Irradiation and Packaging of Fresh Meat and Poultry

MOOHA LEE,1* JOSEPH G. SEBRANEK,1 DENNIS G. OLSON,1 and JAMES S. DICKSON2

1Meat Laboratory, Department of Animal Science, and 2Department of Microbiology, Immunology and Preventive Medicine, Iowa State University, Ames, Iowa 50011, USA

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ABSTRACT

Extensive research on the irradiation of fresh meat and poultry has been carried out during the past 40 years; yet there is a need for consideration of combined use with other technologies such as modified atmosphere (MA) packaging. Some of the past work has focused on spoilage microorganisms and pathogens, whereas other reports emphasize the sensory quality of fresh meat and poultry. Reports published indicate that the effects of irradiation in conjunction with packaging vary depending upon the kind of meat and poultry and the atmosphere composition in the package. Irradiation may result in off-flavor and/or odor and discoloration of fresh meat and poultry in packages containing air (oxygen). One concern is that pathogens may grow and/or produce toxins in irradiated meat or poultry packaged using modified atmospheres because of a lack of competing organisms. This is of even greater concern if spoilage is suppressed and does not provide the usual warning signals. On the other hand, even though there is some evidence of the growth of pathogens in temperature-abuse conditions, most reports have indicated that spoilage preceded toxin production. Therefore, considering the sensory quality and concerns for safety, the effects of irradiation in combination with vacuum or MA packaging of fresh meat and poultry should be studied further. More complete information is needed to ensure the appropriate use of vacuum or MA packaging in combination with irradiation for the safety of fresh meat and poultry.

Key words: Irradiation, packaging, fresh meat, poultry

WHY LOW-DOSE IRRADIATION?

Food preservation techniques have been part of man's daily life for thousands of years because most foods begin to deteriorate as soon as they are harvested (10).

In the case of meat and poultry, preservation is particularly challenging because meat provides a near-perfect medium for microbial growth if the environment is appropriate (12).

Because food preservation is critical for modern mass food production and distribution, various preservation technologies have been developed and adopted successfully. However, in most instances foods are modified from their natural state as a result of preservation processes. Even refrigeration, in which the natural character of foods can be maintained, is limited by a relatively short time of effectiveness. Furthermore, there has not been any generally successful way to eliminate pathogenic microorganisms without changing the natural character of fresh meat and poultry.

Since Proctor and his associates at MIT (62) reported the first work on hamburger meat preservation using x-rays in 1943, utilization of ionizing radiation has offered a possible method of preservation in which the natural character of foods might be maintained for reasonably longer periods of time without much change. Food irradiation can be applied to fresh meat and poultry as an effective method not only for reducing losses by extending the shelf life, ensuring hygienic quality, and facilitating wider international trade (33, 45, 83), but also for tenderization (12). The concept of tenderization is based on continued proteolytic enzyme activity while microorganisms are suppressed. Irradiation effects on enzymes are limited and considerable enzyme activity remains (34).

Originally, the use of high-energy beta or gamma-ray irradiation seemed to be one of the most promising methods for so-called cold sterilization of fresh meat and poultry. However, when meat was irradiated at dosages that are required for complete sterilization (~4.8 Mrad or 48 kGy), noticeable changes in odors, flavors, and colors resulted unless precautions were taken to inactivate enzymes and to irradiate at carefully controlled temperatures. This, and the difficulty of finding an agreed-upon protocol for testing the wholesomeness of irradiated foods led to a decline of interest in radiation technology. However, since the late 1960s, an increasing public concern about the use of food additives and the presence of chemical residues in food, as well as several outbreaks of food poisonings and illnesses, have reestablished the interest in low-dose irradiation of food (67). Recently, food illnesses attributable to Salmonella, Campylobacter, Listeria monocytogenes and Escherichia coli 0157:H7 from meat and poultry have become major concerns for public safety in the United States. It was estimated that the total cost of foodborne illnesses (both parasitic and bacterial) attributable to meat and poultry products is $3,880 to $4,330 million annually (63).
The use of various packaging systems has been shown to suppress spoilage and extend the shelf life of meat and poultry products (18, 21, 29). Because packaging systems represent a generally bacteriostatic treatment while irradiation represents a potentially bactericidal treatment, combining these two barriers to microbial growth could be a very effective technology. Thus, it becomes important to consider the applications of various packaging systems to meat and poultry and to review the potential role irradiation might play in combination with packaging systems.

