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Irradiation-induced oxidative changes and production of volatile compounds in sausages prepared with vitamin E-enriched commercial soybean oil

C. Jo[a], D.U. Ahn[b], M.W. Byun[a,*]

[a]*Team for Radiation Food Science and Biotechnology, Korea Atomic Energy Research Institute, PO Box 105, Yusong, Taejon, South Korea, 305-600.*
[b]*Department of Animal Science, Iowa State University, Ames, IA 50011-3150, USA*

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Abstract

Pork sausages were prepared with backfat or commercial soybean oil enriched with vitamin E to determine the effect of irradiation on lipid oxidation and volatile production during storage. The sausages prepared with soybean oil had significantly higher amount of linoleic acid than the control. Lipid oxidation was increased by irradiation at Day 0 in aerobically packaged sausages prepared with both fat sources. The TBARS of aerobically packaged sausages increased with storage, but that of vacuum-packaged did not. The TBARS of sausages prepared with soybean oil was lower than that with the backfat ($P<0.05$), probably due to higher vitamin E content in the soybean oil than the backfat. Irradiated sausages, prepared with soybean oil, had higher TBARS than the nonirradiated at Day 0, but storage had no effect on the TBARS of vacuum-packaged sausages. Irradiation increased the production of most volatile compounds in aerobically packaged sausages at Day 0. The production of volatiles with very short retention time (<1.80 min) was the most sensitive to irradiation. Hexanal content in pork sausages increased by irradiation at day 0 or after storage in aerobic packaging. However, hexanal production in the sausages was significantly suppressed by vacuum packaging, and especially those prepared with soybean oil, because of the high vitamin E content in the sausages.

Keywords: Lipid oxidation; Volatile compounds; Vitamin E; Sausage; Soybean oil

1. Introduction

As with other food processing technologies, such as pasteurization and sterilization, the objective of using ionizing radiation is to destroy pathogenic and spoilage microorganisms without compromising the nutritional properties and sensory quality of the food (WHO, 1999). With this advantage, the US Food and Drug Administration (FDA) permitted irradiation up to 4.5 kGy for refrigerated and 7.0 kGy for frozen red meats. However, concerns about the development of lipid oxidation and the production of off-odour in irradiated meat still remain. Lipid oxidation is a complex process whereby unsaturated fatty acids react with molecular oxygen via a free radical chain mechanism and form fatty acid acyl hydroperoxides (Gray, 1978). Irradiation generates hydroxyl radicals that can initiate the lipid oxidation process in meat because over 75% of muscle cells are composed of water (Thakur & Singh, 1994). Breakdown products of lipid oxidation, such as aldehydes, ketones, carbonyl compounds, hydrocarbons, and furans, can contribute to flavour deterioration of muscle foods.

Saturated fatty acids are reported to raise plasma levels of cholesterol and low-density lipoproteins, and are well correlated to the increased risk of coronary heart diseases (Mattson & Grundy, 1985). Therefore, high amounts of mono- or polyunsaturated fatty acids in meat products may help reduce those risks. Lipid oxidation is, however, one of the major concerns in foods that contain high proportion of polyunsaturated fatty acids. Rhee, Anderson, and Sams (1996) reported that 2-thiobarbituric acid-reactive substances (TBARS) were higher in chicken muscles than in red meats

* Corresponding author. Tel.: +82-42-868-8060; fax: +82-42-868-8043.
E-mail address: mwbyun@kaeri.re.kr (M.W. Byun).

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because of the higher lipid oxidation potential of cooked chicken than cooked beef or pork muscles. Volatile compound analyses demonstrated that *Longissimus dorsi* muscle, from pigs fed 4 or 6% safflower diets, contained more pentanal, hexanal, 2-heptanone, *trans*-2-heptanal, 2-pentylfuran, 2-ethyl-1-hexanol, decanal, and undecanal than those fed 6% tallow diet (Larick, Turner, Schoenherr, Coffey, & Pilkington, 1992).

