JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

Effect of Electron Beam Irradiation and Storage at 5 °C on Thiobarbituric Acid Reactive Substances and Carbonyl Contents in Chicken Breast Meat Infused with Antioxidants and Selected Plant Extracts

TAHA RABABAH,† NAVAM HETTIARACHCHY,*,† RONNY HORAX,† SATCHITHANANDAM ESWARANANDAM,† ANDRONIKOS MAUROMOUSTAKOS,‡ JAMES DICKSON,§ AND STEVEN NIEBUHR§

Department of Food Science and Agricultural Statistics Department, University of Arkansas, 2650 North Young Avenue, Fayetteville, Arkansas 72704, and Department of Microbiology, Iowa State University, Ames, Iowa 50011

This study evaluated the effectiveness of synthetic and natural antioxidants, green tea, commercial grape seed extracts/combinations, and TBHQ, with varying concentrations of lipid oxidation of nonirradiated and irradiated chicken breast meats stored at 5 °C for 12 days. Fresh boneless and skinless chicken breast meats were vacuum-infused with varying concentrations of antioxidants: green tea, grape seed extracts alone/in combination, and TBHQ. The irradiation dosage was 3.0 kGy. Carbonyl values of raw chicken meat and thiobarbituric acid reactive substances (TBARS) values of raw and cooked chicken meat were determined for 0−12 days at 5 °C storage. TBARS values for 0−12 days of storage at 5 °C ranged from 1.21 to 7.3 and 1.22 to 8.51 mg malondialdehyde/100 g chicken for nonirradiated and irradiated raw chicken, respectively. TBARS values of cooked chicken ranged from 2.19 to 35.83 and 2.45 to 45.72 mg malondialdehyde/100 g chicken for nonirradiated and irradiated chicken, respectively. Irradiation increased TBARS values of both controls and plant extracts. The carbonyl content in meat lipid ranged from 1.7 to 2.9 and 1.7 to 4.41 μmol acetophenone/10 g of nonirradiated and irradiated chicken meat, respectively, and meat protein ranged from 1.4 to 2.07 and 1.41 to 2.72 μmol/10 g meat. Infusion of chicken meat with selected plant extracts is an effective method to minimize lipid oxidation and volatiles developments caused by irradiation.

KEYWORDS: Irradiation; antioxidants; TBHQ; carbonyl; TBARS

INTRODUCTION

Irradiation has been known as one of the most effective technologies in reducing the number of pathogenic microorganisms in food products exposed to radiant energy. The Food and Drug Administration in the United States approved low-level irradiation (1.5−3.0 kGy) for poultry in May 1990 to reduce the incidence of illness resulting from the ingestion of pathogenic microorganisms (*1*). However, irradiation can reduce the quality of food by developing lipid oxidation and producing off-odors and flavors (*2*, *3*). Antioxidants can reduce lipid oxidation by scavenging free radicals produced in irradiated meat. Natural antioxidants such as sesamol, quercetin, rutin and rosemary, and BHT, a synthetic antioxidant, have demonstrated a reduction of thiobarbituric acid reactive substances (TBARS) values in irradiated raw meats (*4*).

Synthetic antioxidants have been widely used to retard lipid oxidation in foods (*5*). However, because of toxicological concerns of synthetic antioxidants, there have been increasing interests in identifying plant extracts to minimize/retard lipid oxidation in lipid-based products (*6*). Grape seed has been documented to contain a large amount of antioxidants (*7*). Green tea contains 50% flavonoids that have antioxidant properties (*8*). Also, in our previous study, grape seed and green tea extracts demonstrated the highest antioxidant activities within several plant extracts evaluated. The effect of green tea and grape seed extracts and a combination to prevent/minimize lipid oxidations that occur during irradiation needs investigation.

TBARS have been used to quantify malondialdehyde (MDA) in meat compounds (*9*, *10*). Several studies have shown that irradiation increases TBARS values in meats due to lipid oxidation (*6*, *11*−*13*).

