Effect of Irradiation on the Quality Parameters of Raw Beef

DOI:10.31274/air.12043

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Summary and Implications

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. The 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, 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, which was further confirmed by 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.

Introduction

With the growing demands and the globalization of the market, the shelf-life extension of fresh beef becomes increasingly important. Fresh meat is highly perishable by microorganisms during shipping, handling, and storage, and irradiation technology has been confirmed as an effective method for the prevention of food spoilage as well as the control of pathogens. However, irradiation can change the oxidation-reduction potential of meat systems, which results in accelerated lipid and protein oxidation, color changes, and off-taste and off-odor production. With the approval of irradiation to improve the safety of raw meat, 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 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 a 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.

Materials and methods

A total of 16 raw beef outside rounds (semitendinosus) 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). The packaged meats were irradiated at four target dose levels (0, 1.5, 3.0, and 4.5 kGy) using an electron beam accelerator at 4 °C. The energy level used was 10 MeV and the average dose rate was 107.1 kGy/min. 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. Lipid oxidation was measured using the thiobarbituric acid reactive substances (TBARS) method, protein oxidation using the 2,4-dinitrophenyl hydrazine (DNPH) derivatization method, color using a Konica Minolta Color Meter, and nucleotides degradation products using the HPLC method. Volatiles were analyzed using a dynamic headspace GC/MS and an E-tongue was used to profile raw beef taste. Data were analyzed by the GLM procedure of SAS for different treatments. The differences in the mean values were compared by Tukey's multiple comparison method at $P < 0.05$.

Results and Discussion

Quality parameters of raw beef: 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 indicating that the higher oxidative changes were in proteins than lipids. Hexanal is the major product of lipid oxidation in meat, but lipid oxidation products (e.g., hexanal) make a minor contribution to the off-odor in irradiated meat. All the color values (L*, a*, and b*values) 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) and

Iowa State University Animal Industry Report. 2021. 17(1):14446. https://doi.org/10.31274/air.12043.

the hydroxyl radicals produced from water by ionizing radiation can easily convert myoglobin to metmyoglobin, or even remove the ferric iron from heme and force it to become a catalyst to accelerate lipid oxidation. In fresh meat, meat pigments are in the ferrous form and O_2 can form ligands with myoglobin to produce a cherry red color. However, the trend of declining a* value indicated the degradation or denaturation of meat pigments by irradiation.

Nucleotides and nucleotide degradation products were also significantly impacted by irradiation: ADP decreased by 23% under irradiation doses from 0 to 4.5 kGy and a 4-fold increase in AMP under the same irradiation dose range. The amounts of IMP and inosine decreased by 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). It was proposed that the degradation pathway of nucleotides from ADP to AMP, IMP, inosine, and hypoxanthine in model and meat systems, but hypoxanthine can be degraded into uric acid and other components under high irradiation doses (> 3.0 kGy). 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. Also, there is a strong synergistic interaction of umami that occurs between L-α-amino acids with IMP, and the quality of fish can be maintained as long as IMP is not depleted. However, inosine and hypoxanthine produce a bitter taste and contribute to the off-flavor.

Twenty-eight volatiles including 1 sulfur compound, 3 aldehydes, 3 ketones, 1 benzene, and 20 hydrocarbons was identified from the meat samples (Table 3). The amount of dimethyl disulfide increased linearly ($R^2 = 0.9365$). Hexanal, 2-methyl-butanal, and 3-methyl-butanal were the three aldehydes detected in the irradiated raw beef round eye. Hexanal is suggested as an indicator of lipid oxidation, and 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, which was validated by the newly produced volatiles of 2-methyl-butanal and 3-methyl-butanal at 4.5 kGy. 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. Benzene was detected in all the irradiated raw beef round eye, but not in the control group. This suggested that the side chains of aromatic amino acids are the major sources of benzene and benzene derivatives by irradiation. Twenty hydrocarbons were found in the irradiated raw beef. 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-trimethylheptane, and two other carbons larger than octane including 2,5,6-trimethyl- decane and 2,2,8-trimethyl-decane were newly produced. This observation further suggested that octane plays a central role in producing new volatiles after irradiation through cracking, isomerizing, or polymerizing. PCA was performed on volatile compounds to provide visualization of the data set in a reduced dimension (Fig. 1).

Electronic tongue analysis: Principal component analysis was used to profile the tastes of the irradiated raw beef (Fig. 2). The first principal component (PC1) explained 70.26% and the second principal component (PC2) explained 13.75% of the variation. 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. Also, the irradiated meat at 4.5 kGy was in opposite directions to the control group, which further confirmed that irradiation can change the taste properties of meat by increasing sour notes and degrading umami-related chemical compounds.

