ^B	6.68 ^A	6.46 ^A	6.50 ^A	6.61 ^{Aab}	0.086
21	7.25 ^B	6.61 ^A	6.18 ^A	6.21 ^A	6.25 ^{Aab}	0.081
28	7.18 ^B	6.39 ^A	6.18 ^A	6.07 ^A	6.18 ^{Aa}	0.084
SEM	0.081	0.086	0.083	0.090	0.084	
Juiciness						
0	7.54 ^B	6.71 ^A	6.29 ^A	6.25 ^A	6.46 ^A	0.108
7	7.25 ^B	6.39 ^A	6.39 ^A	6.25 ^A	6.07 ^A	0.098
14	7.46 ^B	6.89 ^A	6.54 ^A	6.39 ^A	6.43 ^A	0.087
21	7.18 ^B	6.75 ^B	5.96 ^A	6.04 ^A	6.14 ^A	0.092
28	7.29 ^B	6.43 ^A	6.11 ^A	5.96 ^A	6.07 ^A	0.089
SEM	0.061	0.103	0.096	0.096	0.080	
Saltiness						
0	5.79 ^B	4.61 ^A	4.46 ^A	4.43 ^A	4.64 ^A	0.099
7	5.93 ^B	4.71 ^A	4.61 ^A	4.46 ^A	4.50 ^A	0.100
14	5.71 ^B	4.50 ^A	4.25 ^A	4.39 ^A	4.50 ^A	0.097
21	5.50 ^B	4.64 ^A	4.54 ^A	4.32 ^A	4.64 ^A	0.094
28	6.00 ^B	4.57 ^A	4.46 ^A	4.18 ^A	4.36 ^A	0.109
SEM	0.091	0.095	0.092	0.090	0.079	
Overall acceptability						
0	7.46 ^B	6.46 ^A	6.07 ^A	6.36 ^{Ab}	6.50 ^{Ab}	0.099
7	7.36 ^B	6.93 ^B	6.32 ^A	6.43 ^{Ab}	6.21 ^{Aab}	0.082
14	7.57 ^C	6.50 ^B	5.96 ^A	6.36 ^{ABb}	6.14 ^{ABab}	0.083
21	7.36 ^C	6.57 ^B	5.96 ^A	6.14 ^{Aab}	5.93 ^{Aa}	0.081
28	7.50 ^C	6.43 ^B	5.89 ^A	5.79 ^{Aa}	5.93 ^{Aa}	0.082
SEM	0.076	0.077	0.069	0.076	0.073	

¹⁾Low-salt sausages were non-irradiated (L-control) or irradiated with gamma-ray (γ-ray), electron-beam (E-beam), X-ray at 5 kGy, respectively.

²⁾SEM: the standard error of the means (n=3).

^{A-D}Means that different letters within the same row were significantly different (p<0.05).

^{ab}Means that different letters within the same column were significantly different (p<0.05).

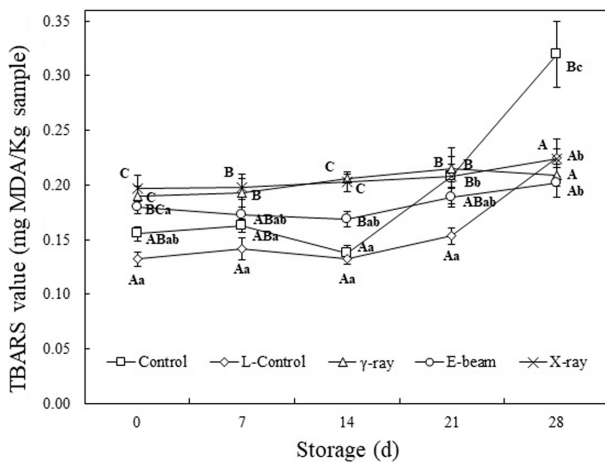


Fig. 1. Change in TBARS value of irradiated/low-salt sausages during refrigerated storage. Treatments: Control (□), sausage with 1.5% NaCl; L-control (◇), sausage with 0.75% NaCl; γ -ray (△), gamma-ray irradiated sausage with 0.75% NaCl; E-beam (○), E-beam irradiated sausage with 0.75% NaCl; X-ray (×), X-ray irradiated sausage with 0.75% NaCl. ^{A-C}Means sharing different letters within each storage day are significantly different ($p < 0.05$). ^{a-c}Means sharing different letters within each treatment are significantly different ($p < 0.05$).

2-Thiobarbituric acid-reactive substances (TBARS)

The effect of irradiation source on TBARS values of irradiated/low-salt sausages during 28 d of refrigerated storage is shown in Fig. 1. At initial storage time (0 d), L-control sausage (0.13 mg MDA/kg sample) had a slightly lower TBARS value than control sausage (0.16 mg MDA/kg sample), while it was not significant. However, irradiation obviously increased TBARS value of low-salt sausages, when compared to L-control sausage ($p < 0.05$). As refrigerated storage period increased, TBARS value of all sausage treatment significantly increased. From 21 d of storage time, in addition, the TBARS value of control sausage noticeably increased. At the end of storage, the highest TBARS value was found at control ($p < 0.05$), in which there was no significant difference in TBARS value between low-salt sausages. It could be interest to note that irradiated/low-salt sausages showed the delayed lipid oxidation compared to control sausage, since it has been known that irradiation accelerates lipid oxidation of meat products (Ahn *et al.*, 2000). In general, lipid oxidation of processed meat products is highly dependent on the addition level of NaCl (Love and Pearson, 1971). Jin *et al.* (2012) reported that the TBARS value of pork muscle was greatly increased with increasing the adding amount of NaCl (0.5-4%). According to Lee *et al.* (1997), the

addition of NaCl over 1% could accelerate lipid oxidation of pork meat during 4 wk of storage. In this current study, thus, the accelerated lipid oxidation of control sausage from 21 d could result from the relatively high amount of NaCl. As well as, E-beam irradiation could slowly accelerate lipid oxidation of low-salt sausages than γ -ray or X-ray irradiation. Ham *et al.* (2017) recently reported that gamma-ray or X-ray irradiation significantly increased the TBARS value of processed meat products, when compared to E-beam irradiation. Lee *et al.* (2008) reported that the gamma ray more affects the decomposition of the long chain of fatty acids and the double bonds of unsaturated fatty acids than E-beam, when irradiated at the same dose.