Nonvolatile carbonyl compounds are mainly produced from lipids, proteins, and amino acids, where those derived from proteins and amino acids are characteristics of irradiation (*14*). Carbonyls in proteins can be generated by direct oxidation of amino acid side chains, reaction with reducing sugar, and

* To whom correspondence should be addressed. Tel: 479-575-4779. Fax: 479-575-6936. E-mail: nhettiar@mail.uark.edu.
† Department of Food Science, University of Arkansas.
‡ Agricultural Statistics Department, University of Arkansas.
§ Department of Microbiology, Iowa State University.

10.1021/jf049147q CCC: $27.50
Published on Web 12/07/2004

fragmentation of the peptide backbone (*15*). Two main carbonyl compounds in meat lipids are generated from lipid fractions and hydrazone derivatives. Carbonyl compounds in meat and meat products can be determined by converting them to their 2,4-dinotrophenylhydrazones (DNPH) in an aqueous medium and measuring them using a spectrophotometer (*16*). Sweetie et al. (*17*) reported that carbonyl contents in lipids and TBA values of nonirradiated samples of ground chicken meat were lower than those of irradiated samples. Currently, no literature information is available on the effect of plant extracts and their combinations to prevent/minimize carbonyl and TBARS changes of irradiated poultry during 12 days of storage at 5 °C.

The objective of this study was to evaluate the effectiveness of synthetic and natural antioxidants including green tea, commercial grape seed extracts/combinations, and TBHQ, with varying concentrations on lipid oxidation of nonirradiated and irradiated raw and cooked chicken breast meats stored at 5 °C for 12 days.

MATERIALS AND METHODS

Materials. Fresh boneless and skinless chicken breast meats were provided by a local poultry industry. Green tea (Celestial Seasoning, Inc., Boulder, CO) and Zip-lock plastic bags were purchased from a local supermarket. TBHQ/*tert*-butylhydroquinone (Tenox 20A, contains 20% TBHQ) was purchased from Eastman Chemical Company (Kingsport, TN). Cryovac Packaging bags were provided by the Department of Microbiology at Iowa State University (Ames, IA).

Methods. Green tea, commercial grape seed, and their combinations (for synergistic effect) were used at 3000 and 6000 ppm [based on chicken lipids (2.5%)]. These two concentrations were selected based on antioxidant activities, solubility, color, cost, and appearance.

Green Tea Extracts Preparation. Green tea was ground in a coffee grinder (Braun Aromatic KSM2, Braun Canada Div., Gillette Canada Company) for 1 min. Ground tea powder was mixed with water (1:10) and boiled for 10 min. The extract in the supernatant was recovered through vacuum filtration. The filtrate was then frozen to −20 °C and freeze-dried at <100 mL vacuum. The resulting extract was stored at 4 °C until use.

Chicken Breast Infusion with Plant Extracts and TBHQ. Chicken breasts were marinated via a pressurized tumbling method with green tea/commercial grape seed extracts/and their combinations, and TBHQ. Green tea and grape seed/combinations were used at 3000 and 6000 ppm, and TBHQ was used at 200 ppm based on 2.5% chicken fat. For the water control, chicken breast meats were marinated with deionized water, and the controls "as is", without marination, were included for comparison.

Eight kilograms of chicken breast meat for each treatment was vacuum tumbled with 320 mL of antioxidant solutions (4% for 8 kg of chicken) for 20 min under a vacuum of 25 in.-Hg using a Vacuum Tumbler model LT-4 (LyCo, Janesville, WI). All marinations and infusions were conducted in a walk-in cooler at 5 °C. The samples were then packaged in Cryovac bags (four pieces of chicken breast per bag) and sealed by a vacuum impulse sealer (model PVS-GA18, PAC Packaging Aids Corporation, San Rafael, CA) with a sealing time of 4 s and a cooling time of 9 s. Packaging and sealing were done at atmosphere conditions. All packages were then double bagged with zip plastic bags. Bags for each treatment were separated equally for irradiated and nonirradiated for comparison.

