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

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Keywords
antioxidant, double-packaging, irradiated restructured chicken rolls, lipid oxidation, volatiles

Disciplines
Animal Sciences | Food Biotechnology | Food Microbiology | Food Processing | Poultry or Avian Science

Comments
This article is published as Yim, Dong-Gyun, Dong U. Ahn, and Ki-Chang Nam. "Effect of packaging and antioxidant combinations on physicochemical properties of irradiated restructured chicken rolls." *Korean journal for food science of animal resources* 35, no. 2 (2015): 248. doi:10.5851/kosfa.2015.35.2.248.

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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

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 irradiat-
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 α-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 humidity 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 \(O_2/m^2/24\) 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 IIIIR, 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 |
|-----------|---------------|------------|
| Antioxidant | Vacuum packaging | Vacuum packaging | Aerobic packaging | Double packaging | Double-S+E |
| 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 |
| | 7 to 10 d | Vacuum | Vacuum | 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 id., 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-
that irradiated vacuum-packaged pork chops appeared re-

found similar finding. Luchsinger 0.05). This is agreement with Nam and Ahn (2002) who instructed at 0 d (p<0.05). Many studies have shown that red-

deness 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 nonirradiated 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 re-

dder 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 pig-

ments 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 anti-

oxidants with double packaging showed a synergistic ef-

fect in reducing the redness of irradiated meat. The pres-

eence of oxygen could accelerate the dissociation of CO-

Mb, whereas antioxidants could inhibit radiolytic genera-

tion 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 combi-

nations (G+E) was lower than that of other treatments re-

gardless of the storage period (p<0.05). Irradiated restruc-

tured 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

| Storage | Nonirradiated | Irradiated | SEM |
|---------|---------------|------------|-----|
|         | Vacuum packaging | Vacuum packaging | Aerobic packaging | Double packaging | Double-S+E |
| **L* value** | | | | | |
| Day 0 | 47.6<sup>a</sup> | 49.1<sup>b</sup> | 53.8<sup>b</sup> | 51.0<sup>b</sup> | 50.2<sup>b</sup> |
| Day 10 | 51.2<sup>ab</sup> | 51.8<sup>ab</sup> | 50.9<sup>ab</sup> | 50.9<sup>ab</sup> | 49.8<sup>bc</sup> |
| SEM | 0.5 | 0.4 | 0.5 | 0.4 | 0.4 |
| **a* value** | | | | | |
| Day 0 | 5.4<sup>b</sup> | 7.5<sup>a</sup> | 5.9<sup>a</sup> | 6.8<sup>bc</sup> | 6.7<sup>bc</sup> |
| Day 10 | 5.6<sup>b</sup> | 7.4<sup>a</sup> | 3.1<sup>c</sup> | 5.9<sup>b</sup> | 5.4<sup>b</sup> |
| SEM | 0.1 | 0.2 | 0.2 | 0.1 | 0.2 |
| **b* value** | | | | | |
| Day 0 | 20.0<sup>ab</sup> | 19.1<sup>a</sup> | 16.8<sup>bc</sup> | 16.0<sup>c</sup> | 17.8<sup>c</sup> |
| Day 10 | 18.9<sup>b</sup> | 17.9<sup>b</sup> | 13.6<sup>c</sup> | 17.7<sup>c</sup> | 19.0<sup>c</sup> |
| SEM | 0.2 | 0.3 | 0.4 | 0.2 | 0.4 |

<sup>1</sup>Vacuum-packaged for 7 d then aerobically packaged for 3 d.

<sup>2</sup>Double packaging with sesamol (100 ppm) and a-tocopherol (100 ppm) added.

<sup>a</sup>-<sup>d</sup>Means with different letters within a row are significantly different (p<0.05); n=4.

<sup>x</sup>-<sup>y</sup>Means with different letters within a column with same color value are significantly different (p<0.05).
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)

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

| Storage       | Nonirradiated | Irradiated |
|---------------|---------------|------------|
|               | Vacuum packaging | Vacuum packaging | Aerobic packaging | Double packaging | Double-S+E | SEM |
| Day 0         | 0.57<sup>a</sup> | 0.61<sup>b</sup> | 0.89<sup>c</sup> | 0.64<sup>d</sup> | 0.24<sup>e</sup> | 0.02 |
| Day 10        | 0.60<sup>d</sup> | 0.68<sup>e</sup> | 5.19<sup>fx</sup> | 1.79<sup>fx</sup> | 0.32<sup>fx</sup> | 0.07 |
| SEM           | 0.01          | 0.02        | 0.08           | 0.08           | 0.01          |      |

<sup>1</sup>Vacuum-packaged for 7 d then aerobically packaged for 3 d.
<sup>2</sup>Double packaging with sesamol (100 ppm) and a-tocopherol (100 ppm) added.
<sup>a-d</sup>Means with different letters within a row are significantly different ($p<0.05$); n=4.
<sup>x-z</sup>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 α-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,

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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 packaging¹ | Double-S+E² |     |
|---------|-----------------|-------------|-----------------|-----------------|---------------|-----|
| Day 0   | -2.5³           | -95.5⁴      | -65.4⁶         | -141.2⁷        | -125.2³       | 9.1 |
| Day 10  | -82.7⁸         | -67.9⁹      | -42.5³         | -50.3³         | -48.5³        | 5.2 |
| SEM     | 5.1             | 9.8         | 4.1            | 10.0           | 5.8           |     |

