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# Effect of Electron Beam Irradiation and Storage on the Quality Attributes of Sausages with Different Fat Contents

## Abstract

Sausages with different fat contents (16 or 29%) were purchased from local stores, vacuum-packaged in oxygen-impermeable bags, and irradiated at 0 or 5 kGy using a linear accelerator. The changes in quality attributes of irradiated sausages were determined during storage at 4°C. The 2-thiobarbituric acid-reactive substance values of sausages were not affected by fat content but were increased after irradiation (5 kGy). Storage for 60 d increased the 2-thiobarbituric acid-reactive substance values of nonirradiated sausages ( $P < 0.05$ ) but had no effect on irradiated sausages. The numbers of volatile compounds and the amounts of total volatiles were increased by irradiation in both the high-fat (29% fat) and low-fat (16% fat) sausages. Dimethyl sulfide was detected only in irradiated sausages, regardless of fat content ( $P < 0.05$ ), but it disappeared after 60 d of storage. Pentane and 1-heptene were detected only in irradiated samples after 60 d of storage. Low-fat sausages had greater  $L^*$  values, but had lesser  $a^*$  and  $b^*$  values than high-fat sausages. Irradiation and storage had little effect on either the exterior or interior color ( $L^*$ ,  $a^*$ , and  $b^*$  values) of sausages. Fat content had no effect on the sensory variables of sausages, regardless of irradiation and storage. However, irradiated sausages had significantly stronger off-odors and off-flavors than nonirradiated sausages regardless of fat content ( $P < 0.05$ ). This indicated that fat content in sausages had a minimal effect on the quality of irradiated sausages during storage.

## Keywords

Fat content, irradiation, quality, sausage

## Disciplines

Agriculture | Animal Sciences | Meat Science

## Comments

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# Effect of electron beam irradiation and storage on the quality attributes of sausages with different fat contents

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**ABSTRACT:** Sausages with different fat contents (16 or 29%) were purchased from local stores, vacuum-packaged in oxygen-impermeable bags, and irradiated at 0 or 5 kGy using a linear accelerator. The changes in quality attributes of irradiated sausages were determined during storage at 4°C. The 2-thiobarbituric acid-reactive substance values of sausages were not affected by fat content but were increased after irradiation (5 kGy). Storage for 60 d increased the 2-thiobarbituric acid-reactive substance values of nonirradiated sausages ( $P < 0.05$ ) but had no effect on irradiated sausages. The numbers of volatile compounds and the amounts of total volatiles were increased by irradiation in both the high-fat (29% fat) and low-fat (16% fat) sausages. Dimethyl sulfide was detected only in irradiated sausages,

regardless of fat content ( $P < 0.05$ ), but it disappeared after 60 d of storage. Pentane and 1-heptene were detected only in irradiated samples after 60 d of storage. Low-fat sausages had greater  $L^*$  values, but had lesser  $a^*$  and  $b^*$  values than high-fat sausages. Irradiation and storage had little effect on either the exterior or interior color ( $L^*$ ,  $a^*$ , and  $b^*$  values) of sausages. Fat content had no effect on the sensory variables of sausages, regardless of irradiation and storage. However, irradiated sausages had significantly stronger off-odors and off-flavors than nonirradiated sausages regardless of fat content ( $P < 0.05$ ). This indicated that fat content in sausages had a minimal effect on the quality of irradiated sausages during storage.

**Key words:** fat content, irradiation, quality, sausage

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## INTRODUCTION

The primary purpose for treating foods by irradiation is to control pathogens, spoilage microorganisms, and pests without compromising the nutritional and sensory properties of foods (Farkas, 2006). During the past one-half century, an enormous amount of research work has been done on irradiation of food commodities such as tuber and bulb crops, fruits and vegetables, stored grains, dried ingredients, meats, poultry, and fish (Wilkinson and Gould, 1998). Recently, however, interest in food irradiation has been focused on ensuring food safety by preventing food poisoning among consumers through the elimination of spoilage microorganisms and pathogens, particularly in meat, fish, fresh-cut produce, and cooked-chilled foods (Farkas, 2001).

Currently, more than 50 countries have approved irradiation for 1 or more food items, and it is used commercially in approximately 40 countries (Farkas, 2006; International Atomic Energy Agency, 2006). In many countries, irradiation has been approved for many different types of sausages to control pathogenic and nonpathogenic microorganisms (International Atomic Energy Agency, 2006). Although the US government permits irradiation up to 4.5 kGy for refrigerated red meats and up to 7.0 kGy for frozen red meats, irradiation of processed meats has not yet been approved.

