Off-Odor Volatiles and Pink Color Development in Precooked, Irradiated Turkey Breast During Frozen Storage[1]

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ABSTRACT The effect of irradiation on color, lipid oxidation, and volatile production of precooked, irradiated turkey breast during frozen storage was studied. Turkey breast muscles were precooked, aerobically or vacuum-packaged, irradiated at 0, 2.5, or 5.0 kGy using a linear accelerator (electron beam), and then frozen-stored at –40 C. Lipid oxidation, volatiles, color values, gas production, and oxidation-reduction potential (ORP) of meat were determined during 3-mo storage periods. Ionizing radiation produced characteristic off-odor volatiles (dimethyldisulfide and methylthioethane) and lipid oxidation products in precooked, frozen turkey breast. The production of volatiles was accelerated by the confounding effect of high irradiation dose, aerobic packaging, and increased storage time. Volatile production and color changes in irradiated, precooked turkey breast were induced by different mechanisms. Irradiation increased pink color in precooked, vacuum-packaged turkey breast, and the pink color was stable during frozen storage. Decreased ORP and increased CO in irradiated meat indicated that denatured CO-heme pigments could be responsible for the pink color in precooked, irradiated turkey breast. Vacuum packaging was better than aerobic packaging in preventing lipid oxidation and oxidation-dependent volatile production, but pink color in precooked, irradiated turkey breast during frozen storage was maintained.

(*Key words*: irradiation, lipid oxidation, volatiles, color, cooked turkey)

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INTRODUCTION

Oxidative changes such as development of rancidity or off-flavor and discoloration are major concerns in the storage of cooked poultry meat. Cooked poultry meat is highly susceptible to oxidative changes because of its high unsaturated fatty acids composition. The cooking process denatures antioxidant components, damages cell structure, and exposes membrane lipids to extracellular environments (Ahn et al., 1993). Irradiation of poultry meat can provide consumers with products safe from foodborne pathogens (Thayer, 1990), but ionizing radiation generates free radicals in meat systems. The formation of highly reactive free radicals may initiate free-radical chain reactions, such as lipid oxidation, pigment discoloration, or interaction between lipids and heme pigments (McMillin, 1996). Therefore, irradiation of precooked poultry meats can accelerate the development of lipid oxidation and off-flavor, and attention is needed when precooked poultry meats are irradiated.

Irradiated raw meat developed a characteristic off-odor compared with the nonirradiated control (Lynch et al., 1991). Ahn et al. (2001) reported that sulfur-containing compounds such as mercaptomethane and dimethyldisulfide, not related with lipid oxidation, were responsible for most of the irradiation off-odor in pork, but the sulfur compounds volatilized quickly during aerobic storage. Irradiation of oil emulsions containing several sulfur-containing amino acids produced similar volatile compounds to irradiated meat systems. This finding indicated that radiolysis of proteins played an important role in off-odor generation of irradiated meat (Jo and Ahn, 2000). Irradiation also increased red color in raw poultry breast meat (Millar et al., 2000; Du et al., 2000). The generation of pink color in precooked, irradiated meat can be regarded as undercooked or contaminated. Our unpublished data showed that irradiation of meat increased reducing power and generated gas compounds that can act as a sixth ligand of myoglobin.

The quality changes in meat can be different depending upon the reactions between meat components and free radical species produced by irradiation. The quality deterioration of meat by irradiation can also be reduced or delayed by excluding oxygen from meat or freezing meat.

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Abbreviation Key: GC/MS = gas chromatography/mass spectrometry; ORP = oxidation-reduction potential; TBARS = TBA-reactive substances.

The oxidative stability of meat components can be enhanced in frozen state as in refrigerated storage. With decreased mobility under frozen states, free radicals tend to recombine with the original substances rather than diffuse through the food and react with other food components (Taub et al., 1979).

Although many researchers have studied oxidative changes in irradiated meat systems, little information on quality changes in precooked turkey breast meat during frozen state is available. The objective of this study was to determine the effect of irradiation on color, lipid oxidation, and volatile production in precooked, irradiated turkey breast during frozen storage.

