Irradiation and additive combinations on the pathogen reduction and quality of poultry meat[1]

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ABSTRACT Reduction of foodborne illnesses and deaths by improving the safety of poultry products is one of the priority areas in the United States, and developing and implementing effective food processing technologies can be very effective to accomplish that goal. Irradiation is an effective processing technology for eliminating pathogens in poultry meat. Addition of antimicrobial agents during processing can be another approach to control pathogens in poultry products. However, the adoption of irradiation technology by the meat industry is limited because of quality and health concerns about irradiated meat products. Irradiation produces a characteristic aroma as well as alters meat flavor and color that significantly affect consumer acceptance. The generation of a pink color in cooked poultry and off-odor in poultry by irradiation is a critical issue because consumers associate the presence of a pink color in cooked poultry breast meat as contaminated or undercooked, and off-odor in raw meat and off-flavor in cooked meat with undesirable chemical reactions. As a result, the meat industry has difficulties in using irradiation to achieve its food safety benefits. Antimicrobials such as sodium lactate, sodium diacetate, and potassium benzoate are extensively used to extend the shelf-life and ensure the safety of meat products. However, the use of these antimicrobial agents alone cannot guarantee the safety of poultry products. It is known that some of the herbs, spices, and antimicrobials commonly used in meat processing can have synergistic effects with irradiation in controlling pathogens in meat. Also, the addition of spices or herbs in irradiated meat improves the quality of irradiated poultry by reducing lipid oxidation and production of off-odor volatiles or masking off-flavor. Therefore, combinations of irradiation with these additives can accomplish better pathogen reduction in meat products than using them alone even at lower levels of antimicrobials/herbs and irradiation doses. Effects of irradiation and additive combinations on the pathogen reduction and quality of poultry meat will be discussed in detail.

Key words: foodborne illness, safety and quality, poultry product, irradiation, additive

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INTRODUCTION

The CDC (2010) reported that bacterial foodborne illnesses in the United States account for approximately 48 million cases, 128,000 hospitalizations, and 3,000 deaths, and caused $152 billion monetary loss annually (Scharff, 2010). It means that each year roughly 1 in 6 Americans gets sick due to foodborne diseases. The report noted that about 90% of estimated illnesses, hospitalizations, and deaths were due to the following 7 pathogens, in descending order of concern: *Salmonella*, norovirus, *Campylobacter*, *Toxoplasma*, *Escherichia coli* O157, *Listeria monocytogenes*, and *Clostridium perfringens*, and meat is among the major sources for the pathogens. Therefore, control of pathogens in meat is an important safety issue.

The intervention of pathogens in meat can be accomplished through the preslaughter reduction of microorganisms in livestock and the postslaughter decontamination on carcass and meat. The reduction of bacteria in animals can be achieved by priming their immune system by dietary supplementation of immune stimulants. Postslaughter interventions use various physical, chemical, and physical and chemical method combinations during slaughtering or processing steps (or both). Irradiation is among the most effective technology for microbial decontamination technologies for inactivat-

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ing foodborne pathogens and improving the safety of meats. The major advantages of irradiating meat include the following: 1) the nonthermal processing maintains the integrity of products and leaves no chemical residues and causes minimal damages to nutrients, 2) the products can be treated after final packaging, which prevents further cross contamination during postprocessing handling, and 3) destroying pathogenic microorganisms also result in reduction in numbers of spoilage microorganisms to increase shelf-life of meats (Olson, 1998; Farkas, 2006).

High doses of irradiation can be the most effective way in reducing microbial population in meat, but can have negative effects on the sensory characteristics of meats. Irradiation is known to produce a characteristic aroma as well as alters meat flavor, changes color, and increase oxidative changes that significantly affect consumer acceptance. Consumer surveys and research indicated that both the safety (84%) and the taste (83%) of meat are very important for consumers (Huskey, 1997), and consumers were willing to pay a premium price for irradiated meat (Hayes et al., 1995). However, consumers did not like the irradiated meat when the meat had quality issues such as off-odor and color changes (Lee et al., 2003). Currently, only a small fraction of meat (<0.5%) is irradiated (Kume et al., 2009) because of lukewarm consumer acceptance and the sales of irradiated meats is through mail order to targeted consumers such as immune-compromised patients or people who are enthusiastic about irradiated meat. For the vast majority of other consumers, acceptance of irradiated meats is largely based on maintenance of desirable quality characteristics that they expect in these products. Therefore, developing methods to minimize quality changes are critical if producers and marketers intend to increase consumer acceptance of irradiated meat.

FOOD IRRADIATION

Since the US Army Medical Department began to assess irradiated food in 1955, many researchers evaluated the safety of irradiated foods including toxicology, microbiology, and wholesomeness (WHO, 1994). In 1980, the World Health Organization (**WHO**) announced that "irradiation of any food commodity up to an overall average dose of kGy presents no toxicological hazard and introduces no special nutritional or microbiological changes; hence toxicological testing of foods so treated is no longer required" (WHO, 1981). However, the commercial application of food irradiation has been delayed because of consumers' perception that irradiation is linked to the atomic bomb and nuclear radiation.