Processed meat products are popular in the United States but are frequently contaminated with pathogens, such as *Listeria monocytogenes*, postprocessing. Because *L. monocytogenes* is able to grow at refrigerated temperatures and is resistant to salt and nitrite (Lou and Yousef, 1999), any *L. monocytogenes* contaminating cured meat products (e.g., sausages), which usually have a long shelf life, could proliferate to a threatening amount during refrigerated storage. Irradiation is an effective method of destroying vegetative foodborne pathogens, including *L. monocytogenes* (Patterson et

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al., 1993; Thayer and Boyd, 2000). However, quality changes, such as the development of lipid oxidation and the production of off-odors, after irradiating sausages are important concerns because irradiation is known to accelerate lipid oxidation in meat products. The breakdown products of lipid oxidation, such as aldehydes, ketones, alcohols, hydrocarbons, and furans, can contribute to flavor deterioration in muscle foods (Jo et al., 2002). Although the effects of irradiation on the microbial control and quality properties of fresh or cooked meats and meat products have been studied extensively over the past decades (Maxcy, 1983; Lee et al., 1996; Farkas, 1997, 2001; Ahn et al., 2000a; Sommer et al., 2004), information is limited on radiation-induced quality changes in sausages during storage, especially ones with different fat contents. Fat is one of the most important constituents contributing to quality changes in meat and meat products, but the effect of fat content on the development of lipid oxidation, the production of volatile compounds, sensory properties, and color changes in irradiated sausages has scarcely been investigated. The objective of this work was to determine the effect of electron beam irradiation and subsequent storage on lipid oxidation, production of volatile compounds, color, and sensory properties of commercial sausages with different fat contents.

## MATERIALS AND METHODS

Animal Care and Use Committee approval was not obtained for this study because samples were obtained from a commercial source (Oscar Mayer, Madison, WI).

### *Sample Preparation*

Frankfurter-type (cured) sausages with 2 different fat contents (16 and 29%, made with turkey and pork, Oscar Mayer Wieners) were purchased from local stores. The exact age of the sausages at the time of purchase was not known, but all were less than 10 d old. The sausages were removed from the original packages, vacuum-packaged again in oxygen-impermeable nylon-polyethylene bags (9.3 mL of O<sub>2</sub>/m<sup>2</sup> per 24 h at 0°C; Koch, Kansas City, MO) and stored overnight at 4°C to minimize changes before irradiation. The samples were irradiated at 0 or 5 kGy using a linear accelerator (Circe IIR, Thomson CSF Linac, France) with an average dose rate of 107 kGy/min. To confirm the target dose, 2 alanine dosimeters per cart were attached on the top and bottom surfaces of the sample. The samples were analyzed at 0 d (2 h after irradiation) and 60 d of storage at 4°C. The experiment was replicated 3 times.

### *Lipid Oxidation Measurement*

2-Thiobarbituric acid-reactive substances (TBARS) were used to determine lipid oxidation in meat. Five

grams of sausage was weighed into a 50-mL test tube and homogenized with 50 µL of butylated hydroxyanisole (7.2%) and 15 mL of deionized distilled water in a Polytron homogenizer (Type PT 10/35, Brinkman Instruments Inc., Westbury NY) for 15 s at high speed (22,000 rpm). One milliliter of the meat homogenate was transferred to a disposable test tube (13 × 100 mm), and sulfanilamide (1% wt/vol, 20 µL) was added and mixed thoroughly. The samples were allowed to sit at room temperature for 5 min and then thiobarbituric acid/trichloroacetic acid (15 mM thiobarbituric acid/15% trichloroacetic acid, 2 mL) was added. The mixture was vortex-mixed and incubated in a boiling water bath for 15 min to develop color. Samples were then cooled in ice water for 10 min, mixed again, and centrifuged for 15 min at 3,000 × *g* at 4°C. The absorbance of the resulting supernatant solution was determined at 531 nm against a blank containing 1 mL of deionized distilled water and 2 mL of thiobarbituric acid/trichloroacetic acid solution. The amounts of TBARS were expressed as milligrams of malonaldehyde per kilogram of meat (Zipser and Watts, 1962).

