Effect of Antioxidants on the Quality of Irradiated Sausages Prepared with Turkey Thigh Meat[1]

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ABSTRACT The effects of antioxidants on the flavor and color of electron-beam-irradiated turkey sausages were studied. Sausages were prepared from turkey thigh meat, NaCl (2.0%), phosphate (0.5%), water (10%), and one of five antioxidant treatments (none, vitamin E, sesamol, rosemary extract, or gallic acid at 0.02%). Sausages were stuffed and cooked in an 85 C smokehouse to an internal temperature of 74 C, then chilled and sliced to 1.5-cm thickness, and vacuum-packaged. Packaged sausages were randomly divided into three groups and irradiated at 0, 1.5 or 3.0 kGy, using an electron beam. Volatiles, color, 2-TBA-reactive substances values, and sensory characteristics were analyzed. The antioxidant effect of sesamol was the highest, followed by vitamin E and gallic acid; rosemary extract had the weakest antioxidant effect. Irradiation induced red color in sausages, but addition of gallic acid, rosemary extract, or sesamol reduced it. Gallic acid was very effective in lowering the redness of irradiated and nonirradiated sausages. The redness (a*) values of sausages with added gallic acid that were irradiated at 0, 1.5, and 3.0 kGy were 1.49, 2.03, and 2.29, respectively, whereas those of control sausages under the same irradiation conditions were 2.58, 2.81, and 3.25, respectively. The reduction of redness in irradiated sausages by antioxidants was not related to CO, because antioxidants had no effect on CO production by irradiation. The amount of total volatiles was decreased significantly by antioxidants, but antioxidants had minimal effect on the off-flavor of turkey sausages induced by irradiation.

(*Key words*: turkey thigh meat, sausage, antioxidant, color, irradiation)

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INTRODUCTION

Irradiation induces off-odor and color changes in meats (Patterson and Stevenson 1995; Ahn et al., 20002; Jo et al., 2000), and consumer response to irradiation off-odor has been negative (Du et al., 2001). Consumers respond positively to increased redness in raw meat due to irradiation but responded negatively to this redness in cooked meat (Nanke et al. 1999; Du et al. 2002; Nam and Ahn, 2002a). Because of the importance of irradiation technology to the future of the food industry, the impact of irradiation on the quality of raw meats has been studied extensively. However, information is lacking concerning quality and prevention of quality changes in foods further processed by irradiated.

Irradiation induces fatty acid degradation through a mechanism similar to lipid oxidation, especially when oxygen is available. It is quite possible that antioxidants can prevent irradiation-induced quality changes through the same mechanism by which they prevent lipid oxidation in meat. Ahn et al. (1998) showed that irradiated patties had accelerated oxidative changes and that dietary α-tocopheryl acetate minimized the oxidation and off-odor generation in meat. Besides α-tocopherol, many other antioxidants are reported to be effective in preventing oxidative changes and, thus, can minimize off-odor production in meat. Chen et al. (1999) showed that sesamol, quercetin, and butylated hydroxytoluene were effective in preventing off-odor in irradiated raw and cooked pork during 7 d of storage, whereas rosemary oleoresin and rutin were effective in irradiated raw pork during 3 d of storage. Because irradiation-induced changes in meat follow similar mechanism as lipid oxidation, the use of antioxidants can be effective in preventing flavor and color changes of irradiated meat.

The objective of this study was to determine the effectiveness of selected antioxidants in preventing off-flavor and color changes in turkey sausage by irradiation.