Irradiation and Storage. The boxes of chicken samples at 5 °C were immediately transported after infusion to the Texas A & M University (Collage Station) for irradiation. The irradiation dosage was set at 3.0 kGy. On the same day after irradiation, the samples were transported under refrigeration to our facility and stored at 5 °C. The samples were evaluated for TBARS values of cooked and raw chicken and carbonyl contents of raw chicken meat at 0, 3, 6, 9, and 12 days of storage at 5 °C. For every targeted day of storage time, three chicken breasts of each treatment and the controls (nonirradiated and irradiated) were taken randomly for analyses. The remaining samples were kept at 5 °C for the next targeted day.

TBARS Analysis for Raw and Cooked Meat Samples. A modified fluorometric method was used to determine TBARS values in the raw and cooked chicken breast meats to evaluate lipid oxidation by Jo and Ahn (*10*). Two to 10 gram portions of raw meat samples were liquefied with 40−80 mL of deionized water in a blender (Osterizer Galaxie Dual Range 14, Oster Corp Milwaukee, WI) for 1.5 min. For cooked meat, samples in a zip lock bag were heated in a water bath at 85 °C for 30 min and cooled for 15 min before analysis. To 1.0 mL of homogenate, 200 μL of 8.1% sodium dodecyl sulfate, 1.5 mL of 2 M HCl, 1.5 mL of 20 mM TBA, and 50 μL of 7.2% BHT were added and vortexed. The samples were then heated in 90 °C water bath for 15 min and cooled in cold water for 10 min. After the samples were cooled, 1.0 mL of deionized water and 5.0 mL of *n*-butanol/pyridine (15: 1) were added. The solutions were centrifuged (J2-21 Centrifuge, Beckman, Fullerton, CA) at 3000*g* and 20 °C for 15 min. A blank was made using 1.0 mL of deionized water in place of the samples. The clear upper layer solutions were removed, and readings were taken using Shimadzu model RF-1501 Spectrofluorophotometer at 520 nm excition and 550 nm emission. The calculation was made from the observed fluorescent intensity of samples using an equation of a standard curve of MDA as following:

$$\text{TBARS (in mg MDA/100 g chicken)} = [(0.0331 \times F - 0.1836) \times 50 \times 72]/10$$

where F = fluororescent intensity.

Carbonyl Compounds. Carbonyl compounds in meat and meat products can be determined by converting them to their 2,4-DNPHs in an aqueous medium and measuring them using spectrophotometers (*16*). Carbonyl compounds in meat are mainly produced from lipids, proteins, and amino acids (*14*). Two different methods were used to determine carbonyls in lipids and proteins. Carbonyl compounds in meat lipids can be generated from lipid fractions and hydrazone derivatives (*16*), while in proteins they can be generated by direct oxidation of amino acid side chains and fragmentation of the peptide backbone (*15*).

Carbonyl Content in Meat Lipid (CCML). The carbonyl content was determined by a colorimetric method (*18*). One gram of chicken meat from breast was homogenized in a blender (Osterizer Galaxie Dual Range 14, Oster Corp.) for 2 min. To 1 g of homogenized meat, 20 mL of chloroform/methanol (1:2) was added and homogenized for 2 min and shaken for 30 min. The samples were then filtered through Whitman filter paper no. 4. The solvent was removed using a rotary evaporator (at a bath temperature of 44 °C) and dried with a stream of nitrogen. Then, the dried samples were dissolved in 1 mL of carbonyl-free methanol and added to 1 mL of saturated 2,4-DNPH in methanol and 1 drop of HCl and concentrated and vortexed. The samples were then heated in 50 °C water bath for 30 min and cooled in cold water for 15 min. After the samples were cooled, 5 mL of 10% KOH was added and the solutions were filtered through Whatman filter paper no. 4 to obtain a clear solution. A blank was made using 1.0 mL of chloroform/methanol (1:2) in place of the samples. The absorbance of the solutions was read using a Shimadzu model UV-1601 Spectrophotometer at 480 nm. The calculation was made from the observed absorbance of samples using an equation of a standard curve of acetophenone as following:

$$\text{carbonyl content (in mmol acetophenone/1 g meat)} = (0.00255 + 0.2993 \times A) \times 0.001$$

where A = absorbance.