MATERIALS AND METHODS

Sample Preparation and Irradiation

Turkey breast (pectoralis) muscles were separated from 50 turkey carcasses and randomly grouped into four replications. The muscles were sliced to steaks that were 3 cm thick and were packaged in polyethylene oxygen-permeable zipper bags[3] (4 × 6, 2 mil) or oxygen-impermeable nylon/polyethylene bags[4] (9.3 mL O_2/m^2 per 24 h at 0 C). Four pieces of sliced steaks (one piece from each replication) were packaged in each bag. The packaged samples were fully cooked in an 80 C water bath to an internal temperature of 75 C. After draining meat juice, the cooked meats were repackaged as before cooking. For aerobically packaged meats, four packages were put in a large vacuum bag, vacuum-packaged, and stored at 4 C to minimize oxidative changes before irradiation. The outer bag was cut open before irradiation. The vacuum- and aerobically packaged samples were placed in a single layer on trays and irradiated at 0, 2.5, or 5.0 kGy using a linear accelerator[5] (Circe IIIR). The energy level was 10 MeV, the power level was 10 kW, and the average dose rate was 95.5 kGy/min. The max/min ratio was approximately 1.38 for 2.5 kGy and 1.43 for 5 kGy. To check the applied dose, alanine dosimeters were attached to the top and bottom surfaces of a sample (one sample per cart). The alanine dosimeters were read using a 104 Electron Paramagnetic Resonance Instrument.[6] The meat samples were stored in a dark freezer room (–40 C) for up to 3 mo. Lipid oxidation, color, and ORP values of meat samples were determined at 0, 1.5, and 3 mo, and volatile compounds and gas production were determined at 0 and 3 mo of frozen storage.

[3]Associated Bag Company, Milwaukee, WI 53207.
[4]Koch, Kansas City, MO 64108.
[5]Thomson CSF Linac, Saint-Aubin, France.
[6]Bruker Instruments Inc, Bellerica MA 01821.
[7]Brinkman Instrument Inc., Westbury, NY 11590-0207.
[8]Tekmar-Dohrmann, Cincinnati, OH 45249.
[9]Hewlett-Packard Co., Wilmington, DE 19808-1610.
[10]J&W Scientific, Folsom, CA 95630-4714.

Analysis of TBA-Reactive Substances Value

Lipid oxidation was determined by TBA-reactive substances (TBARS) method (Ahn et al., 1998). A minced sample (5 g) was placed in a 50-mL test tube, together with 15 mL of deionized distilled water, and the sample was homogenized using a Brinkman Polytron[7] (Type PT 10/35) for 15 s at high speed. The meat homogenate (1 mL) was transferred to a disposable test tube (13 × 100mm), and butylated-hydroxytoluene (7.2%, 50 μL) and TBA (20 m*M*)/trichloroacetic acid (15% wt/vol) solution (2 mL) was added. The mixture was vortexed and then incubated in a 90 C water bath for 15 min to develop color. After cooling for 10 min in cold water, the sample was vortexed, centrifuged at 3,000 × *g* for 15 min at 5 C, and then read at 531 nm against a blank containing 1 mL deionized distilled water and 2 mL TBA/trichloroacetic acid solution. The amounts of TBARS were expressed as milligrams of malondialdehyde per kilogram of meat.

Analysis of Volatile Compounds

A purge-and-trap apparatus[8] (Precept II and Purge and Trap Concentrator 3000) connected to a gas chromatograph/mass spectrometer[9] (GC/MS) was used to analyze volatiles responsible for the off-odor in samples (Ahn et al., 2001). The minced sample (2 g) was placed in a 40-mL sample vial and then flushed with helium gas (40 psi) for 5 s. Samples were held in a refrigerated (4 C) sample tray for less than 4 h to minimize oxidative changes during the period before analysis.

