Effect of irradiation on the parameters that influence quality characteristics of raw beef round eye

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A B S T R A C T

The objective of this study was to elucidate the relationships among lipid/protein oxidation, color changes, off-taste and off-odor in irradiated raw beef round eye. Raw beef round eye was prepared and irradiated at 0, 1.5, 3.0 and 4.5 kGy using a linear accelerator. Significant increases in lipid oxidation and protein oxidation were found in irradiated raw beef round eye, while significant decreases were observed in the color values (L*-, a*-, and b*-value). The degradation of nucleotides can contribute to the taste changes (increase in sourness and decrease in umami taste) in the irradiated raw beef round eye, which was further confirmed by the electronic tongue data. The sulfur volatiles (e.g.: dimethyl disulfide) from the sulfur-containing amino acids increased significantly after irradiation, indicating these are closely related to the off-odor of irradiated beef round eye.

1. Introduction

Beef is the third most widely consumed meat (25% of meat), after pork and poultry (at 38% and 30%, respectively), in the world (Raloff, 2003). With the growing demands and the globalization of the market, the shelf-life extension of beef products, especially of fresh beef, becomes increasingly important (Luzardo, Woerner, Geornaras, Hess, & Belk, 2016). Due to their chemical and nutritional compositions, fresh meat is highly perishable by microorganisms during shipping, handling and storage (Lambert, Smith, & Dodds, 1991).

Food irradiation technology has been confirmed as an effective method for the prevention of food spoilage as well as the control of pathogens (WHO, 1999). However, irradiation can change the oxidation-reduction potential of meat systems, which results in accelerated lipid and protein oxidation (Xiao, Zhang, Lee, Ma, & Ahn, 2011), color changes (Nam & Ahn, 2002), and off-taste and off-odor production (Feng, Moon, Lee, & Ahn, 2016a).

Kim, Nam, and Ahn (2002) reported that irradiated meats produced higher 2-thiobarbituric acid reactive substances (TBARS) than the nonirradiated ones regardless of animal species, but beef was the most susceptible to oxidation. Feng, Moon, Lee, & Ahn (2016a & 2017) found that irradiation increased protein oxidation in raw turkey breast meat. They also elucidated the nucleotides degradation pathway by irradiation in turkey meat products as well as in the model systems. Nam and

Ahn (2002) found that irradiation increased the redness of light meats due to carboxymyoglobin formation. Kwon et al. (2012) reported that the major off-odor volatile, dimethyl disulfide, can be used as a potential marker for irradiated meat.

Conventionally, the sensory characteristics of meat products are assessed by the trained sensory panels. However, this conventional technique has some drawbacks, such as difficulties in training, standardization of measurements, reproducibilities, high costs, and taste saturation of the panelists (Kang, Lee, & Park, 2014). In this regard, the electronic tongue is considered as a promising tool for assessing meat products. The electronic tongue is a robotic system with an array of sensors and has good reproducibilities with low detection limits and high sensitivities for screening the taste attributes of foodstuffs (Woertz, Tissen, Kleinebudde, & Breitkreutz, 2010). During the last decade, electronic tongue has been applied as a rapid and low-cost method for the quantitative and qualitative analyses of numerous foodstuffs, including beverages (Fujita et al., 2010) and meat (Zhang et al., 2015). The principle for the electronic tongue is based on the measurement of potential changes of several working electrodes against a reference electrode in zero-current conditions. The electrodes interact with the solution molecules at the surface initiates changes in potentials. Then, the potential changes are compared with the sensor responses of the existing matrix (Ciosek & Wróblewski, 2007; Latha & Lakshmi, 2012).

With the approval of irradiation to improve the safety of raw meat,

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concerns have been raised about the negative effects of irradiation on meat quality, which include lipid oxidation, protein oxidation, color changes, and off-taste and off-odor production. However, the relationships among lipid/protein oxidation, color changes, off-taste, and off-odor in irradiated raw beef round eye are not clear yet.