Correlations: Correlation analysis further illustrated 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, while 2-butanone is usually produced by the conversion of two carboxylic acids upon irradiation. 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. In the meat system, umami is usually provided by disodium salts of the 5′-nucleotides, including IMP, GMP, and AMP. 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. However, no correlations were found between bitterness and quality-related parameters, which was unexpected. After irradiation, the oxidation-reduction potential of the meat was 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 a negative correlation was observed between lipid/protein oxidation and ADP (P < 0.01) and IMP (P < 0.05). These observations confirmed that the production of dimethyl disulfide as the major off-odor volatile and the degradation of nucleotides are the major causes of taste deterioration in irradiated meat.

Conclusion

Irradiation can change the oxidation-reduction potential and taste/odor profiles of meat. After irradiation, lipid and protein oxidation increased significantly, 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 chances of oxidation-reduction potential and off-taste/odor production by irradiation. Thus, the negative effect of irradiation on the sensory quality of meat products can be reduced.

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

Quality parameters	0 kGy	1.5 kGy	3.0 kGy	4.5 kGy
Lipid oxidation[1]	0.25^b	0.23^b	0.31^a	0.36^a
Protein oxidation[2]	0.44^c	0.43^c	0.47^b	0.49^a
Color				
L*-value	46.30^a	45.14^{ab}	44.25^{bc}	42.62^c
a*-value	14.71^a	11.50^b	10.20c	9.64^c
b*-value	5.19^a	4.65^b	4.34c	3.68^d

[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 in vacuum packaging at day 0.

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

[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.

Volatiles	0 kGy	1.5 kGy	3.0 kGy	4.5 kGy	SEM
		Total ion counts (x 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[a]	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[b]	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-d]Means with different letters within a row differ significantly ($P < 0.05$). n=4.

Fig. 1. Principal component (PC) analysis for the volatile compounds (.) of irradiated raw beef (+).

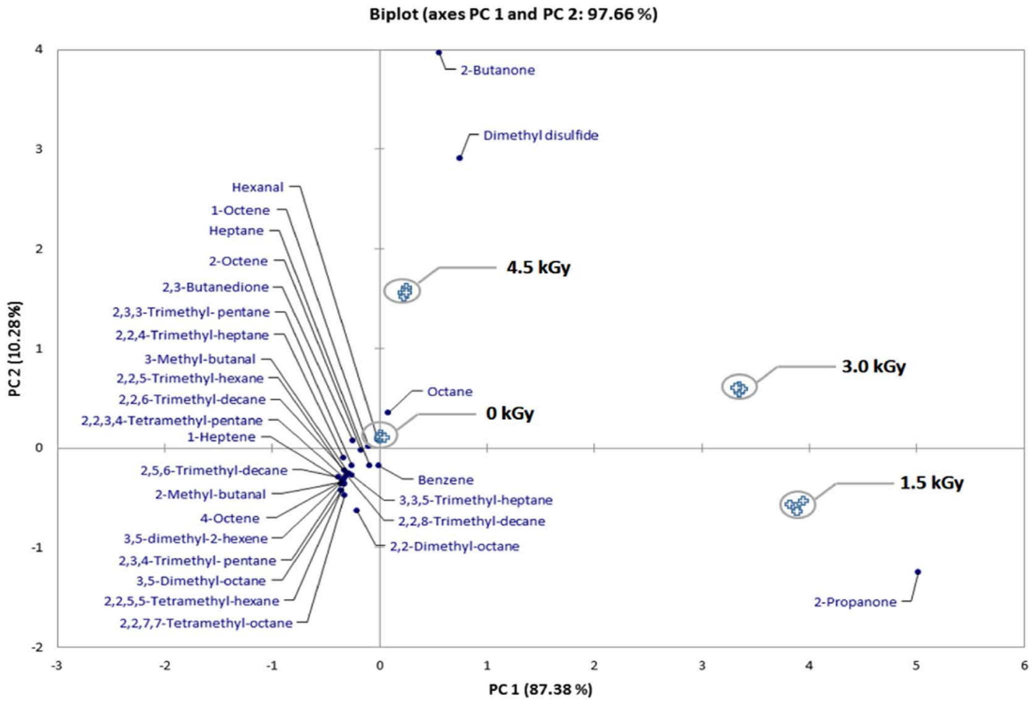

Fig. 2. Electronic tongue (.) separation of irradiated raw beef (+) in vacuum packaging at day 0 using principal component analysis.