The meat sample was purged with helium gas (40 mL/min) for 13 min at 40 C. Volatiles were trapped at 20 C using a Tenax column[7] and desorbed for 2 min at 22 C. The desorbed volatiles were concentrated at –90 C using a cryofocusing unit,[7] thermally desorbed, and injected (30 s) into a capillary column by increasing the temperature to 220 C. An HP-624 column[8] (7.5 m, 0.25 mm i.d., 1.4 μm nominal), an HP-1 column[8] (52.5 m, 0.25 mm i.d., 0.25 μm nominal), and an HP-Wax column[9] (7.5 m, 0.25 mm i.d., 0.25 μm nominal) were connected using a zero dead-volume column connector.[10] Ramped oven temperature was used to improve volatile separation. The initial oven temperature of 0 C was held for 2.50 min. Then the oven temperature was increased to 10 C at 2.5 C per min, increased to 45 C at 10 C per min, increased to 110 C at 20 C per min, then increased to 210 C at 10 C per min, and was held for 2.5 min at that temperature. Constant column pressure at 20.5 psi was maintained. The ionization potential of the mass selective detector[9] (Model 5973) was 70 eV, and the scan range was 18.1 to 300 m/z. Identification of volatiles was achieved by comparing mass spectral data of samples with those of the Wiley library.[9] Standards, when available, were used to confirm the identification by the mass selective detector. The area of each peak was integrated using ChemStation software,[9] and the total ion count × 10^4 was reported as an indicator of volatiles generated from the meat samples.

Color Measurement

CIE color values were measured on the surface of samples using a LabScan color meter[11] that had been calibrated against a black and a white reference tile covered with the same bags as were used for the sample. The CIE L* (lightness), a* (redness), and b* (yellowness) values were obtained using a setting of illuminant A. An average value from two random locations on each sample surface was used for statistical analysis.

Measurement of ORP

A pH/ion meter[12] (Accumet 25) was used to measure ORP. A platinum electrode filled with 4 *M* KCl solution saturated with AgCl was tightly inserted at the center of a meat sample (~100 g). To minimize the effect of air, the smallest possible pore was made by a cutter before the insertion of an electrode. To compensate for the effect of temperature, a temperature-reading sensor was also inserted. ORP readings (mV) were recorded at exactly 2 min after inserting the electrode into a sample.

Analysis of Gas Production

A minced meat sample (10 g) was placed in a 24-mL, wide-mouth, screw-cap glass vial with a Teflon-fluorocarbon resin/silicone septum.[13] The vial was microwaved for 10 s at full power to release gas compounds from the meat sample. After 5 min of cooling at room temperature, the headspace-gas (200 μL) was withdrawn using an airtight syringe and injected to a split inlet (split ratio, 9:1) of a GC. A Carboxen-1006 Plot column[14] (30 m $\times$ 0.32 mm i.d.) was used, and a ramped oven temperature was used (initial temperature was 50 C and was increased to 160 C at 25 C/min).

Helium was the carrier gas at a constant flow of 2.4 mL/min. A flame ionization detector equipped with a Nickel catalyst[9] was used as a detector, and the temperatures of inlet, detector, and Nickel catalyst were set at 250, 280, and 375 C, respectively. Detector air, H_2, and make-up gas (He) flows were 400, 40, and 50 mL/min, respectively. The identification of gas compounds was achieved using standard gases (CO, CH_4, and CO_2) and GC/MS[9] (Model 5873). To quantify the amounts of gases released, each peak area (pA $\times$ s) was converted to a gas concentration (ppm) contained in the headspace (14 mL) of a 10-g meat sample and was compared to the CO concentration existing in air (330 ppm).

Statistical Analysis

The experimental design was to determine the effects of irradiation on lipid oxidation, volatile compounds, color, ORP, and gas production in samples with different packaging and storage times. The data were analyzed using SAS software (SAS Institute, 1985) by the generalized linear model procedure; Student-Newman-Kuel multiple-range test was used to compare the differences among means. Mean values and standard errors of the means (SEM) were reported. Significance was defined at $P < 0.05$.

RESULTS AND DISCUSSION

Lipid Oxidation and Volatile Production

Storage time influenced the TBARS value of precooked turkey breast during frozen storage, especially in aerobic conditions, but irradiation did not (Table 1). Under aerobic conditions, the TBARS values of precooked turkey breast increased with the increase of storage time, regardless of irradiation doses. The TBARS of precooked turkey breast stored for 3 mo at –40 C were approximately two times as great as that at 0 mo. Under vacuum conditions, precooked turkey breast was more stable than under aerobic conditions, regardless of irradiation and storage.

