RESEARCHREPORT

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PORK QUALITY

Title: Analysis and Characterization of Volatile Components Responsible for the Off-flavor Development in Irradiated Pork - **NPB #98-175**

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Date Received: 8/17/1999

1. ABSTRACT

Irradiated muscle strips produced more 2-thiobarbituric acid reactive substances (TBARS) than nonirradiated only in aerobic packaging during storage. Irradiation had no effect on the production of volatiles related to lipid oxidation, but produced a few sulfur-containing compounds not found in nonirradiated meat. This indicates that the major contributor of off-odor in irradiated meat is not lipid oxidation, but radiolytic breakdown of sulfur-containing amino acids. Many of the irradiation-dependent volatiles reduced to 50 to 25% levels during the 5-d storage under aerobic conditions. Irradiated muscle strips produced stronger irradiation odor than nonirradiated, but no irradiation dose or storage effect was found. Irradiation had no negative effect on the acceptance of meat, and approximately 70% of sensory panels characterized irradiation odor as barbecued-corn-like odor.

Oil emulsions containing amino acids, glutathione, bovine serum albumin, gelatin, or myofibrillar proteins were prepared. The emulsions were irradiated at the 0, 2.5, 5.0, or 10.0 kGy absorbed dose and analyzed for volatile compounds. Irradiation increased the production of aldehydes (e.g. hexanal, heptanal, octanal, and nonanal) indicating that lipid oxidation of oil emulsion was accelerated by irradiation. Irradiation produced new volatile compounds from oil emulsions containing leucine, valine, isoleucine, phenylalanine, methionine, or cysteine by radiolytic degradations. This indicated that both radiolyses of proteins and lipid oxidation were important for off-odor generation in irradiated meat. However, the generation of new volatile compounds by irradiation suggested that radiolytic degradation of proteins was more important than lipid oxidation on the off-odor production in irradiated meat.

2. INTRODUCTION

Irradiation is one of the best methods to control pathogenic microorganisms in raw poultry and its use in red meat is also expected to be approved early in 1998. One of the major concerns with irradiated meat is its effect on lipid oxidation and off-flavor production, which significantly impact consumer acceptance of the meat. Currently, our understanding of the effects of irradiation at low to moderate doses on meat quality are

limited. The objectives of this proposed research are to characterize volatiles in irradiated meat and to elucidate the production of volatiles and mechanisms of off-odor in irradiated pork.

This proposed research will identify off-odor volatiles and characterize the off-odor in irradiated pork, and elucidate the mechanisms of volatiles formation and off-odor production by irradiation using buffer systems containing amino acids, proteins, glutathione, and fat. Gas chromatography-mass spectrometry will be used to identify and quantify volatile components, sensory analysis for the characterization of off-odor, and thiobarbituric acid reactive substance assay for lipid oxidation. The interactions of various meat components and/or volatile compounds will be determined to elucidate the major sources and the chemical-level reaction pathways involved in the production of off-odor in irradiated meat, which will be essential to develop methods to minimize off-odor production in irradiated meat.

Although, irradiation is considered as one of the most effective methods to control pathogenic microorganisms in meat, it will not be used if the quality of pork after irradiation is not acceptable. Understanding the mechanisms of lipid oxidation and off-odor development by the irradiation process will provide information necessary to minimize the negative effects of irradiation on meat quality, which will be very important for the meat industry as it implements irradiation technology. At a minimum, the overall safety of meat products will be greatly improved using irradiation technology, which will significantly enhance the U.S. pork industry.

3. OBJECTIVES

1) To identify and quantify volatile compounds produced in raw pork by irradiation.
2) To elucidate mechanisms of off-odor production in irradiated meat.

4. PROCEDURES

Sample preparation: *Longissimus dorsi* muscles from four different pigs were obtained within 48 h after slaughter and muscle strips, approximately 20-mm long, 40-mm wide and 5-mm thick (4 g), were prepared. Four muscle strips (one strip per each pig) were placed in a single layer into each labeled bag and either aerobic or vacuum packaged. Samples in the bags were irradiated at 0, 5, or 10 kGy and stored at 4℃ for 5 d. Fluorescence TBARS method was used to analyze lipid oxidation, and a purge-and-trap/gas chromatography-mass spectrometry (GC-MS) method was used to determine the amount and identity of volatiles components.

Oil emulsions were prepared by blending soybean oil (2 mL), cholesterol (5%, v/v), and Triton X-100 (50 □L) with 200 mL maleate buffer (50 mM, pH 5.8). Amino acid (20 amino acids, 50 mM), glutathione (25 mM), bovine serum albumin (BSA, 5%, w/v), gelatin (2%, w/v), or myofibrillar proteins (20%, w/v) was added in the buffer before blending with a Waring blender for 2 min at high speed. A 10-mL portion of oil emulsion was transferred to 40-mL sample vials, irradiated at the 0, 2.5, 5.0, or 10.0 kGy absorbed dose (dose rate was 86 kGy/min), and analyzed for volatile compounds. Samples were stored in a 4℃-refrigerator until analyzed.

