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ARTICLE

Effect of Packaging and Antioxidant Combinations on Physicochemical Properties of Irradiated Restructured Chicken Rolls

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Abstract

Effects of double packaging (combinational use of aerobic and vacuum conditions) and antioxidants on physicochemical properties in irradiated restructured chicken rolls were determined. Chicken breast treated with antioxidants (none, sesamol+a-tocopherol) was used to process restructured chicken breast rolls. The sliced rolls were vacuum, aerobic, or double packaged (vacuum for 7 d then aerobic for 3 d) and electron beam irradiated at 2.5 kGy. Color, 2-thiobarbituric acid reactive substances (TBARS), oxidation reduction potentials (ORP), and volatile profiles of the samples were determined at 0 and 10 d. Irradiation made restructured chicken rolls redder ($p<0.05$), and the increased redness was more distinct in irradiated vacuum-packaged than irradiated aerobic or double packaged meats. TBARS values of antioxidant-treated double packaged rolls were lower than even nonirradiated vacuum-packaged meat, and those were distinct at 10 d ($p<0.05$). ORP and lipid oxidation values were lower in irradiated vacuum and double packaged samples than those in irradiated aerobic packaged ones at 0 d ($p<0.05$). Irradiation of restructured chicken rolls increased the amount of total volatiles. Considerable amounts of off-odor volatiles were reduced or not detected by double packaging and antioxidant treatment at 10 d. Therefore, the combined use of antioxidants and double packaging would be useful to reduce redness and control the oxidative quality changes of irradiated restructured chicken rolls.

Key words: antioxidant, double-packaging, irradiated restructured chicken rolls, lipid oxidation, volatiles

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Introduction

Restructured meats are prepared from small cuts of meat to increase the yield of marketable product by using muscles of poor quality and trimmings. However, there are many risks to be contaminated to microbiological hazard during the processing of restructuring. The application of an HACCP-based approach as a method for the management of hazards of the food chain demonstrates the need for applying a cold decontamination treatment as a control measure in the production of foods which are to be marketed raw or minimally processed. Irradiation is such a control measure in the production of several types of raw or minimally processed foods such as poultry, meat and meat products (Molins *et al*., 2001).

Irradiation is one of the most effective technologies for eliminating foodborne pathogens and improving the microbial safety of meat. WHO (1999) reported that irradiation technology has positive effects in preventing decay and improving the safety and shelf-stability of food products. The US FDA approved irradiation for red meats and poultry to control food-borne pathogens and extend the shelf-life of products (Gants, 1998). Although irradiating is the best method to ensure the microbiological safety of raw meat (Lambert *et al*., 1991), it caused a few radiolytic meat quality defects. Irradiated pork and poultry meat accelerated lipid oxidation (Ahn *et al*., 2000; Katusin-Razem *et al*., 1992), produced a characteristic off-odor (Ahn *et al*., 2001; Patterson and Stevenson 1995), and developed a pink color (Lynch *et al*., 1991; Nam and Ahn, 2002). The major volatile compounds responsible for the characteristic off-odor in irradiated meats are sulfur compounds (Nam *et al*., 2003). Lipid oxidation is a special problem in irradiated meat when it is stored aerobically because oxygen is the most critical for lipid oxidation (Nam *et al*., 2003).

Packaging is a critical factor affecting quality of irradi-

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ated meat. The color and odor changes in irradiated meats also depended on packaging type. Modification of packaging methods can minimize the quality defect in irradiated meat (Nam *et al*., 2007). Exposing meat to aerobic conditions during irradiation and for certain periods of time during storage could help off-odor volatiles to escape from the meat (Nam and Ahn, 2003). They developed a modified packaging concept of "double packaging" in which the outer vacuum bag of doubly packaged meat (aerobically packaged and then vacuum-packaged doubly) were removed after a certain of storage to expose the samples under aerobic conditions. Double packaging maximized the elimination of off-odor volatiles from irradiated meat during storage (Nam *et al*., 2004). Therefore, an appropriate combination of aerobic- and vacuum-packaging conditions can be effective in minimizing both off-odor volatiles and lipid oxidation in irradiated restructured chicken meat.

Antioxidant additives are added to fresh and further processed meats to prevent oxidative rancidity, retard development of off-flavors, and improve color stability (Xiong *et al*., 1993). Certain antioxidants can interrupt free radical chain reactions by scavenging free radicals (Chen and Ahn, 1998) and using specific antioxidants can reduce lipid oxidation and off -odor formation by irradiation. Free radical scavengers (gallate, sesamol, and tocopherol), metal chelators (Trolox) and intrinsic antioxidant (carnosine), or their combinations can be used to reduce the production of off-odor volatiles in irradiated double-packaged chicken meats.

