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Abstract

Ionizing radiation improves food safety and extends shelf life by inactivating food-borne pathogens and spoilage microorganisms. However, irradiation may induce the development of an off-odor, particularly at high doses. The off-odor has been called “irradiation odor”. Substantial evidence suggests that volatile sulfur compounds (VSCs) play an important role in the development of the off-odor. These compounds include hydrogen sulfide, methanethiol, methyl sulfide, dimethyl disulfide and dimethyl trisulfide among others. The formation of off-odor and VSCs due to irradiation in meat, and fruit juices is presented. It is known that irradiation exerts its effect through radiolysis of water in foods where water is a dominant component. Irradiation of water produces three primary free radicals: hydroxyl, hydrogen atoms, and hydrated electrons. Use of specific scavengers in a model system revealed that hydroxyl radicals are involved in the formation of VSCs. Possible mechanisms for formation of VSC are also discussed. Also discussed are possible remedies for formation of VSCs and off-odor, such as use of antioxidants and double packaging.

Keywords

food safety, shelf life, food-borne pathogens, spoilage microorganisms

Disciplines

Agriculture | Animal Sciences | Meat Science

Comments

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Chapter 12

Volatile Sulfur Compounds in Foods as a Result of Ionizing Radiation

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Ionizing radiation improves food safety and extends shelf life by inactivating food-borne pathogens and spoilage microorganisms. However, irradiation may induce the development of an off-odor, particularly at high doses. The off-odor has been called "irradiation odor". Substantial evidence suggests that volatile sulfur compounds (VSCs) play an important role in the development of the off-odor. These compounds include hydrogen sulfide, methanethiol, methyl sulfide, dimethyl disulfide and dimethyl trisulfide among others. The formation of off-odor and VSCs due to irradiation in meat, and fruit juices is presented. It is known that irradiation exerts its effect through radiolysis of water in foods where water is a dominant component. Irradiation of water produces three primary free radicals: hydroxyl, hydrogen atoms, and hydrated electrons. Use of specific scavengers in a model system revealed that hydroxyl radicals are involved in the formation of VSCs. Possible mechanisms for formation of VSC are also discussed. Also discussed are possible remedies for formation of VSCs and off-odor, such as use of antioxidants and double packaging.

In Volatile Sulfur Compounds in Food; Qian, M., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2011.

Irradiation is a non-thermal processing technology that has been studied for the enhancement of microbial safety, insect disinfestation, sprouting inhibition and shelf-life extension. In general, irradiation at doses for the more common purposes does not affect quality. However, irradiation of many foods at high doses may induce development of an off-odor. The off odor has been called "irradiation odor" and is described as 'metallic', 'sulfide', 'wet dog', and 'wet grain' (*1*, *2*). When beef and pork frankfurters were irradiated at doses of 8 and 32 kGy (irradiation temperature: -34°C), an off-odor and off-flavor were noticed, and the intensity of the off odor increased with radiation dose (*3*). Frankfurters irradiated at 5 and 10 kGy were often scored higher in off-flavor than the non-irradiated ones (*4*). However, ready-to-eat beef luncheon meats irradiated at doses of 2-4 kGy had similar off-flavor as the non-irradiated controls (*5*). Johnson et al. (*6*) showed that the aroma of cooked diced chicken meats and chicken frankfurters irradiated at doses up to 3 kGy (irradiation temperature: 4°C) did not differ from the non-irradiated ones. After 18 days of storage, the aroma of irradiated diced chicken was better than the control, presumably due to inactivation of spoilage microorganisms by irradiation. In a later study by the same group of researchers (*7*), 'wet dog' aroma was detected in chicken frankfurter by panelists immediately after irradiation. However, this aroma decreased and was not present after 7 or 17 days of storage at 4°C. At day 23 after irradiation, 'wet dog' aroma reappeared and received the same low rating as day 2 after irradiation. Hashim and others (*8*) reported that irradiated uncooked chicken thigh had a higher 'blood and sweet aroma' than non-irradiated. Heath and others (*9*) reported that irradiation of uncooked chicken breast and thigh produced 'hot fat', 'burned oil' and 'burned feathers' odors. Ahn et al. (*10*) described the off-odor as 'barbecued corn-like'. Fan (*11*) and Yoo et al. (*12*) found that nonirradiated orange juice was significantly different from irradiated orange juice at doses as low as 0.5 kGy. Sensory panelists described the off-odor in irradiated orange juice as "burning rubber," "chemical," and "alcohol." Other odor descriptions include "bitterness", "medicinal", and "cooked" in irradiated orange juice (*13*). Prakash et al. (*14*) found that irradiated (2.98 and 5.25 kGy) almonds were significantly higher ($p<0.05$) in metallic/chemical/rancid/oxidized/fatty taste than the control samples, but the differences between the two irradiated samples was not significant.