OXYGEN-PERMEABLE PACKAGING

Beef

*Shelf life and safety.* Wolin and his colleagues (89) reported that fresh beef loins inoculated with pseudomonads were successfully irradiated with 44,000 to 66,000 rad (0.44 to 0.66 kGy) of gamma rays at 5°C to extend the shelf life four- to fivefold at 2°C. When beef cuts were irradiated with up to 100,000 rad (1 kGy) of gamma rays and stored at 0°C, the storage life was increased from 7 days for the control to 20 to 29 days for the irradiated cuts (41). Rodriguez et al. (66) showed that 2 kGy gamma irradiation of fresh beef top round gave an average of 17 more days of shelf life than the nonirradiated samples on the basis of psychrotroph counts. According to Cain et al. (6), bacterial survival is dependent on both irradiation dose and temperature; however, most of the early studies did not describe irradiation temperatures.

From the normal flora of ground beef, the residual microorganisms surviving a nonsterilizing dose of irradiation at −30°C were mainly *Moraxella* spp., *Acinetobacter* spp., and *Brevibacterium* spp. Their *D* 10 values ranged from 273 krad (2.73 kGy) to 2,039 krad (20.39 kGy) (87).

Quality deterioration of meat and poultry during storage results not only from microbrial spoilage but also from fat oxidation. Oxidation of fat has been reported to be accelerated by gamma ray irradiation (41). Groninger et al. (23) reported that peroxide values increased greatly as a function of irradiation dose. Peroxides are the primary products of fat oxidation upon ionizing radiation treatment in the presence of oxygen. Lefebvre et al. (43) found that when ground beef was irradiated and stored at 4°C, peroxide value increased with irradiation treatment; however, within the treated groups, the dose level did not seem to influence the peroxide value.

As for food safety aspects, Tarkowski et al. (74) reported that D values for salmonella species, *Yersinia enterocolitica*, and *Campylobacter jejuni* were 0.78, 0.21, and 0.16 kGy, respectively, for the most resistant strains. It was concluded that doses as low as 1 kGy are effective in reducing salmonella by approximately 1.3 to 1.8 log cycles; *Y. enterocolitica* and *C. jejuni* are usually reduced by more than 4 log cycles with this dose. Therefore, irradiation of raw ground beef with a dose of 1 kGy of gamma rays will reduce *Salmonella* spp., *Yersinia enterocolitica*, and *Campylobacter jejuni* (73). When fresh prepackaged buffalo meat was irradiated with 2.5 kGy of gamma rays at 0 to 1°C and stored at 28 to 30°C, *Clostridium* spp. and members of the *Enterobacteriaceae* were not detected, whereas *Staphylococcus* spp. were detected after only 12 h (52). Gamma ray irradiation can also be effectively used for beef to prevent normal growth and reproduction of the tapeworm, *Cysticercus bovis* (76).

*Sensory quality.* Along with the shelf-life and food-safety considerations, the effect of irradiation on sensory quality of beef has been another aspect of concern to many researchers. Potentially undesirable chemical changes resulting from irradiation sterilization are ascribable to free radicals produced in the reaction of ionizing radiation with water (60). Fresh meat and poultry are foods high in moisture content. Undesirable odors in irradiated beef may originate due to sulfur compounds in the water-soluble fraction (2).

Schultz et al. (68) reported that there was a highly significant linear relationship between irradiation dosage and flavor score when ground beef was irradiated in the presence of air using 124,200 rep (ca. 1.155 kGy) to 993,600 rep (ca. 9.24 kGy) of gamma rays. The flavor score was found to decrease by the same amount for each doubling of the dosage. Merritt et al. (50) showed that overall sensory acceptance decreased with an increase in dose and irradiation temperature. Huber et al. (30) found that irradiation with doses in excess of 150,000 rep (ca. 1.4 kGy) beta rays resulted in an objectionable oxidized flavor in beef steaks. Recently, Lefebvre et al. (43) showed that irradiation imparted an unfavorable odor and flavor to ground beef irradiated with 1, 2.5, or 5 kGy. However, cooking the sample seemed to attenuate the radiation effect on odor. They also found that the dose effect was clearly noticeable for odor but not for flavor. On the other hand, when fresh beef was irradiated with 1 kGy of gamma rays and mayonnaise sauce added to prepare filet americain, there were no significant taste differences between nonirradiated and irradiated samples (74). Also, Rodriguez et al. (66) reported that no changes in organoleptic attributes were observed by a trained panel evaluating irradiated beef treated with 2 kGy gamma rays.