### *Analysis of Volatile Compounds*

A vial autosampler (Solatek 72 Multimatrix, Tekmar-Dohrmann, Cincinnati, OH) and a purge-and-trap concentrator (3100, Tekmar-Dohrmann) were used to purge and trap volatile compounds as described by Jo and Ahn (2000), with some modifications. A gas chromatograph (Model 6890, Hewlett-Packard Co., Wilmington, DE) equipped with a mass selective detector (Model 5973, Hewlett-Packard Co.) was used to qualify and quantify volatile compounds. Sample (2 g) was transferred to a 40-mL sample vial, and the headspace was flushed with helium gas (99.999% purity) for 5 s to minimize oxidative changes in sausages during the waiting period before analysis. The sample was purged with helium (40 mL/min) for 15 min at 40°C. Volatile compounds were trapped using a Tenax/silica/charcoal column (Tekmar-Dohrmann), focused in a cryofocusing module (−80°C), and then thermally desorbed into a gas chromatograph column for 60 s at 220°C. A modified column was used to improve the separation of volatile compounds. An HP-Wax column (7.5 m, 250 µm i.d., 0.25 µm nominal; Hewlett-Packard Co.) was combined with an HP-5 column (30 m, 250 µm i.d., 0.25 µm nominal; Hewlett-Packard Co.) using a Glass Press-fit connector (Hewlett-Packard Co.). An increasing oven temperature was used (7°C for 2.5 min, increased to 25°C at 3°C/min, to 120°C at 10°C/min, and then to 200°C at 20°C/min). Liquid nitrogen was used to cool the oven below the ambient temperature. Helium was the carrier gas at a constant column pressure of 23.5 psi. The temperature of transfer lines was maintained at 155°C. The ionization potential of mass spectrometry (MS) was 70 eV; the scanned mass range was 46.1 to 550 to eliminate the carbon dioxide peak, and the scan velocity was 2.94 scan/s. The identifica-

**Table 1.** Effect of irradiation and storage at 4°C for 60 d on lipid oxidation of sausages with different fat contents

Item	TBARS, <sup>1</sup> mg of malonaldehyde/kg of meat					
	d 0			d 60		
	0 kGy	5 kGy	SEM	0 kGy	5 kGy	SEM
Fat content, %						
16	0.48 <sup>b,x</sup>	0.88 <sup>a,x</sup>	0.02	0.80 <sup>a,x</sup>	0.82 <sup>a,x</sup>	0.02
29	0.56 <sup>b,x</sup>	0.94 <sup>a,x</sup>	0.04	0.81 <sup>a,x</sup>	0.89 <sup>a,x</sup>	0.04
SEM	0.03	0.03		0.03	0.03	

<sup>a,b</sup>Different superscript letters within a row are significantly different ( $P < 0.05$ );  $n = 3$ .

<sup>x</sup>Same superscript letters within a column are not different ( $P > 0.05$ ).

<sup>1</sup>TBARS = 2-thiobarbituric acid-reactive substances.

tion of volatile compounds was achieved by comparing mass spectral data with those of the Wiley library (Hewlett-Packard Co.).

### Color Measurement

The exterior and interior color of sausages was measured using a Hunter LabScan Colorimeter (Hunter Laboratory, Inc., Reston, VA) that had been calibrated against black and white reference tiles. The CIE L\* (lightness), a\* (redness), and b\* (yellowness) values were obtained using illuminant A (light source). The area view and port size were 0.63 and 1.0 cm, respectively. An average value from 8 different locations on a sample surface was used for statistical analysis.

### Sensory Evaluation

Eight trained sensory panelists evaluated the overall color, texture (hardness), off-odor, and off-taste of the samples stored for 0 and 60 d at 4°C. Panelists were selected based on interest, availability, and performance in screening tests conducted with samples similar to those to be tested. The panelists selected were trained for aroma attributes of sausages, including nonirradiated and irradiated products. During training, a lexicon of aroma terms to be used on the ballot was developed, and references to anchor the rating scale were identified. To determine off-odor intensity, samples (5 g) were placed in glass scintillation vials that had been labeled with 3-digit numerical codes. Sample containers were closed and the sample temperature was brought to 25°C before samples were presented to panelists. All treatments were presented to each panelist and the order of presentation was randomized. Sensory panelists were asked to rate the intensity of the color, texture (hardness), off-odor, and off-taste on 9-unit linear scales (1 = none, 3 = slightly, 5 = moderately, 7 = very much, 9 = extremely).

### Statistical Analysis

The experiment was designed primarily to determine the effect of electron beam irradiation and subsequent

storage on some quality attributes. The TBARS, volatile compounds, color, and sensory properties of sausages, depending on fat content and storage time, were analyzed independently (SAS Inst. Inc., Cary, NC). Student-Newman-Keuls multiple-range tests were used to compare significant differences among the mean values ( $P < 0.05$ ).

## RESULTS AND DISCUSSION

The TBARS values were greater in high-fat sausages (29% fat) than in low-fat sausages (16% fat) and were significantly increased by irradiation at 5 kGy and subsequent storage at 4°C. The difference in TBARS values between the nonirradiated and irradiated samples, however, disappeared after 60 d of storage at 4°C ( $P < 0.05$ ; Table 1). A similar tendency was reported previously for irradiated cooked pork sausages packaged in aerobic and vacuum conditions, but oxygen availability had a greater influence than irradiation (Jo et al., 1999). This indicated that irradiation and fat content had a significant effect on the lipid oxidation of sausages, but oxygen-impermeable conditions during storage minimized these effects.