Evidence indicates that VSCs are mostly responsible for the off-odors due to irradiation. This evidence includes: 1) The irradiation odor is different from rancidity, which is believed to be caused mainly by lipid oxidation. 2) Irradiation of the lipid (fat soluble) phase of a meat extract does not produce the characteristic off-odor, while irradiation of the aqueous (water soluble) portion of the meat extract results in a typical irradiation odor (*15*). 3). Irradiation of sulfur-containing amino acids or polypeptides produced a similar off-odor as the irradiation odor (*16*). 4) The amount of VSCs increased with radiation dose, while volatiles from lipids were not always correlated with radiation dose (*17*). 4). Food spiked with VSCs at the amounts similar to those in irradiated samples produced off-odor (*18*).

Formation of Volatile Sulfur Compounds from Various Foods

Raw Meats

Several earlier researchers suggested that hydrogen sulfide (H_2S) and methanethiol (MeSH) were important for the development of the off-odor in irradiated meats (*1*, *15*, *19*). Patterson and Stevenson (*20*), using GC-olfactory analysis, showed that dimethyl trisulfide (DMTS) was the most potent off-odor compound in irradiated raw chicken meats followed by *cis*-3- and *trans*-6-nonenals, oct-1-en-3-one and bis(methylthio-) methane. Ahn and his colleagues (*21*) have identified MeSH, dimethyl sulfide (DMS), dimethyl disulfide (DMDS) and DMTS in different types of irradiated raw meats using GC-FID and GC-MS.

Ready-to-Eat Meats

Du and Ahn (*22*) found that irradiation induced formation of MeSH, DMDS and DMTS in turkey sausage. The low levels and reactivity of volatile sulfur compounds complicated accurate detection of these compounds. A pulsed flame photometric detector (PFPD) has been used to detect VSCs. PFPD is very sensitive to sulfur compounds, detecting VSCs in part per trillion (ppt) ranges. Use of the SPME technique avoids the formation of artifacts due to high temperature as used in many other extraction techniques, however, SPME techniques have low repeatability, resulting in larger variations among replicates. Figure 1 illustrates irradiation-induced VSCs in preccoked turkey breasts using SPME-GC-PFPD (*23*). Six VSCs were identified, including H_2S, CS_2, MeSH, DMS, DMDS and DMTS. Most of the VSCs were promoted by irradiation in a dose dependent manner in the ready to eat turkey meat. CS_2 levels, however, were reduced by irradiation. It appears that irradiation can either increase or decrease the levels of H_2S or DMS depending on meat composition, initial concentration of the compounds, packaging type, and gas composition (*11*, *23*). Many of the VSCs are highly reactive and unstable. H_2S and MeSH decreased rapidly during storage at 4°C even under air-impermeable vacuum packaging (*11*, *23*). The disappearance of the low-boiling-point sulfur compounds may be due to their reactivity and instability. For example, H_2S in aqueous solution becomes elemental sulfur upon reacting with oxygen, while DMDS may convert to DMS and DMTS (Fig. 2).

Fruit Juices

It appears that there are contradictions on whether irradiation induces off-flavors in fruit juice. The type and composition of juice may affect the development of off-flavors. Recently, Yoo et al. (*12*) found that concentrations of methyl sulfide and dimethyl disulfide in orange juice increased with radiation dose. Fan (*18*) identified 2 volatile sulfur compounds (H_2S and CS_2) in nonirradiated orange juice and 5 volatile sulfur compounds in irradiated orange juice, including MeSH, DMS, DMDS, and DMTS. Irradiation induced greater amounts of DMS and MeSH than DMDS and DMTS. CS_2 was reduced by irradiation, while H_2S

was not consistently affected. Sensory evaluation indicated that the odor of irradiated juice differed from that of the nonirradiated samples at 0.5, 1, 2, or 3 kGy. To determine whether these 2 compounds were actually involved in the development of off-odor due to irradiation, fresh orange juice was spiked with MeSH and DMS to levels similar to those in the 3 kGy juice. Sensory evaluation revealed that panelists distinguished between samples spiked with MeSH and DMS and the non-spiked sample (Table 1), indicating that those 2 compounds could be involved in the development of off-odor. However, panelists also distinguished between the spiked sample and the 3 kGy samples, indicating that a difference in odor existed between the irradiated samples and the spiked samples. Therefore, other compounds besides the 2 sulfur compounds may be involved in the development of off-odor.