The objectives of this study were to 1) evaluate the effect of irradiation on the lipid/protein oxidation, color, nucleotides and nucleotide degradation products, and volatiles of raw beef round eye, 2) determine the changes of taste profiles under different irradiation doses using the electronic tongue, 3) interpret the relationship among those quality-related parameters using multivariate statistical analysis, and 4) elucidate the key taste components or volatiles responsible for the off-taste and off-odor. The results of this study should provide better understanding of the potential advantages or disadvantages of irradiation on raw beef round eye, and the conclusion can be extrapolated to other parts of the beef carcass.

2. Materials and methods

2.1. Sample preparation

A total of 16 raw beef round eyes (*semitendinous*) were purchased from a local grocery store. The meat samples were cut into 50-g pieces and individually vacuum-packaged in vacuum bags (nylon/polyethylene vacuum bags, 9.3 mL $O_2/m^2/24$ h at 0 °C; Koch, Kansas City, MO). The packaged meats were irradiated at four target dose levels (0, 1.5, 3.0 and 4.5 kGy) using an electron beam accelerator (Titan Corp., San Diego, CA) at 4 °C. The energy level used was 10 MeV and the average dose rate was 107.1 kGy/min. Alanine dosimeters were placed on the top and bottom surfaces of a package and read using an Electron Paramagnetic Resonance Instrument (Bruker Instruments Inc., Billerica, MA) to check the absorbed dose, and the Min/Max ratio was 1.08. Following irradiation, packaged meat samples were immediately placed in coolers with crushed ice and transported to the lab and stored at 4 °C. Lipid oxidation, protein oxidation, color, nucleotides and volatiles were determined within 24 h after irradiation.

2.2. Lipid oxidation and protein oxidation

Lipid oxidation was measured using the thiobarbituric acid reactive substances (TBARS) method of Wang, Jin, Zhang, Ahn, and Zhang (2012). The amounts of TBARS were calculated as milligrams (mg) of malondialdehyde (MDA) per kilogram (kg^{-1}) of meat. Protein carbonyl content was determined using the 2,4-dinitrophenylhydrazine (DNPH) derivatization method (Lund, Hviid, Claudi-Magnussen, & Skibsted, 2008). The carbonyl content was calculated as nmoles per milligram of protein using an absorption coefficient of $22,000\ M^{-1}\ cm^{-1}$ (Levine, Williams, Stadtman, & Shacter, 1994). Three packages of samples (replications) were used for each analysis.

2.3. Color measurement

The color was measured using a Konica Minolta Color Meter (CR-410, Konica Minolta, Osaka, Japan). The colorimeter was calibrated using an illuminate source C (average day light) on a standard white ceramic tile covered with the same film (nylon/polyethylene vacuum bags) as the ones used for meat samples to negate the color and light reflectance properties of the packaging material. The areas selected for color measurement were free from obvious defects that may affect the uniform color readings. Lightness (CIE L*-value), redness (CIE a*-value), and yellowness (CIE b*-value) were recorded using an illuminant C, 2° (light source) with a 53 mm port size. Three packages of samples (replications) were used for each analysis.

2.4. Nucleotides, inosine and hypoxanthine

Nucleotides and nucleotides degradation products were measured using the HPLC method of Feng et al. (2016a) using xanthine as an internal standard. Samples were analyzed on an HPLC system equipped with a diode array detector (Agilent 1100 Series HPLC system, Agilent Technologies, Wilmington, DE, USA). An aliquot (1 μL) was injected using an auto-sampler and the nucleotides were separated on a Synergi Fusion-RP HPLC column (4 μm particle size, 80 Å pore size, 150 mm × 4.6 mm i.d., Phenomenex, Manchester, UK). A two-solvent mobile phase was used for elution: solvent A was a methanol/water mixture (60:40) and solvent B was aqueous KH_2PO_4 (0.02 M, adjusted to pH 5.5 with 1 M potassium hydroxide). The binary gradient consisted of 3–20% A (97 to 80% B) for 16 min, 20% A (80% B) for 5 min. The column was regenerated at the end of each run by reversing the solvent gradient from 20 to 3% A (80–97% B) in 5 min. Detection was done at 254 nm (Aliani, Farmer, Kennedy, Moss, & Gordon, 2013). Three packages of samples (replications) were used for each analysis.