Ginger et al. (19) reported that when fresh ground sirloin butt beef was irradiated with 48,500 (ca. 0.451 kGy) to 2.3 × 10⁶ rep (ca. 21.4 kGy), discoloration increased as irradiation dose increased. Huber et al. (30) also suggested that irradiation of sirloin steak with doses in excess of 150,000 rep (ca. 1.4 kGy) electron beams resulted in a brown discoloration of the pigment. However, Groninger et al. (23) showed that 90% of myoglobin was present as oxymyoglobin in samples irradiated with 0.3 × 10⁶ rep (ca. 2.8 kGy). Recently, Lefebvre et al. (43) reported that the color of the raw irradiated beef was more pleasant than that of a fresh reference sample but a dose effect was not discernible.

Pork

*Shelf life and safety.* In early nonsterilization irradiation research, fresh pork seemed to be of little concern. Therefore, there has not been much work done on fresh pork irradiation in the presence of oxygen. Proctor et al. (61) reported that cellophane-packaged fresh pork sausage irradiated with 10⁶ rep (9.3 kGy) of cathode rays did not...
deteriorate bacteriologically during a storage period of 100 days at 2.2 to 4.4°C. Grant and Patterson (20) reported that D10 values for Salmonella typhimurium NCTC 74, Yersinia enterocolitica NCIMB 11174, Listeria monocytogenes CRA 433, Escherichia coli B 88 4099, and Clostridium perfringens NCTC 8237 in air-packed minced pork were 0.720, 0.208, 0.514, 0.348, and 0.790 kGy, respectively, when selective media were used.

Because of the absence of an inspection program for Trichinella spiralis in fresh pork in the United States, destruction of parasites by irradiation has been suggested as an alternative method for ensuring consumer safety. Taylor and Parfitt (76) reported that even though doses up to 100 krads (1 kGy) did not kill the larvae of Trichinella spp., an inhibitory effect was observable at exposures as low as 10 krads (0.1 kGy). According to Brake et al. (3), gamma irradiation of Trichinella spiralis-infected pork with a dose of 15 to 30 krads (0.15 to 0.3 kGy) blocks maturation of ingested larvae in the host gut and prevents production of larval progeny. Therefore, it is generally agreed that a dose of 30 krads (0.3 kGy) will render trichina-infected pork safe for human consumption. The use of irradiation for pork carcasses at the dose of 30 to 100 krads (0.3 to 1 kGy) has been approved by the USDA (84) to ensure trichina-safe pork.

Sensory quality. Groninger et al. (23) reported that when ground pork was irradiated with up to 10⁶ rep (0.3 kGy), peroxide levels increased as a function of radiation dose, and all irradiated samples had peroxide values above 40, which is considered rancid. The percentage of omyoglobin was relatively high in irradiated samples. However, Schultz et al. (68) found that gamma irradiation of ground pork with 2 × 10⁶ rep (18.6 kGy) did not result in significant differences in flavor scores compared to nonirradiated samples.

Poultry

Shelf life and safety. Chicken meat has been studied more extensively than red meat relative to irradiation processing for various reasons: (i) minced tissue, intact muscle, or whole carcasses can be readily irradiated and studied; (ii) the meat ranges from lightly pigmented breast muscles to more heavily pigmented leg muscle for a range of color effects; (iii) chickens are readily obtained and easily handled on a laboratory scale; and (iv) improved methods of preserving eviscerated chicken carcasses would be of value in the distribution of poultry (25).