Irradiation and packaging were critical factors influencing volatiles production in precooked turkey breast (Table 2). Under aerobic conditions, nonirradiated samples had fewer numbers of volatiles than irradiated, and 2-propanone was the predominant volatile. Acetaldehyde, propanal, and thiobis methane, usually not found in raw meat, were detected in nonirradiated, precooked turkey breast and should have been formed during the cooking and the short exposure to air after cooking. Irradiation of cooked meat not only increased the amounts of hydrocarbons and aldehydes containing five or six carbons but also generated new hydrocarbons such as 2-methylpropane, 1-butene, butane, 1-heptene, heptane and octane, and sulfur compounds. The amounts of newly generated hydrocarbons produced by irradiation were dose-dependent. Among S compounds, 2,3-dimethyldisulfide was found only in irradiated samples, and the amount of thiobismethane increased by irradiation. The characteristic off-odor in irradiated raw pork was caused by S-containing volatiles (e.g., 2,3-dimethyldisulfide) produced by radiolytic degradation of S-containing amino acids (Ahn et al., 2000, 2001). Jo and Ahn (2000) reported that 2,3-dimethyldisulfide was produced from irradiated oil emulsion with S-containing amino acids such as methionine and cysteine.

The amounts of volatiles in vacuum-packaged, precooked nonirradiated turkey were smaller than those of aerobically packaged. After irradiation, however, vacuum-packaged, precooked turkey produced more volatiles than aerobically packaged, and the amounts of volatiles were irradiation dose dependent. At 5.0-kGy irradiation, precooked turkey breast produced more hydrocarbons and dimethyldisulfide than those at 0 or 2.5-kGy irradiation. Heptane and methylthioethane were detected only in precooked turkey breast irradiated at 5.0 kGy. The threshold dose for irradiation off-odor was 1.5

[11]Hunter Associated Labs. Inc., Reston, VA 22090-5280.
[12]Fisher Scientific, Pittsburgh, PA 15205-9913.
[13]I-Chem, Co., Marietta, GA 30062.
[14]Supelco, Bellefonte, PA 16823-0048.

TABLE 1. TBA-reactive substances values of precooked, turkey breast with different packaging, irradiation doses, and storage times at –40 C

Storage	Aerobic packaging				Vacuum packaging			
	0 kGy	2.5 kGy	5 kGy	SEM	0 kGy	2.5 kGy	5 kGy	SEM
	(mg malondialdehyde/kg meat)							
0 Months	2.01^{y}	2.46^{y}	2.22^{z}	0.22	0.90	0.73	0.63^{y}	0.08
1.5 Months	3.46^{x}	3.79^{x}	3.24^{y}	0.61	0.99	0.92	0.94^{x}	0.04
3 Months	3.88^{x}	3.87^{x}	4.10^{x}	0.26	0.99	0.93	0.87^{x}	0.05
SEM	0.47	0.44	0.28		0.07	0.06	0.04	

$^{x\text{-}z}$Different letters within a column with same irradiation dose are significantly different ($P < 0.05$); n = 4.

kGy for raw turkey breast meat (Sudarmadji and Urbain, 1972).

After 3 mo of frozen storage, more volatiles were generated, and the amounts of volatiles that existed at 0 mo also increased (Table 3). Under aerobic conditions, most hydrocarbons, ketones (2-propanone and 2-butanone), and aldehydes (acetaldehyde, propanal, 2-methylpropanal, butanal, 2-methylbutanal, 3-methylbutanal, pentanal, and hexanal) increased proportionally with irradiation dose. Although TBARS values between irradiated and nonirradiated precooked turkey breast were not different, the production of volatile compounds associated with lipid oxidation—mainly aldehydes—were significantly different.

Sulfur-containing volatiles were very sensitive to irradiation dose and were found in large quantity after the 5.0-kGy irradiation treatment. Precooked turkey breast irradiated at 5.0 kGy had methanethiol and methylthioethane, but the 2.5-kGy-irradiated meat did not have any of those. A large amount of 2,3-dimethyldisulfide, a representative off-odor compound in irradiated meat, was found in 5-kGy-irradiated, precooked turkey breast after 3 mo of frozen storage but was found only in a small amount with 2.5-kGy irradiation. Ahn et al. (2001) reported that most S-containing compounds produced by irradiation in raw meat disappeared after aerobic storage. This study, however, showed that the S-containing compounds in precooked, irradiated turkey increased during frozen storage under aerobic conditions.