MATERIALS AND METHODS

Sample Preparation

Forty 15-wk-old turkeys were slaughtered according to USDA guidelines. Carcasses were chilled in ice water

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Abbreviation Key: GC = gas chromatograph; TBARS = 2-thiobarbituric acid reactive substances; TCA = trichloroacetic acid.

for 4 h, drained, stored at 4 C for 14 h, and then deboned. Turkeys were randomly divided into four groups (10 turkeys per group), and thigh meats (with skin) from each group were pooled, ground twice through a 9-mm plate, and used as a replication. The ground thigh meat from each group was further divided into five portions to make sausages by adding NaCl (2.0%), tripolyphosphate (0.5%), and 10% water and one of five selected antioxidants (none, vitamin E, sesamol, rosemary extract, or gallic acid at 0.02%). Tocopherol, sesamol, and gallic acid were purchased from Sigma[3] and rosemary extract was obtained from Ecom Manufacturing Corp.[4] Each antioxidant was dissolved in corn oil or water (50 mL oil or water/g antioxidant, and the amount was balanced in all treatments) and then added to meat. The meat and additive mixture was chopped in a silent cutter for 3 min at full speed. The finished batter was stuffed into 50-mm collagen casing and cooked in an 85 C smokehouse with relative humility of 92% until the center of the sausage reached 74 C. After cooling to room temperature by a cold water shower, the sausages were sliced to 15 mm thick, then individually vacuum-packaged in high oxygen barrier bags (nylon/polyethylene, 9.3 mL O_2/m_2/24 h at 0 C),[5] and irradiated at 0, 1.5, or 3.0 kGy, using a linear accelerator (Circe IIIR).[6] The settings used were 10 MeV and 10 kW, and the average dose rate was 88.5 kGy/min. The maximum-minimum ratio was approximately 1.28. 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.[7]

Color Measurement

The surface color of turkey sausages was measured in the package using a Hunter LabScan colorimeter[8] and expressed as color L* (lightness), a* (redness), and b* (yellowness) values. One colorimeter reading was made on each side of the sample. To eliminate the influence of packaging material on meat color, the same packaging material as used for the sausage was used to cover a standard white plate.

Gas Production

Minced turkey sausage (10 g) was put in a 24-mL screw-cap glass vial with a Teflon × fluorocarbon resin-silicone septum.[9] The vial was microwaved for 10 s at full power (1,200 W) to release gas compounds from the meat sample. After 5 min of cooling at ambient temperature, headspace air (200 μL) was withdrawn using an airtight syringe and injected into a gas chromatograph (GC).[10] A Carboxen-1006 plot column[11] (30 m × 0.32 mm i.d.) was used to analyze gas compounds produced by irradiation in turkey sausage. The initial oven 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[10] 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, hydrogen, 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[12], CH_4, CO_2[13]) and a GC-mass spectrometer (Model 5873).[10] The area of each peak was integrated using the ChemStation software.[10] To quantify the amounts of gases released, each peak area (pA × s) was converted to a gas concentration (ppm) contained in the headspace air (14 mL) of 10-g meat samples using the concentration of CO_2 in air (330 ppm) (Nam and Ahn, 2002a).

TBA-Reactive Substances Measurement

Five grams of sausage was weighed into a 50-mL test tube and homogenized with 15 mL of deionized distilled water (DDW) using a Polytron homogenizer (Type PT 10/35)[13] for 10 s at the highest speed. One milliliter of the meat homogenate was transferred to a disposable test tube (3 × 100 mm), and butylated hydroxyanisole (50 μL; 7.2%) and TBA-trichloroacetic acid (TCA) (15 m*M* TBA-15% TCA; 2 mL) were added. The mixture was vortexed, incubated in a boiling water bath for 15 min to develop color, cooled in cold water for 10 min, vortexed again, and centrifuged for 15 min at 2,500 × *g*. The absorbance of the resulting supernatant solution was determined at 531 nm against a blank containing 1 mL of DDW and 2 mL of TBA-TCA solution. The amounts of TBA-reactive substances (TBARS) were expressed as milligrams of malonaldehyde per kilogram of meat.

