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Meat Irradiation and Meat Safety: Prevention of Quality Changes in Irradiated Meat and Meat Products

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SUMMARY

Irradiation is the best-known intervention strategy that can ensure safety of meat and meat products. Recently, major meat processors have announced that they are going to irradiate their products and some grocery chains have indicated that they are going to sell irradiated products. To be acceptable by general consumers, however, the quality of irradiated meat should be maintained. It is well known that irradiation produces off-odor, changes color, and accelerates lipid oxidation in meat. The volatiles responsible for off-odor were S-containing compounds such as methanethiol, dimethyl sulfide, dimethyl disulfide, and dimethyl trisulfide generated by the radiolytic degradation of sulfur amino acids. The pigment responsible for pinking in irradiated light meats was carbon monoxide-myoglobin (CO-Mb) and the changes of oxidation-reduction potential (ORP) in meat by irradiation played an important role in the formation of CO-Mb. All irradiated meat produced significant amount of CO and irradiation lowered ORP of meat. The mechanisms of color changes in red meats, however, were different from that in light meat. Lipid oxidation in meat can be a problem only under aerobic conditions and the volatiles produced by lipid oxidation had no correlation with irradiation off-odor in meat. Most of the chemical changes in meat by irradiation are related to free radical reactions: off-odor volatiles and CO are produced by the radiolytic degradation of meat components, and lipid oxidation can be initiated by free radicals.

The sulfur volatiles responsible for irradiation off-odor were highly volatile and could be eliminated by storing the irradiated meat under aerobic conditions. Exposing irradiated meats to aerobic conditions also increases ORP and CO **vs** O_2 competition, which reduces the chances for CO-Mb ligand formation and decrease pink color intensity. However, aerobic conditions accelerate lipid oxidation in meat. Vacuum packaging prevents lipid oxidation in irradiated meat during storage, but maintains reduced conditions of meat and keeps off-odor volatiles inside the bag. The addition of antioxidants and acid-chelator combinations were effective in minimizing oxidative changes and pinking. Appropriate combinations of vacuum/aerobic packaging and additives, therefore, can be effective in controlling color, off-odor volatiles, and lipid oxidation of irradiated raw meat during storage. The prevention of quality changes in irradiated meat by packaging and additive combinations will be discussed.

Keywords:

meat irradiation, meat products, quality changes, color changes, off odor, volatile compounds

INTRODUCTION

Irradiation is among the best-known methods for control of potentially pathogenic microorganisms in raw meat, but its application is limited because of quality and health concerns about irradiated meat. Irradiation produces a characteristic aroma as well as alters meat flavor and color that significantly impact upon consumer acceptance. The generation of off-odor and pink color defect is a critical issue for the use of irradiation in meat because consumers associate the presence of off-odor and off-flavor with undesirable chemical reactions, and a pink color in raw and cooked poultry breast meat with contaminating or undercooking. As a result of these consumer perceptions, the meat industry has difficulties in using irradiation to achieve its food safety benefits. The government has made exhaustive research and consumer education efforts to establish that the use of irradiation is a safe process. They have assured the public that irradiation does not result in any compositional changes in raw and cooked meat. However, when consumers find unusual color or odor/flavor changes in a familiar meat or meat product, this may cast unnecessary doubts in their minds as to what other changes may have occurred. Therefore, developing methods that can control off-odor for raw meat, and off-flavor, pinking and lipid oxidation for cooked meat are especially important to improve consumer acceptance of irradiated meat.

Production of Off-Odor in Irradiated Meat

Off-odor in irradiated meat can be produced by two mechanisms: lipid oxidation and radiolytic degradation of amino acid and fatty acids. However, volatiles produced by radiolytic degradation of amino acids are more important than those from lipid oxidation. The mechanisms of lipid oxidation in irradiated meat are not fully understood, but are likely to be similar to those in non-irradiated meat. Ionizing radiation generates hydroxyl radicals in aqueous (Thakur and Singh, 1994) or oil emulsion systems (O'Connell and Garner, 1983). Therefore, irradiation would produce a large amount of hydroxyl radicals and generate lipid oxidation-induced off-odor in meat because muscle cells contain 75% or more of water. Lipid oxidation, however, was a significant problem in irradiated meat only when it was irradiated and stored under aerobic conditions (Merritt et al., 1975; Ahn et al. 1997; 2000a). Effects of raw-meat packaging, irradiation and cooked-meat packaging on lipid oxidation of cooked pork patties during storage indicated that the initial oxidation status of cooked meat was determined by the degree of lipid oxidation in raw meat before cooking. As shown previously (Ahn et al., 1992, 1993), oxygen played more important role on the development of lipid oxidation in meat than irradiation, especially in cooked meat. Shahidi and Pegg (1994) reported that aldehydes contributed the most to oxidation flavor and rancidity in cooked meat and hexanal was the predominant volatile aldehyde. A study with oil emulsion systems showed that longer storage time increased the amount of aldehydes and TBARS values in oil emulsions, but irradiation had minimal effect on the increase of aldehydes and TBARS. Also, volatiles from lipids accounted for only a small part of the off-odor in irradiated samples (Table 1).