Food irradiation is a process in which radiation energy, which travels through space of matters in invisible waves, is applied to kill microorganisms or insects in foods (Josephson and Peterson, 2000). Food irradiation under the recommended conditions does not involve the reaction of atomic nucleus, but the electron cloud surrounding the nucleus initiates a chemical reaction. The primary effects are nonspecific and are produced by energetic electrons interacting with the components of the food materials, which result in one or more of 3 outcomes: ionization (removal of an electron), dissociation (loss of a hydrogen atom), or excitation (raising the energy of molecule to a higher energy level). The first target of highly energized electrons is water molecule in biological materials (Woods and Pikaev, 1994). The hydroxyl radical (HO•), the primary radiolytical product of water, is a powerful oxidizing agent and free radicals promote various secondary reactions to form stable products (Taub et al., 1978). The cellular components such as DNA, pigments, fatty acids, and membrane lipids can be damaged by ionizing radiation (Olson, 1998). Because dispersion and capture of electrons are purely random, large molecules and compounds have a greater probability of being affected than smaller molecules. Therefore, humans can have greater damage than microorganisms when they are exposed to radiation energy. Thus, a higher dose of radiation energy is required to kill microorganisms than bigger size animals (Thayer, 1995).

Accelerated electrons, gamma-rays, and x-rays are used as sources for ionizing radiation because they have high energy to create ions or free radicals from atoms (CAST, 1989). Gamma irradiation has a high penetration power and can treat bulk foods on shipping pallets. Cobalt 60 is generally used as a gamma irradiation source. Electron beam irradiation uses a stream of high-energy electrons generated from an e-beam machine, but the electrons can only penetrate a few centimeters into the food and is used to treat thin layers of a particular food product. Although electrons are less penetrable than gamma rays, they can be useful for irradiating large volumes of free-flowing food items such as grains or packages of fish fillets with no more than 8 to 10 cm thickness. X-irradiation has intermediate properties of the 2 irradiation methods discussed above (Sadler et al., 2001). Each of these sources has specific advantages and disadvantages (Jarrett, 1982). The advantages of ^{60}Co include high penetration and dose uniformity, allowing treatment of products of variable sizes, shapes, and densities; a long history of satisfactory use in similar applications; ready availability; and low environmental risk. The disadvantages include 12% of the source must be replaced annually because of its short half-life (5.3 yr) and a rather slow processing rate compared with electron beam irradiation. A linear accelerator can be turned off when not in use, does not need to be replenished, and has a high throughput rate, but the machine is complex, needs regular maintenance, and requires high electric power and cooling. X-rays have relatively high penetrating power but are not used in food irradiation due to poor conversion of accelerated electrons to x-rays (Hayashi, 1991). The quantity of energy absorbed by something (food) as it passes through a radiation field is called "radiation absorbed dose." The unit (SI) for irradiation dose is Gray (Gy), which is equal to the absorption of energy equivalent to 1 Joule per kilogram of absorbing material (1 Gy = 1 J·kG^{-1} = 6,200 billion MeV absorbed/kg of food = 0.01 calorie/lb of food = 100 rad, 1 rad = 100 erg/g; Dragnic and Dragnic, 1963).

Currently, irradiation of food and agricultural products is allowed by about 57 countries and approximately 71 commercial irradiation facilities are operating in the world (Kume et al., 2009). In the United States, spices and seasonings, fresh fruits, and dry substances (USDA-FSIS, 1986), poultry (USDA-FSIS, 1992), red meats (USDA-FSIS, 1999), shell eggs (FDA, 2000), mollusks (FDA, 2005), and other fresh produce such as iceberg lettuce and spinach (FDA, 2008) are approved for irradiation (Table 1). A petition for irradiating processed meats was filed by a coalition of more than 30 food industry trade associations, health organizations, and academic groups under the leadership of the Food Products Association in 1999. Although the use of irradiation could significantly reduce the processed meats from the risk of microbial pathogens, especially *Listeria monocytogenes*, which has not yet been approved by the US Food and Drug Administration (O'Bryan et al., 2008).

Irradiation is very effective in controlling foodborne pathogens and can be applied in foods to increase safety and shelf-life, improve quality, and maintain nutrient content during storage. Currently, irradiation is extensively used in spices and in some fruits and vegetables in the United States (Kume et al., 2009). However, use of irradiation in meat is limited because of its influences on meat quality and health concerns about some compounds produced by irradiation process. Irradiation is reported to produce a characteristic aroma and alters flavor and color that significantly affect consumer acceptance of meat. The generation of a pink color in cooked poultry, brown/gray color in raw beef, and off-odor in meat and poultry by irradiation is a critical issue because consumers associate the presence of a pink color in cooked poultry breast meat and pork loin as contaminated or undercooked, the brown/gray color in raw beef with old or low quality products, and off-odor and off-flavor with undesirable chemical reactions. As a result, the meat industry has difficulties in using irradiation to achieve its food safety benefits. Therefore, understanding the chemical changes in meat by irradiation and developing methods that can prevent those changes are important to improve consumer acceptance of irradiated meat.

MICROCIDAL EFFECTS OF IRRADIATION

The bacteriocidal action of ionizing irradiation is mainly linked to the damage of bacterial DNA by free radicals produced during the irradiation process and the extent of damages is dose-dependent (Verma and Singh, 2001). Another important mechanism of irradiation-induced cell death is associated with the ionizing radiation-generated reactive oxygen species, which results in oxidative damage to cell membranes (Mishra, 2004). The damage in membrane structure interferes with the normal metabolism of cells such as generation of energy, and inhibits cell growth and eventually leads to cell death (Verma and Singh, 2001). The radiation-mediated lipid damage can be modified by the inclusion of structure-modulating agents (e.g., cholesterol) and antioxidants (e.g., tocopherol, eugenol; Mishra, 2004).