Vitamin E is generally accepted as a fat stabilizer because it can terminate the oxidation chain reaction. Increased dietary levels of vitamin E resulted in higher tissue tocopherol concentrations and a greater stability of these tissues towards lipid oxidation (Bartov, Basker, & Angel, 1983). Tocopherols are mainly located in cell membranes and protect membrane fatty acids and cholesterol from oxidative damage caused by reactive free radicals. Ashgar et al. (1991) observed lower TBARS in high vitamin E-containing chops than the control after being frozen and thawed. But the antioxidant effect of dietary tocopherol was effective only a short time after cooking (Ajuyah, Ahn, Hardin, & Sim, 1993). The α-tocopherol content was significantly reduced by irradiation in turkey plasma fed different levels of dietary α-tocopheryl acetate (Ahn et al., 1997). However, the relationship between lipid oxidation and vitamin E content of irradiated meat products with different fatty acid compositions is still unclear. The objective of the present study is to determine the effect of irradiation on lipid oxidation and volatile production in irradiated, cooked pork sausages of different fatty acid compositions and vitamin E content.

2. Materials and methods

2.1. Sample preparation and irradiation

Lean pork was purchased from a local meat packer and ground twice through a 9-mm plate. Pork sausages were prepared with the lean meat, fat sources [backfat or soybean oil (Preferred Products, Inc., Eden Prairie, MN 55334), 10% of lean meat], NaCl (2%), and ice water (10%). The α- and γ-tocopherol content of the soybean oil were 99.8 μg/g and 691 μg/g, respectively. Emulsified meat batters were prepared, stuffed into collagen casings (3 cm in diameter), and then cooked in a smokehouse to an internal temperature of 72 °C. After cooling in ice water for 20 min, sausages were sliced to 2 cm-thick pieces (approximately 30 g) and then individually vacuum packaged into oxygen-impermeable nylon/polyethylene bags (9.3 ml $O_2/m_2/24$ h at 0 °C; Koch, Kansas City, MO) to minimize oxidative changes between sample preparation and delay before irradiation. After storing overnight in a 4 °C refrigerator, half of the samples were left as vacuum-packaged and the other half were cut open and flushed with air to produce aerobic-packaged conditions before irradiation. Sausages were irradiated at 0, 2.5, or 4.5 kGy absorbed dose, by using a Linear Accelerator (Circe IIIR, Thomson CSF Linac, Saint-Aubin, France). The temperature during irradiation was around 20 °C and, to confirm the target dose, two alanine dosimeters per cart were attached to the top and bottom surfaces of the sample. Irradiated samples were stored in a 4 °C refrigerator for up to 7 days.

2.2. Lipid oxidation, fat content, and fatty acid composition

Lipid oxidation was determined using a spectrophotometer (DU series 600, Beckman Instruments, Inc., Harbor Blvd., Fullerton, CA) as described by Ahn et al. (1997). The TBARS values were expressed as mg malondialdehyde (MDA) per kg meat. Total fat content was determined by the Folch's extraction method (Folch, Less, & Sloane-Stanely, 1957). Fatty acids were methylated using BF_3-methanol (14% solution, Supelco, Bellefonte, PA). The fatty acid methyl esters were separated by a Hewlett Packard Gas Chromatograph (GC, Model 6890, Hewlett Packard Co., Wilmington, DE) equipped with a flame ionization detector. A split inlet (split ratio, 29:1) was used to inject samples into a HP-5 capillary column (0.25 mm×30 m×0.25 μm), and ramped oven temperature was used (80 °C for 0.3 min, increased to 180 °C at 30 °C/min, and increased to 230 °C at 6 °C/min). Inlet temperature was 180 °C and detector was 280 °C. Helium was the carrier gas at constant flow of 1.1 ml/min. Detector air, H_2, and make-up gas (He) flows were 300, 30, and 28 ml/min, respectively.