Carbonyl Content in Meat Protein (CCMP). A modified method of Srinivasan and Hultin (*19*) was used to determine the carbonyl content in chicken meat protein. Five gram portions of chicken meat from minced skinless breast chicken were liquefied with 100 mL of 40 mM phosphate buffer, pH 6.8, in a blender (Osterizer Galaxie Dual Range 14, Oster Corp.) for 1 min. A 0.5 mL amount of homogenate was added to 4 mL of 10 mM 2,4-DNPH in 2 N HCl, vortexed, and incubated at room temperature for 1 h. Another 0.5 mL of sample treated with 4 mL of 2 N HCl served as the control. Five milliliters of

Table 1. Effect of Storage Time (12 Days) on Plant Extract- and Antioxidant-Infused Nonirradiated and Irradiated Raw Chicken Breast Meats Stored at 5 °C on TBARS (mg MDA/100 g Chicken) Values

		nonirradiated				irradiated				
	level	days				days				
treatment	ppm	0	3	6	9	0	3	6	9	12
control "as is"		1.22 a9[a]	2.61 b7	3.10 b6	7.00 b5	2.97 b8	4.16 b4	7.12 b3	7.56 b2	7.80 b1
water control		1.27 a9	2.89 a8	3.27 a7	7.30 a4	3.36 a6	5.61 a5	7.39 a3	8.02 a2	8.51 a1
green tea extracts	3000	1.27 a8	1.31 de8	2.31 d7	3.96 c6	2.61 c5	2.81 c5	4.20 c3	4.80 c2	4.91 c1
green tea extracts	6000	1.21 a7	1.24 f7	1.36e6	3.41 f2	1.37 g6	2.32 e5	3.11 f4	3.33 f3	3.57 f1
grape seed extracts	3000	1.25 a9	1.37 d8	2.29d7	3.49 e4	2.52 c6	2.65 d5	3.77 d3	4.56 d2	4.73 d1
grape seed extracts	6000	1.22 a7	1.25 f67	1.33 e6	2.99 g3	1.84 e5	1.90 g5	2.65 h4	3.10 g2	3.45 g1
grape seed + green tea	3000	1.26 a8	1.45 c7	2.45 c6	3.80 d3	2.41 d6	2.71 d5	3.39 e4	3.97 e2	4.46 e1
grape seed + green tea	6000	1.24 a8	1.33 ce7	1.38 e7	3.31 f2	1.69 f6	2.22 f5	2.89 g4	3.17 g3	3.40 h1
TBHQ	200	1.25 a6	1.26 ef6	1.26 f6	2.33 h3	1.38 g5	1.73 h4	2.32 i3	2.44 h2	2.84 i1

[a] Means followed by different letters (a–i) in the same column or different numbers (1–9) in the same row are significantly different ($p < 0.05$). Nonirradiated samples (12 days) were not determined due to spoilage.