The changes in volatile compounds in irradiated commercial sausages with different fat contents (16 and 29%) were analyzed after 60 d of storage at 4°C. Electron-beam irradiation produced dimethyl sulfide, but this sulfur compound disappeared after 60 d of storage (Tables 2 and 3). Dimethyl disulfide is usually found in irradiated raw and cooked meat (Nam et al., 2001) and usually evaporates during storage (Ahn et al., 2001), which is in good agreement with our results for sausages. After 60 d of storage,  $\alpha$ -terpinolene was detected in both nonirradiated and irradiated sausages, whereas pentane and 1-heptene were detected only in irradiated samples. Ahn et al. (1999) previously reported that the production of 1-heptene and 1-nonene in meat was irradiation dose-dependent, and could be used as an indicator for irradiation in cooked sausages. Greater amounts ( $P < 0.05$ ) of pentane, 1-heptene, and 1-nonene were detected in irradiated high-fat sausages than in irradiated low-fat ones. No other specific volatiles were increased by irradiation and subsequent storage in samples with

**Table 2.** Volatile compounds of irradiated sausage with 16% fat during storage at 4°C for 60 d

Volatile compound	d 0			d 60		
	0 kGy	5 kGy	SEM	0 kGy	5 kGy	SEM
Pentane	0	0	0	0 <sup>b</sup>	777 <sup>a</sup>	37
2-Propanone	14,286 <sup>b</sup>	41,497 <sup>a</sup>	2,288	12,077 <sup>b</sup>	39,795 <sup>a</sup>	1,243
Ethanol	2,069 <sup>b</sup>	12,277 <sup>a</sup>	1,189	2,615 <sup>b</sup>	17,081 <sup>a</sup>	363
2-Propanol	13,895 <sup>a</sup>	13,497 <sup>a</sup>	1,473	15,296 <sup>a</sup>	17,142 <sup>a</sup>	662
2-Butanone	5,748 <sup>a</sup>	7,415 <sup>a</sup>	886	4,583 <sup>b</sup>	9,373 <sup>a</sup>	194
Ethyl acetate	1,143 <sup>a</sup>	1,082 <sup>a</sup>	42	0 <sup>b</sup>	857 <sup>a</sup>	26
3-Methyl butanal	1,610 <sup>a</sup>	1,836 <sup>a</sup>	277	1,867 <sup>b</sup>	2,332 <sup>a</sup>	78
2-Methyl butanal	970 <sup>a</sup>	819 <sup>b</sup>	38	1,043 <sup>a</sup>	1,419 <sup>a</sup>	106
3-Methylthio-1-propene	1,816 <sup>a</sup>	186 <sup>b</sup>	359	0	0	0
1-Heptene	0	0	0	0 <sup>b</sup>	671 <sup>a</sup>	19
2-Pentanone	0	0	0	1,583 <sup>a</sup>	1,495 <sup>a</sup>	64
Pentanal	0 <sup>b</sup>	929 <sup>a</sup>	134	1,751 <sup>a</sup>	1,652 <sup>a</sup>	54
Dimethyl disulfide	0 <sup>b</sup>	1,922 <sup>a</sup>	380	0	0	0
Octane	289 <sup>b</sup>	427 <sup>a</sup>	17	0	0	0
Hexanal	1,635 <sup>a</sup>	2,369 <sup>a</sup>	449	2,151 <sup>a</sup>	2,228 <sup>a</sup>	277
Cyclopentanone	1,002 <sup>a</sup>	1,096 <sup>a</sup>	97	1,127 <sup>a</sup>	1,313 <sup>a</sup>	51
Heptanal	863 <sup>a</sup>	924 <sup>a</sup>	108	545 <sup>a</sup>	412 <sup>b</sup>	17
α-Thujene	832 <sup>a</sup>	615 <sup>a</sup>	110	630 <sup>a</sup>	676 <sup>a</sup>	22
α-Pinene	4,765 <sup>a</sup>	3,639 <sup>a</sup>	645	3,585 <sup>b</sup>	4,228 <sup>a</sup>	117
Camphene	498 <sup>a</sup>	566 <sup>a</sup>	77	434 <sup>a</sup>	533 <sup>a</sup>	49
Sabinene	2,037 <sup>a</sup>	1,531 <sup>a</sup>	255	971 <sup>a</sup>	977 <sup>a</sup>	45
β-Pinene	4,365 <sup>a</sup>	3,259 <sup>a</sup>	486	3,251 <sup>b</sup>	3,512 <sup>a</sup>	66
Myrcene	1,275 <sup>a</sup>	972 <sup>a</sup>	145	1,146 <sup>b</sup>	1,274 <sup>a</sup>	22
1-Phellandrene	1,030 <sup>a</sup>	816 <sup>a</sup>	163	763 <sup>a</sup>	892 <sup>a</sup>	48
3-Carene	2,989 <sup>a</sup>	2,374 <sup>a</sup>	380	2,500 <sup>b</sup>	3,130 <sup>a</sup>	90
α-Terpinene	1,185 <sup>a</sup>	889 <sup>a</sup>	132	1,896 <sup>a</sup>	1,893 <sup>a</sup>	163
Octanal	1,683 <sup>a</sup>	1,323 <sup>a</sup>	203	722 <sup>a</sup>	693 <sup>a</sup>	32
Limonene	5,599 <sup>a</sup>	4,350 <sup>a</sup>	596	5,276 <sup>b</sup>	5,962 <sup>a</sup>	107
Para-cymene	6,592 <sup>a</sup>	4,876 <sup>a</sup>	687	4,877 <sup>b</sup>	5,341 <sup>a</sup>	78
<i>trans</i> -β-Ocimene	0	0	0	485 <sup>a</sup>	660 <sup>a</sup>	45
γ-Terpinene	2,406 <sup>a</sup>	1,910 <sup>a</sup>	322	7,619 <sup>a</sup>	6,067 <sup>b</sup>	181
2-Furancarboxaldehyde	16,644 <sup>a</sup>	6,987 <sup>b</sup>	805	0	0	0
1-Octene-3-ol	938 <sup>a</sup>	613 <sup>a</sup>	95	0	0	0
α-Terpinolene	0	0	0	1,249 <sup>a</sup>	1,477 <sup>a</sup>	108
Nonanal	2,104 <sup>a</sup>	2,020 <sup>a</sup>	92	1,133 <sup>a</sup>	889 <sup>a</sup>	181
Linalool	1,423 <sup>a</sup>	703 <sup>b</sup>	78	3,019 <sup>a</sup>	312 <sup>a</sup>	75
Camphor	4,195 <sup>a</sup>	3,251 <sup>a</sup>	350	692 <sup>b</sup>	732 <sup>a</sup>	4