2.3. Volatile compound analysis

Precept II and Purge-and-Trap concentrator 3000 (Tekmar-Dohrmann, Cincinnati, OH) were used to purge and trap the volatile compounds. A GC (Model 6890, Hewlett Packard Co., Wilmington, DE) with a Flame Ionization Detector was used to identify the volatile compounds compared with pure standard compounds purchased from Chromatography Research Supplies Inc. (Addison, IL). Samples (2 g) were placed in a sample vial (40 ml), capped tightly, and placed on the sample holder maintained at refrigerated temperature (3 °C). Samples were purged at 40 °C with helium (40 ml/min) for 11 min. Volatiles were trapped using a Tenax/silica/charcoal column (Tekmar-Dohrmann, Cincinnati, OH), and desorbed for 1 min at 220 °C. The temperature of transfer lines was maintained at 155 °C. A split inlet (split ratio, 49:1) was used to inject volatiles into an HP wax-bonded polyethyleneglycol column (60 m, 250 μm i.d., 0.25 μm nominal), and ramped oven temperature was used (32 °C for 1 min, increased to

Table 1
Composition of major fatty acids (%) in cooked pork sausages prepared with pork backfat or commercial soybean oil[a]

Fat source	IR dose	C14:0	C16:0	C16:1	C18:0	C18:1	C18:2
Backfat	0 kGy	0.08	22.32a	0.29	25.06a	46.51a	5.74b
	2.5 kGy	0.12	23.77a	0.32	25.96a	44.71a	5.22b
	4.5 kGy	0.03	22.81a	0.32	24.54a	47.01a	5.29b
Soybean Oil	0 kGy	0.01	13.79b	0.17	8.85b	30.45b	46.73a
	2.5 kGy	–	13.77b	0.20	8.28b	32.90b	44.85a
	4.5 kGy	–	13.74b	0.20	7.97b	34.05b	44.04a
	S.E.M.	0.033	0.564	0.051	0.366	1.154	0.779

[a] Means with different letters within a column are significantly different ($P<0.05$), $n=18$. S.E.M., standard errors of the mean.

Table 2
TBARS values (mg malondialdehyde/kg meat) of aerobically packaged and irradiated cooked pork sausages prepared with backfat or soybean oil[a]

Storage (day)	Backfat (mg MDA/kg)				Soybean oil (mg MDA/kg)			
	0 kGy	2.5 kGy	4.5 kGy	S.E.M.	0 kGy	2.5 kGy	4.5 kGy	S.E.M.
0	1.3bz	1.5by	2.0az	0.09	1.1bz	1.0by	1.5ay	0.03
3	4.7y	5.0x	4.9y	0.18	2.8by	3.2ax	3.1ax	0.12
7	6.1x	6.0x	6.3x	0.25	4.2x	4.0x	4.3x	0.30
S.E.M.	0.25	0.29	0.30		0.21	0.24	0.25	

[a] Means with different letters (a,b) within a row with the same fat source are significantly different ($P<0.05$), $n=12$. Means with different letters (x–y) within a column with the same fat source are significantly different ($P<0.05$), $n=12$. S.E.M. standard errors of the mean.

40 °C at 2 °C/min, to 50 °C at 5 °C/min, to 70 °C at 10 °C/min, to 140 °C at 20 °C/min, to 200 °C at 30 °C/min and held for 5 min). Helium was the carrier gas at constant flow of 1.1 ml/min. The peak area was reported as the amount of volatiles released.

2.4. Vitamin E analysis

Sausage (2 g) was homogenized in 10 ml (w/v) of phosphate-EDTA buffer (pH 7.0). The amounts of α- and γ-tocopherol were determined using high performance liquid chromatography (HPLC, Shimadzu Co., Kyoto, Japan) as described by Ahn, Kawamoto, Wolfe, and Sim (1995).

2.5. Statistical analysis

Two-way analyses of variance (SAS Institute, 1985) were used to determine the effect of irradiation dose and fat sources. The total number of sample used for the experiment was 144 (three irradiation doses × two fat sources × two packaging methods × three storage × four replications), and determined significance level was $P<0.05$. The results of volatile analyses were reported only at day 0 and day 7. The Tukey's multiple range test (Steel & Torrie, 1980) was used to compare differences among mean values. Mean values and standard errors of the mean (S.E.M.) were reported.

3. Results and discussion

3.1. Fat content, fatty acid composition, and vitamin E content

As expected, the sausage prepared with soybean oil had a significantly higher amount of linoleic acid (C18:2) than that with backfat (Table 1). Irradiation dose did not change fatty acid composition of the products. Hau, Liew, and Yeh (1992), however, reported that irradiation of frozen grass prawns at 10 kGy reduced the levels of polyunsaturated fatty acids by 25–32% because of oxidation and decomposition of lipids into volatile compounds. The fat content in the sausage prepared with soybean oil (11.5% fat) was about 1.3% higher than that prepared with backfat (12.8%) because actual fat content in backfat is only about 90%. The α- and γ-tocopherol contents in cooked sausages prepared with soybean oil were 35.1 and 42.7 μg/g fat, respectively, and were significantly higher than those prepared with backfat which were shown 1.09 and 0.22 μg/g fat. The added vitamin E in commercial soybean oil remained in sausages during processing.