Volatile Analysis

A purge-and-trap dynamic headspace (Precept II and purge-and-trap 3000)[13] GC-mass spectrometry system (Model 5973)[10] was used to identify and quantify the volatile compounds. Two grams of minced turkey sausages was placed in a 40-mL sample vial, and the vial was flushed with He gas (99.999%) for 5 s at 40 psi. After capping with a Teflon-lined open-mouth cap, the vial was placed in a refrigerated (4 C) sample tray. The maximum sample holding time in the sample tray before determination of volatiles was less than 10 h to minimize oxidative changes (Ahn et al., 1999). Samples were heated to 40 C and purged with He gas (40 mL/min) for 11 min. Volatiles were trapped with a Tenax trap column[14] at 20 C, desorbed for 2 min at 220 C, concentrated with a cryofocusing unit[15] at −100 C, and then desorbed into a GC column

[3]Sigma, St. Louis, MO.
[4]Ecom Manufacturing Corp. Scarborough, ON, Canada.
[5]Koch, Kansas City, MO.
[6]Thomson CSF Linac, Saint-Aubin, France.
[7]Bruker Instruments Inc, Bellerica, MA.
[8]Hunter Laboratory, Inc., Reston, VA.
[9]I-Chem Co., New Castle DE.
[10]HP 6890, Hewlett Packard Co., Wilmington, DE.
[11]Supelco, Bellefonte, PA.
[12]Aldrich, Milwaukee, WI.
[13]Praxair, Danbury, CT.
[14]Brinkman Instruments Inc., Inc., Westbury, NY.
[15]Tekmar-Dorham, Cincinnati, OH.

TABLE 1. The color of irradiated turkey sausage with different antioxidant treatments

Color variable	Irradiation	Control	Vitamin E	Sesamol	Rosemary	Gallic acid	SEM
L*	0 kGy	73.72	74.41^{x}	74.13	74.38	73.73	0.29
	1.5 kGy	73.50^{ab}	73.95^{abx}	73.94^{ab}	74.37^{a}	73.06^{b}	0.31
	3 kGy	72.75^{b}	73.05^{aby}	73.60^{ab}	74.12^{a}	73.14^{ab}	0.31
	SEM	0.30	0.29	0.30	0.31	0.31	
a*	0 kGy	2.58^{ay}	2.45^{aby}	2.37^{aby}	2.26^{by}	1.49^{cz}	0.07
	1.5 kGy	2.81^{ay}	2.69^{aby}	2.50^{bcy}	2.34^{cy}	2.03^{dy}	0.08
	3 kGy	3.25^{ax}	3.48^{ax}	2.74^{bx}	2.62^{bx}	2.29^{cx}	0.11
	SEM	0.09	0.10	0.08	0.08	0.08	
b*	0 kGy	19.21^{ax}	19.38^{ax}	19.43^{ax}	19.49^{ax}	17.76^{b}	0.10
	1.5 kGy	18.73^{ay}	18.93^{ay}	18.95^{ay}	18.93^{ay}	17.93^{b}	0.11
	3 kGy	18.73^{ay}	18.63^{ay}	18.58^{az}	18.69^{ay}	17.61^{b}	0.12
	SEM	0.11	0.12	0.11	0.10	0.11	

$^{a-d}$Different letters within a row of same category differ significantly ($P < 0.05$); n = 4.

$^{x-z}$Different letters within a column of same category differ significantly ($P < 0.05$).

for 30 s at 220 C. A GC equipped with a mass selective detector was used to separate, identify, and quantify the volatile compounds in irradiated samples. An HP-624 column (7.5 m, 250 μm i.d., 1.4 μm nominal), an HP-1 column (52 m, 250 μm i.d., 0.25 μm nominal), and an HP-Wax column (7.5 m, 250 μm i.d., 0.25 μm nominal) were combined with zero-volume connectors and used for volatile analysis. A ramped oven temperature was used: the initial oven temperature was set at 0 C for 2.5 min, then increased to 10 C at 5 C/min, to 45 C at 10 C/min, to 110 C at 20 C/min, and to 210 C at 10 C/min, and held for 2.5 min). Liquid N was used to cool the oven below ambient temperature. He was the carrier gas at constant pressure of 20.5 psi. The ionization potential of MS was 70 eV, and scan range was 18.1 to 350 m/z. The identification of volatiles was achieved by comparing mass spectral data with those of the Wiley library[10] and authentic standards. The peak area was reported as the amount of volatiles released (Ahn et al., 1999).