All irradiated meat products produced a characteristic, readily detectable aroma, which was distinctly different from that of warmed-over flavor in oxidized meat. Hashim et al. (1995) described the characteristic of irradiation odor as a "bloody and sweet" aroma, and Ahn et al. (2000a) described it as a "barbecued corn-like" odor. Batzer & Doty (1955) reported that methyl mercaptan and hydrogen sulfide were important to irradiation odor, and Patterson & Stevenson (1995) found that dimethyl trisulfide was the most potent off-odor compound, followed by **cis**-3- and **trans**-6-nonenals, oct-1-en-3-one, and bis(methylthio-)methane in irradiated chicken meat. However, the volatile profiles of meat indicated that mercaptomethane, carbon disulfide, dimethyl sulfide, methyl thioacetate, dimethyl disulfide and

Table 1. Production of aldehydes and TBARS value in emulsions prepared with arachidonic and linolenic acid, and fish oil

Volatiles	Arachidonic acid		Linolenic acid		Fish oil	
	0 kGy	5 kGy	0 kGy	5 kGy	0 kGy	5 kGy
	total ion counts x 10^4					
Day 0						
2-Propenal	0	0	0	0	179	287
Propanal	0	0	0	1519	0	0
Butanal	0	0	0	0	465	175
Pentanal	0	0	0	0	323	81
Hexanal	0	0	0	0	0	0
Total aldehydes (%)	0	0	0	0.5	5.3	7.8
TBARS (mg/1000g)	2.58	1.41	4.51	1.27	2.27	2.38
Day 10						
2-Propenal	11435	27531	4426	3393	7070	2775
Propanal	794	0	32297	30809	24403	10899
Butanal	0	223	117	0	1314	455
Pentanal	1180	2494	0	0	580	248
Hexanal	28864	58702	0	0	0	0
Total aldehydes (%)	33.2	47.9	9.5	6.8	79.4	87.1
TBARS (mg/kg oil)	143.43	140.10	103.68	76.37	54.26	26.86

Lee and Ahn (2003).

dimethyl trisulfide were important in irradiation off-odor (Ahn et al., 1999; 2000b; 2001; Ahn and Lee, 2002). The production of hexanal, the major volatile related to oxidative changes in meat, was not influenced by irradiation but by storage and packaging methods

Jo and Ahn (2000) reported that the radiolytic degradation of amino acids, especially sulfur amino acids, was the main mechanism of off-odor production in irradiated meat. The profiles and amounts of volatiles in irradiated meats showed that these S-volatiles were higher in vacuum-packaged than aerobically packaged meats because they were highly volatile under aerobic conditions (Ahn et al., 2000a; Ahn et al., 2001; Nam et al., 2001). Therefore, aerobic packaging will be more beneficial in reducing the characteristic irradiation off-odor during refrigerated storage than vacuum packaging, unless lipid oxidation is a problem.

The perception of odor from samples containing sulfur volatiles changed greatly depending upon their composition and amounts present in the sample. Sulfur compounds were not only produced by the radiolytic cleavage of side chains (primary reaction), but also by the secondary reactions of primary sulfur compounds with other compounds around them. The amounts and kinds of sulfur compounds produced from irradiated methionine and cysteine indicated that methionine was the major amino acid responsible for irradiation off-odor (Ahn, 2002). The total amount of sulfur compounds produced from cysteine was only about 0.25-0.35% of methionine even after the proportion of cysteine or methionine in each of the dimmer, trimer or tetramer was considered. Therefore, the contribution of methionine to the irradiation odor was far greater than that of cysteine (Table 2).

Table 2. Production of volatile compounds from sulfur-containing amino acid tetramer or oligomers by irradiation

Volatiles	0 kGy	5 kGy
	total ion counts x 10^4	
Glutathione (g-Glu-Cys-Gly)		
Carbon disulfide	0^b	589^a
Dimethyl disulfide	0^b	214^a
Met-Gly-Met-Met		
Mercaptomethane	0^b	17325^a
Dimethyl sulfide	0^b	201541^a
(Methylthio) ethane	0^b	2053^a
1-Heptanethiol	0^b	94^a
3-(Methylthio)-1-propene	0^b	122^a
Ethanthioic acid, S-methyl ester	0^b	170^a
2-Methyl-2-(methylthio) propane	92^b	149^a
Dimethyl disulfide	1430^b	351320^a
Methyl ethyl disulfide	0^b	1935^a

^{a,b} Means with no common superscript differ significantly ($p < 0.05$), Ahn (2002).