<sup>a,b</sup>Different superscript letters within a row on the same storage day are significantly different ( $P < 0.05$ );  $n = 3$ .

different fat contents. Although propanal, a major lipid oxidation product, was not found in sausages irradiated at 5 kGy, 2-propanol and pentanal in low-fat samples showed the same trend as TBARS values, which increased with irradiation and storage (Jo et al., 1999). Carbon disulfide, methyl-2-propenyl disulfide, and dodecane were detected only in high-fat samples, regardless of irradiation and storage. In addition, heptadecane and nonane were found in 60 d-stored sausages with a high fat content. Although pentanal was detected only in irradiated samples at d 0, it was found in both non-irradiated and irradiated low-fat sausages after 60 d of storage at 4°C. 3-Methylthio-1-propene, octane, 2-furan carboxaldehyde, and 1-octene-3-ol showed no tendency in their changes based on irradiation, fat content, and storage.

Irradiation at 5 kGy did not cause significant changes in exterior color  $L^*$  and  $b^*$  values of the sausages, regardless of fat content. However, high-fat sausages (29%) had greater ( $P < 0.05$ ) exterior  $L^*$  values and

decreased  $a^*$  and  $b^*$  values compared with low-fat sausages (16%; Table 4). Irradiation and increased fat content caused decreases in interior color  $a^*$  and  $b^*$  values ( $P < 0.05$ ). The interior of sausages had greater  $L^*$  color values (lightness) but lesser  $b^*$  (yellowness) and  $a^*$  values (redness) than the exterior. Storage of sausages for 60 d at 4°C had little effect on interior or exterior color, regardless of irradiation and fat content (Tables 4 and 5). Houser et al. (2005a) reported that irradiation up to 4.5 kGy reduced Hunter  $a^*$  and  $b^*$  values of vacuum-packaged hams after 0 and 7 d of storage, but did not affect color values for the ham or frankfurters after 6 wk of storage (Houser et al., 2005b). Jo et al. (1999) reported that storage in a refrigerator for 7 d increased Hunter  $L^*$  values in vacuum-packaged sausages and that  $a^*$  values of sausages were greater in low-fat than in high-fat sausages. On the other hand,  $a^*$  values in vacuum-packaged, uncured cooked pork sausages increased with irradiation, regardless of the fat source used (Jo et al., 2000).