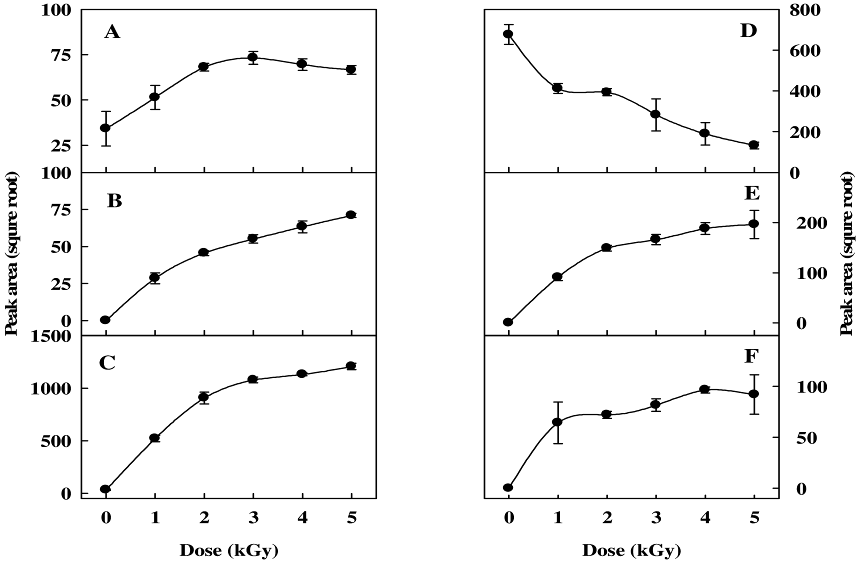

Figure 1. Effect of irradiation dose on the concentration of hydrogen sulfide (A), sulfur dioxide (B), methanethiol (C), carbon disulfide (D), dimethyl disulfide (E), and dimethyl trisulfide (F) of precooked turkey breast. Concentrations of sulfur compounds were expressed as square root of peak area. Vertical bars represent standard deviation of means. (adopted from Fan et al. (23) with permission).

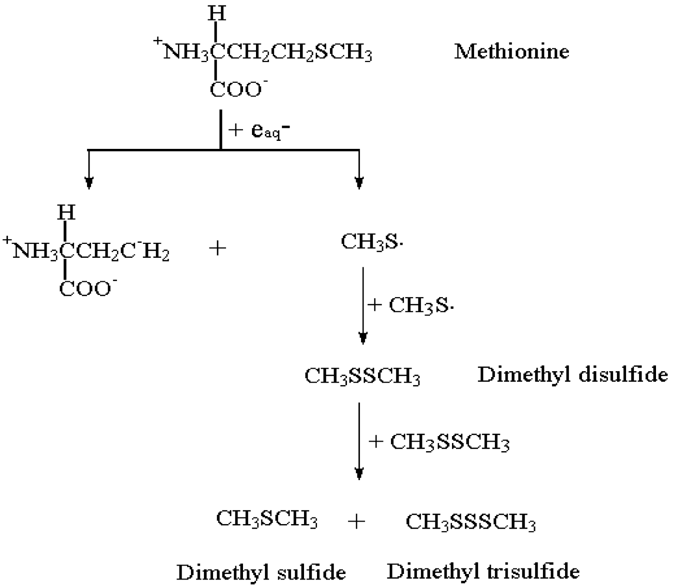

Figure 2. Proposed formation of methyl sulfide, dimethyl sulfide, dimethyl disulfide and dimethyl trisulfide from methionine. (adopted from Yoo et al. (12) with permission).

Mechanism of Volatile Sulfur Compounds Formation

Upon irradiation of water at 25°C, the following reaction occurs: $H_2O \rightarrow e_{aq}^-$ (2.8) + H_3O^+ (2.8) + $\cdot OH$ (2.8) + $\cdot H$ (0.5) + H_2 (0.4) + H_2O_2 (0.8). The numbers in parenthesis are the relative amounts expressed as G-values (number of species per 100 eV absorbed) (*24*). The primary free radicals generated from radiolysis of water are hydrated electron (e_{aq}^-), hydroxyl radicals ($\cdot OH$) and hydrogen atoms ($\cdot H$). The VSCs found in irradiated meat products and juices are likely formed from sulfur containing compounds reacting with the free radicals generated from the radiolysis of water. These sulfur containing compounds may include amino acids in the form of either free amino acids (methionine, cysteine), peptides (glutathione and cystine) or proteins, and others (thiamine, coenzyme A).