With whole eviscerated chickens irradiated with 250 krads (2.5 kGy), 500 krads (5.0 kGy), and 825 krads (8.25 kGy) of gamma rays, Ingram and Thornley (31) reported that doses up to 825 krads (8.25 kGy) increased the storage life at 1°C from 10 to 25 to 40 days, an effect greater than has been attained with chlorotetracycline treatment. At doses exceeding 250 krads (2.5 kGy), the survival curve of bacteria ceased to be exponential with dose, indicating the survival of a somewhat more resistant group of organisms. When the composition of the mixed organisms was examined, Achromobacter spp. and yeasts were 11% and 89% of the population, respectively, at 250 krads (2.5 kGy) and yeasts 100% at the 500-krad (5.0-kGy) level. When whole eviscerated chickens were irradiated with 0.083 Mrad (0.83 kGy) or 0.415 Mrad (4.15 kGy) and stored at various temperatures, irradiated chickens had a longer microbiological storage life than unirradiated chickens. Unirradiated chickens were spoiled after 11 days at 1.1°C, whereas chickens irradiated with 0.83 kGy were spoiled at 20 days, and chickens irradiated with 4.15 kGy were not spoiled after 20 days. The delay in microbial spoilage was proportionally greater at lower storage temperatures. At the highest temperature tested, 14.4°C, no extension of storage was achieved (48). Coleby et al. (8) also showed that when whole eviscerated chicken carcasses were irradiated with gamma rays and stored at 1 to 3°C, the time required for microbial spoilage was two times longer with 0.25 Mrad (2.5 kGy) of irradiation than that for nonirradiated samples. When a gram-negative bacterial count of 8 log CFU/cm² was used as an index of incipient spoilage, the shelf life of whole chicken carcasses irradiated with 2.5 kGy of gamma rays increased by ≥9 days (40). Hanis et al. (24) reported that Pseudomonas aeruginosa survived doses up to 1 kGy of gamma rays, whereas Serratia marcescens survived up to 2.5 kGy in whole chicken carcasses irradiated at 10°C. According to Thornley et al. (82), for whole eviscerated chicken irradiated with up to 0.5 Mrad (5 kGy) of gamma rays, the viable count was reduced by a factor of 10³ with 0.25 Mrad, but an additional 0.25 Mrad (2.5 kGy) only gave a further 10-fold reduction.

When tray-packed cut-up chickens were irradiated with 0.1, 0.3, or 0.5 Mrad (1, 3, or 5 kGy) of gamma rays, extension of shelf life ranged from 7 days to more than 2 weeks (49). The irradiation of thigh and breast pieces with 100, 200, and 300 Krads (1, 2, and 3 kGy) reduced the aerobic plate counts but did not eliminate the organisms (28). The total population of the chicken wings were reduced by a gamma radiation dose of 1.4 kGy from an average 10² to 44 CFU/cm². On chicken wings inoculated with 1,000 or 10,000 CFU/cm², viable CFU were detected with 1.8 kGy but not on those irradiated with 2.7 kGy or more (81).

When chicken half breasts were irradiated with 2.5 kGy of gamma rays, the aerobic bacteria counts were reduced by about two log cycles, reaching the level of 10⁶ CFU/g near day 19 postslaughter (44).

As for food poisoning microorganisms, irradiation of chilled broiler carcasses with 250 krads (2.5 kGy) reduced the total number of naturally occurring Salmonella by 2.5 log cycles (51) or in some instances completely eliminated them (40). Steenson et al. (71) reported that a level of 4 kGy was sufficient to eliminate inoculated Salmonella (10⁶ CFU per piece) in chicken and turkey drumsticks. However, in whole chicken carcasses inoculated with 10⁶ Salmonella typhimurium cells per g, a dose of 5 kGy was not sufficient for elimination, though no Salmonella survived 10 kGy (24). When broiler breasts and thighs were irradiated with electron beams, a level as low as 100 krads (1 kGy) eliminated Salmonella (27). When chicken wings were irradiated, surviving CFU of Salmonella typhimurium were not found at gamma radiation doses exceeding 1.42 kGy (81).

Lescano et al. (44) reported that when chicken half
breasts were irradiated with 2.5 kGy of gamma rays, E. coli, enterococci, and presumptive Salmonella spp. were not detected. In chicken wings irradiated with 1.42 kGy, E. coli were not found in the irradiated samples until after 3 days of storage when the mean number of E. coli was 22 CFU/cm² (81).

Irradiation of whole chicken carcasses with 2.5 kGy of gamma rays significantly reduced Yersinia and Campylobacter counts by 3.03 and 4.19 log units, respectively (40).