2.5. Volatile compounds

Volatiles of samples were analyzed using a Solatek 72 Multimatrix-Vial Autosampler/Sample Concentrator 3100 (Tekmar-Dohrmann, Cincinnati, OH, USA) connected to a GC/MS (Model 6890/5973; Hewlett-Packard Co., Wilmington, DE, USA) according to the method of Nam et al. (2007). The area of each peak was integrated using ChemStation™ software (Hewlett-Packard Co.) and the total peak area was reported as an indicator of volatiles generated from the samples. Four packages of samples (replications) were used for each analysis.

2.6. Electronic tongues

The α-Astree 2 *E*-tongue (Alpha M.O.S., Toulouse, France) was used to profile the tastes of raw beef round eye. Raw beef round eye (10 g) was chopped to small pieces and homogenized with 20 mL distilled water in a Waring blender for 1 min to extract water-soluble components of meat. The homogenate was centrifuged at 3000 × *g* for 30 min and the supernatant was collected. The precipitant was re-extracted with 30 mL distilled water and centrifuged as above. The supernatants were pooled and 5 mL of this supernatant was diluted 5 times, and then used for the electronic tongue analysis.

Prior to analysis of samples, the sensors of the electronic tongue were conditioned (0.01 mol/L hydrochloric acid), calibrated (0.01 mol/L hydrochloric acid) and tested (diagnostic, 0.01 mol/L each of hydrochloric acid, sodium chloride, caffeine, glucose and monosodium glutamate) for proper functioning and stability. Following successful calibration, each meat sample was analyzed ten times for a period of 120 s. Two packages of samples (replications) were used for each analysis. To avoid carryover effects, the sensors were rinsed in deionized water after each measurement. The raw data thus obtained were multivariate in nature and expressed as voltage vs time (Kang et al., 2014; Raithore et al., 2015).

2.7. Statistical analysis

Data were analyzed by the GLM procedure of SAS (SAS 9.4 software package 2013) for different treatments. The differences in the mean values were compared by Tukey's multiple comparison method, and mean values and standard error of the means were reported ($P < 0.05$). Principal component analysis was conducted in order to explore relationships between quality characteristics and raw beef round eye under different irradiation doses using XLSTAT (2015). Two principal components, PC1 and PC2 were retained to determine treatment scores. The CORR procedure of SAS was used to determine Pearson correlation coefficients.

Table 1
Lipid oxidation, protein oxidation and color of the irradiated raw beef round eye in vacuum packaging at day 0.

	0 kGy	1.5 kGy	3.0 kGy	4.5 kGy	SEM
Lipid oxidation[1]	0.25[b]	0.23[b]	0.31[a]	0.36[a]	0.004
Protein oxidation[2]	0.44[c]	0.43[c]	0.47[b]	0.49[a]	0.002
Color					
L*-value	46.30[a]	45.14[ab]	44.25[bc]	42.62[c]	0.20
a*-value	14.71[a]	11.50[b]	10.20[c]	9.64[c]	0.12
b*-value	5.19[a]	4.65[b]	4.34[c]	3.68[d]	0.02

[a,b,c,d]Means with different letters within a row differ significantly ($P < 0.05$). $n = 3$.
[1] Thiobarbituric acid reactive substances (TBARS) (mg malonaldehyde/kg meat).
[2] Carbonyl content (nmoles/mg protein).

Table 2
Effect of irradiation on nucleotides and nucleotide degradation products in the raw beef round eye in vacuum packaging at day 0.

	0 kGy	1.5 kGy	3.0 kGy	4.5 kGy	SEM
ADP	3.58[a]	3.79[a]	3.13[b]	2.74[c]	0.02
AMP	0.11[c]	0.19[c]	0.28[b]	0.55[a]	0.01
IMP	3.06[a]	3.02[a]	1.86[b]	0.77[c]	0.02
Inosine	6.78[a]	6.88[a]	5.87[b]	2.88[c]	0.02
Hypoxanthine	15.37[b]	15.77[b]	17.93[a]	15.52[b]	0.10

[a,b,c,d]Means with different letters within a row differ significantly ($P < 0.05$). $n = 3$.