Table 1. Number of panelists correctly identifying the odd juice samples in triangle tests. There were a total of 54 panelists. MeSH and DMS were added into spiked samples. Adopted from Fan (*18*) with permission

Comparison	*Number of correct responses*	
	Exp# 1	*Exp# 2*
0.5 kGy and 0 kGy	29/54 **	29/54 **
1.0 kGy and 0 kGy	33/54 **	31/54 **
2.0 kGy and 0 kGy	40/54 **	43/54 **
3.0 kGy and 0 kGy	38/54 **	40/54 **
Spiked and 0 kGy	26/54 *	37/54 **
3 kGy and spiked	28/54 **	37/54 **

* and ** indicate that the differences are significant at 5% ($P<0.05$) and 1% ($P<0.01$) levels, respectively.

Ahn and Lee (*21*) reported that the majority of volatiles newly generated and increased by irradiation were sulfur compounds. This indicated that sulfur-containing amino acids are among the most susceptible amino acid groups to irradiation. Sensory panels described the odor by the newly produced sulfur compounds as “hard-boiled egg,” “boiled sweet corn,” “sweet and sulfury,” or “steamed vegetable”, which was different from lipid oxidation odor but similar to the typical odor of the irradiated meat sample. Ahn suggested that methionine produced far greater amounts of sulfur compounds than cysteine and is the most important amino acid in the production of irradiation off-odor. The sulfur compounds produced from sulfur-containing amino acid dimer or oligomers by irradiation is listed in Table 2.

Ahn (*16*) indicated that more than one site on amino acid side chains was susceptible to free radical attack, resulting in formation of primary VSCs such as MeSH, DMS, DMDS and DMTS. Many more volatiles can be produced by secondary chemical reactions after the primary radiolytic degradation of side chains (Table 2). Furthermore, the amounts and kinds of sulfur compounds produced from irradiated methionine and cysteine indicated that methionine is the major amino acid responsible for irradiation off-odor. The total amount of sulfur compounds produced from cysteine is only about 0.25 to 0.35% of methionine. It has been proposed that formation of DMS, DMDS and DMTS is result of methionine reacting with hydrated electrons (e_{aq}^-) (Fig. 2). Many other free radicals may be involved in the formation of VSCs.

Table 2. Production of volatile compounds from sulfur-containing amino acid dimer or oligomers by irradiation. Adopted from Ahn (*16*) with permission

Volatiles	*0 kGy*	*5 kGy*	*SEM*
	--------- Total ion counts × 10^3 ---------		
Glutathione (γ-Glu-Cys-Gly)			
Carbon disulfide	0^b	589^a	24
Hexane	316^b	496^a	39
Methyl cyclopentane	0^b	82^a	5
Cyclohexane	119^a	0^b	2
Dimethyl disulfide	0^b	214^a	47
Met-Ala			
2-Methyl-1-propene	614^a	0^b	11
Acetaldehyde	0^b	2910^a	230
Methanethiol	0^b	11842^a	709
2-Propanone	1244^a	0^b	456
Dimethyl sulfide	0^b	166244^a	6183
2-Methyl propanol	0^b	114^a	3
Hexane	281^b	1146^a	47
Methyl thiirane	0^b	4177^a	174
(Methylthio) ethane	1376^a	0^b	47
2-Ethoyxy-2-methyl propane	1299^a	344^b	114
Ethyl acetate	3290	4467	415
Cyclohexane	1565^a	0^b	13
3-(Methylthio)-1-propene	0^b	186^a	11
Methyl thioacetate	0^b	106^a	7
2-Methyl-2-(methylthio) propane	86^a	0^b	1
Dimethyl disulfide	5043^b	346229^a	9385
Methyl benzene	591^a	0^b	23
Methyl ethyl disulfide	0^b	2221^a	80
2,4-Dithiapentane	0^b	825^a	25
Met-Gly-Met-Met			
2-Methyl-1-propene	270^a	0^b	8
Acetaldehyde	2264^a	0^b	224

Continued on next page.