Patterson (56) reported that D₁₀ values for Lactobacillus sp., Moraxella phenylpyruvica, Escherichia coli, Salmonella typhimurium, Staphylococcus aureus, Streptococcus faecalis, and Pseudomonas putida in air-packed minced chicken meat were 0.593, 0.858, 0.351 (in selective medium), 0.436 (in selective medium), 0.419, 0.651, and 0.080 kGy, respectively. Patterson (57) also reported that D₁₀ values for Listeria monocytogenes on poultry meat were 0.417 to 0.533 kGy depending on the strain and plating medium used. The D₁₀ values for L. monocytogenes were similar to those reported for Salmonella spp. irradiated under similar conditions. Therefore, irradiation doses suggested to eliminate Salmonella spp. from poultry carcasses would be sufficient to remove L. monocytogenes. When whole chickens were inoculated with 2 × 10⁷ CFU/g of Listeria monocytogenes, irradiation with 2.5 kGy gamma rays eliminated them completely and there was no recovery during storage for 15 days at 4°C (86). If the initial inoculum exceeded 10⁷ CFU/g, some of the pathogens would survive the irradiation process at 2.5 kGy. However, the lag phase was most affected and increased significantly after the irradiation dose of 2.5 kGy. Therefore, even if low numbers of the pathogen were to survive the process, the additional time required for them to recover from the damage would be significant and consequently their growth is less likely to be a problem during the normal shelf life of poultry meat (58).

The USDA final rule published 21 September 1992 permits packaged, fresh, or frozen poultry and poultry products, including ground and mechanically separated poultry products, to be irradiated with a dose of between 1.5 and 3.0 kGy. This does not apply to cooked or cured poultry products or poultry products with added ingredients. Also, packaging materials approved by the FDA should allow the passage of oxygen but not moisture or microorganisms (85), which means that vacuum or modified atmosphere packaging should not be used. Irradiated uncooked, packaged poultry has been introduced recently to grocery stores in Florida and the midwestern United States (63).

Sensory quality. Although not considered objectionable at doses up to 1 Mrad (10 kGy), a slight irradiation odor for carcasses treated with doses exceeding 0.125 Mrad (1.25 kGy) was reported by experienced observers (8). However, the panel failed to detect irradiation odor for heated samples from carcasses receiving doses up to 0.8 Mrad (8 kGy) (8). Similarly, Mercuri et al. (49) reported that raw or cooked thighs from 0.1 and 0.3 Mrad (1 and 3 kGy) irradiated chickens did not exhibit significantly greater irradiation off-flavors than those from unirradiated control chicken. However, raw meat from 0.5 Mrad (5 kGy) treated chicken exhibited an off-odor during the first few days of refrigerated storage. Cooking tended to mask irradiation off-odors. Heat treatment of irradiated poultry seemed to diminish or even eliminate the negative sensory effects of irradiation (24, 44). However, Heath et al. (24) reported that a detectable odor in raw and cooked chicken thighs and in raw chicken breasts was produced after 200 and 300 Krad (2 and 3 kGy) electron beam irradiation. The flavor of samples irradiated at 3.8 kGy and 4.5 kGy was significantly different from the control even after cooking (44). Hanis et al. (24) showed that irradiation off-odor of chicken meat increased with the dose and temperature during irradiation.

It seems likely that increasing doses of gamma-ray irradiation may cause an overall increase in the amounts of volatile compounds in meat and a decrease in odor acceptability. Because the compounds identified can be formed by decomposition of fatty acid hydroperoxides, exclusion of oxygen during irradiation should inhibit their formation (26). Hanis et al. (24) reported that high temperatures during irradiation with up to 10 kGy gamma rays resulted in a higher increase in thiobarbituric acid (TBA) and peroxide values. On the other hand, rancidity and free fatty acids were reduced in samples irradiated with 2.5 kGy of gamma rays; high radiation doses enhanced this effect (44). Electron-beam irradiation of up to 300 krad (3 kGy) did not increase TBA values (27).

Coley et al. (8) reported that irradiated chicken carcasses, even at doses as low as 0.125 Mrad (1.25 kGy), seemed more pink than untreated carcasses. The change in appearance was thought to be due to carotenoids in the surface fat being partly destroyed, giving a whiter appearance to the skin, and the muscle seemed to show an increased transparency, which seemed to intensify the red color. A slight pinkish color on irradiated half breasts from chicken has been reported by others (44). Therefore, some potential for color changes with irradiation seems likely.