The survival of microbial cells upon irradiation treatments is influenced by the nature and extent of direct damage to the cell; the number, nature, and longevity of irradiation-induced chemical species; and the inherent ability of cells to repair damages. Extracellular conditions such as pH, temperature, and chemical composition of the food in which the microorganisms are suspended also have a very strong impact on the survival of microorganisms upon irradiation. The presence of oxygen almost always sensitizes cells to irradiation damage. The extent of destruction of meat-borne microorganisms at a given irradiation dose may be reduced under anaerobic conditions or very low water activity (a_W) because of the lower rate of oxidizing reactions that generate free radicals and toxic oxygen products. Meats contain high levels of proteins, which

Table 1. Approval of food irradiation in the United States

Date	Products	Dose (kGy)	Purpose
1964, 1965	Potatoes	0.05 to 0.15	Inhibit sprouting
1983	Spices and dry seasonings	<30	Disinfestation and decontamination
1985	Pork	0.3 to 1.0	Control of *Trachinella spiralis*
1985, 1986	Dehydrated enzymes	<10	Control insects and microbes
1986	Fruits and vegetables	<1	Delay maturation and disinfection
1986	Herbs, spices, and seasonings	<30	Control of microorganisms
1990	Poultry, fresh and frozen	<3.0	Control of microorganisms
1995	Meat, frozen and packaged	>44	Sterilization only for National Aeronautics and Space Administration (NASA)
1997, 1999	Red meat, chilled	<4.5	Control of microorganisms
	Red meat, frozen	<7.5	
2000	Shell eggs	<3.0	Control of *Salmonella* Enteritidis
2000	Sprouts	<8.0	Control of pathogens in seeds
2005	Fresh or frozen molluscan Other shellfish	<5.5	Control of *Vibrio* species and foodborne pathogens
2008	Iceberg lettuce and spinach	<4.0	Control of foodborne pathogens and extension of shelf-life

Table 2. D-values of foodborne pathogens[1]

Pathogen	D10 (kGy)	Medium	Temperature (°C)
Listeria monocytogenes	0.42 to 0.44	Ground pork	0 to 5
Clostridium perfringens	0.826	Ground pork	10
Salmonella spp.	0.61 to 0.66	Ground beef	4
Escherichia coli O157H7	0.24	Beef	2 to 4
Campylobacter jejuni	0.11 to 0.19	Ground turkey	0 to 4
Staphylococcus aureus	0.40 to 0.66	Chicken	0
Vibrio parahemoliticus	0.053 to 0.357	Crab meat	24
Yersina enterocolitica	0.164 to 0.204	Ground pork	10
Clostridium sporogenes (spore)	6.3	Beef fat	4
Moraxella phenylpyruvica	0.63 to 0.88	Chicken	4
Pseudomonas putida	0.08 to 0.11	Chicken	4
Streptococcus fecalis	0.65 to 0.7	Chicken	4

[1] Data from Olson (1998), Food. Technol. 56:56–62; Mendonca (2002), Control of Foodborne Microorganisms. V. Juneja and J. Sofos (ed). Marcel Dekker Inc., New York, NY, p. 75–103; and Raut et al. (2012), Rad. Phys. Chem. 81:82–85.

can protect microorganisms against the damaging effects of irradiation by neutralizing free radicals (Diehl, 1995). This neutralizing effect of proteins may explain the relatively high radiation resistance of microorganisms in meats and dairy products compared with nonprotein foods of similar moisture content. Other meat constituents such as carnosine and vitamin E compete for free radicals formed by the radiolysis of water. During irradiation, free fatty acids, carbonyl compounds, hydrogen peroxide, and hydroperoxides are produced from fats, but fat content of meat does not influence the microbial destruction by irradiation (Thayer et al., 1995). Microorganisms in meat exhibit a greater sensitivity to irradiation at ambient temperatures than at subfreezing temperatures because freezing reduces water activity and ice impedes the migration of free radicals to other parts of the frozen product (Nam et al., 2002c). The presence of large populations of microorganisms reduces the effectiveness of a given irradiation dose. Therefore, decontamination of meat using irradiation would be more effective if the meat to be treated is of good microbial quality.

The microbial sensitivity to irradiation in meats can vary among microbial types, and more complex life forms have a higher sensitivity to irradiation than simpler life forms: viruses have the highest sensitivity to radiation, followed by bacterial spores, bacterial vegetative cells, and then fungi (yeast and molds). The bacteria in the exponential phase are more sensitive to irradiation than lag-phase or stationary phase cells. More importantly, meat-borne bacteria that have adapted to certain environmental stress demonstrate even greater radiation resistance than stationary-phase bacteria (Mendonca et al., 2004). The D_{10} values of food-borne pathogens and spoilage bacteria are shown in Table 2. The populations of most common enteric pathogens such as *Campylobacter jejuni*, *E. coli* O157:H7, *Staphylococcus aureus*, *Salmonella* spp., *L. monocytogenes*, and *Aeromonas hydrophila* can be significantly decreased or eliminated by low-dose (<3.0 kGy) irradiation. Only enteric viruses and endospores of genera *Clostridium* and *Bacillus* are highly resistant to ionizing radiation, but even these are affected significantly by irradiation (Thayer, 1995). The presence of high levels of antioxidants in meat can decrease the antimicrobial efficacy of ionizing radiation because they neutralize free radicals before free radicals attack the DNA of microorganisms (Steccheni et al., 1998). Increasing NaCl concentrations and decreasing water content in the products decrease the effectiveness of irradiation in killing pathogenic bacteria because chloride ions scavenged hydroxyl radicals and the decreased availability of extracellular water resulted in decreased production of free radicals to kill bacteria (Thayer et al., 1995).

