KOREAN J. FOOD SCI. ANI. RESOUR. Vol. 24. No. 4, pp. 373~385(2004)

Effect of Gamma Irradiation on Quality of Meats and Meat Products

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Abstract

Irradiation offers an effective and simple means to extend shelf-life of meat and improve processing properties of meat products. Many researches have been conducted to evaluate the effects of irradiation on meats and meat products. There were some interesting reports such as increase of redness and tenderness of meat and decrease of carcinogenic N-nitrosamines and residual nitrite in cured meat products by irradiation. And, the safety of irradiated products have been also studied. Lipid oxidation and off-odor induced by irradiation can be minimized by appropriate controls of irradiation and storage condition such as addition of antioxidants or oxygen exclusion packaging. The objective of this paper is to introduce the effect of gamma irradiation on quality of meats and meat products reported from the previous researches.

Key words : irradiation, shelf-life, meat, meat products, nitrite, nitrosamine

Food Irradiation

Considering the tremendous importance of microbial and parasitic diseases related to foods, food safety should be guaranteed at the retail and possibly at the consumer level and preventive programmes should receive a high priority, including development and implementation of better food processing technologies. Elimination or reduction of foodborne pathogens in foods is especially important to people with compromised immune systems, such as the elderly, AIDS patients and leukemia. While thermal pasteurization of liquid foods is well established and satisfactory as a decontamination treatment of such commodities, it does not suit solid foods and dry ingredients well. The chemical sanitizing procedures have inherent problems concerning residues and environmental pollution.

Food irradiation is a means of food preservation that has been in development since the early part of the 20th century. If applied properly, irradiation can be an effective way to reduce the incidence of foodborne disease and treat a variety of potential problems in our food supply. The benefits of irradiation also include the fact that products can be processed in the package, as a terminal treatment, eliminating the possibility of contamination until it is removed from it and ready to be used. Radiation can inactivate organisms in foods that are in the frozen state, without thawing them up. Irradiation, however, is not a cure-all process. It is not necessarily suitable for every food, and it cannot reverse spoilage that has already occurred.

Many national and international committees, organizations and regulatory agencies have reviewed the safety of irradiated foods. These include the World Health Organization (WHO), the Food and Agricultural Organization of the United Nations (FAO), and the Codex Alimentarius Commission. These organizations have all concluded that food irradiation is safe when Good Manufacturing Practices (GMPs) and Good Irradiation Practices are used. For the evaluation of safety, three main areas of concern were addressed: potential toxicity, nutritional adequacy, and potential microbiological risk. The US Food and Drug Administration (FDA) has also evaluated the safety of irradiation for several foods and is currently evaluating several additional requests for this process (Morehouse, 2002).

Basic Effects of Ionizing Radiation on Foods

Chemical breakdown of the major components of food is aconsequence of decomposition of primary entities (excited

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molecules and ions) or by the reaction of the latter species with neighboring molecules (Nawar, 1978). An excited molecule can lose its energy by a number of pathways, including emission of energy as a photon, internal conversion to heat, transfer to a neighboring molecule, or via a number of chemical reactions. Normally, excited species retain their energy for a period of only 10^{-8} s and thus do not persist after irradiation (Hall et al., 1963).

When food is irradiated, the chemical changes that occur may arise as a result of direct action on the carbohydrates, proteins, fats, and other compounds, or by indirect action mediated through the reactive intermediates formed on radiolysis of water. Since the latter is a major component of foods such as meat and poultry, the indirect effects are important, while direct effects would be more applicable to foods having a high dry matter content, for example, herbs and spices. This also applies to mixtures of substances, since there can be direct action on individual substances as well as in direct action caused by reactive species produced by other component of the system. Therefore, in a multicomponent matrix such as food, the constituent components exert a certain degree of mutual protection, and thus the extent of change in any one component is reduced. This emphasizes the care required when extrapolating results obtained using pure aqueous solutions of, for example, vitamins, to complex food systems. It is also important to note that radiolytic changes that occur in food on irradiation are minimal and are no more significant than those produced by other food processing technologies. In fact, the Joint FAO/IAEA/WHO Study Group on High Dose Irradiation (WHO, 1999) concluded that "irradiation to high doses is essentially analogues to conventional thermal processing, such as canning of low-acid foods, in that it eliminates biological hazards (that is, pathogenic and spoilage microorganisms) for foodstuffs intended for human consumption, but dose not result in the formation of physical or chemical entities that could constitute a hazard". Moreover, the nature of the radiolytic changes is generally predictable on the basis of the composition of the food and the irradiation conditions employed. From a consumer point of a view, it is also reassuring that the study group concluded that the levels of radioactivity or radiolysis products present in irradiated food are similar to those found in non-irradiated foodstuffs.