Volatile compounds analysis: Precept II and Purge-and-Trap Concentrator 3000 were used to purge and trap volatiles potentially responsible for the off-odor in meat. A GC unit equipped with a mass selective detector was used to characterize and quantify the volatile compounds. A four-gram muscle strip was placed in a sample vial (40 mL) and purged with helium gas (40 mL/min) for 15 min. Volatiles were trapped at 30℃ using a Tenax/Silica gel/Charcoal column (Tekmar-Dorham, Cincinnati, OH) and desorbed for 1 min at 220℃. A split inlet (split ratio, 39:1) was used to inject volatiles into a GC

column, and ramped oven temperature conditions (30℃ for 2 min, increased to 40℃ @ 2℃/min, increased to 50℃ @ 5℃/min, increased to 100℃ @ 10℃/min, increased to 140℃ @ 20℃/min, increased to 200℃ @ 30℃/min, and held for 4.5 min) were used. Inlet temperature was 180℃. Helium was used as a carrier gas, and column flow was 1.1 mL/min. The identification of volatiles was achieved by comparing mass spectral data with those of the Wiley library. The area of each peak was integrated using ChemStation software, and total ion counts x 10^3 was reported as an indicator of volatiles generated from the meat samples. For oil emulsion study, 2-mL sample was used for volatile analysis. The peak area (total ion counts) less than 20,000 was discarded and was considered as no production.

Sensory analysis: The intensity and descriptive characteristics of odor of meat samples were determined using 13 trained sensory panelists. Training sessions were conducted to familiarize panelists with the irradiation odor, the scale to be used, and with the range of attribute intensities likely to be encountered during the study. For evaluation of odor, samples in coded, capped scintillation vials (glass) were presented to each panelist in isolated booths. A 15cm linear hedonic scale, anchored with the words 'no irradiation odor' and 'very strong irradiation odor', and 'not acceptable' and 'highly acceptable' at opposite ends, were used to rate the samples on the intensity of irradiation odor and acceptance of irradiation odor. The responses from the panelists were expressed in numerical values ranging from 0 (no irradiation odor or not acceptable) to 15 (strong irradiation odor or highly acceptable) to the nearest 0.5 cm. Sensory panels were also asked to characterize the odor that best describe it. The relationship between lipid oxidation, volatile composition, and odor intensity and characteristics was evaluated using correlation coefficients.

5. RESULTS

A. Lipid oxidation of *Longissimus dorsi* muscle strips

Spectrophotometric analysis of TBARS: Irradiated *Longissimus dorsi* (LD) muscle strips had higher TBARS than those of non-irradiated in all storage and packaging conditions. However, only the muscle strips irradiated at 10 kGy had higher TBARS than non-irradiated after 0 and 5 days of storage. No storage effect on the TBARS of muscle strips was found in both vacuum and aerobic packaging conditions (Table 1).

Fluorometric analysis of TBARS: Irradiated pork produced more TBARS than non-irradiated only in aerobic packaged muscle strips at Day 0. LD muscle strips stored for 5 days in aerobic packaging produced higher TBARS than those of 0-day storage. The TBARS analyzed using fluorometric method were higher than those of spectrophotometric and more sensitive to the oxidative changes in raw meat (Table 1).

B. Volatiles production of *Longissimus dorsi* muscle strips

At Day 0 with vacuum packaging, irradiated muscle strips produced a few volatiles not found in non-irradiated meat. They were thiobis methane, 3-methoxy-1-propene, ethanethioic acid S-methyl ester, 2,3-dimethyl disulfide, methylbenzene and 2,3-dimethyl trisulfide. Most of the new volatiles were sulfur compounds and the amount of 2,3-dimethyl disulfide was the highest, which accounted for approximately 75% of all the total new volatiles produced by irradiation. We assume that these new volatile compounds are responsible for the irradiation odor and are originated from proteins by radiolytic reactions of irradiation. However, irradiation-dose effect on the production of new radiolytic products was significant only in 3-methoxy-1-propene, 2,3-dimethyl

disulfide, and methylbenzene. On the other hand, the amount of carbon disulfide, 1-octanol, 3-chloropyridine, piperdine carboxyaldehyde, 2,2,8-trimethyl decane, 2,2,4,6,6-pentamethyl heptane, 2,6-dimethyl octane, and 2,8-dimethyl undecane in vacuum packaged muscle strips at Day 0 were decreased by irradiation. The amounts of lipid oxidation products, such as aldehydes, ketones and alcohols, were either not influenced or decreased by irradiation. This indicates that the major contributor of off-odor in vacuum packaged irradiated meat is not lipid oxidation but radiolytic breakdown of sulfur containing amino acids (Table 2).