Ready-to-eat (**RTE**) meat products are the major sources of listeriosis because elimination of *L. monocytogenes* from contaminated RTE meats postpackaging is not easy. *Listeria monocytogenes* is a gram-positive, non-sporeforming, highly mobile, rod-type, facultative anaerobic bacterium (Farber and Peterkin, 1991), which is ubiquitously found in processing environments (Beresford et al., 2001). The organism can be easily eliminated by heating (Shamsuzzaman et al., 1995), but has high tolerances in low temperature (McClure et al., 1997), and high salt and pH changes (Ralovich, 1992). Therefore, both the prevention and elimination of *L. monocytogenes* contamination in processed meats are critically important to improve the safety of such products.

In-package thermal pasteurization, irradiation, and the formulation of meat products with antimicrobial additives are common approaches to control *L. monocytogenes* in RTE meat postpackaging (Bedie et al., 2001; Muriana et al., 2002; Samelis et al., 2002; Foong et al., 2004). In-package thermal pasteurization is generally effective in eliminating contaminated *L. monocytogenes* cells (McCormick et al., 2003), but its effectiveness vary depending upon, packaging materials used, processing temperature and time, pH characteristics, product surface characteristics (Murphy et al., 2003), and *L. monocytogenes* strains present (Lemaire et al., 1989). In-package thermal pasteurization process, however, can cause quality issues such as shrinkage and drip loss in the products.

Doses of irradiation used alone for microbial decontamination of meat may result in adverse sensory changes in these food products. To avoid the undesirable sensory characteristics of irradiated meats reduced doses of irradiation can be applied by combining it with relatively mild antimicrobial agents. Sommers et al. (2003) reported that combinations of irradiation and antimicrobials such as sodium diacetate (**SDA**), potassium lactate (**PL**), and potassium benzoate (**PB**) greatly increased the sensitivity of *L. monocytogenes* to both gamma- and e-beam radiation, but Zhu et al. (2008) also reported that adding PB (0.1%) or sodium lactate (**SL**; 2%) in turkey rolls failed to prevent *L. monocytogenes* from growing during refrigerated storage. Irradiating turkey rolls added with PB+SL or SL+SDA at 1.0 kGy was effective in suppressing the growth of *L. monocytogenes* for about 6 wk when stored at 4°C (Figure 1). Jin et al. (2009) reported that the combination of pectin-nisin films with ionizing radiation enhanced the microcidal effects of irradiation. Combinations of organic acid and irradiation were more effective than each intervention used alone for controlling growth of total microbial counts and coliforms in pork during storage (Kim et al., 2004). Generally, the combined treatments did not negatively alter the sensory characteristics of the frankfurters (Chen et al., 2004).

QUALITY CHANGES IN MEAT BY IRRADIATION

Irradiation is expected to accelerate lipid oxidation in meat because ionizing radiation generates hydroxyl radicals, a strong initiator of lipid oxidation, from meat. Hydroxyl radicals, the most reactive oxygen species that can initiate lipid oxidation in meat, are generated from water molecules by ionizing radiation (Thakur and Singh, 1994; Diehl, 1995). Generally meat contains about 75% or more of water, and irradiation can generate hydroxyl radicals in meat. Because hydroxyl radicals can initiate lipid oxidation, irradiation is expected to accelerate lipid oxidation in meat and meat products. Irradiation-induced oxidative changes in meat are dose-dependent. However, Ahn et al. (2000b) and Du et al. (2002) reported that irradiation increased 2-thiobarbituric acid reactive substances (**TBARS**) in raw and cooked meat only under aerobic packaging conditions. Under aerobic conditions, TBARS had very strong correlations with the amounts of aldehydes, total volatiles, and ketones in irradiated meat, but had no correlations with the volatiles under vacuum conditions. Ahn et al. (1998) reported that preventing oxygen exposure after cooking was more important for cooked meat quality than packaging, irradiation, or storage conditions of raw meat (Ahn et al., 1999, 2000b). The TBARS of aerobic- or vacuum-packaged sausages with higher polyunsaturated fatty acids (**PUFA**) was higher than those with lower PUFA. Halliwell and Gutteridge (1990) reported that hydroxyl radicals can be formed from oxygen through the Fenton reaction in the presence of iron. Therefore, the presence of oxygen has a significant effect on the development of lipid oxidation and odor production in meat (Merritt et al., 1975).

Cured RTE meat products were more resistant to oxidative changes than uncured meat products even after irradiation (Zhu et al., 2004a,b; Houser et al., 2005) because of the strong antioxidant effects of nitrite added in cured meat products. Ahn et al. (1992) suggested that excluding oxygen from meat after cooking was very important in preventing oxidative chain reactions in meat products. In addition, preventing oxygen exposure of cooked meat was more important for cooked meat quality than packaging and storage conditions of raw meat either before or after irradiation (Ahn et al., 2000b).