Table 2. Effect of Storage Time (12 Days) on Plant Extract- and Antioxidant-Infused Nonirradiated and Irradiated Cooked Chicken Breast Meats Stored at 5 °C on TBARS (mg MDA/100 g Chicken) Values

		nonirradiated				irradiated				
	level	days				days				
treatment	ppm	0	3	6	9	0	3	6	9	12
control "as is"		2.25 a9[a]	13.35 b7	19.24 b5	32.46 b4	6.37 b8	17.53 b6	37.49 b3	42.69 b1	37.35 b3
water control		2.28 a9	13.81 a6	20.20 a5	35.83 a4	7.93 a8	18.89 a7	40.58 a2	45.72 a1	37.79 a3
green tea extracts	3000	2.29 a9	5.30 c7	6.64 c6	7.35 c5	4.12 c8	9.54 c4	9.99 c3	11.89 c1	12.62 c2
green tea extracts	6000	2.44 a7	2.94 d5	3.58 d6	5.47 d3	2.93 e5	4.55 e4	5.61 e3	6.67 d1	6.15 f2
grape seed extracts	3000	2.18 a8	5.18 c6	6.56 c5	7.22 c4	3.71 d7	8.38 d3	9.51 d2	11.75 c1	9.18 e2
grape seedextracts	6000	2.19 a7	2.72 d6	3.27 d5	5.28 d3	2.94 e56	4.31 e4	5.35 e3	6.41 d1	5.78 f2
grape seed + green tea	3000	2.30 a9	5.16 c7	6.73 c6	7.26 c5	3.64 d8	8.35 d4	9.43 d3	11.77 c2	11.43 d1
grape seed + green tea	6000	2.29 a6	2.96 d5	3.91 d4	5.52 d2	2.79 ef5	4.35 e3	5.56 e2	6.49 d1	5.85 f2
TBHQ	200	2.26 a5	2.28 e45	2.76 e23	2.99 e12	2.45 f345	2.67 f234	2.96 f12	3.05 e12	2.83 cb12

[a] Means followed by different letters (a–f) in the same column or different numbers (1–9) in the same row are significantly different ($p < 0.05$). Nonirradiated samples (12 days) were not determined due to spoilage.

20% TCA was added to precipitate the protein, centrifuged at 11000*g* and 20 °C for 5 min, and washed three times with 4.0 mL of an ethanol:ethyl acetate mixture (1:1) until the ethanol:ethyl acetate extract was virtually colorless with the third wash, indicating complete removal of unreacted DNPH. The supernatant was discarded, and the pellet was dissolved in 2 mL of 6 M guanidine in 20 mM potassium phosphate. The absorbance of the solutions was read using a Shimadzu model UV-1601 Spectrophotometer at 370 nm. The difference in the observed absorbance at 370 nm between HCl-treated samples and DNPH-treated samples was taken as a measure of reacted carbonyl groups using a molar extinction coefficient of 2.2×10^4 M^{-1} cm^{-1} of *m*-nitrobenzaldehyde (*20*).

Statistical Analysis. Data were presented as means of three determinations and analyzed using Pdmix mixed model procedure of analysis of variance using SAS Version 8.2 software package (SAS Institute Inc., Cary, NC) (*21*). The multiple range was tested with least significant difference (LSD) analysis at a LSD of 0.05 *p*-value.