Sensory Evaluation

Sixteen trained sensory panelists characterized the flavors and colors of irradiated sausages. Panelists were selected based on interest, availability, and performance in screening tests conducted with samples similar to those being tested. Training sessions were conducted to familiarize panelists with the irradiation color, smell, and flavor caused by irradiation; the scale to be used; and the range of attribute intensities likely to be encountered during the study. Fifteen-centimeter linear horizontal scales, anchored with descriptors at opposite ends, were used to rate the stimuli of color (plain to red), off-smell (weak to strong), and off-flavor (weak to strong) of turkey sausage. The responses from the panelists were expressed as numerical values from 0 to 15. All samples presented to panelists were labeled with random three-digit numbers. Also, sensory panelists were asked to describe color and flavor characteristics of irradiated turkey sausages.

Statistical Analysis

Completely randomized design was used. Data collected were processed by the general linear models procedure of SAS software (SAS Institute, 2000). Mean values and standard errors of means were reported. Errors were defined as the differences among replications. The significance of antioxidant and irradiation treatments

TABLE 2. Gas production of turkey sausage (ppm) with different antioxidant treatments

Gas	Irradiation	Control	Vitamin E	Sesamol	Rosemary	Gallic acid	SEM
				(ppm)			
N_2	0 kGy	105.2^{abx}	108.8^{ax}	105.6^{abx}	98.8^{abx}	87.5^{b}	5.1
	3 kGy	88.8^{y}	86.6^{y}	84.8^{y}	85.7^{y}	80.7	2.3
	SEM	3.7	4.7	3.9	3.0	4.3	
CO	0 kGy	114.2^{y}	126.5^{y}	104.7^{y}	114.2^{y}	101.5^{y}	6.6
	3 kGy	221.2^{x}	213.1^{x}	204.4^{x}	218.9^{x}	198.1^{x}	6.7
	SEM	5.2	6.8	6.9	6.1	8.0	
Methane	0 kGy	0^{y}	0^{y}	0^{y}	0^{y}	0^{y}	0
	3 kGy	24.3^{x}	21.1^{x}	22.7^{x}	25.1^{x}	21.9^{x}	1.0
	SEM	0.6	0.5	0.6	0.9	0.9	

$^{a-b}$Different letters within a row of same gas differ significantly ($P < 0.05$); n = 4.

$^{x-y}$Different letters within a column of same gas differ significantly ($P < 0.05$).

TABLE 3. TBA-reactive substances (TBARS) values of turkey sausages with different antioxidant treatments

Irradiation	Control	Vitamin E	Sesamol	Rosemary	Gallic acid	SEM
	TBARS (mg MDA[1]/kg meat)					
0 kGy	2.93^{ay}	1.95^{cx}	0.90^{d}	2.72^{by}	2.04^{cx}	0.06
1.5 kGy	3.15^{ax}	2.00^{cx}	0.98^{e}	2.99^{bx}	1.83^{dxy}	0.05
3 kGy	2.12^{az}	1.52^{cy}	0.91^{d}	1.78^{bz}	1.67^{bcy}	0.06
SEM	0.06	0.04	0.04	0.06	0.08	

[a-e]Different letters within a row differ significantly ($P < 0.05$); n = 4.

[x-z]Different letters within a column differ significantly ($P < 0.05$).

[AUTH QUERY: Define MDA]

was determined by the SNK (Student-Newman-Keul's) multiple-range test.