3.2. Lipid oxidation

The TBARS of aerobically packaged sausage prepared with backfat were increased by irradiation at 4.5

Table 3
TBARS (mg malondialdehyde/kg meat) of vacuum-packaged and irradiated cooked pork sausages prepared with backfat or commercial soybean oil[a]

Storage (day)	Backfat (mg MDA/kg)				Soybean oil (mg MDA/kg)			
	0 kGy	2.5 kGy	4.5 kGy	S.E.M.	0 kGy	2.5 kGy	4.5 kGy	S.E.M.
0	1.0	1.1	1.1	0.05	0.9b	0.8b	1.2a	0.07
3	1.2	1.0	1.2	0.06	1.0	1.1	1.0	0.03
7	1.2	1.1	1.1	0.04	0.9	0.9	1.0	0.04
S.E.M.	0.04	0.03	0.04		0.03	0.03	0.04	

[a] Means with different letters within a row with the same fat source are significantly different ($P<0.05$). $n=12$. S.E.M., standard errors of the mean.

Table 4
Production of volatiles (pA × s) in aerobically packaged and irradiated pork sausages with different fat sources at Day 0[a]

Volatile compounds (pA × s)	Backfat (pA × s)				Soybean oil[b] (pA × s)			
	0 kGy	2.5 kGy	4.5 kGy	S.E.M.	0 kGy	2.5 kGy	4.5 kGy	S.E.M.
Up to 1.80	46.0b	104a	107a	3.2	37.3c	67.1b	96.2a	2.4
Propanal	0b	8.7a	8.2a	0.5	0b	1.4b	4.7a	0.8
2-Methylpropanal	8.7	9.9	9.9	0.5	10.3	11.0	12.2	0.5
Butanal	1.3a	0b	0b	0.3	0	0	0	–
t-Butanol	100.1	78.6	45.9	18.5	43.0	41.7	43.0	0.7
2-Methylbutanal	22.3b	47.7a	43.6ab	5.4	22.6	33.6	41.7	5.6
Isopropanol	5.5b	8.5a	8.4a	0.5	6.8	7.9	8.7	0.6
Pentanal	1.3b	10.5a	10.6a	1.4	2.7b	7.4a	11.1a	2.4
3-Pentanone	26.2b	63.9a	67.2a	7.8	40.4	58.4	69.5	9.8
sec-Butanol	8.9b	30.9a	33.2a	2.8	16.9	25.2	31.1	4.1
1-Dodecanone	10.4b	25.2a	31.2a	3.3	20.5b	27.6ab	33.4a	4.7
n-Hexanal	0b	51.8a	50.2a	2.8	16.7b	20.3b	28.7a	3.3
1-Butanol	4.6ab	4.2b	5.5a	0.3	3.0b	6.2a	6.2a	0.9
3-Hexanol	0	0	0	–	1.7	0	0	0.7
1-Pentanol	0b	6.2a	5.7a	0.2	9.7a	4.8b	5.1b	1.6
Total	384b	731a	745a	54.4	345c	595b	735a	101.0

[a] Means with different letters within a row are significantly different ($P<0.05$), $n=12$. S.E.M., standard errors of the mean.
[b] Soybean oil: commercial soybean oil containing 99.8 and 691.1 μg/g of α- and γ-tocopherol, respectively.

kGy (Table 2). Storage for 7 days, exposed to air, increased the TBARS significantly. However, no irradiation effect in aerobically packaged sausages prepared with backfat was seen at 3 and 7 days of storage. The TBARS of sausages prepared with soybean oil also increased by irradiation at Day 0 and Day 3 (Table 2). TBARS of aerobically packaged sausages, prepared either with backfat or soybean oil, increased during storage. However, the rate of TBARS increase during storage was higher in the sausages prepared with backfat than with soybean oil ($P<0.05$). Meynier, Genot, and Gandemer (1999) reported that TBARS levels were lower in phospholipids from turkey fed tallow than when fed soya oil or rapeseed oil. Thus, in this study, the vitamin E in the sausages, prepared with commercial soybean oil, reduced oxidation rate (in aerobically packaged sausages).