RESULTS AND DISCUSSION

TBARS for Raw and Cooked Chicken Breast. Tables 1 and **2** show the effect of storage time at 5 °C of nonirradiated and irradiated antioxidant-infused raw and cooked chicken breast meats and controls on TBARS. Commercially, under normal conditions, chicken breast meat soon after postharvest and processing is kept very close to freezing temperature but not frozen. It takes about 2 days for the breast meat to reach the retailer. In the retailer store, chicken breast is kept at 4−5 °C in the packaging with the sell by date for 7 days. TBARS values for 0−12 days of storage ranged from 1.21 to 7.3 and 1.22 to 8.51 mg MDA/100 g chicken for nonirradiated and irradiated raw chicken, respectively. TBARS values of cooked chicken ranged from 2.19 to 35.83 and 2.45 to 45.72 mg MDA/100 g chicken for nonirradiated and irradiated chicken, respectively. There were significant differences ($p < 0.05$) for nonirradiated and irradiated chicken breast meats without antioxidant infusion of raw and cooked breast chicken. The nonirradiated and irradiated antioxidant-infused raw and cooked chicken meat had similar effects on reducing TBARS values. As compared to controls, the TBARS values of antioxidant-infused nonirradiated chicken breast meat were generally lower and decreased with increasing antioxidant concentration. TBHQ was the most effective antioxidant to decrease lipid oxidation followed by grape seed and green tea extracts at high levels (6000 ppm) and low levels (3000 ppm), respectively. The higher level (6000 ppm) of each extract (grape seed and green tea extracts) was more effective in minimizing lipid oxidation than the lower level (3000). This observation could be due to higher levels (6000 ppm) of plant extracts, which have more antioxidant activities than lower levels (3000 ppm). In our previous study (*23*), higher levels of plant extracts had higher induction time (h) values than lower levels using an oxidative stability instrument. Grape seed was slightly more effective in decreasing TBARS values during storage as compared with green tea. This could be due to the fact that different types of phenolics have different antioxidant activities. In our previous study, grape seed extracts had higher amounts of antioxidant activities. As compared with controls, antioxidant infusions minimized lipid oxidation in both

Table 3. Effect of Storage Time (12 Days) on Plant Extract- and Antioxidant-Infused Nonirradiated and Irradiated Raw Chicken Breast Meats Stored at 5 °C on Carbonyl Content as Lipid (in μmol Acetophenone/10 g Meat)

		nonirradiated				irradiated				
	level	days				days				
treatment	ppm	0	3	6	9	0	3	6	9	12
control "as is"		1.74 a9a	1.98 a7	2.06 a6	2.88 a3	1.86 a8	2.19 a5	2.79 a4	3.43 a2	4.37 a1
water control		1.75 a9	1.99 a7	2.08 a6	2.90 a3	1.87 a8	2.20 a5	2.81 a4	3.45 a2	4.41 a1
grape seed extracts	3000	1.73 a5	1.79 b45	1.82 b34	1.86 b3	1.74 b5	1.83 b34	1.89 b23	1.94 b2	2.01 b1
grape seed extracts	6000	1.72 a4	1.78 bc234	1.80 b123	1.82 b12	1.72 b4	1.75 c34	1.81 c123	1.84 c12	1.86 c1
green tea extracts	3000	1.74 a5	1.80 b45	1.83 b4	1.87 b34	1.76 b5	1.86 b34	1.90 b23	1.95 b2	2.02 b1
green tea extracts	6000	1.7a53	1.78 b345	1.80 b234	1.83 b123	1.72 b5	1.76 c45	1.82 c1234	1.86 c12	1.88 c1
grape seed + green tea	3000	1.70 a7	1.79 b56	1.82 b45	1.86 b34	1.73 b67	1.82 b45	1.89 b23	1.94 b2	2.02 b1
grape seed + green tea	6000	1.72 a5	1.77 bc345	1.79 b234	1.82 b123	1.72 b5	1.75 c45	1.80 c1234	1.84 c12	1.87 c1
TBHQ	200	1.71 a1	1.71 c1	1.71 c1	1.72 c1	1.70 b1	1.71 c1	1.71 d1	1.72 d1	1.73 d1

[a] Means followed by different letters (a–d) in the same column or different numbers (1–9) in the same row are significantly different ($p < 0.05$). Nonirradiated samples (12 days) were not determined due to spoilage.