At Day 0 with aerobic packaging, all the new volatiles, except for 2,3-dimethyl trisulfide, found in vacuum-packaged irradiated muscle strips were also found in aerobic-packaged meat. The amount of carbon disulfide in aerobic packaged irradiated meat was also significantly lower than that in irradiated meat as in vacuum packaged. However, the amounts and the changes of volatiles influenced by irradiation were smaller in aerobic packaging than in vacuum packaging. This indicates that most of these volatiles either newly produced or influenced by irradiation are highly volatile (Table 2).

After 5 days of storage in vacuum packaging, the volatile compounds found in muscle strips were very similar to those at Day 0 but the compositions of volatiles in muscle strips were different from those of Day 0. The amount of thiobis methane increased by 4-6 folds and propanal by 50% but that of octanol was decreased to 40-70%, 3-chloropyridine to 25-50%, 2,3-dimethyl disulfide to 50-70%, piperdine carboxyaldehyde to 25-30%, and 3,5-dimethyl octane to 50-60% of the Day 0 values over the 5-day storage period. 1-Butene, not found at Day 0, was also found in muscle strips at Day 5. However, these changes in volatiles during the 5-day storage in vacuum packaging were not severe enough to influence overall odor characteristics of the muscle strips (Table 3).

After 5 days of storage in aerobic packaging, the amount of all the volatile components except for propanal, thiobis methane, and carbon disulfide decreased to 25 to 50% of the Day 0 values. Many of the new volatile compounds formed by irradiation disappeared or reduced to very low levels during the 5-day storage in aerobic conditions, and the amounts of total volatiles were also reduced to 50 to 25% levels of the Day 0 values. The amounts of total volatiles in aerobic packaged muscle strips were less than 1/2 or 1/3 of those found in vacuum packaged meat with the same irradiation dose (Table 3). Result from Tables 2 and 3 indicate that irradiation has the strongest, packaging has intermediate, and storage time has the lowest effects on the volatile composition and production of raw muscle strips.

With vacuum packaging, only 2,5-dimethyl undecane had significant negative correlation with TBARS of nonirradiated muscle strips. With aerobic packaging, 3-methoxy-1-propene, methylbenzene, 3-ethyl-4-methyl hexane, 2,2,8-trimethyl decane, 2,2,4,6,6-pentamethyl heptane, 2,5-dimethyl undecane, and 2,8-dimethyl undecane were positively correlated with TBARS of irradiated muscle strips (Table 4). With aerobic packaging, 3-methoxy-1-propene, 1-octanal, and piperdine carboxyaldehyde had significant correlations with TBARS of nonirradiated muscle strips. However, none of the volatiles produced in irradiated muscle strips had significant correlations with TBARS (Table 4). This indicates that volatiles produced in aerobic packaged nonirradiated meat are related to lipid oxidation but most of the volatiles produced by irradiation are not related to lipid oxidation. However, the contribution of lipids and protein (amino acids) interactions on the production of new volatiles during irradiation and subsequent storage should not be overlooked to understand the mechanisms of off-odor production in irradiated meat.

In vacuum packaging, irradiated LD muscle strips produced significantly stronger irradiation odor than nonirradiated but no irradiation dose or storage effect was found. As in vacuum packaging, irradiation produced significant irradiation odor in aerobic packaged muscle strips. Irradiation of muscle strips at 10 kGy produced stronger irradiation odor than that at 5 kGy, and 5-day storage reduced the intensity of irradiation odor in muscle strips but the reduction was significant in samples irradiated at 5 kGy. Irradiation had no negative effect on the preference of meat under all packaging and storage conditions (Table 5). Many of the sensory panels characterized irradiation odor as barbecued corn-like odor but some described as burnt, bloody, sweet, old, sulfur, or pungent. Many sensory panels were used to boiled corn-like odor and showed no objection to the irradiation odor. We assume that this would be true for the majority of U.S. customers but more detailed sensory studies are required to confirm it.

Volatiles of Irradiated Oil Emulsion

Irradiated oil emulsions produced larger number of volatile compounds than nonirradiated controls regardless of compounds added in oil emulsions (Tables 6-9). More volatile compounds than those listed in the tables were produced by irradiation, but the amounts of some volatile compounds were negligible or inconsistent. Chloroform was produced from all samples, but the amount was not influenced by irradiation dose. Several aldehydes quantified and listed in Tables 1 - 4 were produced only in irradiated samples. The amounts of 1-heptene and 1-nonene produced by irradiation were dose-dependent. However, 1-heptene was produced only in irradiated oil emulsion containing no amino acid, isoleucine, valine, or glutathione (Tables 6 and 9) because of differences in the column and method used for the present study. 1,1-Oxybis ethane was one of the major compounds produced from irradiated oil emulsion containing aliphatic, hydroxyl, basic side chain group amino acids, and myofibrillar protein (Tables 6-9). The 2-methyl-1-propene, 2,2,6,6-tetramethylheptane, and 2,2,4-trimethyl-1-pentane were found in almost all samples, but the effect of irradiation was not significant.