The TBARS value of vacuum-packaged sausages prepared with backfat or soybean oil was not changed by irradiation dose or storage (Table 3). The pork sausage, prepared with soybean oil and irradiated at 4.5 kGy initially had higher TBARS value than that at 0 or 2.5 kGy in vacuum-packaged products, but no difference was found after 3 and 7 days of storage. The TBARS values of the vacuum-packaged sausages prepared with backfat and soybean oil were not statistically different, although they have the different fatty acid composition.

3.3. Volatile compound analysis

With aerobic packaging, the production of volatile compounds with retention time up to 1.80 was significantly increased by irradiation at Day 0 (Table 4). Other volatile compounds, except for 2-methylpropanal, butanal, *t*-butanol, 1-butanol, and 3-hexanol, were also increased by irradiation in aerobic-packaged sausages and those prepared with backfat. Irradiated sausages produced greater amounts of total volatile compounds than the nonirradiated control. The amounts of volatile compounds eluting before 1.80 min of retention time, increased in a dose-dependent manner (Table 4).

Table 5
Production of volatiles (pA × s) in vacuum-packaged and irradiated pork sausages with different fat sources at Day 0[a]

Volatile compounds	Backfat (pA × s)				Soybean oil[b] (pA × s)			
	0 kGy	2.5 kGy	4.5 kGy	S.E.M.	0 kGy	2.5 kGy	4.5 kGy	S.E.M.
Up to 1.80	30.8b	54.0a	57.9a	2.4	28.3c	54.6b	78.8a	1.8
Propanal	0b	2.9a	0b	0.6	3.4	0	0	2.0
2-Methylpropanal	11.7b	15.4a	14.5a	0.5	10.0	13.4	14.1	2.0
Butanal	0	0	0	–	0	0	0	–
t-Butanol	128a	108b	86.4c	4.4	75.8a	73.1a	67.5b	1.2
2-Methylbutanal	45.5	48.3	48.3	8.1	41.4	33.6	46.0	4.8
Isopropanol	1.6	3.1	1.5	1.6	7.2	6.8	7.9	0.4
Pentanal	7.6	7.4	9.4	4.1	9.1	7.5	12.2	2.5
3-Pentanone	60.8	59.9	66.0	8.1	68.3	57.9	75.8	7.5
sec-Butanol	25.9	26.6	28.3	4.0	27.6	24.0	31.3	3.2
1-Dodecanone	21.9	20.5	24.2	3.6	29.9	27.2	34.9	3.6
n-Hexanal	18.9b	31.4a	24.2ab	3.1	7.7	7.4	7.6	0.4
1-Butanol	10.7a	5.1b	5.2b	1.0	5.0b	6.9a	6.7a	0.5
3-Hexanol	0	0	0	–	0.8	0	0	0.3
1-Pentanol	4.1b	5.4a	4.6ab	0.3	4.0	3.9	3.9	0.1
Total	634	632	654	69.0	617	592	747	58.9

[a] Means with different letters within a row are significantly different ($P<0.05$), $n=12$. S.E.M., standard errors of the mean.
[b] Soybean oil: commercial soybean oil containing 99.8 and 691.1 μg/g of α- and γ-tocopherol, respectively.

Table 6
Production of volatiles (pA × s) in aerobically-packaged and irradiated pork sausages with different fat sources at Day 7[a]