Relative to other physical properties, irradiation with gamma rays has been reported to reduce the water-holding capacity of chicken breast meat, causing irradiated chicken to have firmer flesh than that of the nonirradiated. Irradiation resulted in an initial decrease in the water content of chicken breast meat, and this effect became more pronounced as the radiation dose increased (44). However, electron-beam irradiation with up to 300 krad (3 kGy) had no effect on shear values and moisture content of chicken pectoralis superficialis removed from carcass immediately after evisceration (not aged) or from carcasses held for 18 hr at 4°C (aged). On the other hand, irradiation did not affect cooking losses from aged breast tissue but resulted in the reduction of cooking losses from breast tissue which was not aged (27).

VACUUM PACKAGING

Vacuum packaging of fresh meat and poultry, especially vacuum skin packaging is known to have many advantages: (i) extended shelf life; (ii) leak-proof packages; (iii) enhanced juiciness and flavor of the meat; (iv) visibility of the meat; (v) longer and more convenient storage at home in the refrigerator or freezer; (vi) opportunity for centralized fabrication of cuts; and (vii) reduced labor costs at indi-
individual stores (55, 59, 75). At the same time, vacuum packaging may cause several problems: (i) surface discoloration; (ii) purge; (iii) changes in composition of microorganisms in the package due to the anaerobic environment; and (iv) biogenic amine production (32, 55, 70).

In irradiation treatments, both the oxygen surrounding the foodstuff, as well as the oxygen dissolved in the foodstuff, are subject to activation by ionizing radiation, followed by interaction with acceptor groups in the foodstuff, the net result being potential changes in taste, odor, color, or texture. Consequently, in foodstuffs, undesirable changes can be drastically reduced or eliminated if products have been thoroughly freed of oxygen prior to irradiation (30). Therefore, it seems likely that irradiation would be more effective for products with vacuum packaging than oxygen-permeable packaging.

The irradiation of fresh meat and poultry in vacuo has not been studied very extensively. This might be because irradiation in vacuo requires a higher radiation dose for a given degree of bacterial inactivation than is required in aerobic atmospheres (60). Also, using oxygen-permeable film for packaging at the retail level for color and cost advantages is common. Whereas color concern may limit vacuum-packaging applications for beef, more studies on pork and poultry may be appropriate because color is not as much of a problem.

**Beef**

*Shelf life and safety.* According to Niemand et al. (53), application of doses of 2 kGy gamma rays to vacuum-packed beef cuts at 25°C caused a considerable change in the bacterial population by elimination of the pseudomonads, species of the Enterobacteriaceae, and enterococci. After irradiation, the population was mostly lactic acid bacteria. Cain et al. (6) indicated a significant decrease in survivors of a radio-resistant micrococcus with increasing doses. The radiation-resistant bacteria in beef irradiated either in vacuum packages or under atmospheric conditions seemed to be the same (87). Radurization of minced beef with a dose of 2.5 kGy completely eliminated pseudomonads, species of the Enterobacteriaceae, and Brochothrix thermosphacta, and they could not be detected during the subsequent storage period at 4°C (54).

A doubling in shelf life was attained by the irradiation of vacuum-packaged beef cuts with 2 kGy gamma rays when compared with nonirradiated samples (53). The irradiation of vacuum-packed beef rib cuts at the level of 0.35 Mrad (3.5 kGy) delayed the onset of microbial spoilage at 5°C until the sixth week (64). Dempster et al. (11) reported that doses of 1.03 and 1.54 kGy reduced the total bacterial numbers in vacuum-packaged beefburgers by 82% and 92%, respectively. An irradiation dose of not less than 1.5 kGy improved the shelf life of beefburgers by at least 7 days at 3°C. In minced beef irradiated with 2.5 kGy in vacuo the total aerobic bacteria were drastically reduced and the shelf life was extended to well over 9 days when evaluated by bacteriological criteria (54).

*Sensory quality.* Cain et al. (6) reported that peroxide and TBA values of vacuum-packaged ground beef were decreased with increasing doses of gamma rays from 0.5 × 106 to 2.0 × 106 rep (4.65 to 18.6 kGy). However, Dempster et al. (11) showed that 1.03 and 1.54 kGy gamma irradiation of vacuum-packaged beefburger gave significantly higher peroxide values than for the raw control.