Isobutylaldehyde and 3-methylbutanal were produced in irradiated oil emulsion containing leucine, and the amounts of these compounds increased in a dose-dependent manner up to 10 kGy (Table 10). The irradiation dose-dependent production of 2-methylbutanal from oil emulsion containing isoleucine suggests the deamination and decarboxylation of isoleucine by irradiation. Deamination and decarboxylation are the primary reactions of free radicals by irradiation in aliphatic amino acid. He also indicated that deamination plays a greater role than decarboxylation in irradiated alanine. Valine, which has a similar structure to leucine, produced isobutylaldehyde as leucine but the production rate was much higher than that of leucine, indicating that deamination and decarboxylation were major reactions of radiolysis (Table 10). Among the amino acids with aromatic side chains, phenylalanine produced benzaldehyde and benzene acetaldehyde upon irradiation. Phenylalanine readily reacts with the transient species of water radiolysis and induces hydroxylation of the aromatic ring as the principal reaction. Therefore, *o*-, *m*-, and *p*-tyrosine can be formed by irradiation and subsequent oxidation converts these to various isomers of dihydroxyphenylalanine. The reactions of electron adducts to aromatic residues would give hydrogenated derivatives, thus benzene rings can be converted to cyclohexadiene derivatives. Other aromatic amino acids (tyrosine, tryptophane and histidine) were also known as irradiation-sensitive, but no characteristic volatile compounds were found in this study.

Sulfur-containing amino acids (cysteine, cystine and methionine) react with free radicals more easily than aliphatic amino acids. Electron reaction with sulfhydryl derivatives leads to formation of H_2S and is of considerable concern in irradiation

technology due to its unpleasant odor. However, H_2S was not detected in this study because the molecular scan range used was 46.1 to 550. The volatile compounds detected in oil emulsion containing cysteine were carbon oxide disulfide and carbon disulfide (Table 10). It is known that aqueous electrons (e^-_{aq}) generated by irradiation exclusively attack -SH and not the $-NH^{3+}$ group of cysteine, and induce □-radiolysis. It was also assumed that cysteine underwent dimerization reaction to form cystine. In contrast to cysteine, cystine produced carbon disulfide from nonirradiated oil emulsion but carbon disulfide was not found in irradiated oil emulsions (Table 10). The carbon oxide sulfide was also produced from the irradiated oil emulsion containing glutathione due probably to cysteine in the structure. The amount of carbon oxide sulfide from glutathione was much smaller than that from cysteine and probably the cysteine present as part of a peptide is less susceptible to free radical reaction. Four new sulfur-containing compounds were created by irradiation from oil emulsion containing methionine (Table 10). These compounds have been suggested as the main off-odor generators, and produced via the radiolytic degradation of sulfur-containing amino acids. Interestingly, 2-propenal, which generates aggressive odor, was also produced by irradiation in a dose-dependent manner. Probably 2-propenal was produced by splitting of the $-SCH_3$ group followed by deamination and decarboxylation from methionine. However, the dimethylthio-group (-C-S-C-) has a low reactivity with aqueous electrons (e^-_{aq}). Therefore, methionine would undergo chemical reaction more likely with secondary reaction substances such as hydroxyl radicals from water radiolysis.

Bovine serum albumin (BSA), gelatin, and myofibrillar protein produced many benzene-containing compounds, but irradiation at the 2.5-kGy dose could not create these products except for benzaldehyde from BSA (Table 10). Again, the rigid spatial structure of protein molecules, which increased the resistance of amino acids in polypeptides to radiolytic degradation more than any singular amino acid, protected amino acid side chains from radiolytic degradation. Radicals formed by irradiation can be held in position and be recombined. Therefore, radiation damage to certain amino acids in proteins is quite limited, and the proteins tested may not be affected at low dose irradiation <2.5 kGy). Oil emulsion containing myofibrillar protein produced 3-methylbutanal and 2-methylbutanal, but the amounts of these compounds were not influenced by irradiation doses between 0 and 10 kGy.

Hexanal is known as the most sensitive indicator for lipid oxidation and flavor deterioration in meat products. Irradiation significantly increased the amount of hexanal in oil emulsion containing different compounds (Table 11). The result indicated that lipid oxidation was accelerated by irradiation. Irradiation-induced oxidative chemical changes were dose-dependent and the presence of oxygen had a significant effect on the rate of lipid oxidation. Other aldehydes such as propanal, heptanal, octanal, and nonanal were also produced but the trends were similar to that of the hexanal.

The cumulated evidence and present results suggest that the radiolytic products of proteins and lipids are the major sources of off-odor in irradiated meat. Volatile compounds produced by lipid oxidation during and after irradiation in the presence of oxygen also could contribute to the development of off-odor in irradiated meat. Irradiation produced significant amounts of volatile compounds not found in nonirradiated oil emulsion containing aliphatic side chains and sulfur-containing amino acids indicating that these compounds are closely related to off-odor generation in irradiated meat. To identify the major volatile compounds responsible for irradiation off-odor, information on the odor characteristic of individual volatile compounds found from radiolysis of amino acids is necessary. Once the origin of off-odor volatile compounds in

irradiated meat is identified, methods that can prevent or reduce the off-odor can be established.