All irradiated meat produced characteristic, readily detectable, irradiation odor regardless of degree of lipid oxidation (Ahn et al., 1999). Some sensory panels characterized the irradiation odor as a “bloody and sweet”

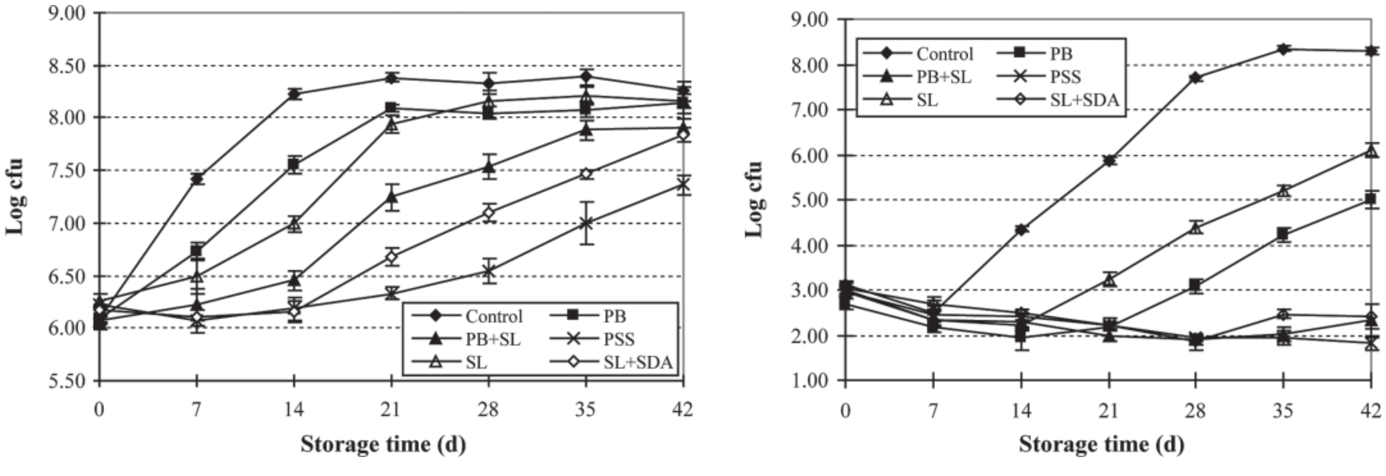

Figure 1. Growth of *Listeria monocytogenes* in nonirradiated and irradiated vacuum-packaged ready-to-eat turkey roll. Adapted from Zhu et al. (2005), Poult. Sci. 84:613–620. PB = potassium benzoate; SL = sodium lactate; PSS = potassium benzoate+sodium lactate+sodium acetate; SL = sodium lactate; SDA = sodium diacetate.

aroma (Hashim et al., 1995), whereas others described it as "barbecued corn-like" (Ahn et al., 2000a). Methyl mercaptan and hydrogen sulfide were considered as the major volatile compounds responsible for the irradiation odor (Batzer and Doty, 1955), the involvement of other volatile compounds such as dimethyl trisulfide, *cis*-3- and *trans*-6-nonenals, oct-1-en-3-one, and bis(methylthio-)methane in the off-odor of irradiated chicken meat was also reported (Patterson and Stevenson, 1995). A series of recent studies indicated that irradiation greatly increased or newly produced many volatile compounds such as 2-methyl butanal, 3-methyl butanal, 1-hexene, 1-heptene, 1-octene, 1-nonene, hydrogen sulfide, sulfur dioxide, mercaptomethane, dimethyl sulfide, methyl thioacetate, dimethyl disulfide, and trimethyl sulfide from meat (Ahn et al., 2000a; Fan et al., 2002).

Sensory results, however, clearly indicated that sulfur-containing compounds were the major volatile components responsible for the characteristic off-odor in irradiated meat. Ahn et al. (2000a) reported that cooking also produced sulfur compounds from meat, but the amounts produced by irradiation were much higher than those generated through cooking. The odor intensity of sulfur compounds was much stronger and stringent than that of other compounds (Lee and Ahn, 2003a). Most sulfur compounds have low odor thresholds and were considered important for irradiation odor (Gemert, 2003). The perception of odor from samples containing sulfur volatiles changed greatly depending upon their composition and amounts present in the sample. Sensory panelists confirmed that all irradiated liposomes containing "sulfur amino acids" produced similar odor characteristics to irradiated meat, indicating that sulfur amino acids are mainly responsible for irradiation odor (Ahn, 2002). Zhu et al. (2004b) reported that the contents of sulfur compounds and sulfury odor intensity in RTE turkey ham were irradiation-dose-dependent. Volatiles from lipids accounted for only a small part of the irradiation odor (Lee and Ahn, 2003b), and the odor was distinctly different from that of warmed-over flavor in oxidized meat.

Several researchers have tested the sulfur theory for off-odor production in irradiated meat using model systems: Ahn (2002) found that side chains of amino acids were susceptible to radiolytic degradation. Ahn and Lee (2002) showed that the odor characteristic of irradiated sulfur-containing amino acid homopolymers have similar odor characteristics to irradiated meat (Table 3). Methionine and cysteine were the major sulfur-containing amino acids among meat components, but methionine was responsible for more than 99% of the total sulfur compounds produced by irradiation. This indicated that the side chain of methionine was highly susceptible to radiolytic degradation. Sulfur compounds were not only produced by the radiolytic cleavage of side chains (primary reaction), but also by the secondary reactions of primary sulfur compounds with other compounds around them. Irradiation induces radiolytic degradation of amino acids via deamination and Strecker degradation (Dogbevi et al., 1999; Mottram et al., 2002). Hydroperoxides can be produced from both side chains and the amino acid backbone (at α-carbon positions) by irradiating *N*-acetyl amino acids and peptides in the presence of oxygen (Davies, 1996), and 3-methyl butanal and 2-methyl butanal are produced from leucine and isoleucine, respectively, by the radiolytic degradation of amino acid side chains (Jo and Ahn, 2000). Besides amino acids, fatty acids are also radiolyzed by irradiations. When triglycerides or fatty acids are irradiated, hydrocarbons are formed by cutting CO_2 and CH_3COOH off from fatty acids in various free-radical reactions. The yield of these radiolytically generated hydrocarbons was linear with absorbed dose (Morehouse et al., 1993). Radiolytic degradation of fatty acid methyl ethers were affected by irradiation dose, irradiation temperature, oxygen pressure, and fatty acid components. Polyunsaturated fatty acids are more susceptible to radiolysis than monounsaturated or saturated fatty acids, and irradiation caused a significant reduction in PUFA (Formanek et al., 2001). Ahn et al. (2000a) reported that irradiated vacuum-packaged patties maintained irradiation off-odor during 2-wk storage period, but the intensity of irradiation off-odor in aerobically packaged pork disappeared after 1 wk or longer of refrigerated storage. This indicated that packaging played a very important role in the odor of irradiated meat.