Volatile compounds	Backfat (pA × s)				Soybean oil[b] (pA × s)			
	0 kGy	2.5 kGy	4.5 kGy	S.E.M.	0 kGy	2.5 kGy	4.5 kGy	S.E.M.
Up to 1.80	134	172	166	9.7	114	129	135	9.1
Propanal	10.3b	18.3a	21.2a	2.0	4.2	17.9	10.7	1.6
2-Methylpropanal	11.6b	34.5a	28.8a	3.7	17.4b	23.9ab	26.8a	1.7
Butanal	2.5	3.6	2.9	0.6	4.3	4.1	3.9	0.2
t-Butanol	124a	80.1b	65.6b	11.0	45.4	56.8	49.2	6.2
2-Methylbutanal	22.3	23.4	31.6	1.9	31.1	32.7	32.6	1.7
Isopropanol	14.1a	5.4b	5.9b	0.9	9.9a	5.7b	6.1b	0.5
Pentanal	6.5	5.2	8.6	1.1	9.4	9.4	9.7	0.5
3-Pentanone	35.8b	39.9b	51.0a	2.8	59.1	58.2	58.2	3.1
sec-Butanol	23.7c	31.4b	39.7a	1.7	31.9	36.0	31.4	1.7
1-Dodecanone	18.0b	18.6ab	23.9a	1.4	29.1	28.6	30.4	1.5
n-Hexanal	144	137.9	155	12.0	206a	205a	127b	18.0
1-Butanol	6.9a	5.2b	6.5a	0.2	7.1	6.9	6.8	0.3
3-Hexanol	26.3ab	35.6a	25.0b	1.0	18.2a	14.0b	11.9b	0.9
1-Pentanol	20.0a	12.4b	13.5b	0.8	19.8a	15.4b	11.6c	0.8
Total	833	840	906	37.5	937	959	876	30.5

[a] Means with different letters within a row are significantly different ($P<0.05$), $n=12$. S.E.M., standard errors of the mean.
[b] Soybean oil: commercial soybean oil containing 99.8 and 691 μg/g of α- and γ-tocopherol, respectively.

Aerobically packaged and irradiated pork sausage, prepared with soybean oil, produced more propanal, pentanal, 1-dodecanone, *n*-hexanal and 1-butanol than the nonirradiated control at Day 0 (Table 4). The amounts of total volatiles also increased with increase of irradiation dose.

With vacuum-packaging, irradiation of sausage prepared with backfat increased the production of volatile compounds with very short retention times (<1.80 min), and *n*-hexanal and 1-pentanol, but decreased the amounts of *t*-butanol and 1-butanol (Table 5). However, the amount of total volatile compounds was not influenced by irradiation. The sausages prepared with soybean oil produced more volatile compounds with short retention time (<1.80 min) and 1-butanol as the irradiation dose increased, but other volatile compounds were not influenced by irradiation dose. Larick et al. (1992) found that meat from animals fed high safflower diet produced more pentanal, hexanal, 2-heptanone, *trans*-2-heptanal, 2-pentylfuran, 2-ethyl-1-hexanol, decanal, and undecanone those fed from high tallow diets. The amounts of total volatiles from sausages prepared with backfat and soybean oil, however, were not different (Table 5). This suggests that vitamin

Table 7
Production of volatile compounds (pA × s) in vacuum-packaged and irradiated pork sausages with different fat sources at Day 7[a]

Volatile	Backfat (pA × s)				Soybean oil[b] (pA × s)			
Compounds	0 kGy	2.5 kGy	4.5 kGy	S.E.M.	0 kGy	2.5 kGy	4.5 kGy	S.E.M.
Up to 1.80	56.7c	78.7b	140a	4.3	58.5b	86.9a	86.0a	3.4
Propanal	2.9ab	1.9b	6.1a	0.9	0	0	0	–
2-Methylpropanal	15.4b	15.5b	18.1a	0.4	15.2b	16.7a	17.3a	0.3
Butanal	2.7b	2.3c	4.2a	0.1	3.8	3.8	3.7	0.2
t-Butanol	135	130	125	32.0	77.8a	73.6ab	68.3b	1.9
2-Methylbutanal	58.0	53.7	55.6	3.6	53.2	54.2	51.6	2.0
Isopropanol	7.2	5.9	7.8	2.0	7.4	7.5	7.3	0.2
Pentanal	20.0a	16.9ab	14.5b	1.4	16.3	16.2	16.0	0.6
3-Pentanone	91.0a	82.0ab	72.8b	3.7	88.7	87.0	88.8	3.2
sec-Butanol	39.1a	34.0ab	30.2b	1.8	31.9	31.1	32.3	1.2
1-Dodecanone	40.9a	36.4ab	31.1b	2.0	39.8	37.6	42.3	1.5
n-Hexanal	35.3a	23.2b	26.3b	2.0	9.4	7.7	8.6	0.6
1-Butanol	12.9a	7.3ab	6.1b	1.5	5.1	5.2	4.9	0.3
3-Hexanol	51.9	50.0	50.8	2.6	46.5	43.6	37.1	2.6
1-Pentanol	5.1	4.4	4.7	0.2	3.9	3.6	3.6	0.1
Total	112	938	941	49.9	875	886	904	26.6