RESULTS AND DISCUSSION

Color and Gas Production of Irradiated Turkey Sausages

The CIE color values of irradiated sausages with different antioxidants are shown in Table 1. There was no difference for L* values among sausages with different antioxidant treatments before irradiation. After irradiation, however, rosemary-treated sausage had higher L* values than the control, but the overall difference was small. Irradiation had only a minor effect on L* values of sausages.

Irradiation increased the redness of sausages in all treatments. Antioxidant treatments and irradiation caused significant changes in a* values; gallic acid decreased a* value greatly for irradiated and nonirradiated sausages. Rosemary and sesamol treatments also reduced the a* values of sausages, but rosemary was more effective than sesamol. The a* values of sausages containing sesamol and irradiated at 1.5 kGy and of those containing rosemary and irradiated at 3.0 kGy were about the same as sausages of the nonirradiated, no antioxidant-added control sausages (Table 1). This result suggested that addition of rosemary or sesamol was effective in reducing irradiation-induced redness in sausages. Vitamin E, however, was not effective in preventing irradiation-induced redness. Gallic acid treatment significantly lowered b* values, but other antioxidants had no effects on b* values of turkey sausages (Table 1).

Table 2 shows a dramatic increase in CO and methane production in sausages after irradiation. Millar et al. (2000) and Nam and Ahn (2002a) reported that the color changes induced by irradiation were related to CO pro-

TABLE 4. The volatile profiles of nonirradiated (0 kGy) sausage with different antioxidant treatments

Volatiles	Control	Vitamin E	Sesamol	Rosemary	Gallic acid	SEM
	Area (pA × 10^4)					
Butane	143^{b}	94^{b}	0^{c}	232^{a}	141^{b}	20
Acetaldehyde	384^{ab}	360^{ab}	454^{a}	323^{ab}	133^{b}	63
1-Pentene	125^{a}	122^{a}	64^{b}	111^{a}	81^{b}	10
Pentane	$14,917^{a}$	$11,635^{a}$	$2,140^{b}$	$12,915^{a}$	$13,177^{a}$	1,216
2-Pentene	169^{a}	221^{a}	24^{b}	153^{a}	174^{a}	19
Propanal	$1,742^{a}$	984^{b}	522^{c}	$1,513^{a}$	$1,017^{b}$	106
2-Propanone	625^{b}	549^{b}	$1,011^{a}$	$1,015^{a}$	548^{b}	78
Carbon disulfide	242	244	439	425	450	72
2-Methyl-propanol	264^{ab}	306^{a}	324^{a}	203^{b}	186^{b}	24
Hexane	511^{a}	521^{a}	309^{b}	377^{ab}	292^{b}	47
Butanal	293^{b}	187^{c}	0^{d}	504^{a}	223^{c}	18
3-Methyl-butanal	439^{a}	381^{b}	477^{a}	489^{a}	470^{a}	18
2-Methyl-butanal	343^{ab}	304^{b}	373^{a}	390^{a}	347^{ab}	14
Heptane	665^{a}	489^{a}	157^{b}	437^{a}	448^{a}	60
2-Ethyl-furan	190^{a}	148^{a}	0^{b}	115^{a}	138^{a}	21
Pentanal	$3,876^{a}$	$2,513^{b}$	$1,711^{c}$	$3,983^{a}$	$2,653^{b}$	242
Dimethyl-disulfide	281^{b}	279^{b}	195^{bc}	556^{a}	123^{c}	27
Toluene	118^{b}	113^{b}	113^{b}	147^{a}	103^{b}	5
1-Octene	485	496	372	515	467	47
Octane	$2,776^{ab}$	$3,242^{a}$	$2,324^{b}$	$2,203^{b}$	$1,859^{b}$	240
2-Octene	244	253	178	286	250	25
1-Nonene	368	398	310	412	384	47
Nonane	327^{c}	434^{b}	336^{c}	402^{bc}	626^{a}	25
Hexanal	$33,081^{a}$	$22,343^{b}$	$5,991^{c}$	$31,905^{a}$	$21,469^{b}$	1,741
Decane	228	237	173	174	195	36
Nonadecane	204	167	147	133	129	19
Total	$63,035^{a}$	$47,016^{b}$	$18,142^{c}$	$59,917^{a}$	$46,082^{b}$	2,731

[a-d]Different letters within a column differ significantly ($P < 0.05$); n = 4.