Table 1. TBARS values of irradiated pork *Longissimus dorsi* muscle strips with different packaging.[1]

	Vacuum packaging			Aerobic packaging		
IR (kGy)	0 d	5 d	SEM	0 d	5 d	SEM
	TBARS value (mg MDA/kg meat)					
-						
0	0.42	0.48	0.061	0.33^{by}	0.86^{a}	0.112
5	0.41	0.60	0.075	0.52^{bx}	0.93^{a}	0.047
10	0.54	0.60	0.022	0.50^{bx}	1.04^{a}	0.030
SEM	0.037	0.072		0.038	0.095	

[1]Samples were analyzed using a fluorometric method. n = 4.

^{a,b}Different letters within a row with same packaging are significantly different ($p<0.05$).

$^{x-z}$Different letters within a column are significantly different ($p<0.05$).

Abbreviations: TBARS, 2-thiobarbituric acid reactive substances; MDA, malonaldehyde.

Table 2. Production of volatiles in irradiated pork *Longissimus dorsi* muscle strips after 0 d storage.[1]

	Vacuum packaging				Aerobic packaging			
Volatiles	0 kGy	5 kGy	10 kGy	SEM	0 kGy	5 kGy	10 kGy	SEM
	Area (ion counts x 1000)							
Propanal	673	622	803	92.4	557	633	729	74.2
Dimethyl sulfide	nd^{b}	216^{a}	138^{a}	42.2	nd^{b}	61^{a}	95^{a}	11.8
Carbon disulfide	457^{a}	19^{b}	20^{b}	25.3	241^{a}	65^{b}	44^{b}	38.5
3-Methoxy-1-propene	nd^{c}	132^{b}	271^{a}	29.5	nd^{c}	96^{b}	175^{a}	8.2
2-Ethyl-1-butanol	99	94	119	12.1	80	100	86	16.9
Cloroform	131	87	72	26.9	62	58	73	10.4
1-Octanol	461^{a}	187^{b}	163^{b}	63.3	47	40	25	13.3
Thioacetic acid methyl ester	nd^{b}	158^{a}	191^{a}	45.1	nd^{b}	53^{ab}	122^{a}	25.4
2,3-Dimethyl disulfide	nd^{b}	2701^{a}	3044^{b}	401.1	nd^{c}	685^{b}	1457^{a}	192.9
Toluene	nd^{c}	191^{b}	321^{a}	14.1	nd^{b}	133^{a}	224^{a}	33.7
3-Chloropyridine	1225^{a}	568^{b}	492^{b}	130.9	206	169	136	53.2
3-Ethyl-4-methyl hexane	241	93	138	40.5	169	214	298	74.8
2,3-Dimethyl trisulfide	nd^{b}	121^{a}	69^{ab}	28.5	nd	nd	nd	-
Piperdine carboxyaldehyde	534^{a}	218^{b}	265^{b}	67.0	184	231	208	48.4
2,2,8-Trimethyl decane	317^{a}	103^{b}	188^{b}	38.4	260	400	527	127.4
2,2,4,6,6-Pentamethyl heptane	142^{a}	41^{b}	77^{b}	16.9	106	170	223	59.5
3,5-Dimethyl octane	940	844	908	148.2	1077	1274	1592	277.4
Undecane	92	52	77	17.4	85	124	162	36.6
2,6-Dimethyl octane	524^{a}	206^{b}	342^{ab}	66.5	542	804	1026	221.2
2,5-Dimethyl undecane	271^{a}	103^{b}	171^{ab}	31.7	275	421	537	114.3
2,8-Dimethyl undecane	276^{a}	90^{b}	167^{b}	31.8	270	405	516	109.8
Total volatiles	6382	6844	8033	792.2	4159	6143	8253	1127.4

[1]Samples (4-g) were purged immediately after sampling. n = 4.

$^{a-c}$Different letters within a row with same packaging are significantly different ($p<0.05$).

SEM, standard error of the mean.