[a] Means with different letters within a row are significantly different ($P<0.05$), $n=12$. S.E.M., standard errors of the mean.
[b] Soybean oil: commercial soybean oil containing 99.8 and 691 μg/g of α- and γ-tocopherol, respectively.

Table 8
Statistical significance (Pr < *F*) of main effects on the major volatile compounds of irradiated cooked pork sausage prepared with backfat or soybean oil

Volatile compounds	Fat source	Irradiation	Packaging	Storage day
Retention time < 1.80 min	0.0001	0.0001	0.0001	0.0001
Hexanal	0.0536	0.2812	0.0001	0.0001
Total	0.6053	0.0026	0.0030	0.0001

E, added to products during processing, has a significant effect on the production of total volatile compounds.

After 7 days of storage, the amounts of 2-methylpropanal, 3-pentanone, sec-butanol, 1-dodecanone, and 1-butanol in sausages prepared with backfat, were increased by irradiation (Table 6). However, the production of *t*-butanol, isopropanol, 1-butanol, and 1-pentanol, in sausages prepared with backfat, showed decreasing trends by irradiation. The amount of 2-methylpropanal in the sausages prepared with soybean oil increased, but other compounds were not changed or decreased by irradiation. The amounts of total volatiles in irradiated sausages prepared with backfat or soybean oil were not different. The amount of total volatile increased significantly during storage in both treatments ($P<0.05$) with aerobic packaging.

The amounts of volatile compounds with short retention times (<1.8 min), i.e. propanal, 2-methylpropanal, and butanal were increased by irradiation in sausages prepared with backfat when vacuum packaged, but the majority of volatile compounds were decreased by irradiation (Table 7). Irradiated sausages, prepared with soybean oil, produced greater amounts of volatile compounds with short retention times (<1.80 min) and 2-methylpropanal but produced less *t*-butanol than the nonirradiated control. During 7 days of storage, the amount of total volatile compounds in vacuum-packaged sausages, prepared with backfat and soybean oil, increased ($P<0.05$), mainly due to the increase of pentanal, 3-pentanone, 1-dodecanone, and 3-hexanol (Tables 5 and 7).

Hexanal can be produced from autoxidation of linoleic acid via the cleavage of the linolyl residue at carbon 13, and has a very high correlation with flavour scores of oxidized vegetable oils (Grosch, 1989). Ahn, Sell, Jo, Chen, Wu, and Lee (1998) reported that hexanal and propanal were well correlated with TBARS ($r^2=0.71$ and 0.70, respectively). However, the production of hexanal in sausages was suppressed by vacuum-packaging, even in sausages prepared with soybean oil (Table 5). High vitamin E content, in the sausages prepared with soybean oil, reduced the development of oxidative changes during the 7-day storage in vacuum packaging. However, the hexanal content of sausages, prepared with soybean oil, dramatically increased during the 7-day storage in aerobic packaging and was even higher than that prepared with backfat (Table 6). The total volatile compounds in aerobically packaged sausages also increased mostly due to the increase in hexanal content. General statistical significance of main

effects on the production of major volatile compounds, is shown in Table 8.

In terms of the beneficial effects of polyunsaturated fatty acids in human health and disease, certain polyunsaturated fatty acid containing vegetable oils can be used to produce the processed meat products if sensory quality meets consumer expectation. With an appropriate method to suppress the lipid oxidation, such as vitamin E addition, the use of irradiation technology for sanitation purposes can be expanded. Vacuum-packaging is very effective for inhibiting irradiation-induced lipid oxidation and, combined with antioxidants, the volatile compounds related to lipid oxidation can be significantly reduced. Additional sensory analysis including properly conducted consumer tests, should be performed to support the potential application.

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