TABLE 5. Volatile profiles of irradiated turkey sausage (3 kGy) with different antioxidant treatments

Volatiles	Control	Vitamin E	Sesamol	Rosemary	Gallic acid	SEM
	Area (pA × 10^4)					
1-Propene	236	201	222	188	190	22
Butane	422^a	253^{ab}	181^b	409^a	271^{ab}	44
Acetaldehyde	$3,733^a$	$3,816^a$	$1,299^b$	$1,260^b$	$3,412^a$	146
Methanethiol	217	493	519	165	294	105
1-Pentene	372^a	285^{ab}	238^b	402^a	272^{ab}	33
Pentane	$16,830^a$	$10,211^b$	$3,125^c$	$16,664^a$	$12,037^b$	1,267
2-Pentene	247^a	225^a	47^b	228^a	224^a	30
Propanal	$4,539^a$	$3,583^b$	475^d	$2,362^c$	$3,063^{bc}$	297
2-Propanone	$3,108^a$	$3,325^a$	$1,179^b$	714^b	$4,170^a$	373
Carbon disulfide	292	282	353	327	327	32
2-Methyl-propanal	672^a	644^a	607^{ab}	519^b	635^a	30
1-Hexane	241	185	184	246	230	27
Hexane	738	626	621	812	650	87
Butanal	580^a	445^a	0^b	502^a	462^a	36
Benzene	241^a	218^a	177^b	227^a	211^a	8
3-Methyl-butanal	$1,416^a$	$1,423^a$	$1,064^c$	$1,187^b$	$1,480^a$	36
2-Methyl-butanal	$1,708^a$	$1,572^{ab}$	$1,372^b$	$1,614^{ab}$	$1,528^{ab}$	73
Heptane	930^a	578^b	449^b	$1,012^a$	600^b	59
2-Ethyl-furan	128^a	127^a	0^b	161^a	146^a	20
Pentanal	$6,356^a$	$5,255^a$	$1,609^b$	$6,325^a$	$5,034^a$	434
1-Heptyne	356^a	286^{ab}	244^b	351^a	273^{ab}	21
Dimethyl disulfide	$6,805^a$	$6,717^a$	$4,407^b$	$5,940^a$	$4,572^b$	325
Toluene	627^a	568^{ab}	515^b	615^a	547^b	18
1-Octene	535	375	407	502	448	68
Octane	2,451	2,401	2,829	2,418	2,848	443
2-Octene	292	212	195	301	266	37
1-Nonene	333	234	259	343	281	56
Nonane	755^a	523^{ab}	562^{ab}	672^a	376^b	70
Hexanal	$40,573^{ab}$	$31,820^c$	$7,721^d$	$45,181^a$	$34,738^{bc}$	2,168
Decane	187	165	157	129	213	22
Nonadecane	152	115	151	194	211	25
Dimethyl trisulfide	$2,179^a$	$2,397^a$	887^b	$1,859^a$	$1,744^a$	233
Total	$98,246^a$	$79,557^b$	$32,050^c$	$93,824^{ab}$	$8,1746^b$	4,361

[a-c]Different letters within a row differ significantly ($P < 0.05$); n = 4.

duction during irradiation. Thus, the big increase of CO in meat should have been the main factor contributing to irradiation-induced redness (Nam and Ahn, 2002a); however, there was no difference in CO production among sausages treated with different antioxidants for irradiated and nonirradiated turkey sausages. This result indicated that gallic acid, rosemary, and sesamol decreased the redness of sausages by a mechanism unrelated to CO production.