Table 2. (Continued). Production of volatile compounds from sulfur-containing amino acid dimer or oligomers by irradiation.

Volatiles	*0 kGy*	*5 kGy*	*SEM*
Methanethiol	0^{b}	17325^{a}	866
Pentanal	0^{b}	341^{a}	18
Dimethyl sulfide	0^{b}	201541^{a}	939
2-Propanone	4010^{a}	0^{b}	289
Acetonitrile	3485^{a}	356^{b}	414
Hexane	285^{b}	780^{a}	26
2,2-Oxybis propane	17951^{a}	3843^{b}	183
(Methylthio) ethane	0^{b}	2053^{a}	15
2-Butanone	206^{a}	0^{b}	35
Ethyle acetate	116873^{a}	77893^{b}	4084
Cyclohexane	988^{a}	0^{b}	21
Benzene	0^{b}	210^{a}	1
1-Heptanethiol	0^{b}	94^{a}	1
3-(Methylthio)-1-propene	0^{b}	122^{a}	1
Mathyl thioacetate	0^{b}	170^{a}	8
2-Butanamine	0^{b}	156^{a}	6
2-Methyl-2-(methylthio) propane	92^{b}	149^{a}	2
Dimethyl disulfide	1430^{b}	351320^{a}	1247
Methyl ethyl disulfide	0^{b}	1935^{a}	15
Ethyl benzene	0^{b}	38116^{a}	322
1,3-Dimethyl benzene	0^{b}	60346^{a}	823
1,4-Dimethyl benzene	0^{b}	11550^{a}	164
Isopropyl benzene	0^{b}	725^{a}	20

[a,b]Means with no common superscript differ significantly ($p < 0.05$), $n = 4$. SEM=standard errors of means.

Involvement of Hydroxyl Radicals

Free radical scavengers have been used to study the involvement of the primary species in radiation-induced chemical changes. In the presence of *tert*-butyl alcohol in Ar-purged solutions, ·OH radicals are converted to the non-reative $CH_2(CH_3)_2COH$ radical, via an H atom abstraction process, leaving e_{aq}^- as the dominant reactive species (*25*). A study was conducted to investigate the involvement of hydroxyl radicals generated through water radiolysis in the formation of VSCs. Fifteen g diced turkey breast was added to 29.55 m water containing 0.45 ml *tert*-butanol, and the mixture was homogenized for 2 min. Then 5 g homogenate was added to 15 ml vials, sealed with septum and caps and flushed with argon for 3 min at 120 ml/min through needles. A control sample without *tert*-butyl alcohol was similarly prepared and flushed with air. Samples were exposed to gamma radiation at a dose of 5 kGy. Immediately after irradiation, internal standards (~1 ppb ethyl sulfide and 1 ppm 2-methyl pentanal) were added. Volatile compounds were then extracted using the solid phase microextraction (SPME) technique. The vials were incubated at 40°C for 35 min before the SPME fiber was inserted and exposed for 30 min. Volatile compounds were analyzed using GC-MS-PFPD. Standard curves were established for DMDS and DMTS in the turkey breast homogenate in the presence of air, and in the presence of the combination of argon and 1% *tert*-butanol. Results showed that irradiation induced formation of volatile sulfur compounds such as DMDS and DMTS. In the presence of *tert*-butanol, the formation of DMDS was reduced by 89% while DMTS was reduced by about 60% (Figure 3), suggesting that irradiation-induced formation of volatile sulfur compounds was partially due to the hydroxyl radicals produced from radiolysis of water. Other VSCs including H_2S and MeSH were also indentified but not quantified. Figure 4 shows a proposed pathway for the formation of volatile sulfur compounds from the reaction of hydroxyl radicals with methionine.