**Table 3.** Volatile compounds of irradiated sausage with 29% fat during storage at 4°C for 60 d

Volatile compound	d 0			d 60		
	0 kGy	5 kGy	SEM	0 kGy	5 kGy	SEM
Pentane	0	0	0	0 <sup>b</sup>	1,382 <sup>a</sup>	170
Carbon disulfide	19,647 <sup>a</sup>	19,052 <sup>a</sup>	249	14,494 <sup>a</sup>	18,703 <sup>a</sup>	1,999
2-Propanone	1,246 <sup>b</sup>	17,527 <sup>a</sup>	1,471	2,818 <sup>b</sup>	12,772 <sup>a</sup>	463
Ethanol	1,241 <sup>b</sup>	13,935 <sup>a</sup>	1,718	2,625 <sup>b</sup>	16,789 <sup>a</sup>	534
2-Propanol	5,876 <sup>b</sup>	18,175 <sup>a</sup>	3,127	7,453 <sup>a</sup>	8,778 <sup>a</sup>	442
2-Butanone	0 <sup>b</sup>	8,658 <sup>a</sup>	466	1,089 <sup>b</sup>	3,552 <sup>a</sup>	61
3-Methyl butanal	1,602 <sup>b</sup>	2,338 <sup>a</sup>	117	1,401 <sup>b</sup>	2,422 <sup>a</sup>	97
2-Methyl butanal	939 <sup>a</sup>	922 <sup>a</sup>	171	1,173 <sup>b</sup>	1,921 <sup>a</sup>	46
1-Heptene	0	0	0	0 <sup>b</sup>	1,202 <sup>a</sup>	114
Heptane	0	0	0	0 <sup>b</sup>	633 <sup>a</sup>	75
Pentanal	0 <sup>b</sup>	879 <sup>a</sup>	61	0 <sup>b</sup>	421 <sup>a</sup>	34
Dimehtyl disulfide	0 <sup>b</sup>	2,644 <sup>a</sup>	364	0	0	0
Octane	474 <sup>a</sup>	458 <sup>a</sup>	50	479 <sup>a</sup>	675 <sup>a</sup>	61
Hexanal	2,099 <sup>b</sup>	3,056 <sup>a</sup>	98	1,242 <sup>b</sup>	2,979 <sup>a</sup>	118
Heptanal	858 <sup>a</sup>	837 <sup>a</sup>	80	0 <sup>b</sup>	537 <sup>a</sup>	14
α-Thujene	922 <sup>a</sup>	432 <sup>a</sup>	126	1,047 <sup>a</sup>	835 <sup>a</sup>	69
α-Pinene	19,982 <sup>a</sup>	14,634 <sup>b</sup>	625	21,473 <sup>a</sup>	18,106 <sup>a</sup>	1,494
Camphene	1,254 <sup>a</sup>	489 <sup>a</sup>	334	1,093 <sup>a</sup>	777 <sup>b</sup>	61
Methyl-2-propenyl disulfide	578 <sup>a</sup>	349 <sup>b</sup>	26	743 <sup>a</sup>	385 <sup>a</sup>	114
Sabinene	929 <sup>a</sup>	282 <sup>b</sup>	43	3,169 <sup>a</sup>	2,189 <sup>b</sup>	112
β-Pinene	0	0	0	10,511 <sup>a</sup>	9,364 <sup>a</sup>	525
Myrcene	1,877 <sup>a</sup>	944 <sup>b</sup>	83	1,847 <sup>a</sup>	1,055 <sup>b</sup>	142
1-Phellandrene	2,253 <sup>a</sup>	1,418 <sup>a</sup>	577	1,999 <sup>a</sup>	889 <sup>b</sup>	202
3-Carene	2,969 <sup>a</sup>	1,571 <sup>a</sup>	625	3,399 <sup>a</sup>	2,386 <sup>b</sup>	215
α-Terpinene	1,961 <sup>a</sup>	2,119 <sup>a</sup>	85	3,009 <sup>a</sup>	1,930 <sup>b</sup>	253
Octanal	1,643 <sup>a</sup>	2,695 <sup>a</sup>	993	1,045 <sup>a</sup>	622 <sup>b</sup>	70
Limonene	4,321 <sup>a</sup>	3,329 <sup>a</sup>	263	4,772 <sup>a</sup>	3,767 <sup>b</sup>	216
Para-cymene	0	0	0	4,063 <sup>a</sup>	3,860 <sup>a</sup>	97
1,3,7-Octatriene	0	0	0	1,652 <sup>a</sup>	707 <sup>b</sup>	233
Heptadecane	0	0	0	4,501 <sup>a</sup>	3,060 <sup>b</sup>	198
γ-Terpinene	2,714 <sup>a</sup>	2,343 <sup>a</sup>	328	1,456 <sup>a</sup>	629 <sup>b</sup>	131
Nonane	0	0	0	2,331 <sup>a</sup>	794 <sup>b</sup>	310
2-Furan carboxaldehyde	9,237 <sup>a</sup>	8,871 <sup>a</sup>	616	2,156 <sup>a</sup>	806 <sup>b</sup>	282
Dodecane	2,389 <sup>a</sup>	907 <sup>b</sup>	193	787 <sup>a</sup>	854 <sup>a</sup>	272
α-Terpinolene	0	0	0	3,613 <sup>a</sup>	1,683 <sup>b</sup>	347
1-Octene-3-ol	0	0	0	3,409 <sup>a</sup>	1,451 <sup>a</sup>	592
Nonanal	2,210 <sup>a</sup>	2,755 <sup>a</sup>	248	848 <sup>a</sup>	792 <sup>a</sup>	152
Camphor	601 <sup>b</sup>	2,932 <sup>a</sup>	514	459 <sup>a</sup>	568 <sup>a</sup>	31