Improvement of Shelf Stability of Meats and Meat Products

Meats

Foods of animal origin, such as unprocessed meat, usually contain large numbers of spoilage microorganisms as well as possible pathogens. Contamination with microorganisms occurs by contact with the ground or by trimming of meat which is used as the raw material of meat products. The amount of contamination in the final products is dependent on the initial level of contamination. In spite of all past efforts in avoidance of contamination, relatively high percentages of foods of animal origin are contaminated with potentially pathogenic bacteria, resulting in increasing food infections and foodborne illness. Irradiation is one possible method to help assuring meat safety, when combined with GMPs (Gants, 1996; WHO, 1981). The advantages of irradiation in controlling microorganisms in different kinds of meat such as pork (Lebepe, et al., 1990; Mattison, et al., 1986; Thayer, 1993; Thayer et al., 1995), chicken (Luchsinger et al., 1997), and ground beef (Murano, 1995), are well known. Urbain (1986) concluded that treatment with low doses of ionizing radiation is considered as an effective procedure for meat decontamination and shelf-life extension at refrigerated temperatures. Byun et al. (1999) reported that the addition of sodium nitrite slightly inhibited the growth of natural microbes in pork loin hams. However, the growth inhibition was independent of the addition level of sodium nitrite (Table 1). After curing, gamma irradiation, heating, and smoking could extensively prolong the shelf life of the pork loin hams by the initial killing effect of the contaminating microorganisms. Both the aerobic and anaerobic bacteria were not grown on hams irradiated with 5 kGy, regardless of the addition of sodium nitrite. In hams treated with 3 kGy, microorganisms were observed within 20 days, and the effect of the addition of sodium nitrite was not significantly different from the control. Byun et al. (2000) also reported that the growth of both aerobic and anaerobic bacteria was not observed in the Bologna sausage made with 5 kGy-irradiated beef during storage for 15 days. These results showed that decontamination of raw meat could extend the shelf-life of final product.

Meat Products

Extensive research has been conducted over the years on the radiation doses required for reduction in numbers of various microorganisms of public health significance in meats and meat products (Table 2). *Clostridium botulinum* is the microbial pathogen of interest in radiation sterilization of meat products,

Table 1. Total aerobic plate count (CFU/g) in gamma irradiated and cooked pork loin hams during storage at 10℃

NO_2 (ppm)	Dose (kGy)	Storage period (days)			
		0	10	20	30
0	0	6.2×10^{1}	5.7×10^{3}	4.8×10^{5}	8.5×10^{8}
	3	NG[1)]	7.3×10^{0}	8.6×10^{1}	6.8×10^{3}
	5	NG	NG	NG	NG
50	0	1.3×10^{2}	9.7×10^{3}	1.3×10^{6}	1.5×10^{8}
	3	NG	5.8×10^{1}	7.0×10^{2}	2.1×10^{3}
	5	NG	NG	NG	NG
100	0	6.7×10^{0}	7.9×10^{2}	1.1×10^{5}	7.4×10^{7}
	3	NG	8.2×10^{0}	5.4×10^{2}	1.1×10^{3}
	5	NG	NG	NG	NG
150	0	4.2×10^{1}	8.6×10^{3}	5.9×10^{5}	3.1×10^{8}
	3	NG	9.5×10^{0}	8.4×10^{1}	2.1×10^{3}
	5	NG	NG	NG	NG
200	0	4.1×10^{0}	5.9×10^{2}	1.7×10^{6}	4.5×10^{8}
	3	NG	6.1×10^{0}	7.8×10^{1}	3.7×10^{3}
	5	NG	NG	NG	NG

1) NG: no growth on plate.