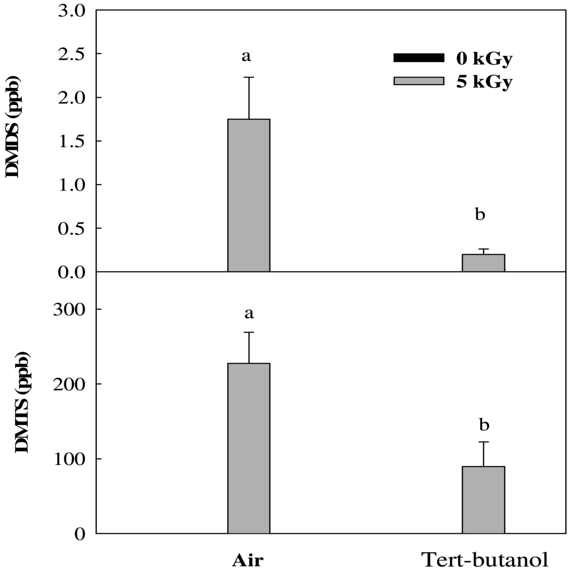

Figure 3. Effect of tert-butanol on irradiation-induced formation of dimethyl disulfide (DMDS) and dimethyl trisulfide (DMTS) in cooked turkey breast homogenates. Turkey breast pieces, homogenized with tert-butanol and flushed with Argon, were irradiated at 5 kGy. Volatile sulfur compounds were measured. Vertical bars represent standard errors (n=3).

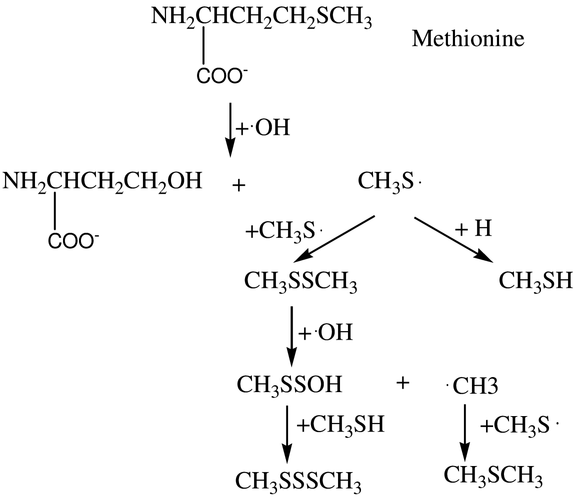

Figure 4. A proposed pathway for the formation of methanethiol, dimethyl sulfide, dimethyl disulfide and dimethyl trisulfide as a result of reaction of hydroxyl radicals with methionine.

Reduction of VSCs and Off-Odor

Developing prevention methods to reduce VSCs and off-odor production in irradiated foods are very important for the adoption of irradiation technology in the food industry. To prevent or minimize VSCs and off-odor production in irradiated foods, various additives and packaging types have been tested.

Use of Antioxidants and Natural Plant Extracts

Many researchers have used and suggested various antioxidants to control off-odor in irradiated meat. Generally, antioxidants interrupt autoxidation of lipids, either by donating a hydrogen atom or quenching free radicals (*26*). Therefore, addition of antioxidants may be effective in reducing the oxidative reactions in irradiated meat by scavenging free radicals produced by irradiation (*27*, *28*). Even though synthetic antioxidants including BHT, BHA and propyl gallate usually show strong antioxidant effects in preventing oxidative rancidity and retarding development of off-flavors (*29*, *30*), natural antioxidants such as ascorbic acid and alpha-tocopherol also have been widely tested in recent years because consumers prefer natural antioxidants (*31*, *32*).

To reduce VSCs and off-odor production of irradiated meats, antioxidants can be added in animal feeds as a dietary supplement or added directly to ground meat and ready-to-eat cooked meat as additives. α-Tocopheryl acetate has been used as dietary supplement of vitamin E in chicken feed (*20*), turkey feed (*33*), and cattle feed (*34*). Dietary antioxidant treatments showed strong effects in stabilizing lipids in membranes and reduced the extent of lipid oxidation in irradiated meat during storage, but had marginal effects in reducing sulfur-containing volatiles in irradiated meat (*35*).

Various studies, in which antioxidants were added directly to irradiated raw meat before irradiation, showed stronger effects in preventing oxidative rancidity and retarding off-flavor development than dietary treatments. Antioxidants such as ascorbate, citrate, tocopherol, gallic esters, and polyphenols were effective in reducing the off-odor of irradiated meat after adding directly to irradiated meat (*1*). Ascorbic acid and sesamol (3,4-methylenedioxyphenol) + tocopherol also were reported to reduce the amounts of dimethyl disulfide in irradiated ground beef (*36*). Rice hull extract applied to irradiated turkey breast was as effective in reducing dimethyl disulfide as sesamol or rosemary oleoresin (*37*).