¹Vacuum-packaged for 7 d then aerobically packaged for 3 d.
²Double packaging with sesamol (100 ppm) and α-tocopherol (100 ppm) added.
³⁴Means with different letters within a row are significantly different (p<0.05); n=4.
³⁵Means with different letters within a column with same color value are significantly different (p<0.05).
who indicated that irradiation produced significant amou-
0.05). This is consistent with results from Brewer (2004)
the dimethyl disulfide of the vacuum-packaged meat (\(10 \text{ d}\) in vacuum conditions. Dimethyl disulfide decreased
disulfide was not detected in nonirradiated meat at 0 and
1-Pentene 0.0 287a 341 a 365 a 390 a 44
Methanethiol 0 153 0 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 a 461 a 0c 389 b 507 b 43
Carbon disulfide 2863 b 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 b c 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 c 122 a 0 b 0 b 0 b 3
2,3,3-Trimethyl pentane 0 c 129 a 0 b 0 b 0 b 23
Dimethyl disulfide 0 c 807 a 217 b 708 ab 489 b 132
Toluene 231 b 871 b 904 a 844 b 975 b 69
4-Octene 410 789 317 461 431 110
Octane 893 b 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 a 685 a 0 b 0 b 95
Nonane 0 b 39 176 a 79 b 60 ab 29
Total 7187 b 23960 ab 29567 a 24027 ab 12599 a 1584

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

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

and hexanal) and 1-alkenes (1-pentene, 1-hexene, 1-hepen-
ene, 1-octene), which were newly generated (Table 5). The
major sulfur volatiles produced in samples by irradiation
were methanethiol and dimethyl disulfide. Dimethyl disul-
 sulfide is usually found in irradiated raw and cooked meat
and usually evaporates during storage (Ahn et al., 2001). Di-
methyl disulfide and other sulfur compounds were de-

erived from degradation of amino acids and were sugge-

ted to be the major volatile compounds imparting irra-
diation off-odor (Ahn et al., 2001). 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 amou-
ts of sulfur volatiles under vacuum conditions and these
compounds disappeared after storage in aerobic conditions.
S-containing volatiles, such as dimethyl disulfide pro-
duced 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 con-
ditions (Nam and Ahn, 2003). The amount of hexanal in
irradiated samples under aerobic packaging condition was
detected or higher than that of other samples \((p<0.05)\). Hexa-

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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 | Double-S+E | |
| 2-Methyl-1-Propene      |               |            |        |        |            | |
| Butane                  | 0a            | 598b       | 0b     | 279b   | 402b       | 58 |
| 1-Butene                | 1248b         | 1381b      | 4065b  | 1212b  | 925b       | 93 |
| 1-Pentene               | 0b            | 380b       | 0b     | 0b     | 0b         | 20 |
| Pentane                 | 14874bc       | 16645c     | 40980a | 20218bc| 6025d      | 1624 |
| Ethanol                 | 1971c         | 0b         | 0b     | 0b     | 0b         | 87 |
| 2-Pentene               | 0b            | 0b         | 322b   | 0b     | 0b         | 10 |
| Propanal                | 0b            | 0b         | 1334b  | 0b     | 0b         | 31 |
| Dimethyl sulfide        | 425b          | 504a       | 0d     | 216c   | 18         | |
| Carbon disulfide        | 2539a         | 2520a      | 0b     | 42b    | 0b         | 1326 |
| 2-Methyl propanal       | 0             | 0          | 133    | 0      | 0          | 31 |
| 1-Hexene                | 0c            | 292a       | 348a   | 167b   | 163b       | 22 |
| Hexane                  | 1387c         | 2090b      | 4979a  | 1781bc | 888d       | 260 |
| Benzene                 | 0d            | 928a       | 336b   | 431bc  | 373c       | 46 |
| 3-Methyl butanal        | 184b          | 0b         | 897a   | 0b     | 0b         | 166 |
| 2-Methyl butanal        | 477b          | 0b         | 1450b  | 0b     | 0b         | 22 |
| 1-Heptene               | 0c            | 519a       | 0c     | 400ab  | 292b       | 54 |
| Heptane                 | 2262c         | 3625b      | 9059a  | 2957eh | 991d       | 491 |
| 2-Ethyl furan           | 0b            | 0b         | 228b   | 0b     | 0b         | 7  |
| Pentanal                | 0b            | 0b         | 2891b  | 0b     | 0b         | 177 |
| 2,3,4-Trimethyl pentane | 25b           | 164a       | 0b     | 0b     | 0b         | 74 |
| 2,3,3-Trimethyl pentane | 50b           | 175a       | 0b     | 0b     | 0b         | 82 |
| Dimethyl disulfide      | 0c            | 251a       | 125b   | 0b     | 0b         | 28 |
| Toluene                 | 305b          | 965a       | 607b   | 508b   | 481b       | 91 |
| 4-Octene                | 204b          | 0c         | 521b   | 290b   | 0b         | 44 |
| Octane                  | 3090bc        | 5625db     | 7432b  | 3456bc  | 1462e      | 977 |
| 2-Octene                | 525a          | 662a       | 832b   | 230b   | 194a       | 201 |
| 3-Methyl-2-heptane      | 82            | 677        | 78     | 100    | 184        | 370 |
| 2-Octene                | 164           | 390        | 437    | 166    | 154        | 182 |
| Hexanal                 | 79b           | 0b         | 30296a | 30b    | 0b         | 1307 |
| Nonane                  | 0b            | 142ab      | 224b   | 108ab  | 0b         | 39 |
| Total                   | 29897bc       | 38912bc    | 107576d| 32626d | 12970f     | 3170 |

1Vacuum-packaged for 7 d then aerobically packaged for 3 d.

2Double packaging with sesamol (100 ppm) and a-tocopherol (100 ppm) added.

a-dDifferent 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.

Acknowledgements

This work was supported from Radiation Technology R&D program (2013M2A2A6043308) through the National Research Foundation of Korea funded by the Ministry of Science, ICT & Future Planning.

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