Table 2. Radiation decimal deduction dose (D_{10}) for major microorganisms in various meat and meat products[1)]

Microorganism	Product	Temp. (℃)	D_{10}[2)] (kGy)
Aeromonas hydrophilia	Ground beef	2	0.14~0.19
Acrobacter butzleri	Ground beef	-	0.27
Bacillus cereus cells	MDCM[3)]	5	0.18~0.45
Bacillus cereus spores	MDCM	5	2.56
Campylobacter jejuni	Ground beef	5	0.16
	Beef	3	0.15
Candida zeylanoides	Sausage	4	1.00
Clostridium botulinum E spores	Cooked beef	25	3.45~3.60
Clostridium botulinum A spores	Canned beef	-	3.9~4.8
E. coli O157:H7	Beef and pork	5	0.30
	Ground beef patties	5	0.27~0.38
Lactobacillus spp.	Minced beef	Refrigerated	0.28~0.88
Listeria monocytogens	Beef an pork	5	0.45~0.48
Salmonella spp.	Ground beef	3	0.55~0.78
	Beef	5	0.70
Staphylococcus aureus	Beef and pork	5	0.46~0.51
Yersinia enterocolitica	Beef	3	0.10~0.21

1) Adapted from Molins (2001).
2) Dose necessary to destroy 90% of vegetative cells or spores.
3) Mechanically deboned chicken meat.

because the products are vacuum-packaged and stored at ambient temperature, thereby providing excellent conditions for its multiplication and toxin production. Similar to heat sterilization at high temperature, irradiation requires high enough radiation doses to inactivate bacterial spores, specifically those of the most radiation-resistant strains of *C. botulinum* (Urbain, 1978). These doses are based on 12D reduction values that must be determined for each individual product and set of conditions. Kreiger et al. (1983) calculated a 12D value for *C. botulinum* in pork, ham, or chicken microsystems of 38~48 kGy. It was also reported that high dose irradiation (10 to 50 kGy) considerably decreased both the level of residual nitrite and the inhibition of *C. botulinum* spores in cured meat (Szczawinski and Szulc, 1989). However, high dose irradiation induces detrimental effects of sensory properties of meats and meat products. Consequently, radiation of meat products usually must be complemented with heat treatment and minimal level of sodium nitrite for the purpose of sterilization of *C. botulinum.*

Lee et al. (1999) reported that total aerobic and lactic acid bacteria increased in beef patties irradiated at doses of 0 and 1.5 kGy during storage at 5℃. However, microorganisms were not observed in the patties irradiated at a dose of 3 kGy until 30 days of storage (Table 3). This results is supported by Murano et al. (1998)'s report that the shelf-life of irradiated-ground beef patties was extended to 55 days when they were stored at 4℃.

Natural Casing

Natural casings made from the intestines of animals are usually salted and dried to inhibit growth of microorganisms, but enteric or exogenous microorganisms in the natural casing are inevitable and also the number of microorganisms increases during processing and distribution, especially under unhygienic treatment or high storage temperature (Trigo and Fraqueza, 1998). Trigo and Fraqueza (1998) reported that the total aerobic bacteria, *Enterobacteriacea*, and coliform bacteria in pork small casing were 7.54, 7.45, and 7.55 log CFU/g, respectively, after stripping and washing. Gabbis and Silliker (1974) initially studied an improvement of the microbiological quality of natural casings and found that by pH-adjusting saturated brine with acetic acid or sodium hydroxide, *Salmonella* was eliminated. Following this study, several investigations with the use of chemicals such as lactic acid, tartaric acid, citric acid, and hydrogen peroxide or ethanol, alone or in combination, were conducted (Labie, 1987). However, those chemicals used in studies brought out problems such as remaining toxic residues or reducing the casing's physical characteristics (resistance or retracatability), thus the use of those methods is still limited.

Byun et al. (2001) reported that the number of total aerobic bacteria, *Enterococcus* and coliform bacteria in the irradiated natural casing or sausage prepared from irradiated casing were significantly decreased or eliminated compared to those of nonirradiated control (Table 4). The total working force of shear of the sausage were decreased in irradiated casings but the sensory evaluation showed no difference (Jo et al., 2002). Therefore, the gamma irradiation was a useful technique to sanitize the natural pork and lamb casings and to extend shelf-life of the sausage made with natural casings.