Table 4. Effect of Storage Time (12 Days) on Plant Extract- and Antioxidant-Infused Nonirradiated and Irradiated Raw Chicken Breast Meats Stored at 5 °C on Carbonyl Content as Protein (in μmol/10 g Meat)

		nonirradiated				irradiated				
	level	days				days				
treatment	ppm	0	3	6	9	0	3	6	9	12
control "as is"		1.44 a7[a]	1.60 a6	1.83 a4	2.06 a3	1.71 a5	1.85 a4	2.50 a2	2.71 a1	2.70 a1
water control		1.42 a7	1.61 a6	1.84 a4	2.07 a3	1.71 a5	1.87 a4	2.51 a2	2.70 a1	2.72 a1
grape seed extracts	3000	1.46 a4	1.46 bc4	1.52 b34	1.61 b12	1.49 bc34	1.55 b23	1.51 bc34	1.60 bc12	1.64 b1
grape seed extracts	6000	1.46 a4	1.46 bc4	1.50 b34	1.57 b123	1.47 c4	1.54 b23	1.46 bc4	1.60 bc12	1.62 b1
green tea extracts	3000	1.43 a3	1.48 b23	1.54 b2	1.62 b1	1.54 b2	1.53 b2	1.51 b2	1.64 b1	1.66 b1
green tea extracts	6000	1.45 a5	1.46 bc45	1.50 b45	1.58 b23	1.47 c45	1.53 b34	1.49 bc45	1.61 bc12	1.65 b1
grape seed + green tea	3000	1.45 a2	1.47 bc2	1.51 b2	1.60 b1	1.49 bc2	1.52 b2	1.49 bc2	1.59 bc1	1.62 b1
grape seed + green tea	6000	1.44 a5	1.46 bc45	1.50 b345	1.57 b12	1.45 c5	1.52 b234	1.46 c45	1.55 c123	1.61 b1
TBHQ	200	1.40 a1	1.41 c1	1.41 c1	1.42 c1	1.41 d1	1.41 c1	1.42 c1	1.43 d1	1.43 c1

[a] Means followed by different letters (a–d) in the same column or different numbers (1–7) in the same row are significantly different ($p < 0.05$). Nonirradiated samples (12 days) were not determined due to spoilage.

nonirradiated and irradiated samples for 0−12 days. The results demonstrated that antioxidants and extracts were effective in preventing lipid oxidation in irradiated meat. Descriptive sensory analysis of green tea- and grape seed extracts/combination-infused nonirradiated and irradiated chicken meats also showed that irradiation did not affect the sensory flavor attributes except for brothy flavor, and irradiation increased texture attributes of hardness, cohesiveness, and hardness and cohesiveness of mass. Consumer results showed that green tea extract and water control gave the best desirable color. The colors of green tea + grape seed extracts and grape seed extract alone treated chicken breasts were second and third choices by the consumers based on color. The panel also indicated that irradiation decreased the tenderness of the irradiated control, and green tea extract infusion at 3000 ppm minimized this change. Plant extracts were effective in minimizing textural changes caused by irradiation. Plant extract infusion also decreased the amount of major volatiles, hexanal and pentanal, produced during storage of irradiated chicken breast meat. The infusion of chicken meat with antioxidants and selected plant extracts is an effective method to minimize lipid oxidation caused by irradiation.

Although the underlying lipid oxidation mechanisms in irradiated meat are not fully understood, they may be similar to those in nonirradiated meat (*24*). For this reason, the adaptation of irradiated muscle tissues to lipid oxidation is closely related to the nature, degrees of saturation in fatty acids, proportion, and the composition of phospholipids in cell membrane. Grape seed and green tea extracts/combinations, which contain a larger amount of polyphenolic and phenolic compounds, minimized lipid oxidation in both nonirradiated and irradiated chicken breast samples. This could be due to either inhibition of formation of free radicals during the initiation step or interruption of the propagation of the free radical chain reaction by acting as an electron donor (*5*, *25*). Also, minimizing lipid oxidation by grape seed and green tea extracts/combinations could be attributed to scavengers of free radicals in irradiated meat samples (*3*). In comparison, several studies have shown that irradiation increases TBARS values in meat due to lipid oxidation (*6*, *11*−*13*). Addition of antioxidants and plant extracts minimized lipid oxidation in irradiated and nonirradiated chicken breast meats (*13*). Also, they demonstrated that TBHQ-synthetic antioxidant was more effective than plant extracts.