Various factors such as irradiation dose, animal species, muscle type, additives, and packaging type affect color changes in irradiated meat (Luchsinger et al., 1996; Nanke et al., 1999). The a* value (redness) of poultry breast was increased by irradiation in both aerobically and vacuum-packaging systems (Luchsinger et al., 1997), but vacuum-packaged meat was significantly redder than aerobically packaged ones during storage (Nanke et al., 1998, 1999). Sensory panelists and consumers preferred the color induced by irradiation to nonirradiated ones because the red color of irradiated light meat looked fresher in appearance (Du et al., 2002). If the red color is retained in meats after cooking, however, this can cause a problem because the meat may be considered undercooked or contaminated. Irradiation of uncured cooked meat produced a pink color (Du et al., 2002), but irradiation induced color fading (decrease in redness values) in cured cooked products (Jo et al., 1999; Houser et al., 2005).

Tappel (1956) proposed that the bright red color in irradiated light meat was due to the formation of oxymyoglobin from metmyoglobin after reacting with hydroxyl radicals. However, the red pigment cannot be an oxymyoglobin because the red color formed by irradiation can be produced under anoxic conditions. Nam and Ahn (2002a,c) proposed the pigment responsible for the red color in irradiated light meat as carbon monoxide-myoglobin (**CO-Mb**). Carbon monoxide could be produced from organic components such as alcohols, aldehydes, ketones, carboxylic acids, amides,

Table 3. Odor study—amino acid homopolymers[1]

Item	Major volatiles (5 kGy)	Odor characteristic
Amino acid polymer		
Amino acid homopolymers		
Poly-aspartic acid	2-Propanone, methyl cyclopentane	No odor
Poly-glutamic acid	Acetaldehyde, 2-propanone	Sweet, honey
Poly-alanine	Acetaldehyde, 2-propanone	Seaweed
Poly-glycine	Acetaldehyde, 2-methyl propanal, 2-methyl butanal, 3-methyl propanal	Seashore odor
Poly-proline	2-Propanone, hexane	Organic solvent
Poly-serine	Acetaldehyde, 2-propanone	Cattle barn odor
Poly-threonine	Acetic acid ethyl ester, 2-ethoxy butane	Chinese herbal medicine
Poly-asparagine	Methyl cyclopentane	No odor
Poly-glutamine	Acetaldehyde, 1,1-oxybis ethane, 2-propanone	Hospital odor
Poly-tyrosine	Acetaldehyde, tetrahydrofuran, cyclohexane	Seaweed or seashore
Poly-histidine	2-Methoxy-2-methyl propane	Sweet
Poly-lysine	Acetaldehyde, propanal, butanal	Coleslaw, sour
Sulfur amino acids		
Glutathione (g-Glu-Cys-Gly)	Carbon disulfide, dimethyl disulfide, methyl cyclopentane	Hard-boiled eggs, sulfury
Met-Ala	Acetaldehyde, mercaptomethane, dimethyl sulfide, methyl thiirane 3-(methylthio)-1-propene, dimethyl, disulfide, ethanoic acid-S-methyl ester, methyl ethyl disulfide, 2,4-dithiapentane, 2-methyl propanal	Boiled eggs, sulfury, rotten vegetable
Met-Gly-Met-Met	Mercaptomethane, pentanal, dimethyl sulfide, (methylthio)-ethane, benzene, 1-heptanethiol, 3-(methylthio)-1-propene, ethanoic acid-S-methyl ester, dimethylm disulfide, methyl ethyl disulfide, 2-butanamine	Boiled cabbage, sulfury, rotten vegetable

[1] Data from Ahn (2002), J. Food Sci. 67:2565–2570.

and esters by irradiation (Furuta et al., 1992). Meat components such as glycine, asparagine, glutamine, pyruvate, glyceraldehydes, α-ketoglutarate and phospholipids were also good substrates for CO production by irradiation (Lee and Ahn, 2004). Irradiation produces hydrated electrons (aqueous e^-), a radiolytic radical, that can act as a powerful reducing agent and decreased the oxidation-reduction potential (**ORP**) of meat. Giddings and Markakis (1972) proposed that oxymyoglobin-like pigment was formed by the reduction of ferricytochrome to ferrocytochrome by the hydrated electrons, and the oxygenation from either residual oxygen or generated oxygen during irradiation. The decrease of ORP in meat played a very important role in CO-Mb formation because the CO-Mb complex can only be formed when heme pigment is in reduced form (Nam and Ahn, 2002a,c).