Although the effect of antioxidants have been demonstrated on controlling oxidative reactions in meat, very few studies have been done on the effects of double-packaging and antioxidant combinations on lipid oxidation and off-odor volatiles in irradiated restructured chicken meat. Therefore, this study was conducted to determine the effects of double-packaging and antioxidant combinations on color, lipid oxidation, and volatiles of irradiated restructured chicken.

Materials and Methods

Processing and treatments

Breast muscles from 6 chickens were pooled and used as a replication. Meats for each replication were ground through a 3-mm plate and 4 replications were prepared. Five different treatments were prepared using antioxidant, packaging method, and irradiation conditions (Table 1). Vitamin E + sesamol combination was selected to use in this study because it was the most effective in reducing lipid oxidation and off-odor volatiles in irradiated turkey meat (Nam and Ahn, 2003). Sesamol (3,4-methylenedioxyphenol; Sigma Chemical Co., USA) plus a-tocopherol (Aldrich Chemical Co., USA) was mixed with the ground chicken meat at each 100 ppm level (final 200 ppm) using a bowl mixer (Model KSM 90; Kitchen Aid Inc., USA). Breast meats were ground through a 15-mm plate twice, and then mixed with 2.0% of NaCl and 0.5% of polyphosphate (Brifisol 450 Super, BK Ladenburg Corp., USA) under vacuum for 3 min. The mixture was stuffed into 150 mm collagen casings and then cooked in an 85°C smoke house with relative humility of 92% until the center temperature reached 74°C. After cooling to room temperature by a cold-water shower, the rolls were cut into 10-mm thick slices and individually vacuum-packaged in high oxygen-barrier bags (nylon/polyethylene, 9.3 mL O_2/m^2/24 h at 0°C), aerobically packaged in polyethylene oxygen-permeable bags, or doubly packaged. For double-packaging, aerobically packaged patties were repackaged in oxygen impermeable vacuum bags.

The packaged patties were irradiated at 2.5 kGy using a Linear Accelerator (Circe IIIR, Thomson CSF Linac, France) with 10 MeV of energy, 10 kW of power level, and 86.2 kGy/min of average dose rate. To confirm the target dose, two alanine dosimeters per cart were attached to the top and bottom surfaces of the sample and they were read using a 104 Electron Paramagnetic Resonance instrument (EMS-104, Bruker Instruments Inc., USA). Nonirradiated vacuum-packaged patties were prepared as

Table 1. Packaging, irradiation and antioxidant treatments used in this study

Treatment	Nonirradiated	Irradiated			
	Vacuum packaging	Vacuum packaging	Aerobic packaging	Double packaging	Double-S+E
Antioxidant					
Sesamol	None	None	None	None	100 ppm
α-Tocopherol	None	None	None	None	100 ppm
Irradiation	0 kGy	2.5 kGy	2.5 kGy	2.5 kGy	2.5 kGy
Packaging					
0 to 7 d	Vacuum	Vacuum	Aerobic	Vacuum	Vacuum
7 to 10 d	Vacuum	Vacuum	Aerobic	Aerobic	Aerobic

a control. The outer vacuum bags of doubly packaged meat were removed after 7 d of storage at 4°C to expose the samples under aerobic conditions. Color, lipid oxidation and volatile compounds of the irradiated raw meats were determined at 0 and 10 d of refrigerated storage.

Color measurement

CIE color values were measured on the surface of sample using a LabScan color meter (Hunter Associated Labs. Inc., USA) that had been calibrated against a black and a white reference tiles covered with same packaging materials as used for samples. The CIE L* (lightness), a* (redness), and b* (yellowness) values were obtained using an illuminant A (light source) with an area view of 0.25" and a port size of 0.40".

Analysis of 2-thiobarbituric acid reactive substances (TBARS)

Lipid oxidation was determined by a TBARS method (Ahn *et al*., 1998). Meat sample (5 g) was placed in a 50-mL test tube and homogenized with 15 mL of deionized distilled water (DDW) using a Brinkman Polytron (Type PT 10/35, Brinkman Instrument Inc., USA) for 15 s at high speed. The meat homogenate (1 mL) was transferred to a disposable test tube (13×100 mm), and butylated hydroxytoluene (7.2%, 50 mL) and thiobarbituric acid/trichloroacetic acid [20 mM TBA and 15% (w/v) TCA] solution (2 mL) were added. The mixture was incubated in a 90°C water bath for 15 min. After cooling for 10 min in cold water, the samples were centrifuged at 3,000 *g* for 15 min at 5°C. The absorbance of the resulting upper layer was read at 531 nm against a blank prepared with 1 mL DDW and 2 mL TBA/TCA solution. The amounts of TBARS were expressed as mg of malonedialdehyde (MDA) per kg of meat.