Table 3. Production of volatiles in irradiated pork *Longissimus dorsi* muscle strips after 5-day storage at 4°C.[1]

	Vacuum packaging				Aerobic packaging			
Volatiles	0 kGy	5 kGy	10 kGy	SEM	0 kGy	5 kGy	10 kGy	SEM
	---------- Area (ion counts x 1000) ----------							
1-Butene	37^{c}	248^{b}	358^{a}	18.1	nd^{c}	76^{b}	169^{a}	11.4
Propanal	889	960	1185	108.7	601	841	762	82.8
Dimethyl sulfide	36^{b}	1387^{a}	554^{b}	172.2	nd^{c}	76^{a}	38^{b}	9.4
Carbon disulfide	780^{a}	413^{ab}	233^{b}	123.6	248	134	91	42.8
3-Methoxy-1-propene	nd^{b}	160^{a}	214^{a}	20.1	54^{b}	105^{a}	132^{a}	11.2
2-Ethyl-1-butanol	88	84	153	19.0	60	53	46	8.5
Cloroform	110	94	95	15.8	42^{a}	nd^{b}	nd^{b}	7.1
1-Octanol	323^{a}	77^{b}	40^{b}	34.3	nd	nd	nd	-
Thioacetic acid methyl ester	nd	87	180	55.6	nd	nd	nd	-
2,3-Dimethyl disulfide	nd^{b}	1947^{a}	1765^{a}	333.3	nd	nd	nd	-
Toluene	nd^{b}	113^{a}	155^{a}	13.4	nd^{b}	40^{a}	155^{a}	13.4
3-Chloropyridine	608^{a}	203^{b}	132^{b}	75.1	132	97	49	23.4
3-Ethyl-4-methyl hexane	68	74	93	13.6	37	29	44	8.7
2,3-Dimethyl trisulfide	nd^{c}	28^{b}	59^{a}	5.3	nd	nd	nd	-
Piperdine carboxyaldehyde	148	72	68	20.7	42	39	28	3.8
2,2,8-Trimethyl decane	125	86	141	23.7	67	45	74	16.5
2,2,4,6,6-Pentamethyl heptane	52	36	54	11.0	30	23	31	4.2
3,5-Dimethyl octane	562	417	606	75.6	386	260	348	58.7
Undecane	50	34	38	9.3	21	22	27	4.0
2,6-Dimethyl undecane	399	249	341	75.5	236	171	237	52.8
2,5-Dimethyl undecane	271	105	197	58.4	126	85	111	30.2
2,8-Dimethyl undecane	187	92	183	40.2	136	88	105	38.4
Total volatiles	4729	6963	6832	613.5	2217	2182	2351	261.5

[1]Samples (4-g) were purged immediately after sampling. n = 4.

$^{a-c}$Different letters within a row with same packaging are significantly different ($p<0.05$). nd, not detected. SEM, standard error of the mean.

Table 4. Correlation coefficients between the amount of volatile compounds and TBARS of irradiated and nonirradiated pork *Longissimus dorsi* muscle strips.

	Vacuum packaging		Aerobic packaging	
Volatiles	Nonirradiated	Irradiated	Nonirradiated	Irradiated
1-Butene	-0.24	-0.13	-	0.32
Propanal	-0.43	-0.06	-0.31	-0.28
Dimethyl sulfide	-0.37	-0.48	-	-0.41
Carbon disulfide	-0.50	-0.46	0.30	-0.17
3-Methoxy-1-propene	-	0.53*	-0.74*	0.39
2-Ethyl-1-butanol	-0.26	0.28	0.11	-0.44
Cloroform	0.04	-0.21	0.56	-0.10
1-Octanol	0.32	0.37	0.90**	-0.20
Thioacetic acid methyl ester	-	-0.15	-	0.09
2,3-Dimethyl disulfide	-	0.12	-	0.03
Toluene	-	0.52*	-	-0.10
3-Chloropyridine	0.33	0.33	0.61	-0.27
3-Ethyl-4-methyl hexane	0.17	0.57*	0.68	-0.23
2,3-Dimethyl trisulfide	-	-0.02	-	-
Piperdine carboxyaldehyde	0.35	0.38	0.79*	-0.35
2,2,8-Trimethyl decane	-0.03	0.64**	0.59	-0.23
2,2,4,6,6-Pentamethyl heptane	-0.04	0.62*	0.49	-0.25
3,5-Dimethyl octane	-0.19	0.42	0.68	-0.23
Undecane	-0.18	0.38	0.59	-0.25
2,6-Dimethyl octane	-0.50	0.40	0.49	-0.23
2,5-Dimethyl undecane	-0.81*	0.58*	0.43	-0.23
2,8-Dimethyl undecane	-0.55	0.61*	0.32	-0.23
Total volatiles	-0.19	0.25	0.60	-0.21

n = 8 for nonirradiated and n = 16 for irradiated.□□□□□□□

*Significant at p<0.05, **significant at p<0.01. □□□□□□□

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Table 5. Sensory characteristics of irradiated pork *Longissimus dorsi* muscle strips refrigerated for 5 d.

	Vacuum packaging			Aerobic packaging		
Irradiation	0 d	5 d	SEM	0 d	5 d	SEM
Irradiation odor intensity						
0 kGy	3.49^{y}	3.27^{y}	0.808	5.09^{y}	3.10^{z}	0.966
5 kGy	9.90^{x}	8.40^{x}	0.804	8.19^{ax}	5.26^{by}	0.769
10 kGy	10.49^{x}	8.94^{x}	0.670	9.27^{x}	7.72^{x}	0.577
SEM	0.730	0.768		0.858	0.652	
Acceptance of meat odor						
0 kGy	7.40	5.63	0.889	5.07	6.61	0.884
5 kGy	6.11	4.68	1.000	5.40	5.10	0.916
10 kGy	6.15	3.74	1.049	6.22	6.30	1.154
SEM	1.039	0.864		1.055	0.841	

[a,b]Different letters within a row with same packaging are significantly different ($p<0.05$).