Effect on the Quality of Meats and Meat Products

Color

Byun et al. (1999) reported that an increase in redness (*a* value) was observed in the irradiated raw pork loins and cooked pork loins in both pre-irradiation and post-irradiation condition, depending on dose, and Hunter *L* and *b* values slightly increased (Table 5). In irradiated pork loins, the desirable bright pink color appeared on both inner and outer surfaces as shown by the increase of *a* value. Whitehair et al. (1964a) reported that *L*, *a*,

Table 3. Total aerobic and lactic acid bacteria counts in irradiated beef patties during storage at 5℃ (CFU/g)

	Irradiation dose (kGy)	Storage period (day)					
		0	5	10	15	20	30
APC[1)]	0	9.3×10^1	9.2×10^2	9.5×10^4	4.8×10^6	9.9×10^7	1.2×10^9
	1.5	NG[2)]	2.0×10^0	3.0×10^0	2.2×10^1	7.0×10^1	4.0×10^2
	3.0	NG	NG	NG	NG	NG	NG
LAC	0	NG	4.3×10^1	1.5×10^2	5.8×10^3	9.3×10^4	6.5×10^5
	1.5	NG	2.0×10^0	1.9×10^1	3.6×10^2	8.0×10^2	1.7×10^4
	3.0	NG	NG	NG	NG	NG	NG

1) APC and LAC indicate total plate count and lactic acid bacteria count, respectively.

2) NG indicates no growth on the plate.

Table 4. Microbial population changes on irradiated natural pork and lamb casing (log CFU/g)

Medium[1)]	Irradiation dose (kGy)	Pork casing		Lamb casing	
		Salted[2)]	Washed[3)]	Salted	Washed
PCA	0	6.78	4.23	6.61	4.49
	3	3.15	1.62	3.87	1.78
	5	1.11	ND[4)]	1.08	ND
ENT	0	5.61	3.04	5.32	3.95
	3	1.62	ND	1.85	ND
	5	ND	ND	ND	ND
EMB	0	5.54	3.93	5.51	2.84
	3	1.70	ND	1.48	ND
	5	ND	ND	ND	ND

1) PCA, plate count agar used for total aerobic bacteria; ENT, Enterococcus agar used for *Enterococci*; EMB, eosin methylene blue agar used for coliform bacteria.

2) Casing used were salted and semidried.

3) Salted casing was washed with deionized water.

4) ND means not detected.

Table 5. Hunter color values of raw and cooked pork loins before and after irradiation during storage at 10℃

Storage period (days)	Dose (kGy)	Raw pork loin			Cooked pork loin					
					Before irradiation			After irradiation		
		L[1)]	*a*	*b*	*L*	*a*	*b*	*L*	*a*	*b*
0	0	56.52a[2)]	12.78a	5.90a	69.88a	8.38a	7.35a	69.62a	9.12a	7.05a
	3	58.03b	16.81b	6.16b	70.72b	11.43b	7.45a	70.27ab	10.34b	6.82a
	5	58.58b	18.02c	6.30c	71.25b	12.53c	7.40a	70.62b	12.78c	7.22b
10	0	55.89a	13.01a	5.78a	69.43a	8.87a	8.05a	69.82a	9.31a	6.92a
	3	57.24b	17.23b	5.96ab	71.23b	10.58b	7.86a	70.36ab	10.75b	7.12ab
	5	58.43c	18.28c	6.18b	72.34c	12.56c	7.73a	70.81b	13.28c	7.37b
20	0	57.15a	13.08a	5.93a	69.12a	9.02a	8.15a	70.54a	9.15a	7.05a
	3	57.82b	17.10b	5.86a	70.35a	11.13b	7.65b	70.37a	10.45b	7.02a
	5	57.57b	17.98c	5.99a	71.51b	13.17c	7.94ab	71.12b	12.42c	7.14a
30	0	56.32a	12.98a	5.91a	70.76a	8.43a	7.46a	68.97a	9.27a	6.95a
	3	58.91b	17.31b	5.78a	72.32b	11.32b	7.51a	70.15b	11.05b	7.15ab
	5	58.65b	18.32c	6.03a	72.52b	12.85c	7.85a	70.47b	13.08c	7.32b

1) L, Hunter L (±, lightness/darkness); *a*, Hunter *a* (±, red/green); *b*, Hunter *b* (±, yellow/blue).

2) Hunter mean values within the same storage periods with different letters in the same column were significantly different ($p<0.05$).

hue, and saturation were increased by radiation treatment. Gamma irradiation also gave cooked pork a bright pink color, which is the advisable color of meats cured with sodium nitirte or color pigment. This effect was observed regardless of whether the cooking occurred before or after irradiation. Oxygen atoms activated by irradiation may react with iron-porphyrin prosthetic heme groups and endow a bright pink color to irradiated meat due to the formation of nitrosyl ferrohemochromogen in heat-processed cured meats with sodium nitrite (Shahidi et al., 1991). During storage, the differences in Hunter color value were not significant in all samples.