Irradiation has been shown to significantly decrease water-holding capacity in meat because of the damage to muscle fibers and myofibrils (Yoon, 2003) and the denaturation of muscle proteins (Lynch et al., 1991). The mechanism for irradiation-induced water loss could be caused by 1) the damage in the membrane structure of muscle fibers (Yoon, 2003) and 2) denaturation of muscle proteins (Lynch et al., 1991) by irradiation. However, other researchers reported that irradiation had minimal effects on texture of frozen, raw, and precooked meat and meat products (Sommers et al., 2002; Zhu et al., 2004c).

Cabeza et al. (2009) reported that irradiation of vacuum-packed dry fermented sausages at ≤2 kGy had negligible effects on their sensory characteristics (appearance, odor, and taste). The aroma and flavor quality of irradiated frankfurters formulated with potassium lactate/sodium diacetate solution were retained for 4 wk under aerobic conditions or for 8 wk under vacuum packaged conditions at 4°C (Knight et al., 2007). Irradiation at 1 and 2 kGy had negligible effects on sensory, color, and rheology in irradiated RTE meats (Hoz et al., 2008; Cambero et al., 2012). However, irradiation of dry-cured ham at 3 and 4 kGy increased the intensity of off-odors and off-flavors.

CONSUMER ATTITUDE AND ACCEPTANCE OF IRRADIATED MEAT

Consumers easily distinguished odor differences between nonirradiated and irradiated meat (Lynch et al., 1991). Consumers preferred the odor of aerobically packaged irradiated meats to vacuum-packaged meats because S-compounds responsible for irradiation off-odor volatilized during storage under aerobic packaging conditions. Lee and Ahn (2003a) reported that antioxidants had no significant effect on the off-odor intensity of irradiated turkey meat in the consumer acceptance test but prevented lipid oxidation. Therefore, the combined use of aerobic packaging and antioxidants is recommended to improve consumer acceptance of irradiated poultry meat (Lee et al., 2003). Surveys showed that the public viewed food irradiation as a health risk (Lee et al., 2003). Frenzen et al. (2001) found that consumers' willingness to buy irradiated foods was associated with sex, education level, income, exposure to irradiated food products, and geographic location (Bord and O'Connor, 1989; Lusk et al., 1999). Market simulation studies showed that the acceptance of irradiated meat and poultry increased when the participants received additional information about food irradiation (Hashim et al., 1995). Consumer education was very important for the acceptance of food irradiation (Bruhn, 1995; Resurreccion and Galvez, 1999). A favorable description of irradiation increased willingness to pay, and an unfavorable description decreased willingness to pay. When both positive and negative descriptions about irradiation were given, however, the negative description dominated.

The primary reason for the limited application of irradiation technology by the meat industry today is due to consumer acceptance of irradiated meat (AMIF, 1993). Many consumers still misunderstand the effectiveness, safety, and functional benefits of irradiation, even though governments and industries have openly supported the introduction of irradiated foods to the marketplace for several years (Fox et al., 2002). However, the most important factor for the acceptance of irradiated foods is consumers' knowledge and understanding about irradiated foods (Lusk et al., 1999).

CONTROL OF OFF-ODOR PRODUCTION AND COLOR CHANGES

To implement irradiation technology by meat industry, developing prevention methods for quality changes in irradiated meat are very important. Various additives and packaging methods have been used to prevent or minimize the quality changes in irradiated meat. Synthetic antioxidants such as free radical terminators or metal chelating agents are usually added in meat products during processing to prevent oxidative rancidity and color changes, and improve sensory quality of meat (Xiong et al., 1993; Morrissey et al., 1997). In recent years, however, due to consumer demands, natural antioxidants such as sesamol, quercetin, ascorbyl palmitate, α-tocopherol, and β-carotene have also been widely tested for use in irradiated and nonirradiated meat products (Chen et al., 1999; Lee et al., 2003). Plant extracts such as green tea and grape seed extracts also inhibited irradiation-induced TBARS numbers and nonvolatile carbonyl compounds in the cooked chicken breast (Rababah et al., 2004).

Some phenolic compounds are believed to interrupt autoxidation of lipids either by donating hydrogen atom or quenching free radicals. Therefore, addition of phenolic antioxidants may be effective in reducing the oxidative reactions in irradiated meat by scavenging free radicals produced by irradiation (Nam and Ahn, 2003c). Dietary antioxidant treatments also have shown to stabilize lipids in membranes and reduce the extent of lipid oxidation in meat during storage (Morrissey et al., 1997). However, the antioxidant effects of dietary tocopherol in chicken meat differ among muscles types (Ahn et al., 1998).

Packaging was the major factor influencing the amounts and types of volatiles detected in irradiated meat. Vacuum packaging prevented oxidative changes and color fading but retained S-volatiles such as methanethiol, dimethyl sulfide, dimethyl disulfide, and dimethyl trisulfide inside the packaging bag during storage, which reduced the odor acceptance of irradiated meat. Vacuum packaging is an excellent strategy to inhibit lipid oxidation in meat during storage because oxygen is essential for the progress of lipid oxidation (Ahn et al., 2001). Failure to remove oxygen (to less than 1%) completely, however, can result in oxidizing conditions associated with low partial oxygen pressure.