During frozen storage of precooked meat, vacuum packaging was more beneficial than aerobic packaging in reducing oxidative changes. Although the volatile profiles were not much different in either packaging condition, the amounts of volatiles, especially aldehydes including hexanal, in vacuum-packaged, precooked turkey breast were much less than those in aerobically packaged breast. Hexanal and pentanal had a strong correlation with TBARS and off-flavor in meats (Ang and Lyon, 1990; Ahn et al., 1999). The two aldehydes were produced less in vacuum-packaged than aerobically packaged, precooked turkey breast. The production of hexanal and pentanal agreed with TBARS results of precooked turkey. However, the amount of dimethyldisulfide in vacuum-packaged turkey was greater than that in aerobically packaged, and it also increased dramatically during frozen storage. Acetaldehyde, pentane, 2-propanone, and

TABLE 2. Volatile compounds of precooked, turkey breast with different packaging and irradiation doses at 0 mo of frozen storage

Volatile compounds	Aerobic packaging				Vacuum packaging			
	0 kGy	2.5 kGy	5 kGy	SEM	0 kGy	2.5 kGy	5 kGy	SEM
	(pA × s × 10^4)							
2-Methyl propane	0^{c}	230^{b}	502^{a}	28	0^{c}	237^{b}	687^{a}	27
1-Butene	0^{c}	1,957^{b}	3,254^{a}	136	0^{c}	2,575^{b}	4,392^{a}	258
Butane	0^{c}	683^{b}	1,917^{a}	162	133^{c}	1,076^{b}	1,662^{a}	74
Acetaldehyde	1,251^{a}	0^{b}	0^{b}	69	787	933	757	82
1-Pentene	0^{b}	70^{b}	331^{a}	45	0^{c}	196^{b}	369^{a}	16
Pentane	842^{b}	1,884^{b}	7,633^{a}	443	2,395^{b}	4,319^{a}	3,378^{ab}	390
2-Pentene	0^{b}	0^{b}	168^{a}	1	0	0	0	–
Propanal	540^{a}	0^{b}	0^{b}	32	0	0	0	–
2-Propanone	41,145^{a}	5419^{b}	0^{b}	2,741	11,270^{c}	25,410^{b}	43,993^{a}	4,135
Thiobis methane	1,514^{b}	3,096^{a}	2,604^{a}	188	1,448^{b}	2,666^{a}	3,257^{a}	294
1-Hexene	0^{b}	0^{b}	247^{a}	27	0^{c}	195^{b}	419^{a}	20
Hexane	384^{b}	319^{b}	602^{a}	56	364^{c}	573^{b}	1,045^{a}	64
Methylthio ethane	0	0	0	–	0^{b}	0^{b}	210^{a}	3
2-Butanone	0	0	0	–	0	248^{b}	550^{a}	15
1-Heptene	0^{b}	232^{b}	862^{a}	126	0^{c}	231^{b}	420^{a}	26
Heptane	0^{b}	139^{b}	473^{a}	62	0^{b}	0^{b}	166^{a}	3
Dimethyldisulfide	0^{b}	256^{b}	458^{a}	51	105^{b}	174^{b}	297^{a}	27
Octane	0^{b}	0^{b}	228^{a}	18	0	0	0	–
Total	45,676^{a}	14,285^{b}	19,279^{b}	4,232	16,502^{c}	38,833^{b}	61,602^{a}	5,434

$^{a\text{-}c}$Different letters within a row with same packaging are significantly different ($P < 0.05$); n = 4.