It was also reported that the desired cured color of pork loin ham could be obtained by gamma irradiation without sodium nitrite (Byun et al., 1999). At samples of 5 kGy without sodium nitrite the *a* value was equivalent to that of ham with 200 ppm of sodium nitrite. The *L* value increased slightly, and the *b* value was not influenced by irradiation. The *L* and *b* values increased with the addition of sodium nitrite, depending upon the addition level. Although polyphosphate have been found to be beneficial to the color of cured and pigment-treated meat (Shahidi et al., 1991), their influence on color might be affected by irradiation. Results indicated that the color characteristics of irradiated meats were comparable to the nitrite-cured products. During heating, the globin portion of the myoglobin is denatured and detached. This then allows the addition of a second nitric oxide molecule on the iron atom of the iron-porphyrin ring as confirmed by the use of N^{15}-labeled nitrite (Lee and Cassens, 1976). Irradiation might have increased the reducing potential of sodium ascorbate. Thus, freshly irradiated uncured samples would have a higher Hunter *a* value than that of unirradiated samples. Reduction of denatured metmyoglobin might have also taken place. This was consistent with Giddings and Markakis (1972). They found that oxidized brown surface color of vacuum-packaged meats became purple by irradiation and a bright red color developed in the presence of oxygen.

Texture

The radiation treatment may affect the structure of intra-cellular collagen in muscle or skin (Bowes and Moss, 1962; Horowits et al., 1986; Tzaphlidou et al., 1997) and may accelerate the rate of glycolysis by the activation of some enzymes in cell (von Sonntag, 1987). Yook et al. (2001) studied the effect of gamma irradiation on morphological properties and post-mortem metabolism in bovine *M. sternomandibularis* with special references to ultrastructure, shear force, pH and ATP breakdown. The shortening of sarcomere was not observed in gamma-irradiated muscle and sarcomeres in irradiated muscle seemed to swell on irradiation. This observation suggests that the bonds between myosin and actin are disrupted by irradiation and is supported by the report of Lee et al. (2000), that myosin head part was denatured by gamma irradiation. Horowits et al. (1986) reported that the sarcomere length was not shortened in irradiated muscle because of the destruction of the fibres caused from denaturation of these fibrous proteins by gamma irradiation. During storage at 4℃, the destruction of muscle bundles was faster in the gamma-irradiated muscle than in the non-irradiated and shear force was decreased by gamma irradiation. The decrease of shear force on gamma-irradiated muscle might be induced from the longer sarcomere length and destruction of the bundle. And also, rapid decrease of pH and breakdown of ATP were observed in irradiated muscle. Smulders et al. (1990) reported that panel found the improved tenderness in meat with a longer sarcomere length than meat with ordinary length. It was also reported that gamma-irradiated pork had better texture qualities than non-irradiated control (Whitehair et al., 1964a; Whitehair et al., 1964b). These results indicated that anaerobic metabolism of beef was accelerated by gamma irradiation, and therefore the ageing period to obtain meat tenderness may be shortened.

Sensory

A major concern in irradiating meat is its effect on sensorial quality of meat, mainly because of free radical reactions resulting in the possibility of odor generation during irradiation. Merritt (1966) suggested that the volatile compounds responsible for off-odors in irradiated meat were produced by changes in the protein and lipid molecules and were different from those of lipid oxidation. Schweigert et al. (1954) reported that the precursors of the undesirable odor compounds in irradiated meat were water-soluble and contained nitrogen and/or sulfur and that methyl mercaptan and sulfur dioxide formed from the sulfur (S)-containing compounds (e.g., glutathione) contributed to the undesirable odor. However, many researchers have reported that irradiation had no detrimental effect on sensory attributes of vacuum-packaged raw meat and meat products. Luchsinger et al. (1997) observed that irradiation with 2 and 3.5 kGy had minimal effects on flavor, texture, and aroma of raw and precooked beef patties. Alur et al. (1998) reported that a trained taste panel gave high score for irradiated meat products with 4 kGy in terms of odor, color and texture, so 4 kGy was conceded to be an optimum radicidation dose for meat products. Prachasitthisak and Bunnak (1994) found that sensory quality evaluation showed no significant differences in color, odor, flavor and texture between non-irradiated and irradiated-fermented pork sausage with 1, 2 and 3 kGy doses. Saovapong and Nouchpramool (1996) reported that the 2 kGy dose appeared to be sufficient for improving bacteriological quality and increasing the shelf-life of beef balls without affecting sensory quality. Hashim et al. (1995) reported sensory improvement in irradiated poultry with respect to flavor and tenderness. Byun et al. (2000) reported that no differences on the cooking yield, texture analysis, and palatability were observed in Bologna sausage made with irradiated beef, compared with non-irradiated control (Table 6).