Table 3
Effect of irradiation on the volatile profiles of irradiated raw beef round eye in vacuum packaging at day 0.

	0 kGy	1.5 kGy	3.0 kGy	4.5 kGy	SEM
Total ion counts $\times 10^4$					
Sulfur compounds					
Dimethyl disulfide	0[c]	225[c]	1138[b]	2208[a]	28
Aldehydes					
Hexanal	0[d]	239[b]	158[c]	549[a]	1
2-Methyl-butanal	0[b]	0[b]	0[b]	79[a]	1
3-Methyl-butanal	0[b]	0[b]	0[b]	213[a]	1
Ketones					
2-Propanone	0[c]	6136[a]	0[c]	4976[b]	12
2-Butanone	196[d]	664[c]	2280[a]	1179[b]	29
2,3-Butanedione	0[d]	117[c]	257[a]	150[b]	1
Benzene					
Benzene	0[c]	116[b]	123[b]	396[a]	4
Hydrocarbons					
2,3,3-Trimethyl- pentane	0[c]	97[b]	93[b]	173[a]	7
2,3,4-Trimethyl- pentane	0[b]	0[b]	0[b]	57[a]	1
2,2,3,4-Tetramethyl-pentane	0[b]	56[a]	53[a]	55[a]	3
3,5-dimethyl-2-hexene	0[b]	0[b]	0[b]	102[a]	1
2,2,5-Trimethyl-hexane	0[b]	0[b]	0[b]	182[a]	1
2,2,5,5-Tetramethyl-hexane	0[c]	107[a]	59[b]	0[c]	2
Heptane	0[c]	148[b]	0[c]	475[a]	7
1-Heptene	0[b]	0[b]	0[b]	97[a]	1
2,2,4-Trimethyl-heptane	0[b]	0[b]	124[a]	108[a]	5
3,3,5-Trimethyl-heptane	0[c]	114[a]	57[b]	138[a]	5
Octane	79[c]	335[b]	309[b]	637[a]	18
1-Octene	65[c]	193[b]	157[b]	387[a]	8
2-Octene	41[c]	106[b]	117[b]	348[a]	1
4-Octene	0[b]	0[b]	0[b]	88[a]	1
2,2-Dimethyl-octane	0[b]	346[a]	0[b]	0[b]	1
3,5-Dimethyl-octane	0[b]	54[a]	0[b]	0[b]	1
2,2,7,7-Tetramethyl-octane	0[b]	123[a]	0[b]	0[b]	1
2,2,6-Trimethyl-decane	61[c]	106[b]	132[a]	0[d]	2
2,5,6-Trimethyl-decane	0[b]	0[b]	58[a]	0[b]	1
2,2,8-Trimethyl-decane	0[b]	0[b]	0[b]	180[a]	1

[a,b,c,d]Means with different letters within a row differ significantly ($P < 0.05$). $n = 4$.

3. Results and discussion

3.1. Lipid oxidation, protein oxidation and color changes of raw beef round eye

Irradiation increased lipid oxidation by 44% and protein oxidation by 11% from the control. However, the total amount of protein is about 10 times higher than lipids in beef (Lawrie & Ledward, 2006), this indicated the higher oxidative changes were in proteins than lipids. Hexanal is the major products of lipid oxidation in meat, but lipid oxidation products (e.g., hexanal, etc.) have minor contribution to the off-odor in irradiated meat (Jo & Ahn, 2000). All the color values (L*-value, a*-value and b*-value) significantly decreased by irradiation (Table 1). Irradiation can break water molecules to produce oxidizing (hydroxyl radical) as well as reducing compounds (aqueous electrons, hydrogen atoms) (Thakur & Singh, 1994). The hydroxyl radicals produced from water by ionizing radiation can easily convert myoglobin to metmyoglobin, or even can remove the ferric iron from heme and force it to become a catalyst to accelerate lipid oxidation (Min, Cordray, & Ahn, 2010). In fresh meat, meat pigments are in ferrous form and O_2 can form ligands with myoglobin to produce cherry red color (Judge, Aberle, Forrest, Hendrick, & Merkel, 1989). However, the declining trends of a*-value indicated the degradation or denaturation of meat pigments by irradiation.