The irradiation of ground beef with gamma rays under vacuum resulted in a significantly different flavor (68) and an odor that dissipated after exposure to air (11). According to Rhodes and Shepherd (64), the maximum dose of gamma radiation that can be applied to beef at 0°C in the absence of air, without causing changes in organoleptic qualities detectable by a trained taste panel, was found to be 0.4 Mrad (4 kGy). All samples given 0.3 or 0.4 Mrad (3 or 4 kGy) had normal raw meat odor after 10 weeks at 0°C. However, Sudarmadji and Urbain (72) reported that the threshold dose for the detection of irradiation flavor in vacuum-packaged beef was 250 krad (2.5 kGy).

The surface color of ground beef was judged brighter (redder) following irradiation with 1.54 kGy gamma rays, and surface color was influenced more than internal color (11). When ground beef in saran casings was irradiated at 48,500 to 97,500 rep (ca. 0.451 to ca. 0.907 kGy) of gamma rays, it became slightly discolored, seeming slightly brown with red spots or a red-tan color. When the dosage was increased to 145,000 rep (ca. 1.35 kGy), the samples were acceptable but had a somewhat faded red color (19).

**Pork**

*Shelf life and safety.* Because the vacuum packaging of pork seems to result in less color change than in beef, interest in vacuum-packaged pork has been increasing in the United States.

Irradiation of vacuum-packed fresh bellies with a dose of 0.44 Mrad (ca. 4.1 kGy) of gamma rays delayed spoilage at 5°C from 4 to more than 20 weeks (65). With pork loins irradiated using 3.0 kGy, microbiological shelf life was more than doubled to >91 days from 41 days for nonirradiated controls at 2 to 4°C (42). Mattison et al. (47) reported that irradiation of pork loins with 100 krad (1 kGy) reduced numbers of mesophiles, psychrotrophs, anaerobic bacteria, and staphylococci. Similar results were reported by Ehioba et al. (13) on ground pork with 1 kGy. In addition, these authors indicated that irradiation injured a large portion of the mesophilic flora of vacuum-packaged ground pork but was not always lethal. Also, their report showed that irradiation prolonged the shelf life of ground beef 2.5 to 3.5 days at 5°C. The microflora of the ground pork irradiated with 1 kGy was mainly gram-positive (66%) shortly after irradiation and increased to 97% after 9 days at 5°C, whereas gram-negative microflora changed from 34% to 3% (14).

On the other hand, Thayer et al. (80) reported that when fresh ground pork was irradiated with 0.57 to 7.25 kGy of gamma rays at 2°C, no CFU were observed in plate counts of any sample that received a radiation dose ≥1.91 kGy, even after refrigerated storage for up to 35 days. However, Staphylococcus spp., Micrococcus spp., and yeast species predominated in samples that received 0.57 kGy.

The possibility of unimpeded growth of pathogenic
microorganisms in the event of temperature abuse during handling, because of the reduction of spoilage bacteria after irradiation, has been suggested with implications for public safety. Such concern brought the initial decision by the Food Safety Inspection Service (FSIS) to not approve commercialization of irradiated vacuum-packaged pork (1). This is also true for the current regulation on irradiation of poultry (85). The most recent petition to the USDA for approval of irradiation treatments for red meat, however, included vacuum and MA packaging for irradiated products.

The possibility of pathogen growth was studied by Lebepe et al. (42). They reported that when vacuum-packaged boneless pork loins were irradiated with 3.0 kGy and stored at 2 to 4°C, the process ensured less spoilage bacteria and products which were nearly free of viable pathogenic bacteria. However, temperature abuse increased the growth of mesophiles, lactobacilli, and anaerobic and facultative anaerobic bacteria. Also, Clostridium perfringens and Aeromonas spp. were present in abused samples.

Sensory quality. Irradiation in vacuo seemed to affect the sensory quality of pork less adversely than irradiation in the presence of oxygen. Mattison et al. (47) reported that no detectable difference between irradiated and nonirradiated pork loins was observed in sensory characteristics. Irradiation with 1 kGy did not affect cooking losses or TBA values (13, 47). With a dose of 3.0 kGy, no differences in TBA values or pH could be attributed to irradiation. However, the threshold dose for the detection of slight irradiation flavor in vacuum packaged pork has been reported to be 175 krad (1.75 kGy) (67). In green (uncooked) bacon irradiated with 4.4 kGy, a very slight irradiation odor was detected, but after cooking, no deleterious changes in the flavor or odor were detectable (65). These authors (65) also reported that the peroxide values remained very low after irradiation and free fatty acid values showed no difference because of irradiation.