Color Changes in Meat by Irradiation

The color changes in irradiated meat differ significantly depending on various factors such as irradiation dose, animal species, muscle type, and packaging type (Satterlee et al., 1971; Shahidi et al., 1991; Luchsinger et al., 1996; Nanke et al., 1999). Irradiation increased redness (a-value) of both aerobically and vacuum-packaged raw turkey breast (Table 3). The color changes were not localized in any specific area but evenly distributed over the whole meat sample. The increased redness in raw meat was irradiation dose-dependent, stable during storage, and more intense and stable with vacuum packaging than aerobic conditions during refrigerated storage (Luchsinger et al., 1996). Satterlee et al. (1971) reported that the presence of air slightly inhibited the formation of red color in irradiated bovine metmyoglobin solutions. Grant and Patterson (1991) also reported that irradiated color could be discolored in the presence of oxygen. Therefore, the pigment generated by irradiation cannot be regarded as an oxygen-related pigment. Nam and Ahn (2002a,b) attributed the increased red color in irradiated turkey meat to the formation of carbon monoxide-myoglobin (CO-Mb) complex. Compared with oxymyoglobin, CO-Mb complex is not easily oxidized to brown metmyoglobin, because of the strong binding of CO to the iron-porphyrin in myoglobin molecule (Sorheim et al., 1999). The redness of irradiated aerobically packaged turkey breast was lower than vacuum-packaged breast, but it was still higher than that of the nonirradiated control. After 10 d of storage, the redness of aerobically or doubly packaged turkey breast was not changed, whereas that of vacuum-packaged breast significantly increased. Therefore, exposing irradiated meat to aerobic conditions was effective in reducing pink color in irradiated turkey breast meat. Although the binding affinity of CO to myoglobin is 200-fold stronger than O_2 (Stryer, 1981), the continuous challenge from oxygen under aerobic conditions should have replaced CO-Mb ligand to MbO_2, which oxidized easily to metMb and decreased pink color intensity.

Furuta et al. (1992) and Woods and Pikaev (1994) reported that considerable amount of carbon monoxide (CO) gas was produced by radiolysis of organic components in irradiated frozen meat and poultry. Irradiation generated CO gas in both aerobically and vacuum-packaged meat, but the vacuum-packaged turkey breast showed higher CO than the aerobically packaged turkey breast. After 2 weeks of storage, the amount of CO decreased in aerobically packaged irradiated turkey breast. Most CO gas produced by irradiation escaped under aerobic conditions. On the other hand, a considerable amount of CO remained in vacuum-packaged irradiated turkey breast, and it can be considered that the gas was related to the vivid red color that existed in the vacuum-packaged meat samples stored for 2 weeks (Nam and Ahn, 2002a,b). Irradiation, as well as cooking, produced carbon monoxide. CO was also detected in nonirradiated meat samples, but they increased proportionally with irradiation dose (Table 4). Watts et al.

(1978) found that fresh meat exposed to low levels of CO gas turned red with the formation of CO myoglobin.

Cornforth et al. (1986) reported that hemochrome formation was promoted by reducing conditions and prevented by oxidizing conditions. Irradiation can provide meat with strongly reduced environments. Swallow (1984) reported that hydrated electrons, one of the radiolyzed radicals produced by irradiation, could act as a very powerful reducing agent, and reacted with ferricytochrome and produced ferrocytochrome. We postulate 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. In irradiated raw and cooked turkey breast, therefore, the ORP explains the higher a-values in vacuum-packaged meat samples than in aerobically packaged. The ORP of raw and cooked turkey breast meat initially decreased by irradiation in both aerobically and vacuum-packaged conditions, but vacuum-packaged meat had much lower ORP values than the aerobically packaged meat. As the storage time increased, however, the ORP in irradiated raw turkey breast increased, whereas the ORP in nonirradiated turkey breast decreased in both packaging conditions (Nam and Ahn, 2002a,b). Generally, the ORP of raw meats declines during the initial storage due to the oxygen consumption of meat tissues or microorganisms. Cornforth et al. (1986) reported that microbial growth decreased ORP and thus increased reducing capacity. After 2 weeks of storage, the differences of ORP between nonirradiated and irradiated raw turkey breasts disappeared or reverted within the same packaging condition. Although ORP value decreased in the processing of irradiation, the reduced conditions produced in irradiated raw meat were not maintained during the storage. The red pigments generated by irradiation were fairly stable against the increased oxidative environment stress during the storage time. In cooked meat, both undenatured and denatured heme pigments in cooked turkey may have been involved in heme-complex formations (with ligands available under the conditions), which will be important for the pink color formation. The ORP increased faster under aerobic than vacuum conditions during storage. Within each packaging conditions, however, irradiated samples had lower ORP than the nonirradiated during the storage (Table 5).