TBARS Values and Volatile Profiles

Antioxidant treatments lowered the TBARS of sausages (Table 3). The TBARS of all antioxidant-treated sausages were significantly lower than that of the control. Sesamol caused the most significant reduction in TBARS, vitamin E and gallate were in the middle, and rosemary was least effective in preventing lipid oxidation in sausages among the antioxidants tested. Murphy et al. (1998) reported that rosemary had antioxidant effects in roast beef slices, and Nam et al. (2002) found that 0.02% of sesamol plus vitamin E were highly effective in reducing lipid oxidation.

Lipid oxidation is closely associated with volatile changes. Aldehydes, including hexanal, pentanal, butanal and propanal, were decreased in nonirradiated sausages by sesamol, vitamin E, or gallic acid treatments, whereas rosemary was largely ineffective (Table 4). This result was in agreement with the TBARS results (Table 3). Among the four 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., 2000). Two sulfur compounds, carbon disulfide and dimethyl disulfide, were the major sulfur compounds detected in nonirradiated turkey sausages (Table 4). Gallic acid significantly ($P < 0.05$) reduced the dimethyl disulfide content in nonirradiated turkey sausages, whereas rosemary increased it. Nam et al. (2002) also reported that the mixture of 0.02% gallic acid and vitamin E was effective in reducing sulfur compounds in irradiated

TABLE 6. The sensory analysis for irradiation smell and odor of turkey sausage with different antioxidant treatments

Treatment	Color	Smell	Flavor
Control, 0 kGy	7.0^b	3.8^b	3.3^b
Control, 3 kGy	10.1^a	6.6^{ab}	6.0^{ab}
Vitamin E, 3 kGy	9.3^a	7.8^a	6.9^a
Sesamol, 3 kGy	5.9^b	5.2^{ab}	5.5^{ab}
Rosemary, 3 kGy	7.5^b	5.3^{ab}	4.7^{ab}
Gallic acid, 3 kGy	3.7^c	5.8^{ab}	4.5^{ab}
SEM	0.6	0.7	0.7

[a-c]Different letters within a column differ significantly ($P < 0.05$); n = 16.

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 3-kGy 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. The reason for the reduced production of pentane with sesamol is not clear. Antioxidant-treated sausages produced a smaller amount of total volatile than the control, and the amount of total volatiles in irradiated and nonirradiated sausages added with sesamol were much less than that of other treatments (Tables 4 and 5). Patterson and Stevenson (1995) reported that dietary vitamin E treatment reduced the production of total volatiles in irradiated raw chicken meat, which is in agreement with our results.

Sensory Analysis

Table 6 shows the sensory evaluation results of turkey sausages treated with antioxidants. Sensory panelists found the redness of irradiated control sausages significantly higher than that of the nonirradiated control. But in samples treated with sesamol and rosemary, the redness decreased to a level similar to control samples without irradiation. This result is in agreement with CIE color a* values (Table 1). The redness of sausages treated with gallic acid was very low, and the sensory panelists described that the color of sausages treated with gallic acid as having a blue tint. Nam et al. (2002), however, reported that antioxidants had little effect on the reduction of irradiation-induced redness in raw pork patties.

The off-odor and off-flavor scores of irradiated sausages were not different from each other, and they were significantly higher than those of the nonirradiated control (Table 6). This result showed that antioxidant treatment was largely ineffective in reducing irradiation-induced off-odor in turkey sausages. However, Chen et al. (1999) reported that sesamol reduced off-odor in irradiated pork patties.

Overall, this study indicated that gallic acid at 0.02% dramatically lowered the redness of irradiated and nonirradiated turkey sausages, and sesamol and rosemary also were effective in reducing irradiation-induced redness. Among the antioxidants used in this study, sesamol was the most effective (on weight basis) in preventing lipid oxidation. Antioxidants had only a minor effect in preventing off-odor of sausages induced by irradiation.

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