Oxidation-reduction potential (ORP)

The method of Moiseev and Cornforth (1999) was modified to determine the change of ORP in meat samples. A pH/ion meter (Accumet 25, Fisher Scientific, USA) was used. A platinum electrode filled with a 4 M-KCl solution saturated with AgCl was tightly inserted in the center of a meat sample (100 g). To minimize the effect of air, the smallest possible pore was made by a cutter before inserting the electrode. To compensate for the effect of temperature, a temperature-reading sensor was also inserted. ORP readings (mV) were recorded at exactly 3 min after the insertion of the electrode into the sample.

Analysis of volatile profiles

A purge-and-trap apparatus (Precept II and Purge & Trap Concentrator 3000, Tekmar-Dohrmann, USA) connected to a gas chromatography/mass spectrometry (GC/MS, Hewlett-Packard Co., USA) was used to analyze volatiles produced (Ahn *et al*., 2000). Minced meat sample (3 g) was placed in a 40-mL sample vial and the vials were flushed with He (40 psi) for 5 s. Samples were held in a refrigerated (4°C) sample-holding tray before analysis, and the maximum holding time was less than 7 h to minimize oxidative changes. The meat sample was purged with He (40 mL/min) for 13 min at 40°C. Volatiles were trapped using a Tenax column (Tekmar-Dohrmann) and desorbed for 2 min at 225°C, focused in a cryofocusing module (-90 °C), and then thermally desorbed into a column for 30 s at 225°C. An HP-624 column (i.d. 7.5 m × 0.25 mm., 1.4 μm nominal), an HP-1 column (52.5 m × 0.25 mm i.d., 0.25 μm nominal, Hewlett-Packard Co), and an HP-Wax column (7.5 m × 0.25 mm., 0.25 μm nominal) were connected using zero dead-volume column connectors (J&W Scientific, USA). Ramped oven temperature was used to improve volatile separation. The initial oven temperature of 0°C was held for 2.50 min. After that, the oven temperature was increased to 15°C at 2.5°C/min, increased to 45°C at 5°C/min, increased to 110°C at 20°C/min, increased to 210°C at 10°C/min, and then was held for 4.5 min at the temperature. Constant column pressure at 20.5 psi was maintained. The ionization potential of mass selective detector (Model 5973, Hewlett-Packard Co.) was 70 eV, and the scan range was 18.1-300 m/z.

Statistical analysis

The experiment was designed to determine the effects of double-packaging and antioxidant combinations on color, lipid oxidation, and volatile profiles of the irradiated samples during storage. Analysis of variance was conducted by the generalized linear model procedure of SAS software (SAS Institute, 1995); Student-Newman-Keul's multiple range test was used to compare the mean values of the treatments. Mean values and standard error of the means (SEM) were reported at $p<0.05$ probability level.

Results and Discussion

Color changes

Packaging and irradiation had significant effects on all L*, a* and b* values (Table 2). Irradiated restructured chicken rolls appeared lighter and redder than the nonirradi-

Table 2. CIE color values of irradiated restructured chicken rolls treated by different packaging and antioxidant during the 10 d of storage

Storage	Nonirradiated[1]	Irradiated				SEM
	Vacuum packaging	Vacuum packaging	Aerobic packaging	Double packaging[1]	Double-S+E[2]	
L* value						
Day 0	47.6^{ey}	49.1^{cdy}	53.8^{ax}	51.0^{b}	50.2^{bc}	0.4
Day 10	51.2^{abx}	51.8^{ax}	50.9^{aby}	50.9^{ab}	49.8^{bc}	0.4
SEM	0.5	0.4	0.5	0.4	0.4	
a* value						
Day 0	5.4^{b}	7.5^{a}	5.9^{cx}	6.8^{bx}	6.7^{bx}	0.2
Day 10	5.6^{b}	7.4^{a}	3.1^{cy}	5.9^{by}	5.4^{by}	0.1
SEM	0.1	0.2	0.2	0.1	0.2	
b* value						
Day 0	20.0^{ax}	19.1^{ax}	16.8^{bcx}	16.0^{cy}	17.8^{b}	0.4
Day 10	18.9^{ay}	17.9^{by}	13.6^{cy}	17.7^{bx}	19.0^{a}	0.3
SEM	0.2	0.3	0.4	0.2	0.4	

[1]Vacuum-packaged for 7 d then aerobically packaged for 3 d.
[2]Double packaging with sesamol (100 ppm) and a-tocopherol (100 ppm) added.
[a-d]Means with different letters within a row are significantly different ($p<0.05$); n=4.
[x-z]Means with different letters within a column with same color value are significantly different($p<0.05$).