3.2. Nucleotides and nucleotide degradation products of raw beef round eye

Nucleotides and nucleotide degradation products were also significantly impacted by irradiation: 23% decrease in ADP under irradiation doses from 0 to 4.5 kGy and 4-fold increase in AMP under the same irradiation dose range. The amounts of IMP and inosine decreased with 75% and 58%, respectively, by 4.5 kGy irradiation. A 1.2-fold increase of hypoxanthine was observed with 3.0 kGy irradiation. As the irradiation dose increased further, however, the concentration of hypoxanthine decreased ($P < 0.05$) (Table 2).

Feng et al. (2016a) proposed the degradation pathway of nucleotides from ADP to AMP, IMP, inosine and hypoxanthine in model and meat systems. However, hypoxanthine can be degraded into uric acid and other components under high irradiation doses (> 3.0 kGy) (Canzanell, Guild, & Rapport, 1951; Fellig, 1954). The role of IMP for the generation of meat odor and flavor, and inosine and hypoxanthine for the contributors to the off-flavor has been demonstrated both in the model systems and sensory studies (Lawrie & Ledward, 2006). Kawai, Okiyama, and Ueda (2002) reported there is a strong synergistic interaction of umami occurs between L-α-amino acids with IMP, and the quality of fish can be maintained as long as IMP is not depleted (Sikorski & Kolakowski, 2000). However, inosine and hypoxanthine produce the bitter taste and contribute to the off flavor (Kuchiba-manabe, Matoba, & Hasegawa, 1991; Tikk et al., 2006).

3.3. Volatile profiles of raw beef round eye

Twenty-eight volatiles including 1 sulfur compound, 3 aldehydes, 3 ketone, 1 benzene and 20 hydrocarbons were identified from the meat samples (Table 3). The amount of dimethyl disulfide increased linearly ($R^2 = 0.9365$) as observed in other species (e.g.: raw and cooked turkey) (Feng, Moon, Lee, & Ahn, 2016b; Feng et al., 2017).