Table 3. CIE color a-values of raw and cooked turkey breast with different packaging, irradiation, and storage conditions

Storage	Aerobic packaging			Vacuum packaging		
	0 kGy	2.5 kGy	5.0 kGy	0 kGy	2.5 kGy	5.0 kGy
Raw meat						
0 Week	3.02^{c}	4.69^{b}	6.45^{a}	2.86^{cy}	5.72^{by}	6.93^{ay}
1 Week	3.04^{b}	5.28^{a}	5.61^{a}	2.90^{cy}	5.60^{by}	6.42^{ay}
2 Week	3.49^{c}	4.96^{b}	5.85^{a}	3.73^{cx}	6.77^{bx}	8.64^{ax}
Cooked meat						
a-value						
0 Week	8.09^{c}	9.16^{bx}	10.81^{ax}	7.84^{cy}	9.47^{b}	12.40^{ax}
1 Week	8.56^{b}	9.85^{ax}	10.50^{ax}	9.42^{bx}	9.79^{b}	11.55^{ax}
2 Week	8.48	7.84^{y}	8.10^{y}	7.04^{cy}	8.82^{b}	9.40^{ay}

a-c Different letters within a row with the same packaging are different ($p < 0.05$).
x-z Different letters within a column of the same irradiation dose are different ($p < 0.05$). Nam and Ahn (2002a,b).

Table 4. The production of CO in raw and cooked turkey breast with different packaging, irradiation, and storage conditions[1]

Storage	Aerobic packaging			Vacuum packaging		
	0 kGy	2.5 kGy	5.0 kGy	0 kGy	2.5 kGy	5.0 kGy
				Unit (ppm[1])		
Raw meat						
0 Week	0^{cz}	328^{bx}	593^{ax}	0^{cy}	445^{b}	999^{ax}
1 Week	45^{by}	359^{ax}	509^{ax}	19^{cx}	394^{b}	560^{ay}
2 Week	74^{x}	134^{y}	144^{y}	6^{cxy}	365^{b}	533^{ay}
Cooked meat						
0 Week	220^{cx}	319^{bx}	456^{ax}	227^{cx}	370^{bx}	575^{ax}
1 Week	230^{bx}	210^{by}	261^{ay}	154^{cy}	336^{bxy}	558^{ax}
2 Week	134^{y}	181^{y}	227^{y}	130^{cy}	289^{by}	450^{ay}

[1]Concentration in headspace (14 mL) from 10 g meat. a-cDifferent letters within a row with same packaging are different ($p < 0.05$).
x-zDifferent letters within a column with same irradiation dose are different ($p < 0.05$). Nam and Ahn (2002a,b).

The correlation coefficients between CIE color values, irradiation dose, storage time, and other analytical values indicated that the a-values of turkey breast were positively correlated with irradiation dose and the amount of CO gas produced. The increased a-values in irradiated turkey breast were maintained regardless of increased ORP and lipid oxidation during the 2 weeks of storage.

Remedies to Off-Odor Production and Color Changes

Double-Packaging

Packaging turned out to be the major factor influencing the amounts and types of volatiles detected in irradiated meat. Sulfur compounds, the most critical volatiles for off-odor development in irradiated meat, can easily be eliminated under aerobic conditions. Double packaging is a new packaging concept that we have developed to tackle quality problems associated with irradiation in meat. Two double-packaging models can be used: in model #1, meats are first individually packaged in oxygen-permeable plastic bags. A few of the aerobically packaged meats are then vacuum-packaged in an oxygen-impermeable bag and irradiated. The outer vacuum bags can be removed to expose the inner bag to aerobic conditions for a few days before marketing or consumption. In model #2, meats are aerobically packaged and irradiated first, and then vacuum-packaged after a few days of storage under aerobic conditions.

Irradiation and aerobic packaging promoted the production of aldehydes (propanal and hexanal) related to lipid oxidation in turkey breast and thigh meats. Vacuum-packaged irradiated samples retained S-volatile compounds (methanethiol, dimethyl sulfide, dimethyl disulfide and dimethyl trisulfide), mainly responsible for the irradiation off-odor, during the storage. However, exposing double packaged irradiated turkey meats to aerobic conditions by removing outer vacuum bags a few days before the test (double packaging model #1) or irradiating and storing turkey breast meat for 1 to 3 d under aerobic conditions and then storing under vacuum conditions (double packaging model #2) was effective in controlling both lipid oxidation-dependent (aldehydes) and radiolytic off-odor (S-compounds) volatiles (Table 7). Exposing irradiated meats to aerobic conditions increases ORP and $CO:O_2$ competition, which decreases pink color intensity. However, the use of double-packaging alone was not enough to reduce the pink color of irradiated raw turkey meat (Nam and Ahn, 2003a,b). Therefore, the major advantage of double-packaging concept is the elimination of off-odor problems without ant additives. Pinking on the surface of the meat can also be reduced by double packaging but was not highly effective.

Antioxidants

Irradiated meat homogenates and patties showed that addition of an antioxidant (sesamol, gallate, Trolox, or α-tocopherol) and their combinations decreased, but carnosine did not affect the production of off-odor volatiles and lipid oxidation of pork homogenates and patties by irradiation. Antioxidant combinations showed distinct beneficial reduction in lipid oxidation of aerobically packaged irradiated pork patties. The effect of antioxidant combinations in reducing sulfur volatiles of irradiated pork patties was clearer under vacuum than aerobic conditions. Sesamol, sesamol plus tocopherol, and gallate plus tocopherol were among the best in controlling production of off-odor volatiles and lipid oxidation in irradiated turkey breast or pork meat homogenates and patties (Nam et al., 2002c; Lee and Ahn, 2003).