Consequently, detrimental changes of meat induced by irradiation can be minimized by appropriate controls of irradiation and storage condition such as vacuum packaging.

Lipid Oxidation

Ionizing radiation generates hydroxyl radicals in aqueous (Thakur and Singh, 1994) or oil emulsion systems (O'Connell and Garner, 1983). Hydroxyl radicals may also be produced in irradiated meat because a significant portion of the muscle cells (75%) are water surrounded by lipid bilayers. Thus, it may lead to lipid oxidation (Thakur and Singh, 1994).

Some researchers have reported that some natural antioxidants have an antioxidative effect on meat (Lee et al., 1998; Murphy et al., 1998). Lee et al. (1999) reported that thiobarbituric acid (TBA) values increased in irradiated beef patties dependent on the dose of irradiation. However, lipid oxidation of irradiated beef patties was retarded by the addition of ascorbyl palmitate (AP) and butylated hydroxy anisole (BHA) during storage (Table 7). The level of oxidation was dependent on the type of

Table 6. Texture, palatability and cooking yield of Bologna sausages manufactured with beef irradiated at 0, 3 or 5 kGy

		Irradiation dose (kGy)		
		0	3	5
Texture	Hardness (Kgf)	17.64±0.36	17.14±0.54	17.37±0.54
	Fructurability (cm)	8.15±0.45	7.93±0.76	8.04±0.45
	Elasticity (ratio)	8.66±0.52	8.36±0.37	8.32±0.42
	Cohesiveness (Kgf)	6.19±0.37	5.87±0.35	5.78±0.27
	Break force (Kgf)	5.12±0.16	5.15±0.26	4.96±0.34
Palatability[1)]	Colour	4.58±0.62	4.48±0.31	4.72±0.62
	Texture	3.96±0.94	3.79±0.57	3.87±0.64
	Flavour	4.53±0.87	4.61±0.92	4.47±0.32
Cooking yield (%)[2)]		96.82±0.65	95.37±0.77	95.83±0.85

[1)] The results of palatability indicates 1 (very poor) to 5 (very good) scored from panel tests.

[2)] Cooking yield is the rate of the weight of Bologna sausage after cooking and cooling.

Table 7. Thiobarbituric acid (TBA) values of irradiated beef patties during storage at 5℃

Antioxidant	Dose (kGy)	Storage period (days)					
		0	5	10	15	20	30
Control	0	0.189	0.197	0.204	0.232	0.245	0.297
	1.5	0.201	0.222	0.248	0.259	0.294	0.336
	3	0.205	0.243	0.263	0.277	0.318	0.359
BHA[1)]	0	0.165	0.176	0.180	0.183	0.187	0.194
	1.5	0.179	0.191	0.206	0.213	0.227	0.248
	3	0.191	0.202	0.228	0.237	0.241	0.255
AP	0	0.172	0.181	0.186	0.192	0.209	0.217
	1.5	0.181	0.198	0.210	0.221	0.229	0.249
	3	0.186	0.208	0.221	0.229	0.236	0.252
TOC	0	0.176	0.185	0.192	0.201	0.213	0.228
	1.5	0.194	0.209	0.212	0.237	0.245	0.263
	3	0.202	0.223	0.243	0.256	0.262	0.287
CAR	0	0.174	0.201	0.219	0.221	0.234	0.247
	1.5	0.191	0.224	0.240	0.253	0.269	0.286
	3	0.198	0.237	0.253	0.266	0.285	0.303

[1)] BHA, butylated hydroxy anisole; AP, ascorbyl palmitate; TOC, α-tocopherol; CAR, β-carotene.