Hexanal, 2-methyl-butanal and 3-methyl-butanal were the three aldehydes detected in the irradiated raw beef round eye. Shahidi and Pegg (1994) reported that hexanal can be used as an indicator of lipid oxidation. The significant increase of lipid oxidation and hexanal in the irradiated raw beef round eye from 0 to 4.5 kGy further confirmed this claim. 2-Methyl-butanal and 3-methyl-butanal were usually associated with the Strecker degradation of leucine and isoleucine (Ahn et al., 2016), which was validated by the newly produced volatiles of 2-methyl-butanal and 3-methyl-butanal at 4.5 kGy.
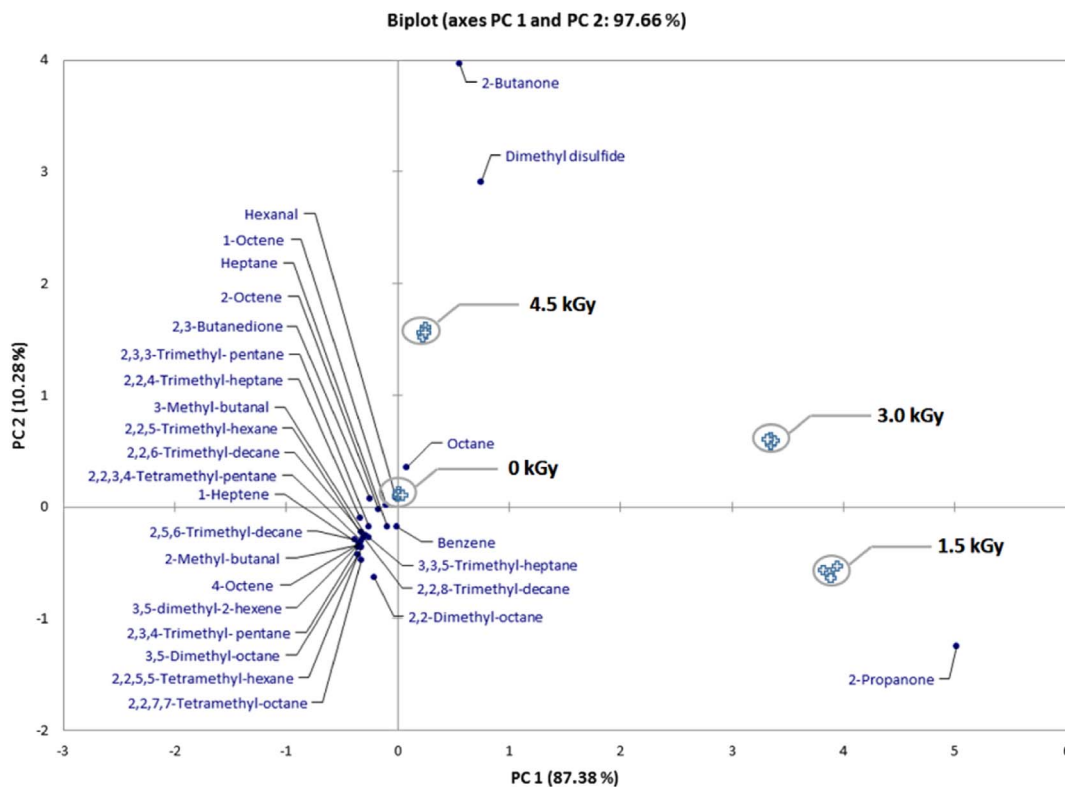
Fig. 1. Principal component (PC) analysis for the volatile compounds (●) of irradiated raw beef round eye (✛).
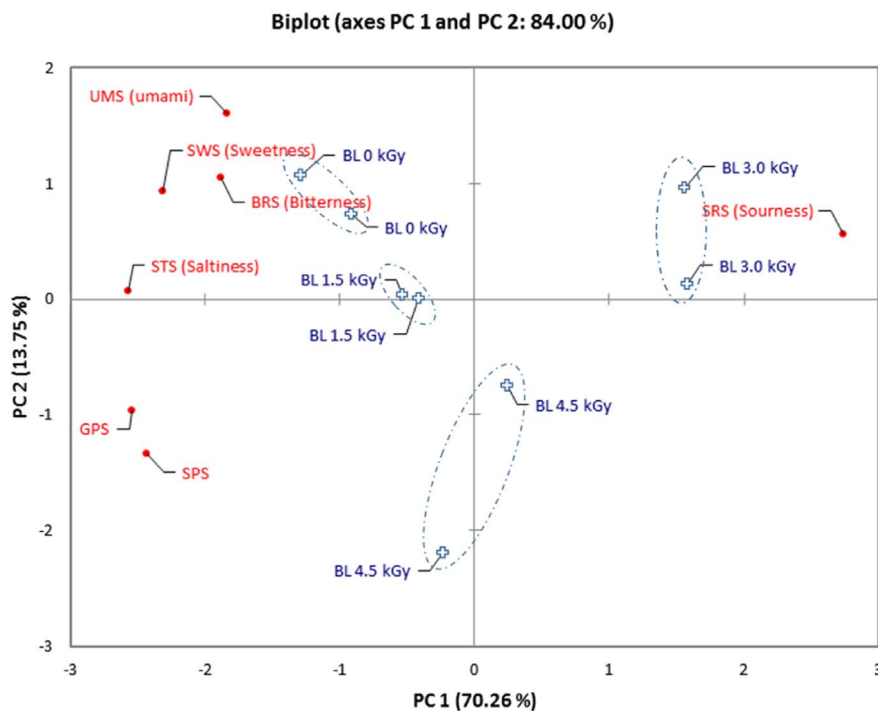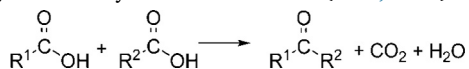

Fig. 2. Electronic tongue (●) separation of irradiated raw beef round eye (✛) in vacuum packaging at day 0 using principal component analysis.

Ketones were usually formed through a ketonic decarboxylation converting two carboxylic acids to a ketone (Renz, 2005):

$$R^1\text{-COOH} + R^2\text{-COOH} \rightarrow R^1\text{-CO-}R^2 + CO_2 + H_2O$$

Two of the three ketones (2-propanone and 2,3-butanedione) were newly produced after irradiation, but only a small amount of 2-butanone was found before irradiation. Similar results were reported by

Machiels, van Ruth, Posthumus, and Istasse (2003) who found that 2-butanone is a common volatile flavor compound in conventional and organic Irish beef meat.