Table 5. Oxidation-reduction potential (ORP) of raw and cooked turkey breast with different packaging, irradiation dose, and storage

	Aerobic packaging			Vacuum packaging		
Storage	0 kGy	2.5 kGy	5.0 kGy	0 kGy	2.5 kGy	5.0 kGy
			Unit (mV)			
Raw meat						
0 Week	-16^{ax}	-174^{bz}	-91^{bz}	-74^{ax}	-193^{b}	-279^{cy}
1 Week	-19^{cx}	12^{by}	34^{ay}	-148^{bz}	-127^{ab}	-110^{ax}
2 Week	-59^{by}	46^{ax}	65^{ax}	-113^{y}	-145	-135^{x}
Cooked meat						
0 Week	-19^{ay}	-49^{by}	-62^{by}	-48^{ay}	-71^{ay}	-104^{by}
1 Week	102^{ax}	68^{bx}	75^{bx}	-49^{ay}	-53^{bxy}	-50^{abx}
2 Week	113^{ax}	84^{bx}	82^{bx}	-18^{ax}	-41^{abx}	-59^{bx}

[a-c] Different letters within a row with the same packaging are different ($p < 0.05$).
[x-z] Different letters within a column of the same irradiation dose are different ($p < 0.05$), n = 8. Nam and Ahn (2002a,b).

Lipid oxidation had significant impact on the volatile profiles of meat: aldehydes – including hexanal, pentanal, butanal and propanal – were decreased in nonirradiated sausages by sesamol, vitamin E, or gallic acid treatments, while rosemary was largely ineffective. Among the antioxidants used in nonirradiated sausages, sesamol was the most effective in reducing aldehydes and TBARS. Sulfur compounds were the most important for flavor in meat (Ahn et al., 2000a,b). Two sulfur compounds, carbon disulfide and dimethyl disulfide, were the major sulfur compounds detected in nonirradiated turkey sausages. Gallic acid significantly ($P < 0.05$) reduced the dimethyl disulfide content in nonirradiated turkey sausages, while rosemary increased it. Nam et al. (2002c) also reported that the 0.02% gallic acid and vitamin E mixture was effective in reducing sulfur compounds in irradiated pork patties. Antioxidant treatments had no effect on the carbon disulfide content in nonirradiated turkey sausages. Sesamol reduced the contents of pentane and pentene, but overall effects of antioxidants on the production of alkane and alkene in nonirradiated sausages were minor. After irradiation, two additional sulfur compounds - methanethiol and dimethyl trisulfide - were produced and overall volatiles production from turkey sausages increased dramatically. The contents of dimethyl disulfide and dimethyl trisulfide in samples treated with sesamol and gallic acid were lower compared with others, but no difference was observed for methanethiol and carbon disulfide. Nam and Ahn (2002b) found that antioxidant combinations -including sesamol, gallic acid, trolox, and vitamin E - were effective in reducing sulfur compounds. As in nonirradiated samples, sesamol treatment greatly lowered aldehyde content in irradiated samples, but other antioxidants were largely ineffective in reducing aldehydes. Sesamol treatment also significantly lowered pentane production in irradiated and nonirradiated turkey sausages (Du and Ahn, 2002). The results also indicated that gallic acid at 0.02% dramatically lowered the redness of both irradiated and nonirradiated turkey sausages, and sesamol and rosemary also were effective in reducing irradiation-induced redness (Table 7).

Double packaging and acid combinations

Citric or ascorbic acid is commonly used in meat processing as a preservative or an antioxidant (Stivarius et al., 2002). The addition of citric acid or ascorbic acid lowered the pH values of turkey breast meat by about 0.4 unit. Irradiation, however, had no effect on the pH of vacuum-packaged meat. The pH of the meat increased a little bit during the 10-d of storage at all treatments. Irradiation increased the a-value of vacuum-packaged turkey breast

Table 6. Color a-values and sulfur-containing volatiles of irradiated raw turkey breast meat with double packaging at Day 10[a]

Compound	NonIr Aerobic	Irradiated Aerobic	A5/V5[1]	A3/V7[2]	A1/V9[3]	Vacuum
Color a-values						
Day 0	2.5^{c}	3.5^{b}	3.5^{b}	3.5^{b}	3.5^{b}	4.9^{a}
Day 10	1.8^{c}	3.3^{b}	3.1^{b}	4.0^{b}	4.0^{b}	5.6^{a}
Sulfur compounds at Day 10			(Total ion counts x 10^4)			
Methanethiol	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	1505^{a}
Dimethyl sulfide	1033^{d}	1024^{d}	1774^{cd}	2576^{c}	5346^{b}	15101^{a}
Carbon disulfide	103^{a}	103^{a}	62^{b}	0^{c}	0^{c}	0^{c}
Methylthio ethane	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	47^{a}
Dimethyl disulfide	0^{b}	40^{b}	34^{b}	31^{b}	116^{b}	8020^{a}
Dimethyl trisulfide	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	638^{a}
Total	1136^{e}	1167^{e}	1870^{d}	2607^{c}	5462^{b}	25311^{a}

[a] Different letters (a-e) within a row are significantly different ($P < 0.05$)
[1] Aerobically packaged for 5 d and then vacuum packaged for 5 d
[2] Aerobically packaged for 3 d and then vacuum packaged for 7 d.
[3] Aerobically packaged for 1 d and then vacuum packaged for 9 d. Nam and Ahn (2003a).