[x-z]Different letters within a column are significantly different ($p<0.05$).

Irradiation odor intensity: 0, no irradiation odor; 15, very strong irradiation odor. Acceptance of meat odor: 0, not acceptable; 15, highly acceptable.

Table 6. Major volatile compounds found in irradiated oil emulsion containing no or aliphatic group amino acids.

	None		Leu		Ile		Val		Gly		Ala		Pro	
Volatile compounds	N	I	N	I	N	I	N	I	N	I	N	I	N	I
1,1-Oxybis ethane	x	x	x	x		x	x	x		x		x		x
2-Propanone			x	x				x						
Hexane	x	x	x	x	x	x				x		x		x
Isobutylaldehyde				x				x						
1-Heptene		x				x		x						
3-Methylbutanal				x										
2-Methylbutanal						x								
Chloroform	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Hexanal		x				x	x	x	x	x	x	x		
Heptanal	x	x		x		x		x	x	x	x	x	x	x
Octanal	x	x		x						x				
Nonanal	x	x			x	x	x	x	x	x		x		x
2-Methyl-1-propene	x	x	x	x	x	x	x	x	x	x	x	x		x
2,2,6,6-Tetramethylheptane	x	x	x	x	x	x	x	x	x	x	x	x		x
2,2,4-Trimethyl-1-pentane	x	x	x	x	x	x	x	x	x	x		x		x

N, nonirradiated; I, irradiated.
Abbreviations: Leu, Leucine; Ile, iosleucine; Val, valine; Gly, glycine, Ala, alanine; Pro, proline.

Table 7. Major volatile compounds found in irradiated oil emulsion containing basic, acidic, or amide side chain group amino acids.

	His		Arg		Lys		Asp		Glu		Asn		Gln	
Volatile compounds	N	I	N	I	N	I	N	I	N	I	N	I	N	I
1,1-Oxybis ethane		x		x										
Chloroform	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Hexanal		x	x	x		x		x		x			x	x
Nonanal			x	x	x		x		x		x			
2-Methyl-1-propene	x	x	x	x	x	x	x	x	x	x	x	x		x
2,2,6,6-Tetramethylheptane	x	x	x	x	x	x	x	x	x	x	x	x		x
2,2,4-Trimethyl-1-pentane	x	x	x	x	x	x	x	x	x	x	x	x		x

N, nonirradiated; I, irradiated.
Abbreviations: His, histidine; Arg, arginine; Lys, lysine; Asp, aspartic acid; Glu, glutamic acid; Asn, asparagine; Gln, glutamine.

Table 8. Major volatile compounds found in irradiated oil emulsion containing aromatic or hydroxyl side chain group amino acids.

	Tyr		Trp		Phe		Thr		Ser	
Volatile compounds	N	I	N	I	N	I	N	I	N	I
1,1-Oxybis ethane							x	x		x
Propanal								x		
2-Propanone								x		
Chloroform	x	x	x	x	x	x	x	x	x	x
Benzaldehyde						x				
Benzeneacetaldehyde						x				
Hexanal	x	x	x	x	x	x	x	x	x	x
Nonanal		x			x	x	x	x		x
2-Methyl-1-propene		x	x	x	x	x	x	x		x
2,2,6,6-Tetramethylheptane							x	x	x	x
2,2,4-Trimethyl-1-pentane				x			x	x		x

N, nonirradiated; I, irradiated.
Abbreviations: Tyr, tyrosine; Trp, tryptophane; Phe, phenylalanine; Thr, threonine; Ser, serine.

Table 9. Major volatile compounds found in irradiated oil emulsion containing sulfur-containing amino acids, glutathione (GSH), bovine serum albumin (BSA), gelatin, or myofibrillar protein (MFP).

	Met		Cys		Cystine		GSH		BSA		Gelatin		MFP	
Volatile compounds	N	I	N	I	N	I	N	I	N	I	N	I	N	I
Pentane										x	x	x		x
Carbon oxide disulfide				x				x						
Methanthiol		x												
1,1-Oxybis ethane													x	x
3-Methylbutanal													x	x
2-Methylbutanal													x	x
Methylbenzene										x				x
Carbon disulfide				x		x								
2-Propenal		x												
1-Heptene								x						
Chloroform	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Dimethyldisulfide		x												
Benzaldehyde										x		x		x
Hexanal		x				x		x	x	x	x	x	x	x
Ethylbenzene										x				x
Trimethyldisulfide		x												
3-Methylthiopropenal		x												
Nonanal		x				x		x		x	x	x	x	x
2-Methyl-1-propene		x	x	x		x	x	x						
2,2,6,6-Tetramethylheptane						x	x	x						
2,2,4-Trimethyl-1-pentane						x	x	x						

N, nonirradiated; I, irradiated.
Abbreviations: Met, methionine; Cys, cysteine; GSH, glutathione; BSA, bovine serum albumen; MFP, myofibrillar protein.