Benzene was detected in all the irradiated raw beef round eye, but not in the control group, which was consistent with the previous report in turkey meat product (Feng & Ahn, 2016). This suggested that the side chains of aromatic amino acids are the major sources of benzene and benzene derivatives by irradiation (Ahn et al., 2016).

Table 4
Pearson correlation between the traits of irradiated raw beef round eye.[1]

Variables	Sourness	Saltiness	Umami	Sweetness	Bitterness	Lipid oxidation	Protein oxidation	ADP	AMP	IMP	Inosine	Hx	Dimethyl disulfide	2-Butanone	2,3-Butanedione
Sourness	1														
Saltiness	−0.874	1													
Umami	−0.557	0.596	1												
Sweetness	−0.933	0.873	0.819	1											
Bitterness	−0.682	0.942	0.673	0.777	1										
Lipid oxidation	0.399	−0.367	**−0.964***	−0.689	−0.453	1									
Protein oxidation	0.443	−0.396	**−0.968***	−0.721	−0.466	**0.999****	1								
ADP	−0.395	0.342	**0.953***	0.681	0.419	**−0.999****	**−0.998****	1							
AMP	0.177	−0.339	−0.910	−0.520	−0.543	0.917	0.900	−0.902	1						
IMP	−0.360	0.411	**0.974***	0.670	0.540	**−0.986***	**−0.980***	**0.978***	**−0.967***	1					
Inosine	−0.075	0.166	0.868	0.427	0.361	−0.932	−0.911	0.924	**−0.978***	**0.957***	1				
Hx	**0.981***	−0.854	−0.390	−0.632	−0.848	0.214	0.261	−0.210	−0.005	−0.175	0.117	1			
Dimethyl disulfide	0.337	−0.429	**−0.969***	−0.654	−0.578	**0.969***	**0.961***	**−0.958***	**0.982***	**−0.997****	**−0.960***	0.154	1		
2-Butanone	**0.965***	−0.926	−0.736	**−0.988***	−0.813	0.575	0.610	−0.564	0.417	−0.563	−0.303	0.907	0.552	1	
2,3-Butanedione	0.893	**−0.983***	−0.728	−0.940	−0.934	0.529	0.557	−0.507	0.472	−0.561	−0.320	0.840	0.571	**0.967***	1

[1]Significant correlation was shown in bold (*: $P < 0.05$, **: $P < 0.01$).

Twenty hydrocarbons were found in the irradiated raw beef round eye. Octane, 1-octene and 2-octene were the only volatiles detected in all beef round eye under different doses, and ten hydrocarbons whose carbon number of the main chain was smaller than octane such as 2,3,3-trimethyl-pentane, 2,2,3,4-tetramethyl-pentane and 3,3,5-trimethyl-heptane, and two other carbons larger than octane including 2,5,6-tri-methyl-decane and 2,2,8-trimethyl-decane were newly produced. This observation further suggested that octane plays as a central role in producing new volatiles after irradiation through cracking, isomerizing or polymerizing.

3.4. Principal component analysis (PCA) for volatile compounds

PCA was performed on volatile compounds in order to provide visualization of the data set in a reduced dimension and two principle components were retained to determine treatment scores (Fig. 1.). The first principal component (PC1) explained 87.38% and the second principal component (PC2) explained 10.28% of the variations. The lower right quadrant of PC indicated that the major volatile component contributing to the irradiated raw beef round eye at 1.5 kGy were 2-propanone. On the other hand, 2-butanone and dimethyl disulfide were located in near the positive axis of PC1 and PC2 (upper right quadrant), which indicated that the irradiated raw beef round eye at 3.0 kGy and 4.5 kGy were highly associated with those volatiles. In contrast, other volatiles contributed little to the off-odor in the irradiated raw beef round eye. Similar results was reported by Kwon et al. (2012), who found dimethyl disulfide could be used as a marker compound for the detection of irradiated beef under the frozen conditions for six months. Houser et al. (2005) also reported that irradiation treatment resulted in the formation of 2-butanone in pork frankfurters.