TABLE 3. Volatile compounds of precooked, turkey breast with different packaging and irradiation doses after 3 mo of frozen storage at –40 C

Volatile compounds	Aerobic packaging				Vacuum packaging			
	0 kGy	2.5 kGy	5 kGy	SEM	0 kGy	2.5 kGy	5 kGy	SEM
	(pA × s × 10^4)							
2-Methyl propane	195[c]	443[b]	1,063[a]	38	0[c]	334[b]	717[a]	41
1-Butene	184[c]	1,692[b]	36,534[a]	63	0[c]	1,866[b]	2,674[a]	209
Butane	1,713[c]	2,884[b]	7,411[a]	220	734[b]	1,847[a]	2,424[a]	209
Acetaldehyde	3,398[b]	26,554[b]	115,072[a]	8,294	4,693[c]	33,109[b]	71,619[a]	3,727
Methanethiol	0[b]	0[b]	6,412[a]	124	0[c]	4,351[b]	7,275[a]	265
1-Pentene	255[c]	411[b]	806[a]	34	0[b]	360[a]	451[a]	29
Pentane	26,293[b]	27,416[b]	52,593[a]	2,568	26,584	16,954	19,871	4,441
2-Pentene	320[b]	273[b]	928[a]	141	227	257	223	40
Propanal	6,671[b]	11,005[b]	29,384[a]	3,253	5,339	6,783	8,775	1,475
2-Propanone	185[b]	1,780[b]	38,605[a]	7,345	29,084	11,702	22,689	7,954
Thiobis methane	373[c]	907[b]	1,452[a]	154	1,165	1,248	1,049	113
2-Methyl propanal	0[c]	1,491[b]	4,615[a]	340	362[c]	1,535[b]	3,710[a]	145
1-Hexene	0[b]	237[b]	488[a]	18	0[c]	262[b]	425[a]	23
Hexane	637[c]	908[b]	1,625[a]	74	604[b]	671[b]	1,195[a]	88
Butanal	428[b]	605[b]	2,751[a]	270	537	520	598	103
Methylthio ethane	0[b]	0[b]	449[a]	38	0[c]	210[b]	396[a]	15
2-Butanone	0[b]	0[b]	3,403[a]	171	1,705[a]	505[b]	698[b]	291
3-Methyl butanal	148[c]	2,091[b]	6,701[a]	408	322[c]	1,919[b]	4,916[a]	278
2-Methyl butanal	0[b]	1,651[b]	6,221[a]	561	0[c]	2,253[b]	5,171[a]	246
1-Heptene	0	0	0	–	243[a]	0[b]	0[b]	23
Heptane	1,282[b]	1,468[b]	3,270[a]	148	1,034	1,064	1,026	192
2-Ethyl furan	0[b]	52[b]	248[a]	31	307[a]	0[b]	0[b]	39
Pentanal	4,588[b]	6,518[b]	30,825[a]	2,815	7,810	3,747	4,992	2,571
3,3-Dimethyl pentane	0[b]	47[b]	540[a]	40	0	0	0	–
Dimethyldisulfide	27[b]	435[b]	21,544[a]	1,486	972[c]	11,945[b]	22,482[a]	2,052
1-Octene	0[c]	112[b]	294[a]	22	0	0	0	–
Octane	813[b]	704[b]	1,688[a]	129	2,011	1,166	1,434	446
2-Octene	428	511	718	76	392	653	675	231
Hexanal	14,968[b]	8,821[b]	114,101[a]	10,194	0	0	0	–
Total	62,909[b]	99,016[b]	489,741[a]	39,055	84,125[b]	105,261[b]	185,485[a]	25,246

[a-c]Different letters within a row with same packaging are significantly different ($P < 0.05$); n = 4.

dimethyldisulfide were predominant volatiles in vacuum-packaged, irradiated turkey breast at 3 mo of storage.

In conclusion, frozen storage of precooked, irradiated turkey breast meat under vacuum was beneficial in preventing lipid oxidation but was not helpful in reducing the amounts of volatiles responsible for irradiation off-flavor.

Pink Color Development

Irradiation, packaging, and storage all influenced the surface color values of precooked turkey breast (Table 4). With vacuum packaging, irradiation increased the redness of precooked turkey breast, and the increases in redness were irradiation-dose dependent. The color changes in vacuum-packaged irradiated turkey breast were distributed over the whole sample, and the pink color was very stable during 3 mo of frozen storage. With aerobic packaging, however, irradiation had little effect on the color of precooked turkey breast. The pink color in irradiated, precooked turkey breast was very sensitive to oxidative environments. Satterlee et al. (1971) reported that the presence of air inhibited the formation of red color in irradiated bovine metmyoglobin solutions. L* values and b* values were decreased with the increase of storage time regardless of irradiation and packaging conditions, and the color of irradiated, precooked turkey breast at 3 mo of storage was much darker than the samples before storage.