<sup>a,b</sup>Different superscript letters within a row of the same storage day are significantly different ( $P < 0.05$ );  $n = 3$ .

The sensory scores on color intensity of nonirradiated sausages ranged from 4.6 to 5.0 on the 9-unit linear scale (1 = none, 9 = extremely) with no significant difference attributable to fat content (Table 6). Storage also had no effect on the color of sausages. The hardness of sausages was not influenced by fat content, but irradiation at 5 kGy significantly decreased ( $P < 0.05$ ) the hardness of low-fat sausages at d 0 (Table 6). The changes in off-odors and off-tastes in sausages during storage as well as with fat content were negligible, but irradiation produced a significant ( $P < 0.05$ ) irradiation off-odor in both low-fat and high-fat sausages. The differences between irradiated and nonirradiated sausages in intensity of off-odors and off-flavors ranged from 1.5 to 2 sensory units in both low-fat and high-fat sausages, but all the irradiated sausages were still within the acceptable ranges (Table 6). Some panelists characterized the irradiation odor as a weak sweet or weak sulfide. Ahn et al. (2000b) reported that many of the sensory panel-

ists characterized the irradiation odor as a barbecued corn-like odor, but some described it as burnt, bloody, sweet, old, sulfur, or pungent. Sulfur-containing volatiles formed by radiolytic AA, such as dimethyl disulfide and dimethyl trisulfide, are regarded as the major compounds responsible for the characteristic off-odor in irradiated meat (Ahn et al., 2001). However, dimethyl sulfide was the only sulfur compound detected in the irradiated sausages in this study, and it disappeared after 60 d of storage (Tables 1 and 2), indicating that sulfur volatiles had little influence on the odor of sausages after 60 d of storage. Therefore, irradiation can be applied to cured meat products such as sausages with few negative effects on their sensory characteristics.

In conclusion, high-fat sausages were more susceptible than low-fat sausages to oxidative changes, regardless of irradiation treatment. However, both high-fat and low-fat sausages developed significant oxidation during storage, regardless of the irradiation treatment.

**Table 4.** Effect of irradiation and storage at 4°C for 60 d on exterior color characteristics of sausages with different fat contents

Color variable	Fat content, %	d 0			d 60		
		0 kGy	5 kGy	SEM	0 kGy	5 kGy	SEM
L*	16	51.74 <sup>a,y</sup>	52.26 <sup>a,y</sup>	0.33	51.87 <sup>a,y</sup>	52.37 <sup>a,y</sup>	0.29
	29	59.32 <sup>a,x</sup>	58.83 <sup>a,x</sup>	0.52	56.45 <sup>a,x</sup>	56.91 <sup>a,x</sup>	0.42
	SEM	0.38	0.48		0.37	0.36	
a*	16	30.79 <sup>a,x</sup>	29.52 <sup>b,x</sup>	0.33	29.73 <sup>a,x</sup>	28.58 <sup>a,x</sup>	0.44
	29	26.29 <sup>a,y</sup>	25.89 <sup>a,y</sup>	0.41	26.86 <sup>a,y</sup>	24.85 <sup>b,y</sup>	0.66
	SEM	0.42	0.32		0.39	0.69	
b*	16	41.96 <sup>a,x</sup>	40.83 <sup>a,x</sup>	0.74	40.18 <sup>a,x</sup>	39.77 <sup>a,x</sup>	0.60
	29	34.74 <sup>a,y</sup>	34.41 <sup>a,y</sup>	0.71	36.09 <sup>a,y</sup>	35.69 <sup>a,y</sup>	0.52
	SEM	0.76	0.70		0.53	0.59	

<sup>a,b</sup>Different superscript letters within a row of the same storage day are significantly different ( $P < 0.05$ );  $n = 3$ .

<sup>x,y</sup>Different superscript letters within a column are significantly different ( $P < 0.05$ ).