ated at 0 d ($p<0.05$). Many studies have shown that redness value of meats increased after irradiation (Du *et al*., 2002; Luchsinger *et al*., 1996). Du *et al*. (2003) indicated that gas production after irradiation could be responsible for the color changes in chicken rolls after irradiation. Many researchers (Lee and Ahn, 2004; Nam and Ahn., 2002) attributed the increased red color in irradiated meat to the formation of carbon monoxide-myoglobin (CO-Mb) complexes. The CO-Mb complex is more stable than oxymyoglobin because of the strong binding of CO to the iron-porphyrin site on the myoglobin molecule (Sorheim *et al*., 1999).

The a* value of aerobically packaged irradiated meat was lower than that of vacuum- and double-packaged irradiated one but still higher than the nonirraidated one at 0 d ($p<0.05$). These results also confirm the results of Nam and Ahn (2003) who reported that irradiation increased the a* value of raw turkey breast, but exposing the irradiated meat to aerobic conditions alleviated the intensity of redness. Nam *et al*. (2004) reported that the packaging conditions during irradiation process were important in determining meat color changes. Grant and Patterson (1991) also reported that irradiated color could be discolored in the presence of oxygen.

Vacuum-packaged and irradiated restructured chicken rolls had higher a* values and more stable red/pink color than the aerobic- and double-packaged irradiated one ($p<0.05$). This is agreement with Nam and Ahn (2002) who found similar finding. Luchsinger *et al*. (1996) reported that irradiated vacuum-packaged pork chops appeared redder and were more stable during storage. The increased redness of vacuum-packaged samples by irradiation was stable even after 10 d of refrigerated storage. However, the redness of aerobic- or double-packaged and irradiated meats decreased significantly after 10 d of storage ($p<0.05$). This result agreed with that of Nam *et al*. (2003) who reported that regardless of irradiation, the color a* values of meat decreased after 7 d of storage under aerobic conditions. Nam *et al*. (2003) indicated that heme pigments were oxidized during the storage period under aerobic conditions, and exposing irradiated meat to aerobic conditions was effective in reducing CO-heme pigment complex formation. Furthermore, the combination of antioxidants with double packaging showed a synergistic effect in reducing the redness of irradiated meat. The presence of oxygen could accelerate the dissociation of CO-Mb, whereas antioxidants could inhibit radiolytic generation of CO (Nam and Ahn, 2003).

Double packaging could lower a* values of irradiated samples to the level of the nonirradiated control after 10 d of storage. From the result of packaging and antioxidant combinations, the L* value of irradiated restructured chicken rolls from double packaging and antioxidant combinations (G+E) was lower than that of other treatments regardless of the storage period ($p<0.05$). Irradiated restructured chicken rolls from double packaging and antioxidant combinations produced significantly lower a* values than the vacuum-packaged irradiated meats ($p<0.05$). Adding a-tocopherol to sesamol or gallic acid did not increase a*values any further. Nam *et al*. (2003) reported

that both irradiation and a-tocopherol increased a*values of turkey breast meat, but irradiation had a stronger impact. Antioxidants have been shown to improve color stability in irradiated fresh meats (Xiong *et al*., 1993). Some phenolic antioxidants (vitamin E) scavenge free-radicals stopping progressive autooxidative damage in meat (Gray *et al*., 1996; Morrissey *et al*., 1998). Therefore, the sesamol plus a-tocopherol in combination with double packaging can be effective in controlling off-color in irradiated meat.

Lipid oxidation and oxidation-reduction potential

Oxidative changes of irradiated restructured chicken rolls treated by different packaging and antioxidant during storage are shown in Table 3. Irradiation, antioxidants, and packaging methods influenced the TBARS values of irradiated restructured chicken rolls during storage. TBARS values of aerobic and double-packaged irradiated one increased during storage ($p<0.05$) due to the oxygen-impermeable conditions during storage. Irradiation and storage time did not affect the TBARS values in vacuum-packaged samples. Previous studies have shown that irradiation promotes lipid oxidation and generates characteristic off-odor volatiles in meats (Nam and Ahn, 2003). Irradiation produced more TBARS than nonirradiated samples, but only in aerobic-packaged samples at 10 d ($p<0.05$). Previous studies indicated that irradiated aerobic-packaged meat produced higher TBARS and off-flavor than the irradiated vacuum-packaged and nonirradiated ones (Ahn *et al*., 2001; Du *et al*., 2002; Patterson and Stevenson, 1995). As storage time increased, lipid oxidation in irradiated meats increased significantly. This result agreed with Nam *et al*. (2003) who reported similar result. The TBARS of meat was highest with aerobic packaging, lowest with double packaging and antioxidant combinations, and in the middle with double packaging ($p<0.05$). The effects of double packaging and antioxidant combinations were distinct after 10 d of storage in inhibiting lipid oxidation. The TBARS of antioxidant-treated double packaging meats were lower than even nonirradiated vacuum-packaging meat at 10 d ($p<0.05$).