Table 7. The color a-value of irradiated turkey sausage with different antioxidant treatments.

Irradiation dose	Control	Vitamin E	Sesamol	Rosemary	Gallic acid
0 kGy	2.58^{ay}	2.45^{aby}	2.37^{aby}	2.26^{by}	1.49^{cz}
1.5 kGy	2.81^{ay}	2.69^{aby}	2.50^{bcy}	2.34^{cy}	2.03^{dy}
3 kGy	3.25^{ax}	3.48^{ax}	2.74^{bx}	2.62^{bx}	2.29^{cx}

[a-c]Different letters within a row of same category differ significantly ($P < 0.05$).
[x-z]Different letters within a column of same category differ significantly ($P < 0.05$). Du and Ahn (2002).

patties and the increased redness was more consistent after 10-d of storage. Double packaging and acid combinations have shown effects mainly in L- and b-values rather than a-value of irradiated turkey meat after 10-d of storage. The acid-treated, double-packaged irradiated turkey meat had higher L- and b-values than the irradiated vacuum-packaged control, regardless of kind of acid or double-packaging method used. Especially, the drastically increased L-values could be caused by the added acid, which had light-scattering effect in lower pH muscle. Swatland (1994) reported that decreasing pH towards the isoelectric point of muscle proteins increased light-reflecting and scattering phenomena in meat, which resulted in increased L-values. In terms of a-value, however, acid had little effect on the redness of irradiated turkey meat indicating that lowered pH of muscle did not influence the formation or stability of CO-Mb complex, which were responsible for the increased redness of irradiated meat. Therefore, the overall color perception of irradiated turkey breast meat was paler and the intensity of red or pink color was lower in acid-treated meat than that of acid-free irradiated meat, by the effect of not decreased a-values but increased L-values. There were little different results between citric acid and ascorbic acid at the color values of irradiated turkey breast patties at 10 d (Table 8).

Citric acid-treated turkey breast had higher TBARS values than ascorbic acid-treated meat, and the difference became highly distinct after 10 d of storage. We speculate that in citric acid-added turkey meat, the loosened muscle structure by lowered pH was more susceptible to the attacks of free radicals generated by irradiation, and lipid oxidation was accelerated during the limited aerobic period. In general, there was a negative correlation between pH post mortem and the TBARS value (Judge and Aberle, 1980). On the other hand, despite aerobic exposure, irradiated ascorbic acid-treated turkey meat had similar levels of TBARS compared with the irradiated vacuum-packaged meat. This result indicates that ascorbic acid showed an antioxidant effect during aerobic storage. Ascorbic acid is capable of inhibiting lipid oxidation by inactivating free radicals and by regenerating α-tocopherol, and the antioxidant effect in muscle food was very dependent on its concentration (Decker and Mei, 1996). Therefore, using ascorbic acid rather than citric acid would be more effective in reducing color intensity of irradiated meat.

In citric acid-treated and irradiated turkey meat samples, packaging conditions were critical factors influencing the volatile profiles and their amounts at 0 d. A3/V7 double-packaged irradiated turkey meats at 0 d (the same as aerobic conditions at 0 d) had less total and less sulfur volatiles than V7/A3 double-packaged irradiated meat at 0 d (the same as vacuum conditions at 0 d). This result shows that most volatiles, including sulfur compounds, were evaporated rapidly during irradiation and sample preparation before analysis under aerobic conditions. The production of total and sulfur volatiles from ascorbic acid-treated meats was lower than that of citric acid-treated meats. Ascorbic acid acted as a powerful antioxidant and an inhibitor of radiolytic degradation of protein side chains in meat. Regardless of acid treatments, exposing the irradiated turkey meat to aerobic condition for 3 d during the 10-d storage was enough to eliminate almost all sulfur volatiles. The amounts of total volatiles and dimethyl sulfide were reduced by 35-56% and 58-73% of the vacuum-packaged irradiated control, respectively. Almost all dimethyl disulfide was evaporated, and dimethyl trisulfide was not found in doubly packaged irradiated turkey breast meat exposed to aerobic conditions for 3 d. The combination sequence of aerobic/anaerobic packaging (double-packaging models) was not a critical factor in the production of off-odor volatiles of irradiated turkey meat (Nam and Ahn, 2002c).