The status of heme iron is very important to the chemical structure of heme pigments responsible for the meat color. Irradiation decreased the ORP of precooked turkey breast (Table 5), indicating that irradiation induced reducing conditions in meat. The decrease of ORP was more distinct under vacuum than aerobic conditions. Therefore, it could be considered that stronger reducing conditions in irradiated meats could have pushed the heme iron into a ferrous state, which made it easy for heme-ligand formation. Hydrated electrons (e_{aq}^-), a free radical formed by irradiation can act as a powerful reducing agent (Swallow, 1984). After 3 mo of frozen storage, the ORP of nonirradiated turkey was lower than that of irradiated turkeys under aerobic packaging. Under vacuum packaging, however, the ORP of irradiated samples was still lower than nonirradiated. Therefore, strong reducing conditions under vacuum packaging stabilized the pink color in irradiated, precooked turkey breast.

Irradiation as well as cooking produced a few carbon-containing gases such as CO and methane, and their amounts in precooked turkey breast were irradiation-dose dependent (Table 6). The amounts of these gases were higher in vacuum packaging than in aerobic packaging. The amounts of the gases, however, decreased under

TABLE 4. CIE color values of precooked, turkey breast with different packaging, irradiation doses, and storage time at –40 C

	Aerobic packaging				Vacuum packaging			
Storage	0 kGy	2.5 kGy	5 kGy	SEM	0 kGy	2.5 kGy	5 kGy	SEM
L* value								
0 Months	91.58^{x}	91.47^{x}	89.16^{x}	0.95	92.14^{x}	91.77^{x}	92.30^{x}	0.68
1.5 Months	86.69^{y}	85.80^{y}	85.96^{y}	0.55	87.07^{y}	86.71^{y}	86.15^{y}	0.60
3 Months	61.05^{z}	64.32^{z}	61.74^{z}	1.28	67.64^{a,z}	63.56^{ab,z}	61.70^{b,z}	1.56
SEM	1.25	0.74	0.86		1.05	1.00	1.07	
a* value								
0 Months	6.53^{x}	6.77^{x}	6.93^{x}	0.46	6.35^{b,y}	8.28^{a}	9.05^{a}	0.40
1.5 Months	4.45^{y}	4.53^{y}	4.33^{y}	0.24	5.91^{b,y}	8.12^{a}	8.27^{a}	0.36
3 Months	5.60^{x}	6.67^{x}	6.65^{x}	0.36	7.59^{b,x}	8.71^{ab}	9.62^{a}	0.47
SEM	0.36	0.30	0.43		0.21	0.42	0.54	
b* value								
0 Months	17.91^{x}	18.37^{x}	18.45^{x}	0.68	17.87	16.44^{x}	16.34^{x}	0.48
1.5 Months	17.29^{x}	16.90^{xy}	16.26^{y}	0.55	17.09^{a}	15.21^{b,xy}	15.14^{b,xy}	0.50
3 Months	12.59^{b,y}	15.83^{a,y}	14.19^{ab,z}	0.36	16.95^{a}	13.55^{b,y}	13.14^{b,y}	0.74
SEM	0.80	0.65	0.62		0.42	0.58	0.72	

$^{a-c}$Different letters within a row with same packaging are significantly different ($P < 0.05$); n = 4.

$^{x-z}$Different letters within a column with same irradiation dose are significantly different ($P < 0.05$); n = 4.

both packaging conditions after 3 mo of storage, but a considerable amount of the gases still remained in the meat. CO has a strong affinity to heme pigments. With the decreased ORP values, ligand formation between CO and denatured heme pigment should have been increased. Our preliminary work with a model system showed that incompletely denatured myoglobin exposed to low levels of CO increased its red color intensity because of CO-myoglobin formation. Therefore, the increased redness in irradiated, precooked turkey could be caused by the CO-myoglobin formation with the help of increased reducing property by irradiation. Nevertheless, only one type of heme pigment cannot account for all the color changes in irradiated, precooked turkey. More study is needed to understand the mechanisms of color changes in irradiated cooked meat and why the CO produced by cooking did not influence the color of turkey breast as much as by irradiation.