In irradiated cooked meat, antioxidants also showed strong effects in reducing lipid oxidation, but they were not effective in reducing production of VSC’s (*22*, *31*). Fan et al. (*38*) manufactured bologna from ground turkey breast containing one of four antioxidant treatments (none, rosemary extract, sodium erythorbate, and sodium nitrite) and then irradiated samples at doses up to 3 kGy. Addition of nitrite, erythorbate, or rosemary extract to raw meat mixtures used for turkey bologna manufacture did not reduce levels of irradiation-induced VSC formation. Some of the VSCs were even promoted by addition of the antioxidants. Dipping diced turkey bologna in antioxidants solutions also did not reduce the production of VSCs due to irradiation (*39*). It appears that antioxidants have very limited effects on irradiation-induced VSCs in ready-to-eat turkey bologna. The limitation of antioxidants suggests that formation of volatile compounds may be resulted in part from direct scission of S-containing amino acids and peptides. Alternatively, antioxidant levels might not be high enough or did not diffuse to places where free radicals were generated.

In conclusion, antioxidants have strong effects in inhibiting lipid oxidation in irradiated meat, but little effect in reducing VSC production. Therefore, instead of using antioxidants to minimize VSC production by irradiation, other approaches such as masking irradiation-induced off-flavor using spices, herbs, or their extracts that reduce sulfur volatiles may be needed.

Packaging

Packaging type and gas compostion (oxygen) are important factors influencing the production of irradiated off-odor (*40*). Irradiation and storage of meat under vacuum-packaging conditions are advantageous in preventing lipid oxidation and aldehyde production. Vacuum-packaged meat, however, retained sulfur volatiles produced during irradiation and maintained the levels during storage (*41*). When irradiated meat was stored under aerobic conditions, significant amounts of volatile aldehydes (propanal, pentanal, and hexanal) related to lipid oxidation were produced (*42*, *43*). Sulfur-containing volatile compounds were highly volatile and disappeared when the irradiated meats were stored under aerobic conditions for a certain period of time. For short-term storage (< 3 days) of irradiated meat in which lipid oxidation is not a great problem, aerobic packaging can be more beneficial than vacuum-packaging, because sulfur volatile compounds responsible for the irradiation off-odor can be significantly reduced under aerobic conditions. The reduction of VSCs in air packaged products under aerobic conditions may be due to escapee of highly volatilized sulfur compounds or oxidation to non-volatile end products. For longer-term storage (> 5 days), however, some combination of aerobic and vacuum-packaging may be needed to control both lipid oxidation and VSCs in irradiated meat during storage.

Nam and Ahn (*41*, *44*) developed a new packaging concept called "double-packaging", which combined the merits of aerobic and vacuum packaging. The term "double-packaging" was used to describe a packaging method in which meat pieces are individually packaged in oxygen permeable bags (aerobic condition) first and then a few of the aerobic packages were vacuum-packaged in a larger vacuum bag before irradiation. The outer vacuum bag is removed after certain storage time and then displayed as aerobic condition until the last day of storage. The aerobic packaging promoted lipid oxidation in irradiated turkey meats and vacuum-packaged irradiated samples retained VSC's. Double-packaging, however, was effective in reducing the production of lipid oxidation-dependent aldehydes and minimizing VCS in the meat (*41*, *44*, *45*). This indicated that both lipid oxidation and irradiation off-odor could be minimized without using any additives. However, double-packaging alone was not enough to prevent oxidative changes in meat during storage.

Nam and Ahn (*46*) used the combination of antioxidants with double-packaging and found that this was more effective than double-packaging alone. The beneficial effects of double packaging and antioxidants were more evident in irradiated cooked meat than raw meat. The total amount of sulfur volatiles in double-packaged irradiated turkey meat with antioxidants (sesamol + vitamin E and gallic acid + vitamin E) was only about 5-7% of that in the irradiated vacuum-packaged cooked meat without antioxidants after 10 days of storage. Production of aldehydes (propanal and hexanal for raw meat, and propanal, pentanal and hexanal) in irradiated cooked turkey breast was almost completely prevented by using the antioxidant and double-packaging combination. Therefore, the combination of double-packaging (vacuum for 7 days then aerobic for 3 days) with antioxidants for irradiated raw turkey breast was very effective in reducing total and sulfur volatiles responsible for the irradiation off-odor without any problem of lipid oxidation (*36*). However, the amounts of sulfur compounds in raw meat were not influenced by antioxidants (Table).