**Table 5.** Effect of irradiation and storage at 4°C for 60 d on interior color characteristics of sausages with different fat contents

Color variable	Fat content, %	d 0			d 60		
		0 kGy	5 kGy	SEM	0 kGy	5 kGy	SEM
L*	16	69.16 <sup>a,y</sup>	69.10 <sup>a,y</sup>	0.13	68.26 <sup>b,y</sup>	68.89 <sup>a,y</sup>	0.16
	29	71.38 <sup>a,x</sup>	71.04 <sup>a,x</sup>	0.26	70.09 <sup>a,x</sup>	70.68 <sup>a,x</sup>	0.21
	SEM	0.26	0.13		0.20	0.17	
a*	16	21.74 <sup>a,x</sup>	19.24 <sup>b,x</sup>	0.12	21.80 <sup>a,x</sup>	18.59 <sup>b,x</sup>	0.08
	29	17.97 <sup>a,y</sup>	16.67 <sup>b,y</sup>	0.09	18.48 <sup>a,y</sup>	16.94 <sup>b,y</sup>	0.12
	SEM	0.11	0.10		0.11	0.10	
b*	16	25.44 <sup>a,x</sup>	23.38 <sup>b,x</sup>	0.10	25.84 <sup>a,x</sup>	23.93 <sup>b,x</sup>	0.15
	29	18.08 <sup>a,y</sup>	18.00 <sup>a,y</sup>	0.13	18.77 <sup>a,y</sup>	18.66 <sup>a,y</sup>	0.24
	SEM	0.11	0.11		0.23	0.18	

<sup>a,b</sup>Different superscript letters within a row of the same storage day are significantly different ( $P < 0.05$ );  $n = 3$ .

<sup>x,y</sup>Different superscript letters within a column are significantly different ( $P < 0.05$ ).

**Table 6.** Sensory properties of irradiated and nonirradiated sausages with different fat contents after 60 d of storage

Sensory variable <sup>1</sup>	Fat content, %	d 0			d 60		
		0 kGy	5 kGy	SEM	0 kGy	5 kGy	SEM
Color	16	4.88 <sup>a</sup>	4.63 <sup>a</sup>	0.16	5.00 <sup>a</sup>	4.13 <sup>b</sup>	0.25
	29	5.00 <sup>a</sup>	5.00 <sup>a</sup>	0.13	4.75 <sup>a</sup>	4.63 <sup>a</sup>	0.26
	SEM	0.88	0.19		0.22	0.28	
Texture (hardness)	16	5.13 <sup>a</sup>	4.38 <sup>a</sup>	0.34	5.13 <sup>a</sup>	4.75 <sup>a</sup>	0.24
	29	5.13 <sup>a</sup>	4.00 <sup>b</sup>	0.34	4.88 <sup>a</sup>	4.75 <sup>a</sup>	0.38
	SEM	0.26	0.40		0.13	0.43	
Off-odor	16	1.50 <sup>b</sup>	3.00 <sup>a</sup>	0.38	1.63 <sup>a</sup>	3.13 <sup>a</sup>	0.52
	29	1.50 <sup>b</sup>	3.00 <sup>a</sup>	0.33	1.38 <sup>b</sup>	2.13 <sup>a</sup>	0.21
	SEM	0.27	0.42		0.30	0.48	
Off-flavor	16	1.25 <sup>b</sup>	2.63 <sup>a</sup>	0.32	1.63 <sup>b</sup>	2.75 <sup>a</sup>	0.32
	29	1.25 <sup>b</sup>	3.63 <sup>a</sup>	0.35	1.25 <sup>b</sup>	2.50 <sup>a</sup>	0.26
	SEM	0.16	0.44		0.22	0.35	

<sup>a,b</sup>Different superscript letters within a row of the same storage day are significantly different ( $P < 0.05$ );  $n = 8$ .

<sup>1</sup>Color score: 1 = very light; 9 = very dark. Texture score: 1 = very soft; 9 = very hard. Off-odor and off-flavor scores: 1 = none; 9 = extreme off-odor or off-flavor.



Dimethyl sulfide and 1-heptene were detected only in irradiated samples, but dimethyl sulfide could not be detected after storage. Irradiation caused no changes in the exterior color of samples, even though  $a^*$  and  $b^*$  values of the interior color decreased significantly with irradiation ( $P < 0.05$ ). Fat content had no effect on the sensory variables of sausages, regardless of irradiation treatment and storage. However, irradiated sausages had significantly stronger off-odors and off-tastes than nonirradiated ones, regardless of the fat content ( $P < 0.05$ ). This indicates that the fat content in sausages is not an important factor influencing the quality of irradiated sausages. The off-odor or off-taste of irradiated sausages was stronger than that of nonirradiated ones, but the taste and odor of irradiated sausages were still acceptable.

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