Double Packaging and Antioxidant Combinations

The effects of antioxidant and double packaging combinations indicated that sesamol+α-tocopherol (S+E)

Table 8. CIE color values of irradiated raw turkey breast meat treated by different acids and packaging conditions during refrigerated storage

	NonIrrad.	Irradiated				
			Citric acid		Ascorbic acid	
Storage	Vacuum	Vacuum	A3/V7[1]	V7/A3[2]	A3/V7[1]	V7/A3[2]
L-value						
Day 0	56.5^{cx}	56.9^{cx}	59.9^{aby}	60.8^{a}	59.1^{by}	60.1^{ab}
Day 10	54.8^{by}	55.5^{by}	61.8^{ax}	60.8^{a}	60.6^{ax}	60.4^{a}
a-value						
Day 0	2.6^{c}	4.9^{by}	6.0^{a}	5.5^{ay}	5.5^{a}	4.9^{by}
Day 10	2.5^{b}	5.5^{ax}	5.7^{a}	5.8^{ax}	5.7^{a}	5.9^{ax}

[1] Aerobically packaged for 3 d then vacuum-packaged for 7 d
[2] Vacuum-packaged for 7 d then aerobically packaged for 3 d.
[a-c] Different letters within a row indicate significant difference ($p \leq 0.05$).
[x, y] Different letters within a column are significant difference ($p \leq 0.05$). Nam and Ahn (2002c).

and gallate+α-tocopherol (G+E) combinations were very effective in preventing lipid oxidation during storage, and the TBARS of the antioxidant-treated meats were lower than even nonirradiated vacuum-packaged raw meat at 10 d. The antioxidant effect on lipid oxidation of turkey meat was even more distinct after cooking. The TBARS of irradiated turkey meat increased rapidly after cooking, but those with antioxidants did not. Therefore, the problem of lipid oxidation in aerobically or double-packaged irradiated raw and cooked turkey breast could be solved by the addition of antioxidant combinations.

Antioxidants lowered the L*-value of vacuum-packaged irradiated meat by about 2 units and a* value by 1 unit. The a*-value of aerobically packaged irradiated meat was lower than that of vacuum-packaged meat, but was still higher than nonirradiated control. After 10 d of refrigerated storage, the redness of double-packaged meat decreased significantly. Furthermore, the combination of antioxidants with double packaging showed a synergistic effect in reducing the redness of irradiated meat: the presence of oxygen should have accelerated the dissociation of CO-Mb, while antioxidants should have inhibited the radiolytic generation of CO.

Irradiated cooked turkey breast meat from double packaging and antioxidant combinations also produced significantly lower a* values than the vacuum-packaged irradiated cooked meat. Gallate+α-tocopherol (G+E) was significantly more effective in reducing the redness than S+E. Therefore, G+E in combination with double packaging can be effective in controlling off-color in irradiated raw and cooked turkey breast meat (Table 9).

Little difference in volatile profiles between vacuum-packaged irradiated and doubly packaged irradiated meats at 0 d was found because they were both in vacuum conditions during irradiation. Antioxidant treatments lowered total volatiles in raw turkey meat, and propanal was not detected when antioxidants were added. After 10 d of refrigerated storage, volatile profiles of irradiated turkey breast were highly dependent upon antioxidant and packaging conditions. Sulfur volatiles were not detected in irradiated aerobically or double-packaged meat. Three days of exposure to aerobic conditions was enough for the sulfur volatiles to escape from the meat. However, aerobically packaged irradiated meat without antioxidants produced large amounts of aldehydes (propanal, hexanal) and 2-butanone at 10 d, which coincided with the result of TBARS. Double-packaged meat had few lipid oxidation products compared with aerobically packaged meat, but antioxidant combinations significantly reduced the amount of pentane. Therefore, the combination of double packaging (vacuum for 3 d then aerobic for 7) with antioxidants in irradiated raw turkey breast was very effective in reducing total and sulfur volatiles responsible for the irradiation off-odor without any problem in lipid oxidation (Table 10).

The beneficial effects of double packaging and antioxidant combinations on volatiles were more clearly shown in irradiated cooked turkey breast. Double packaging itself was more effective than vacuum packaging in reducing sulfur volatiles, and lipid oxidation-dependent volatiles compared with aerobic packaging. However, the combination of antioxidant with double packaging was more effective in reducing both sulfur and lipid oxidation volatiles in irradiated cooked meat. The total amounts of sulfur volatiles in double-packaged irradiated turkey meat with antioxidants were only about 5-7% of the irradiated vacuum-packaged cooked meat without antioxidants. Production of most aldehydes in irradiated cooked turkey breast was prevented by using antioxidants and double packaging.