3.5. Electronic tongues analysis

Principal component analysis also was used to profile the tastes of irradiated raw beef round eye (Fig. 2). The first principal component (PC1) explained 70.26% and the second principal component (PC2) explained 13.75% of the variations. In the upper left quadrant of PC1, the major sensory characteristics contributing to the non-irradiated raw beef round eye were umami, sweetness, saltiness and bitterness. For those attributes, the non-irradiated and irradiated meat samples were separated. Near the positive axis of PC1 and PC2 (upper right quadrant), the irradiated meat at 3.0 kGy was highly associated with sourness. Similar results were reported by Johnson and Resurreccion (2009) who found that the taste attributes of sourness and sweetness were affected by irradiation in Ready-to-Eat poultry frankfurters. In addition, the irradiated meat at 4.5 kGy was in the opposite directions to the control group, which further confirmed that irradiation can change the taste properties of meat by increasing sour notes and degrading of umami-related chemical compounds (Feng et al., 2016a; Luchsinger et al., 1996).

3.6. Correlations

Correlation analysis could be manipulated to further illustrate the relationships among quality related parameters. Sourness was positively correlated with hypoxanthine and 2-butanone ($P < 0.05$). Hypoxanthine is considered as a nucleotide degradation product (Kuchiba-manabe et al., 1991), while 2-butanone is usually produced by the conversion of two carboxylic acids upon irradiation (Renz, 2005). The amounts of these two components were increasing as the irradiation dose increased, which further proved that the sensory quality change of sourness was due to irradiation. The umami taste showed negative correlations with lipid/protein oxidation and dimethyl disulfide ($P < 0.05$), but had positive relationships with ADP and IMP contents ($P < 0.05$). Umami is the fifth basic taste sensation along with sweetness, saltiness, bitterness and sourness (Conn, 1992). In the

meat system, umami is usually provided by disodium salts of the 5′-nucleotides, including IMP, GMP and AMP (Chen & Zhang, 2007). Under irradiation, the hydrophilic groups of nucleotides (N-containing and phosphate moieties) are easily removed and further degraded into inosine or hypoxanthine to cause off-taste (Chen et al., 2012; Kochetkov & Budovski, 1972). However, no correlations were found between bitterness and quality-related parameters, which was unexpected.

After irradiation, the oxidation-reduction potential of the meat were modified, which resulted in increased lipid and protein oxidation ($P < 0.01$). As shown in Table 4, a positive relation was found between lipid/protein oxidation and dimethyl disulfide ($P < 0.05$), while negative correlation was observed between lipid/protein oxidation and ADP ($P < 0.01$) and IMP ($P < 0.05$). These observations confirmed that production of dimethyl disulfide as the major off-odor volatile and the degradation of nucleotides as the major cause of taste deterioration in irradiated meat (Feng et al., 2016).

4. Conclusion

Irradiation can change the oxidation-reduction potential and taste/odor profiles of meat. After irradiation, the lipid and protein oxidation significantly increased, while the heme pigments in raw beef round eye degraded or denatured under the same circumstance. The degradation of nucleotides could be attributed to the taste changes in irradiated meat, which was further confirmed by electronic tongue data (increased sourness but depleted umami taste). Hydrocarbons had little effect on the odor of irradiated raw beef round eye, but a detectable irradiation odor was produced by dimethyl disulfide, the major radiolytic degradation product of sulfur-containing amino acids. Although, 2-butanone has a very high threshold value, the amount was significantly increased by irradiation due to the ketonic decarboxylation reaction. This finding suggested that the use of antioxidants (e.g.: ascorbic acid) or masking agents (e.g.: garlic) could be helpful to minimize the changes of oxidation-reduction potential and off-taste/odor production by irradiation. Thus, the negative effect of the irradiation on the sensory quality of meat products can be reduced.

Abbreviations

ATP	adenosine triphosphate
ADP	adenosine diphosphate
AMP	adenosine monophosphate
IMP	inosine monophosphate
Hx	hypoxanthine

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