The effects of irradiation on meat color are related to oxygen availability and the amount of free radicals formed at the time of irradiation. Nanke et al. (1999) reported that irradiated meat in aerobic packaging discolors more rapidly than nonirradiated samples during display. In general, vacuum packaging or controlled atmosphere packaging is satisfactory measure in preventing color and rancidity problems in nonirradiated raw meat during storage. In irradiated meat, vacuum packaging was better than aerobic packaging in preventing lipid oxidation and oxidation-dependent volatile production, but increased pink color intensity during frozen storage (Nam et al., 2002c,d). Aerobic packaging was more desirable for the irradiated meat color than vacuum packaging if lipid oxidation can be controlled (Ahn et al., 2000b, 2001). Exposing meat samples to aerobic conditions for a certain period of time was helpful in reducing irradiation off-color because of competition between atmospheric oxygen and carbon monoxide produced by irradiation (Nam and Ahn, 2003a). Exposing irradiated meats to aerobic conditions increased oxidation-reduction potential and increased the competition of CO with O_2, which decreased the chances for CO-Mb ligand formation and, thus, pink color intensity (Nam and Ahn, 2003a).

Acid is commonly used as a preservative in further processed meat. Nam and Ahn (2002b) used inorganic acids to reduce color problems in irradiated light meats because color intensity can be lower at a lower pH than at a higher pH, but lowering pH did not significantly affect the redness values of irradiated light meats. Addition of acid to meat lowers the pH and also increases the lightness of meat. The addition of citric or ascorbic acid did not affect the a* values of irradiated meat but increased the L* values, resulted in lighter overall color impression to meat (Xiong et al., 1993; Nam and Ahn, 2002c). Polyphosphates such as sodium tripolyphosphate are excellent metal chelators and inhibitors against lipid oxidation. However, when added to raw meat, they are ineffective due to rapid hydrolysis to monophosphate by endogenous phosphatase enzymes (Lee et al., 1998). Lactic acid showed acceptable cooked appearance and increased myoglobin denaturation during cooking, but produced a tangy off-flavor. In red meat, reducing agents such as ascorbic acid were very effective in maintaining redness and preventing greenish brown discoloration by irradiation (Nam and Ahn, 2003a) because the color mechanisms of irradiated light meat and red meat were different, as discussed previously. In irradiated ground beef, ascorbic acid lowered

ORP values and maintained heme pigments in ferrous status and stabilized color (Nam and Ahn, 2003b).

Addition of antimicrobial agents had synergistic effects with irradiation in killing microorganisms in meat, and generally had positive effects on the quality of meat products: injection of sodium lactate (**SL**) to cooked, vacuum-packaged beef top rounds resulted in higher cooking yields and darker, redder color with less gray surface area. Flavor notes associated with fresh beef were also enhanced by the addition of SL, and flavor deterioration during storage was minimized (Papadopoulos et al., 1991). Sodium lactate increased hardness, springiness, cohesiveness, chewiness, and resilience of turkey breast rolls (Zhu et al., 2004c), but resulted in more rapid surface discoloration in fresh pork sausage (Lamkey et al., 1991). Lactate/diacetate-enhanced chops maintained higher a* and b* values during display and had less visual discoloration, and more tender, juicier and stronger pork flavor than controls (Jensen et al., 2003). Others reported that addition of antimicrobial agents such as lactate, acetate, sorbate, benzoate salts had no effect on the texture, color, and sensory properties of meat products when used within regulatory limits (Choi and Chin, 2003; Sommers and Fan, 2003). Zhu et al. (2004a, 2005) suggested that combined use of irradiation and antimicrobial agents such as lactate, acetate, and sorbate improved the safety of meat products without significant impact on meat quality. The addition of potassium benzoate, however, greatly increased the content of benzene in the volatiles of irradiated RTE turkey ham and breast rolls. Therefore, caution is needed to use benzoate salt in products for irradiation.

The use of nonfluid seasonings in irradiated ground red meat and meat byproducts is permitted (Electronic Code of Federal Regulation, 2009). Garlic (*Allium sativum* L.) and onion (*Allium cepa* L.) are 2 major spices which are widely used in cookery to complement and enhance the flavor of meat products (Tang and Cronin, 2007). The key compounds involved in garlic and onion odor and flavor are organosulfur compounds and their precursors (Silagy and Neil, 1994; Kim et al., 2009). Addition of garlic or onion in irradiated meat produced large amounts of various sulfur compounds and masked or changed the off-odor/flavor characteristics in both raw and cooked irradiated ground beef. Addition of garlic or onion to ground beef at 0.1% garlic or 0.5% onion eliminated the irradiation aroma and flavor in ground beef, but produced a strong garlic/onion aroma and flavor. From the sensory and sulfur compound data, Yang et al. (2011a,b) suggested to use less than 0.5% of onion or 0.01% of garlic for raw ground beef and 0.5% of onion or less than 0.1% of garlic for cooked ground beef to mask or eliminate irradiation off-odor. Tajkarimi et al. (2010) reported that herbs and spices containing essential oils showed antimicrobial activities against pathogens. Therefore, the combined use of selected herbs and spices with ionizing radiation can have a good potential for inactivating pathogens by inflicting physiological and structural damage in those organisms while maintaining or improving sensory characteristics of irradiated meat.

FUTURE RESEARCH

Consumer perception and acceptance of irradiated meat are among the most important factors for the use of irradiation technology in meat. Mechanisms and solutions to the quality changes in raw irradiated meat have been studied extensively, but those for processed meat, especially with regard to taste changes, need further studies. Some components in spices and herbs have various positive effects including antioxidant, antimicrobial, and flavor-enhancing effects in meat. Therefore, extensive works are needed to determine the effects of spices and herbs on the microcidal efficacy of irradiation and masking of the irradiation taste/flavor in irradiated raw and processed meat.

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