Relationship Between Lipid Oxidation and Color Change

Liu et al. (1995) reported that lipid oxidation was positively correlated with pigment oxidation. Lipid oxidation and color changes, however, had no direct correlation in irradiated, precooked turkey breast during frozen storage (Tables 1 and 4). Irradiation accelerated the production of lipid oxidation and off-odor volatiles. Irradiation did not influence the color of aerobically packaged, precooked turkey but produced pinker color in vacuum-packaged precooked turkey. The red pigments formed by irradiation were stable during the storage. From these results, it can be concluded that the free radicals produced by irradiation might have reacted differently with lipids and heme pigments in precooked turkey breast. The free radicals might have played a role in promoting lipid oxidation and volatile production, but generated strong reducing conditions, which is helpful for CO-heme complex formation. Therefore, the results of free radical reactions in irradiated meats can be different, depending on the meat components with which they are reacting.

The ORP and TBARS were determined to elucidate oxidative changes in irradiated turkey breast. The ORP of meat was a better indicator than TBARS in explaining the impact of reduced conditions produced by irradiation on meat color. TBARS was not correlated with the redness of precooked, irradiated turkey breast. In conclusion, irradiation can influence the quality attributes of meat differently depending upon the nature of reactants (meat components and free radicals).

TABLE 5. Oxidation-reduction potential (ORP) of precooked, turkey breast with different packaging, irradiation doses, and storage time at –40 C

	Aerobic packaging				Vacuum packaging			
Storage	0 kGy	2.5 kGy	5 kGy	SEM	0 kGy	2.5 kGy	5 kGy	SEM
	ORP (mV)							
0 Months	–34^{a,y}	–56^{b,z}	–87^{c,y}	5	–55^{a,y}	–115^{b,y}	–104^{b,z}	4
1.5 Months	54^{x}	41^{x}	39^{x}	6	–6^{a,x}	–16^{b,x}	–38^{c,x}	8
3 Months	–24^{b,y}	–4^{a,y}	2^{a,x}	12	–5^{a,x}	–34^{b,x}	–16^{ab,y}	8
SEM	7	2	12		7	8	5	

$^{a-c}$Different letters within a row with same packaging are significantly different ($P < 0.05$); n = 4.

$^{x-z}$Different letters within a column with same irradiation dose are significantly different ($P < 0.05$); n = 4.

TABLE 6. Gas production of precooked, turkey breast with different packaging, irradiation doses, and storage time at –40 C

	Aerobic packaging				Vacuum packaging			
Storage	0 kGy	2.5 kGy	5 kGy	SEM	0 kGy	2.5 kGy	5 kGy	SEM
	(ppm[1])				(ppm[1])			
CO								
0 Months	366^{c}	561^{bx}	732^{ax}	49	280^{cx}	884^{bx}	1138^{ax}	56
3 Months	224^{b}	240^{aby}	290^{ay}	16	158^{cy}	326^{by}	409^{ay}	13
SEM	42	26	39		20	39	52	
	(ppm[1])				(ppm[1])			
Methane								
0 Months	26^{bx}	46^{abx}	66^{ax}	6	23^{cx}	115^{bx}	188^{ax}	6
3 Months	6^{by}	10^{ay}	13^{ay}	3	3^{cy}	25^{by}	56^{ay}	3
SEM	2	2	5		2	2	9	
	(%[1])				(%[1])			
CO_2								
0 Months	5.1^{bx}	6.7^{ax}	5.5^{bx}	0.4	8.4^{bx}	11.2^{ax}	12.6^{ax}	0.6
3 Months	0.9^{y}	1.1^{y}	1.0^{y}	0.1	1.9^{aby}	2.3^{ay}	1.7^{by}	0.1
SEM	0.2	0.4	0.2		0.1	0.1	0.2	

[a-c]Different letters within a row with same packaging are significantly different ($P < 0.05$); n = 4.

[x,y]Different letters within a column with same irradiation dose are significantly different ($P < 0.05$); n = 4.

[1]Gas concentration in headspace (14 mL) from 10 g of meat.

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