The TBARS values increased sharply (five to six-fold) in aerobic packaging during storage. It could be affected by the fact that it is susceptible to oxidative changes. This result agreed with our previous work (Jo *et al*., 1999) and could be interpreted as showing that storage condition or oxygen availability was more important for the development of lipid oxidation than irradiation (Ahn *et al*., 1998). Vacuum-packaged meat was more resistant to lipid oxidation than aerobically packaged meat. In a previous study, Nam and Ahn (2003a) found that the TBARS increase could be proportional to the exposure time to aerobic conditions. Irradiation did not increase the TBARS under vacuum packaging regardless of the storage period. With vacuum packaging, no difference in TBARS was found regardless of irradiation and storage. The added antioxidant effect to reduce TBARS was found in irradiated restructured chicken rolls. Double-packaged irradiated one added by sesamol plus a-tocopherol was significantly lower than other treatments ($p<0.05$). Double-packaged irradiated samples added by antioxidants showed the lowest TBARS value on 0 and 10 d ($p<0.05$). This finding agreed with Nam *et al*. (2007) who found that the irradiated meat with antioxidants and double packaging combinations had lower TBARS than nonirradiated vacuum-packaged meat after 10 d of storage. The combination of sesamol plus g-tocopherol was efficient in inhibiting hydroperoxide formation in oils (Yoshida and Takagi, 1999). Therefore, antioxidant combination was very effective in preventing lipid oxidation during storage, and the TBARS of antioxidant-treated meats were lower than even nonirradiated vacuum-packaged meat at 10 d. Nam *et al*. (2003)

Table 3. TBARS values of irradiated restructured chicken rolls treated by different packaging and antioxidant during the 10 d of storage

Storage	Nonirradiated	Irradiated				SEM
	Vacuum packaging	Vacuum packaging	Aerobic packaging	Double packaging[1]	Double-S+E[2]	
	---------- (mg MDA/kg meat) ----------					
Day 0	0.57^{b}	0.61^{b}	0.89^{ay}	0.64^{by}	0.24^{cy}	0.02
Day 10	0.60^{cd}	0.68^{c}	5.19^{ax}	1.79^{bx}	0.32^{dx}	0.07
SEM	0.01	0.02	0.08	0.08	0.01	

[1]Vacuum-packaged for 7 d then aerobically packaged for 3 d.
[2]Double packaging with sesamol (100 ppm) and a-tocopherol (100 ppm) added.
[a-d]Means with different letters within a row are significantly different ($p<0.05$); n=4.
[x-z]Means with different letters within a column with same color value are significantly different ($p<0.05$).

showed that irradiated restructured pork loins treated with antioxidant and double-packaging had lower TBARS values than vacuum-packaged control after 10 d of storage. Ahn *et al*. (1997) reported that antioxidant reduces oxidative quality deterioration of irradiated meat by quenching free radicals. Nam and Ahn (2003) showed that gallate or sesamol combined with a-tocopherol decreased the production of sulfur volatiles as well as lipid oxidation in irradiated pork patties. Chen *et al*. (1999) also indicated that phenolic antioxidants were effective in reducing lipid oxidation in aerobically packaged irradiated pork patties.

To elucidate the change of oxidative status of the heme pigments of irradiated restructured chicken rolls, ORP values were determined (Table 4). Regardless of the packaging methods, irradiation initially lowered ORP values on 0 d. After 10 d of storage, the differences of ORP between nonirradiated and irradiated samples reversed. While nonirradiated samples under vacuum packaging had higher ORP than irradiated ones on day 0, those had lower on 10 d (p<0.05). In Irradiated samples, vacuum-packaged ones had much lower ORP values than the aerobic-packaged ones (p<0.05). Nam and Ahn (2002) also mentioned that the iron of myoglobin was changed to a ferrous iron under the reduced conditions of irradiated turkey breast, and the reduced iron had stronger affinity to accept a ligand and produced a red color.