Microbial properties

Change in microbial properties of irradiated/low-salt sausages during refrigerated storage is shown in Table 4. The initial total aerobic bacteria (TAB) populations in control and L-control treatments was less than 1 log CFU/g, whereas it was not detected in irradiated/low-salt sausages, regardless of irradiation source. At 28 d of storage time, the TAB population of control sausage and L-control sausage was 3.5 and 6.0 Log CFU/g, respectively. On the other hand, the growth of TAB in low-salt sausages irradiated with γ -ray was not observed until 28 d of storage. Similarly, Park *et al.* (2010) indicated that γ -ray irradiation was more effective in preventing the growth of TAB in beef sausage patty, rather than E-beam irradiation. The coliform and *Enterobacteriaceae* were detected in only L-control, at 14 (3.1 Log CFU/g) and 21 d (1.7 Log CFU/g). *Pseudomonas* spp. are well-known food spoilage gram-negative bacteria and are known to grow at low temperatures of less than 7°C as a halophilic bacteria (Jay *et al.*, 2003; Ventosa *et al.*, 1998). Our result showed no initial growth of *Pseudomonas* spp. in all treatments. At 21 d of storage, only L-control had the population of *Pseudomonas* spp. (2.0 Log CFU/g), but it was not detected in other treatments. Finally, at 28 d, control and L-control sausage had *Pseudomonas* spp. population of 0.6 and 5.1 Log CFU/g, respectively. Thus, the results of this current study indicate that irradiation technology could be the most effective way to inhibit microbial growth of low-salt sausage.

Conclusion

In this study, our findings confirmed that 50% reduction in NaCl (from 1.5% to 0.75%) could decrease some quality attributes of emulsion sausage, particularly textu-

Table 4. Changes in microbial properties (Log CFU/g) of irradiated/low-salt sausage during refrigerated storage

Storage (d)	Control (1.5% NaCl)	Low-salt sausages ¹⁾ (0.75% NaCl)				SEM ²⁾
		L-control	γ-ray	E-beam	X-ray	
Aerobic count plates						
0	1< ^{Aa}	1< ^{Ba}	ND ^A	ND ^{Aa}	ND ^{Aa}	0.062
7	1< ^{Bab}	1< ^{Ba}	ND ^A	ND ^{Aa}	ND ^{Aa}	0.074
14	1.1 ^{Bab}	3.2 ^{Cb}	ND ^A	ND ^{Aa}	ND ^{Aa}	0.328
21	1.2 ^{Bb}	4.2 ^{Cc}	ND ^A	ND ^{Aa}	ND ^{Aa}	0.448
28	3.5 ^{Bc}	6.0 ^{Cd}	ND ^A	1< ^{Ab}	1< ^{Ab}	0.610
SEM	0.372	0.585	-	0.063	0.083	
Coliform						
0	ND ³⁾	ND ^a	ND	ND	ND	0.000
7	ND	ND ^a	ND	ND	ND	0.000
14	ND	1< ^a	ND	ND	ND	0.015
21	ND	1< ^a	ND	ND	ND	0.015
28	ND ^A	3.1 ^{Bb}	ND ^A	ND ^A	ND ^A	0.347
SEM	0.000	0.345	-	-	-	
Enterobacteriaceae						
0	ND	ND ^a	ND	ND	ND	0.000
7	ND	ND ^a	ND	ND	ND	0.000
14	ND	ND ^a	ND	ND	ND	0.000
21	ND	1< ^a	ND	ND	ND	0.015
28	ND ^A	1.7 ^{Bb}	ND ^A	ND ^A	ND ^A	0.156
SEM	0.000	0.155	-	-	-	
Pseudomonas spp.						
0	ND	ND ^a	ND	ND	ND	0.000
7	ND	ND ^a	ND	ND	ND	0.000
14	ND	ND ^a	ND	ND	ND	0.000
21	ND ^A	2.0 ^{Bb}	ND ^A	ND ^A	ND ^A	0.272
28	1< ^A	5.1 ^{Bc}	ND ^A	ND ^A	ND ^A	0.479
SEM	0.124	0.509	-	-	-	

¹⁾Low-salt sausages were non-irradiated (L-control) or irradiated with gamma-ray (γ-ray), electron-beam (E-beam), X-ray at 5 kGy, respectively.

²⁾SEM: the standard error of the means (n=3).

³⁾ND: Not detected.

^{A-C}Means that different letters within the same row were significantly different (p<0.05).

^{a-d}Means that different letters within the same column were significantly different (p<0.05).

ral, sensory and microbial properties. Through irradiation technology, the microbial safety of low-salt emulsion sausages could be effectively improved. However, irradiation could result in negative impacts on sensory acceptance of low-salt emulsion sausages, regardless of irradiation sources. Therefore, this study indicates that irradiation technique could be used to improve microbial safety of low-salt meat products, and suggests that further studies for inhibiting and/or masking radiolytic off-flavor would be performed to ensure its practical use for low-salt meat products.

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