In conclusion, antioxidants reduced lipid oxidation and volatile aldehydes significantly. Packaging was the most critical factor irradiation off-odor in meat. Combination of antioxidant and double packaging (V7/A3) was effective in controlling the oxidative quality changes of irradiated raw and cooked meat. Among the antioxidant and double

Table 9. TBARS and color a* values of of raw turkey breast with different packaging and antioxidants

	NonIr	Irradiated				
	Vacuum	Vacuum	Aerobic	Double pkg		
	pkg	pkg	pkg	None	S+E[2]	G+E[3]
TBARS			(mg MDA/kg meat)			
0 d raw	0.66^{by}	0.84^{ay}	0.91^{ay}	0.83^{ay}	0.42^{dy}	0.55^{c}
10 d raw	0.72^{cy}	0.84^{cy}	2.18^{ax}	1.61^{by}	0.53^{cx}	0.53^{c}
Cooked	1.12^{dx}	1.67^{cx}	2.37^{ax}	2.09^{bx}	0.54^{ex}	0.64^{e}
Color a* values						
0 d raw	4.42^{cz}	7.95^{ay}	7.15^{bx}	7.74^{axy}	6.95^{by}	6.74^{bx}
10 d raw	4.67^{dz}	7.89^{ay}	5.66^{cy}	6.98^{by}	4.68^{dz}	5.63^{cy}
Cooked	7.50^{cx}	10.04^{ax}	5.58^{dy}	8.62^{bx}	7.51^{cx}	5.75^{dy}

1 Vacuum packaged for 7 d then aerobically packaged for 3 d
2 Sesamol (100 ppm) and α-tocopherol (100 ppm) added
3 Gallic acid (100 ppm) and α-tocopherol (100 ppm) added. Nam and Ahn (2003c).

Table 10. Sulfur compounds and aldehydes of raw and cooked turkey breast with different packaging and antioxidants

Sulfur compounds	NonIr Vacuum pkg	Irradiated Vacuum pkg	Irradiated Aerobic pkg	Irradiated Double pkg[1] None	Irradiated Double pkg[1] S+E[2]	Irradiated Double pkg[1] G+E[3]
			(Total ion counts × 10^4)			
Raw meat						
Dimethyl sulfide	$1,304^b$	$1,990^a$	140^d	831^c	676^c	546^c
Carbon disulfide	258^b	306^a	0^c	0^c	0^c	0^c
Dimethyl disulfide	0^b	$22,702^a$	0^b	32^b	0^b	43^b
Dimethyl trisulfide	0^b	554^a	0^b	0^b	0^b	0^b
Cooked meat						
Dimethyl sulfide	$1,008^b$	$2,032^a$	451^d	$1,005^b$	689^c	588^{cd}
Carbon disulfide	419^a	339^{ab}	210^b	271^{ab}	278^{ab}	374^a
Dimethyl disulfide	$17,861^a$	342^b	940^b	412^b	210^b	0^b
Dimethyl trisulfide	$1,007^a$	0^b	118^b	0^b	0^b	0^b
Propanal	233^d	2272^c	$8,637^a$	$5,962^b$	38^d	427^d
Butanal	0^e	127^d	592^a	195^c	302^b	226^c
Pentanal	62^c	875^c	$3,014^a$	$1,667^b$	0^c	31^c
Hexanal	0^b	$3,734^b$	$37,617^a$	$9,686^b$	0^b	0^b
3-Methyl butanal	0^c	100^b	223^a	204^a	131^b	142^b

[1] Vacuum packaged for 7 d then aerobically packaged for 3 d
[2] Sesamol (100 ppm) and α-tocopherol (100 ppm) added,
[3] Gallic acid (100 ppm) and α-tocopherol (100 ppm) added. Nam and Ahn (2003c).

packaging treatments, both S+E and G+E with double packaging were effective in reducing pink color, off-odor and lipid oxidation of irradiated raw and cooked turkey breast, but G+E with double packaging were the most effective in reducing the pink color in cooked turkey breast meat (Nam and Ahn, 2003c).

CONCLUSION

Irradiation accelerates lipid oxidation, changes color, and produces irradiation off-odor in meat. However, lipid oxidation in irradiated meat becomes problem only when meat was irradiated and stored under aerobic conditions. Irradiation increases the redness of light meat but turns the red meat brown. The mechanisms involved in the color changes in light and dark meats by irradiation are different. The pink color compounds in irradiated light meat is characterized as a carbon monoxide-heme pigment complex. Irradiation produced carbon monoxide from meat components and the production of carbon monoxide in meat was irradiation dose-dependent. Irradiation also increases the reducing power of meat, which facilitates carbon monoxide-myoglobin complex formation and the complex increases the red color intensity of heme pigments. Irradiation off-odor in meat is mainly caused by sulfur compounds produced by the radiolytic degradation of methionine and cystene, and lipid oxidation products had minor effect on the off-odor of irradiated meat. The sulfur compounds that caused the irradiation off-odor could be easily removed by storing the irradiated meat under aerobic conditions, and double packaging strategy was very effective in eliminating irradiation off-odor. The combinations of antioxidants (S+T or G+T) and double packaging were highly effective in preventing oxidative change and off-odor production, and reduced color changes in raw and cooked turkey breast meat. Most of the irradiation studies are done with raw meat because irradiation is not permitted to use in further processed or precooked ready-to-eat meat products. Therefore, future studies should be focused on flavor, color and taste changes in further processed and precooked ready-to-eat meat products by irradiation. Methods to prevent quality changes in irradiated further processed or precooked ready-to-eat meat products should also be developed.

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