As the storage time increased, ORP values in irradiated meat increased, whereas the ORP in nonirradiated samples decreased in vacuum packaging conditions. This result is very similar to Nam and Ahn (2002) and Ismail *et al*. (2008). Du *et al*. (2002), reporting similar results with chicken breast meat, hypothesized that the decrease in ORP could be due to the electrons absorbed during irradiation. And they suggested that the ORP changes seen in aerobically packaged fillets may be due to irradiation-induced membrane damage, which increases oxygen permeability into the tissues. Nam and Ahn (2002) also reported an immediate decrease in ORP due to irradiation followed by an increase during storage that was greater in aerobically-packaged than in vacuum-packaged meat. Generally, the ORP of raw meats declined during storage due to the oxygen consumption by meat tissues or microorganisms (Ismail *et al*., 2008). Cornforth *et al*. (1986) elucidated that microbial growth decreased ORP and thus increased reducing capacity. Although ORP value decreased in the processing of irradiation, the reduced condition produced in irradiated meat was not maintained during the storage. The result did not coincide with the red color of stored irradiated meat, because the color of irradiated meats was still redder or pinker than nonirradiated meats during storage. The TBARS values of meat samples were related to ORP and packaging type. Vacuum-packaged samples had lower ORP and TBARS values than aerobically packaged Samples. Therefore, the result of the study showed that use of double-packaging and antioxidant combinations reduced lipid oxidation for all irradiated treatments as the storage period increased.

Off-odor volatiles

Irradiated meats produced more total volatiles than nonirradiated ones with vacuum packaging at 0 d (p<0.05) (Table 5). Many studies have shown that irradiation induced production of several off-odor volatiles compounds (Ahn *et al*., 2001, Kim *et al*., 2002). Nam *et al*. (2003) indicated that irradiation of restructured pork loins increased the amount of total volatiles by about 25%. Ahn *et al*. (2000) indicated that the major contributor of off-odor in irradiated meat is not lipid oxidation, but radiolytic breakdown of sulfur-containing amino acids.

The most distinctive changes in volatile profiles by irradiation were the increase of sulfur volatiles (methanethiol, dimethyl disulfide), aldehydes (2-methylbutanal, pentanal,

Table 4. ORP values of irradiated restructured chicken rolls treated by different packaging and antioxidant during the 10 d of storage

Storage	Nonirradiated	Irradiated				SEM
	Vacuum packaging	Vacuum packaging	Aerobic packaging	Double packaging[1]	Double-S+E[2]	
	---------- (mV) ----------					
Day 0	-2.5^{ax}	-95.5^{c}	-65.4^{by}	-141.2^{dy}	-125.2^{cdy}	9.1
Day 10	-82.7^{cy}	-67.9^{b}	-42.5^{ax}	-50.3^{ax}	-48.5^{ax}	5.2
SEM	5.1	9.8	4.1	10.0	5.8	

[1]Vacuum-packaged for 7 d then aerobically packaged for 3 d.
[2]Double packaging with sesamol (100 ppm) and a-tocopherol (100 ppm) added.
[a-d]Means with different letters within a row are significantly different (p<0.05); n=4.
[x-z]Means with different letters within a column with same color value are significantly different (p<0.05).

Table 5. Volatile profiles of irradiated restructured chicken rolls treated by different packaging and antioxidant at 0 d

Compound	Nonirradiated	Irradiated				SEM
	Vacuum	Vacuum	Aerobic	Double[1]	Double-S+E[2]	
	---------- (Total ion counts ×10[4]) ----------					
2-Methyl-1-Propene	0[c]	432[b]	531[b]	447[b]	547[b]	50
Butane	452[c]	837[b]	1221[a]	1351[a]	1197[a]	93
1-Butene	0[b]	287[a]	341[a]	365[a]	390[a]	44
Methanethiol	0	153	0	0	0	36
1-Pentene	0[b]	313[a]	420[a]	277[a]	282[a]	34
Pentane	4397[b]	8654[a]	8510[a]	10188[a]	2988[b]	745
Dimethyl sulfide	282[b]	461[a]	0c	389[ab]	507[a]	43
Carbon disulfide	2863[a]	2962[a]	1451[b]	2587[a]	506[b]	383
1-Hexene	0[b]	233[a]	264[a]	203[a]	204[a]	20
Hexane	815[b]	995[b]	7606[a]	922[b]	632[b]	112
Benzene	0[c]	706[a]	516[b]	712[a]	497[b]	46
3-Methyl butanal	0[d]	44[b]	405[a]	0[b]	0[b]	26
1-Heptene	0[d]	453[c]	762[a]	410[c]	366[c]	40
Heptane	972[bc]	1158[bc]	2504[a]	1100[bc]	613[c]	142
Pentanal	0[b]	40[b]	304[a]	0[b]	0[b]	27
2,3,4-Trimethyl pentane	0[b]	122[a]	0[b]	0[b]	0[b]	3
2.3.3-Trimethyl pentane	0[b]	129[a]	0[b]	0[b]	0[b]	23
Dimethyl disulfide	0[c]	807[a]	217[bc]	708[ab]	489[ab]	132
Toluene	231[c]	871[b]	904[b]	844[b]	975[ab]	69
4-Octene	410	789	317	461	431	110
Octane	893[c]	2094[a]	2060[a]	2285[a]	1263[b]	115
2-Octene	190[b]	421[a]	135[b]	256[b]	221[b]	47
3-Methyl-2-heptene	373[b]	613[a]	0[b]	250[b]	218[b]	102
2-Octene	158	298	141	186	223	44
Hexanal	0[b]	42[b]	685[a]	0[b]	0[b]	95
Nonane	0[b]	39[b]	176[a]	79[ab]	60[ab]	29
Total	7187[d]	23960[ab]	29567[a]	24027[ab]	12599[c]	1584