Table 10. Amounts of characteristic volatile compounds in irradiated oil emulsion containing amino acids or proteins.

Amino acid or proteins	Volatile compounds	Irradiation dose (kGy) 0	2.5	5.0	10.0	SEM[1]
		---------- total ion counts x 10^3 ----------				
Leucine						
	Isobutylaldehyde	0^{b}	197^{b}	243^{b}	1110^{a}	55
	3-Methylbutanal	0^{d}	9000^{c}	22200^{b}	46700^{a}	2573
Isoleucine						
	Butanal	0^{b}	77^{ab}	166^{a}	160^{a}	37
	2-Methylbutanal	0^{d}	20500^{c}	40500^{b}	73500^{a}	1390
Valine						
	Isobutylaldehyde	0^{d}	5700^{c}	10100^{b}	18500^{a}	520
Phenylalanine						
	Benzadlehyde	0^{d}	224^{c}	284^{b}	390^{a}	17
	Benzene acetaldehyde	0^{d}	1770^{c}	4060^{b}	8000^{a}	755
Methionine						
	Methanthiol	0^{d}	3560^{c}	6000^{b}	24400^{a}	502
	2-Propenal	0^{c}	389^{c}	2470^{b}	6240^{a}	222
	Dimethyldisulfide	0^{d}	7030^{c}	13900^{b}	27500^{a}	645
	Trimethyldisulfide	0^{d}	33^{c}	273^{b}	432^{a}	11
	3-Methylthiopropenal	0^{c}	1280^{bc}	3320^{b}	9370^{a}	668
Cysteine						
	Carbonoxide disulfide	0^{b}	0^{b}	19^{b}	145^{a}	13
	Carbon disulfide	0^{d}	384^{c}	1060^{b}	1530^{a}	101
Cystine						
	Carbon disulfide	742^{a}	0^{b}	0^{b}	0^{b}	28
Glutathione						
	Carbonoxide disulfide	0^{b}	0^{b}	69^{b}	261^{a}	40
Bovine serum						
	Methylbenzene	0^{b}	0^{b}	130^{a}	137^{a}	21
Albumin						
	Ethylbenzene	0^{b}	0^{b}	132^{a}	148^{a}	23
	Benzaldehyde	0^{c}	42^{b}	98^{a}	117^{a}	13
Gelatin						
	Benzaldehyde	0^{b}	0^{b}	152^{ab}	275^{a}	44
Myofibrillar proteins						
	Methylbenzene	0^{b}	0^{b}	210^{a}	227^{a}	37
	Ethylbenzene	0^{b}	0^{b}	214^{a}	199^{a}	39

[a-d]Means with different superscripts in the same row differ significantly ($p<0.05$).
[1]Standard errors of the mean among different irradiation doses (n = 16).

Table 11. Amount of hexanal produced in irradiated oil emulsion containing different amino acids, glutathione, bovine serum albumin, and gelatin.

Amino acids or proteins	Irradiation dose (kGy)				
	0	2.5	5.0	10.0	SEM[1]
	total ion counts x 10^3				
None	0^{d}	484^{c}	1088^{b}	1680^{a}	123.3
Isoleucine	0^{b}	0^{b}	110^{b}	411^{a}	31.3
Threonine	282^{b}	715^{a}	758^{a}	918^{a}	82.1
Serine	0^{c}	517^{b}	590^{b}	917^{a}	34.1
Histidine	0^{b}	1078^{a}	944^{a}	813^{a}	101.9
Lysine	0^{d}	565^{c}	675^{b}	915^{a}	26.7
Aspartic acid	0^{c}	863^{b}	821^{b}	1236^{a}	37.9
Glutamic acid	0^{c}	674^{b}	724^{b}	857^{a}	21.9
Asparagine	143^{c}	732^{b}	678^{b}	986^{a}	74.9
Glutamine	0^{d}	584^{c}	739^{b}	968^{a}	38.8
Tyrosine	225^{b}	802^{ab}	1185^{a}	1343^{a}	195.0
Methionine	0^{d}	190^{c}	303^{b}	458^{a}	18.2
Cystine	0^{d}	744^{c}	926^{b}	1053^{a}	28.7
Glutathione	0^{b}	349^{b}	1101^{a}	1512^{a}	139.2
Bovine serum albumin	583^{b}	1358^{a}	1231^{a}	1703^{a}	192.6
Gelatin	501^{b}	225^{b}	675^{b}	1176^{a}	148.1

[a-d]Means with different superscripts in the same row differ significantly ($p<0.05$).
[1]Standard errors of the mean among different irradiation doses (n = 16).