A study with ground beef indicated that addition of ascorbic acid at 200 ppm was not effective in inhibiting production of volatile aldehydes in aerobically packaged irradiated beef (*43*). However, vacuum packaging or the combination of double-packaging and ascorbic acid was effective in minimizing the production of volatile aldehydes in irradiated ground beef. The levels of off-odor volatiles in double-packaged irradiated ground beef after 6 d storage were comparable to that of aerobically packaged ones, and the degrees of lipid oxidation and color changes were close to those of vacuum-packaged ones. This indicated that lipid oxidation of irradiated ground beef was highly dependent upon the availability of oxygen to meat during storage. Addition of 200 ppm ascorbate to double-packaged ground beef was helpful in slowing down the development of lipid oxidation in irradiated ground beef.

Table 3. Sulfur compounds and aldehydes of raw and cooked turkey breast with different packaging and antioxidants after 10 d of storage. Adopted from Nam and Ahn (*46*)

Sulfur compounds	*NonIr*	*Irradiated*				
	Vacuum pkg	*Vacuum pkg*	*Aerobic pkg*	*Double pkg*[1]		
				None	*S+E*[2]	*G+E*[3]
	---------------------(Total ion counts × 10^{4})----------------------					
Raw meat						
Dimethyl sulfide	1,304^{b}	1,990^{a}	140^{d}	831^{c}	676^{c}	546^{c}
Carbon disulfide	258^{b}	306^{a}	0^{c}	0^{c}	0^{c}	0^{c}
Dimethyl disulfide	0^{b}	22,702^{a}	0^{b}	32^{b}	0^{b}	43^{b}
Dimethyl trisulfide	0^{b}	554^{a}	0^{b}	0^{b}	0^{b}	0^{b}
Cooked meat						
Dimethyl sulfide	1,008^{b}	2,032^{a}	451^{d}	1,005^{b}	689^{c}	588^{cd}
Carbon disulfide	419^{a}	339^{ab}	210^{b}	271^{ab}	278^{ab}	374^{a}
Dimethyl disulfide	0^{b}	17,861^{a}	342^{b}	940^{b}	412^{b}	210^{b}
Dimethyl trisulfide	0^{b}	1,007^{a}	0^{b}	118^{b}	0^{b}	0^{b}
Propanal	233^{d}	2272^{c}	8,637^{a}	5,962^{b}	38^{d}	427^{d}
Butanal	0^{e}	127^{d}	592^{a}	195^{c}	302^{b}	226^{c}
Pentanal	62^{c}	875^{c}	3,014^{a}	1,667^{b}	0^{c}	31^{c}
Hexanal	0^{b}	3,734^{b}	37,617^{a}	9,686^{b}	0^{b}	0^{b}
3-Methyl butanal	0^{c}	100^{b}	223^{a}	204^{a}	131^{b}	142^{b}

[1] Vacuum packaged for 7 d then aerobically packaged for 3 d. [2] Sesamol (100 ppm) and α-tocopherol (100 ppm) added. [3] Gallic acid (100 ppm) and α-tocopherol (100 ppm) added. $^{a\text{-}e}$Different letters within a row of same meat are significantly different ($P < 0.05$). n = 4.

Antioxidants reduced lipid oxidation and volatile aldehydes significantly. Packaging was the most critical factor in the development of irradiation off-odor in meat. Combination of antioxidant and double-packaging (V7/A3) was effective in controlling the oxidative changes of irradiated raw and cooked meat. Among the antioxidant and double-packaging treatments, both sesamol+vitamin E and gallic acid+vitamin E, combined with double-packaging, were effective in reducing pink color, off-odor and lipid oxidation of irradiated raw and cooked turkey breast, but gallic acid+vitamin E with double-packaging was the most effective in reducing the pink color in cooked turkey breast meat. Because color changes in irradiated ground beef is a major defect, addition of ascorbic acid at 200 ppm (w/w) to ground beef prior to irradiation stabilized color. Ascorbate also significantly slowed down the development of lipid oxidation in ground beef with double-packaging during storage. Therefore, double-packaging in combination with ascorbate can be a good strategy to prevent overall quality changes in irradiated ground beef.

In conclusion, irradiation induces formation of VSCs and VSCs are likely responsible for the development of off-odor. Studies have suggested that VSCs result from reactions of amino acids, peptides and other sulfur-containing compounds with free radicals from water radiolysis such as hydrated electron (e_{aq}^-), hydroxyl radicals (·OH). Use of antioxidants and herbs alone or in combination with double-packaging may reduce, but not eliminate production of VSCs and off-odor. Further research is needed to explore means to negate formation of VSCs in various foods.

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