[1]Vacuum-packaged for 7 d then aerobically packaged for 3 d.
[2]Double packaging with sesamol (100 ppm) and a-tocopherol (100 ppm) added.
[a-d]Different letters within a row are significantly different (p<0.05); n=4.

and hexanal) and 1-alkenes (1-pentene, 1-hexene, 1-heptene, 1-octene), which were newly generated (Table 5). The major sulfur volatiles produced in samples by irradiation were methanethiol and dimethyl disulfide. Dimethyl disulfide is usually found in irradiated raw and cooked meat and usually evaporates during storage (Ahn *et al*., 2001). Dimethyl disulfide and other sulfur compounds were derived from degradation of amino acids and were suggested to be the major volatile compounds imparting irradiation off-odor (Ahn *et al*., 2000). In our study, dimethyl disulfide was not detected in nonirradiated meat at 0 and 10 d in vacuum conditions. Dimethyl disulfide decreased during storage regardless of packaging conditions, and aerobically packaged irradiated meat had only one-fourth the dimethyl disulfide of the vacuum-packaged meat (p< 0.05). This is consistent with results from Brewer (2004) who indicated that irradiation produced significant amounts of sulfur volatiles under vacuum conditions and these compounds disappeared after storage in aerobic conditions.

S-containing volatiles, such as dimethyl disulfide produced by radiolytic degradation of sulfur amino acids, are responsible for the off-odor in irradiated meat, and are different from the rancidity caused by lipid oxidation products (Ahn *et al*., 2001). The lower levels of sulfur compounds in aerobically packaged samples might be due to the fact that the aerobically packaged meat had weaker irradiation odor than that of the vacuum-packaged (Du *et al*., 2002). Most of the sulfur volatiles in irradiated turkey breast disappeared under aerobic packaging conditions (Nam and Ahn, 2003). The amount of hexanal in irradiated samples under aerobic packaging condition was detected or higher than that of other samples (p<0.05). Hexanal was the major volatile aldehydes and the increase of aldehydes agreed well with TBARS data. Hexa-

nal and pentanal are a good indicator of lipid oxidation (Shahidi *et al*., 1987) and hexanal is an off-flavor volatile typically associated with oxidative changes (Ahn *et al*., 2001).

When irradiated beef was aerobically stored, the generation of lipid oxidation products was a bigger concern than S-volatiles, because aerobic packaging is very effective in eliminating S-volatiles (Nam *et al*., 2003). Nam and Ahn. (2003) mentioned that double packaging could minimize irradiation off-odor by volatilizing S-volatile compounds in irradiated poultry meat. Double packaging and antioxidant combinations lowered total volatiles in meat, and methanethiol, pentanal, trimethyl pentane and hexanal were not detected ($p<0.05$). In a previous study, double-packaging was effective in minimizing lipid oxidation, pink color defect and sulfur-volatile production in irradiated pork loin during storage (Nam *et al*., 2004), but combination of double-packaging and antioxidants was more effective than double-packaging alone in controlling lipid oxidation and irradiation off-odor (Nam and Ahn, 2003). In a previous study, antioxidants such as gallate, tocopherol, and sesamol were effective in reducing the off-odor volatiles produced by irradiation, but sesamol was the most effective among them. Sesamol plus tocopherol

Table 6. Volatile profiles of irradiated restructured chicken rolls treated by different packaging and antioxidant after 10 d of refrigerated storage