CCML. Table 3 shows the effect of storage time at 5 °C of nonirradiated and irradiated antioxidant-infused raw chicken breast meats and controls on CCML. The CCML values for 0−12 days of storage ranged from 1.7 to 2.9 μmol acetophenone/10 g nonirradiated and 1.7−4.41 μmol acetophenone/10 g irradiated chicken breast. There were significant differences ($p < 0.05$) for nonirradiated and irradiated chicken breast meats without antioxidant infusion of raw breast chicken. As compared with controls, the CCML values of antioxidant-infused nonirradiated chicken breast meat were generally lower and decreased with increasing antioxidant concentration. TBHQ was the most effective antioxidant to decrease the values of CCML followed by grape seed and green tea extracts at both high levels (6000 ppm) and low levels (3000 ppm), respectively. No

significant differences in retarding lipid oxidation were observed with extracts at the same level. Higher concentrations were more effective in decreasing CCML values. CCML values increased during storage in raw irradiated and nonirradiated samples. A similar effect on lipid oxidation of meat with other antioxidants was reported by Sweetie et al. (*17*). They reported that carbonyl content and TBARS values for nonirradiated samples of ground chicken meat were lower than for irradiated samples.

The underlying mechanisms of carbonyls in meat lipids in irradiated meat are not understood but could be due to the generation of free radials during and after irradiation. The free radicals that were generated from ions and excited molecules could react and recombine with the other molecules of lipid meats. These reactions could produce acyl radical, alkyl radical, and acyloxy radical, which could produce ketones and aldehydes (*26*). The addition of grape seed and green tea extracts/combinations minimized carbonyl contents in meat lipid in both nonirradiated and irradiated chicken breast samples. This could be due to inhibition of formation of free radicals during lipid oxidation (*5*, *25*).

CCMP. Table 4 shows the effect of storage time at 5 °C of nonirradiated and irradiated extracts and antioxidant-infused and control raw chicken breast meats on CCMP values. The CCMP values for 0−12 days of storage ranged from 1.4 to 2.07 and 1.41 to 2.72 μmol/10 g chicken meat. There were significant differences ($p < 0.05$) for nonirradiated and irradiated chicken breast meats without antioxidant infusion. Similar to CCML values of raw chicken, CCMP values of nonirradiated chicken infused with antioxidants were slightly lower than controls. TBHQ was most effective as compared with the other antioxidants and controls. The results also demonstrated that both levels of grape seed and green tea had the similar effect on preventing CCMP development.

The mechanisms of carbonyl generated from meat protein of irradiated meats are also not understood. Carbonyl formation in meat proteins has been widely used as a measure of oxidation (*19*). Free radicals that generate from ions and excited molecules during and after irradiation could be responsible for carbonyls in meat proteins. Srinivasan and Hultin (*19*) reported that the increase of carbonyls in meat proteins could be due to production of hydroxyl or oxyl radicals during the oxidation. The addition of grape seed and green tea extracts/combinations minimized carbonyl contents in meat proteins in both nonirradiated and irradiated chicken breast samples. This also could be due to inhibition of production of hydroxyl or oxyl radicals in chicken breast.

The findings of this study demonstrated that irradiation increased lipid oxidation. Infusing antioxidant and plant extracts into chicken breast meat minimized lipid oxidation in irradiated and nonirradiated raw and cooked chicken. TBHQ was the most effective antioxidant in retarding lipid oxidation of chicken breast meat. Grape seed and green tea extracts/combinations at a higher level (6000 ppm) were more effective than at a lower level (3000 ppm) in minimizing lipid oxidation. Infusion of chicken meat with antioxidants and selected plant extracts is an effective method to minimize lipid oxidation caused by irradiation.

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Received for review May 26, 2004. Revised manuscript received October 14, 2004. Accepted November 3, 2004.

JF049147Q