antioxidant and the dose of irradiation. Retardation activity of the antioxidants was ranked as follows: BHA > AP > β-carotene (CAR) > a-tocopherol (TOC). However, no significant differences were observed between CAR and TOC ($p>0.05$). AP is generally recognized as safe with no specific limitations or restrictions. Ingestion of this antioxidant by humans poses no health hazards because metabolic breakdown yields ascorbic acid and palmitic acid, both of which are normal metabolites. Kingston et al. (1998) reported that use of vitamin E and vacuum packaging in pork minimized lipid oxidation. Kanatt et al. (1998) reported that the addition of natural TOC resulted in retardation of oxidative rancidity. The addition of antioxidants to meat batter before cooking and irradiation provided some protection against lipid oxidation as compared to irradiated meat batter containing no antioxidants. TOC may be a valuable ingredient in situations where regulations do not allow the use of more effective synthetic antioxidants or where natural antioxidants are preferred (Dapkevicius et al., 1998; Giese, 1996). The beneficial effects of natural antioxidant, such as sesamol, quercetin, and rutin, in pork patties to be irradiated were also reported by Chen et al. (1999). And, the addition of rosemary to ready-to-eat hamburger steak can be considered for preventing the deterioration of the sensory quality caused by irradiation (Lee et al., 2005).

Volatile Basic Nitrogen (VBN)

The volatile compounds responsible for off-odors produced by changes in the protein and lipid molecules in irradiated meat are different from those of lipid oxidation (Merritt, 1966). Al-Bachir et al. (2001) reported that volatile basic nitrogen (VBN) analysis of luncheon meat, prepared with 0.04% of ascorbic acid, showed no significant differences between irradiated and non-irradiated luncheon meat at 0, 2, and 3 weeks of storage. After 6 and 10 weeks of storage, all doses of gamma irradiation (1, 2, 3 and 4 kGy) significantly decreased ($p<0.05$) the content of VBN (Table 8). Throughout storage, the VBN increased in non-irradiated samples and decreased in irradiated ones. After 10 weeks of storage, the VBN in irradiated samples was significantly lower than those of the non-irradiated controls (Table 8). And, the decrease of the VBN by combination of gamma irradiation and ascorbic acid, may be considered as an indicator of storability improvement of luncheon meat.

Additional Effects of Ionizing Radaition

Destruction of Volatile N-Nitrosamine and Residual Nitrite

N-nitroso compounds are composed of nitrosamines and nitroamides, and most nitrosmaines are volatile and carcinogenic (Mirvish et al., 1972). Volatile N-nitrosamines (VNAs) presents in many foodstuffs (Seel et al., 1994; Zou et al., 1994), rubber products (Novitch, 1983), and tobacco (Tricker et al., 1989). Many VNAs are stable to heat, but they can be cleaved photolytically by UV irradiation because of their chemical properties. Many studies have been performed to inhibit nitrosamine formation with dietary compounds such as ascorbic acid (Vermeer et al., 1999), green tea (Yang and Wang 1993), and phenol compounds (Bartsch et al., 1988).

Wierbicki and Brynjolfsson (1979) reported earlier that irradiation sterilization with Co-60 and Cs-137 reduced nitrite and preformed VNAs level in cured meat products. This research implicated possibility for reducing nitrite and nitrosamines in a wide range of food systems. Since then, no research related to effects of gamma irradiation on VNAs has been reported. Ahn et al. (2002a) studied breakdown of VNAs dissolved in distilled

Table 8. Effect of gamma irradiation on volatile basic nitrogen (VBN %) of luncheon meat during storage at 1～4℃

Irradiation (kGy)	Storage period (week)							
	0	2	3	6	8	10	12	14
0	0.024ab[1)]	0.026a	0.020ab	0.019b	0.014c	0.078c	R[2)]	R
1	0.021a	0.028c	0.019a	0.016a	0.013b	0.019b	0.015c	0.013b
2	0.027b	0.027ab	0.022b	0.016a	0.017e	0.018a	0.015c	0.014c
3	0.025ab	0.026ab	0.021ab	0.016a	0.015d	0.017a	0.011a	0.013b
4	0.024ab	0.027bc	0.021ab	0.016a	0.013a	0.019c	0.013b	0.011a

1) Values within a column followed by the same letter are not significantly different ($p<0.05$).
2) R, rejected due to spoilage.

water, dichloromethane, or ethanol using a gas chromatography coupled to a thermal energy analyzer (TEA). The results show that the solvent had different effects on VNAs after gamma irradiation. Nitrosodimethylamine (NDMA) and nitrosopyrolidine (NPYR) dissolved in distilled water were the most easily broken down by gamma irradiation but those dissolved in ethanol were the least. All of the VNAs were undetectable after irradiation of 5 kGy or above (Ahn et al., 2002a). The authors discussed that water is important for breakdown of those compounds, because water is required for hydrophotolysis of nitrosamines by UV irradiation.