Compound	Nonirradiated	Irradiated				SEM
	Vacuum	Vacuum	Aerobic	Double[1]	Double-S+E[2]	
	---------- (Total ion counts ×10^4) ----------					
2-Methyl-1-Propene	0^{c}	598^{a}	0^{c}	279^{b}	402^{ab}	58
Butane	1248^{b}	1381^{b}	4065^{a}	1212^{b}	925^{b}	93
1-Butene	0^{b}	380^{a}	0^{b}	0^{b}	0^{b}	20
1-Pentene	0^{d}	373^{b}	500^{a}	244^{c}	215^{c}	30
Pentane	14874^{c}	16645^{c}	40980^{a}	20218^{bc}	6025^{d}	1624
Ethanol	1971^{a}	0^{b}	0^{b}	0^{b}	0^{b}	87
2-Pentene	0^{b}	0^{b}	322^{a}	0^{b}	0^{b}	10
Propanal	0^{b}	0^{b}	133^{a}	0^{b}	0^{b}	31
Dimethyl sulfide	425^{b}	504^{a}	0^{d}	0^{d}	216^{c}	18
Carbon disulfide	2539^{a}	2520^{a}	0^{b}	42^{b}	0^{b}	1326
2-Methyl propanal	0	0	133	0	0	31
1-Hexene	0^{c}	292^{a}	348^{a}	167^{b}	163^{b}	22
Hexane	1387^{c}	2090^{b}	4979^{a}	1781^{bc}	888^{d}	260
Benzene	0^{d}	928^{a}	336^{c}	431^{bc}	373^{c}	46
3-Methyl butanal	184^{b}	0^{b}	897^{a}	0^{b}	0^{b}	166
2-Methyl butanal	477^{b}	0^{c}	1450^{a}	0^{c}	0^{c}	22
1-Heptene	0^{c}	519^{a}	0c	400^{ab}	292^{b}	54
Heptane	2262^{c}	3625^{b}	9059^{a}	2957^{bc}	991^{d}	491
2-Ethyl furan	0^{b}	0^{b}	228^{a}	0^{b}	0^{b}	7
Pentanal	0^{b}	0^{b}	2891^{a}	0^{b}	0^{b}	177
2,3,4-Trimethyl pentane	25^{b}	164^{a}	0^{b}	0^{b}	0^{b}	74
2.3.3-Trimethyl pentane	50^{b}	175^{a}	0^{b}	0^{b}	0^{b}	82
Dimethyl disulfide	0^{c}	251^{a}	125^{b}	0^{c}	0^{c}	28
Toluene	305^{b}	965^{a}	607^{b}	508^{b}	481^{b}	91
4-Octene	204^{b}	0^{c}	521^{a}	290^{b}	0^{c}	44
Octane	3090^{bc}	5625^{ab}	7432^{a}	3456^{bc}	1462^{c}	977
2-Octene	525^{a}	662^{a}	832^{a}	230^{b}	194^{b}	201
3-Methyl-2-heptene	82	677	78	100	184	370
2-Octene	164	390	437	166	154	182
Hexanal	79^{b}	0^{b}	30296^{a}	30^{b}	0^{b}	1307
Nonane	0^{b}	142^{ab}	224^{a}	108^{ab}	0^{b}	39
Total	29897^{b}	38912^{b}	107576^{a}	32626^{b}	12970^{c}	3170

[1]Vacuum-packaged for 7 d then aerobically packaged for 3 d.
[2]Double packaging with sesamol (100 ppm) and a-tocopherol (100 ppm) added.
[a-d]Different letters within a row are significantly different ($p<0.05$); n=4.

was the most effective in reducing carbon disulfide, 3-methylbutanal, and total volatiles production (Nam and Ahn, 2003).

The beneficial effects of double packaging and antioxidant combinations on volatiles were more apparent in irradiated after 10 d of refrigerated storage (Table 6). Volatile profiles of irradiated samples were highly dependent upon antioxidant and packaging conditions. Aerobic-packaged irradiated ones had the greatest amounts of total volatiles. The amount of dimethyl disulfide decreased two-four fold compared with that at 0 d ($p<0.05$), and these sulfur volatiles were not detected in irradiated double packaging and antioxidant combinations group. The result at 10 d was similar to Nam *et al*. (2003) who reported most sulfur volatiles reduced regardless of packaging conditions, after 10 d of storage. Three days of exposure to aerobic conditions was enough for the sulfur volatiles to escape from the meat (Nam and Ahn, 2003). However, aerobically packaged irradiated meat without antioxidants produced large amounts of aldehydes (propanal, hexanal) and 2-methyl butanone at 10 d. Double-packaged meat had lower lipid oxidation products compared with aerobically packaged meat, but antioxidant combinations significantly reduced the amount of pentane at 10 d. Therefore, the combination of double packaging (vacuum for 3 d then aerobic for 7) with antioxidants in irradiated samples was very effective in reducing total and sulfur volatiles responsible for the irradiation off-odor without any problem in lipid oxidation. In conclusion, the combination of double packaging and antioxidants was highly effective in controlling lipid oxidation and irradiation off-odor of irradiated restructured chicken rolls.

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