The breakdown products from NDMA and NPYR by gamma rays did not recombine *in vitro* at pH 2, 3, and 4, but recombined in the presence of nitrite, indicating that gamma irradiation has a potential to be applied in real food systems without reformation in the human stomach condition. Ahn et al. (2002b) pointed out with model system sausage study that a residual nitrite content significantly reduced by gamma irradiation, and, in vacuum state, the reduction was dose dependent. The NDMA of the sausage irradiated at 10 kGy or above reduced in aerobic packaging, while a dose of 20 kGy was needed in vacuum packaging. Series of experiments using cooked pork sausage, the irradiation effects on physicochemical characteristics as well as reduction of residual nitrite and nitrosamine (Table 9) were conducted during storage at 4℃ (Ahn et al., 2002b; Ahn et al., 2002c; Jo et al., 2003a; Song et al., 2003). Ahn et al., (2002a) reported that the degradation rate of sodium nitrite fitted a first-order model; a high linear correlation (r^2>0.9) was observed and the degradation rate contstant was 0.009 m^{-1}. The radiolytic products of NDMA and NPYR dissolved in dichloromethane were identified by gas chromatography and mass spectrometry. The major radiolytic components of NDMA were ethyl acetate and 2-dimethyl propanol and those of NPYR were 2-butanone and 2-methyl-6-propylpiperidine (Ahn et al., 2002a).

Biogenic Amines (BAs) Reduction

Biogenic amines (BAs) are found in many kinds of fermented foods during aging, fermentation, and storage. BAs are formed by the action of microorganisms through the decarboxylation of amino acids (Shalaby, 1996; Silla Santos, 1996). These basic nitrogenous compounds are known as toxic substances, which cause disease with food poisoning symptoms such as stimulating nerves and blood vessels in man and animal (Joosten, 1988). BAs are also known as possible precursors of carcinogens and are frequently found in high concentrations in food, such as fish,

Table 9. N-nitrosodimethylamine (NDMA) and N-nitrosopyrrolidine (NPYR) levels (ppb) of sausage prepared with 150 ppm sodium nitrite in different packaging and irradiation dose during storage at 4℃

	Storage (weeks)	Packaging	Irradation dose (kGy)				SEM[1]
			0	5	10	20	
NDMA	0	Air	5.0	3.6	3.1	1.4	1.35
		Vacuum	4.6	3.6	2.6	1.9	1.03
		SEM[2]	1.45	0.80	1.25	1.21	
	4	Air	16.4	11.1	7.9	4.7	8.91
		Vacuum	11.6a[3]	11.2ab	5.2ab	NDb	2.83
		SEM	9.60	7.92	6.74	3.33	
NPYR	0	Air	2.9	ND[4]	ND	ND	0.78
		Vacuum	1.6	ND	ND	ND	0.53
		SEM	1.14	-	-	-	
	4	Air	24.9a	3.3b	NDb	NDb	2.81
		Vacuum	12.7a	12.1a	3.1b	NDb	2.22
		SEM	3.50	2.94	2.17	-	

[1] SEM: Standard error of the means (n=8).

[2] SEM: Standard error of the means (n=4).

[3] Different letters within a same row differ significantly (p<0.05).

[4] ND means not detected.

dried sausage, and fermented soy products (Shalaby, 1996). They are not reduced by high-temperature treatment (Silla Santos, 1996).

Several studies related to the reduction or inhibition of biogenic amine formation have been performed using starter cultures (Bover-Cid et al., 1998; 2000a; Chin and Koehler 1983; Dapkevicius et al., 2000 Fernandez-Garcia et al., 1999) or raw materials or temperature control (Bover-Cid et al., 2000b). Irradiation effects on nine kinds of BAs were studied and significant degradation of putrescine, spermidine, and spermine was observed among the samples when it was irradiated to absorbed doses equal to or greater than 5 kGy (Kim et al., 2004). It is indicated that gamma irradiation is applicable to reduce biogenic amines detected in food by controlling microorganism during fermentation.

In conclusion, irradiation can be effectively used to extend shelf-life and improve qualities of meats and meat products, if used properly.

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(2004. 9. 17. 접수 ; 2004. 12. 3. 채택)