Irradiation in vacuo has been reported to improve red color. Lebepe et al. (42) reported that Hunter “a” (redness) values were consistently greater in chops from irradiated loins than from nonirradiated ones.

Poultry

Shelf life and safety. In a study on sensitivity of bacteria on poultry meat to irradiation, Patterson (56) indicated that among various atmospheres (air, CO₂, N₂, and vacuum) a vacuum during irradiation was found to have the most lethal effect. However, it was reported that gamma irradiation was significantly more lethal for Salmonella typhimurium in the presence of air than in vacuo regardless of the presence of competition from natural flora (78, 79). The radiation was significantly more lethal to the bacterial cells at temperatures above freezing (79).

Varabioff et al. (86) reported that Listeria monocytogenes was recovered after 7-day cold storage from vacuum-packaged, raw chicken irradiated with 2.5 kGy of gamma rays. Even though irradiation was found to be highly effective in destroying Salmonella spp. in chilled broiler carcasses (51), there is concern regarding the growth of anaerobic spores, which may survive temperature abuse, similar to concerns for pork. However, according to Firstenberg-Eden et al. (16), when nonsterilized chicken skins were inoculated with Clostridium botulinum type E spores (ca. 5 × 10⁷/7 cm²), vacuum sealed in pouches, irradiated with 0.3 Mrad (3 kGy) at 5°C, and incubated at 30°C, the surviving natural flora multiplied and produced an off-odor by the time the first toxic sample was detected. They also indicated that an irradiation dose of 0.3 Mrad (3 kGy), but not 0.5 Mrad, left enough of the natural flora to compete with C. botulinum type E cells (if the cells are present) on severely abused (30°C) chicken skins. Therefore, they (17) suggested that there should not be any botulism hazard with chicken irradiated with 0.3 Mrad (3 kGy). Irradiated chicken in which a dose greater than 0.3 Mrad (3 kGy) is used may create a potential C. botulinum type E hazard only if a product is severely abused by holding it at 30°C. Shamsuzzaman and Lucht (69) indicated that radiation D₁₀ values of Clostridium sporogenes spores were much greater in animal fats than in vegetable oils. The greatest resistance was observed in chicken fat, followed by pork fat and beef fat.

Sensory quality. When turkey breast fillets were irradiated with 2.5 kGy and stored at 1°C, the irradiated samples showed negligible growth of microorganisms during 21 days of storage. However, because of an intense off-odor, the irradiated samples in vacuo had low panel acceptability scores. Because there was very little microbial growth, these odors are presumably chemical changes in the meat induced by irradiation (46). The threshold dose for the detection of slight irradiation flavor in vacuum packaged and irradiated chicken was reported to be 250 krad (2.5 kGy) (72).

Radiation in vacuo has been observed to result in an intense pink color in raw and cooked turkey breast meat. It was reported that uncooked myoglobin pigment was reduced by the radiation to an intense pink and stayed pink during the storage in vacuum packages (46). Similar observations have been reported for pork as discussed earlier.

MODIFIED ATMOSPHERE PACKAGING (MAP)

When considering MAP of meats, there are four main areas where the system may impact product characteristics. These include the control of bacterial pathogens and spoilage microorganisms, changes in meat color, control of product weight loss, and changes in meat tenderness by aging. It has been well established that high carbon dioxide concentrations retard meat spoilage but may cause discoloration of meat. However, it has been suggested that discoloration is not always due to carbon dioxide itself, but, in some cases, to small amounts of oxygen contaminating the package atmosphere (18).

Concerns have been raised for the growth of anaerobic pathogens in MAP containing various amounts of carbon dioxide because the growth of pathogens may be allowed or even stimulated by carbon dioxide (15). Even with microorganisms inhibited by carbon dioxide during storage at low temperatures, lack of refrigeration at any time during storage could allow them to grow because the bactericidal and bacteriostatic effects of carbon dioxide are temperature dependent (88). Under conditions of product temperature
abuse, pathogens may grow in almost any atmosphere. Therefore, the development of pathogens relative to that of spoilage organisms is more important than the determination of conditions where pathogens may grow (29).

Because irradiation increases the shelf life of meat and poultry by inactivating spoilage microorganisms, additional treatments may also be needed to control chemical spoilage, such as rancidity in fresh meat. The combination of MAP in conjunction with irradiation offers opportunities for incorporating package atmospheres which may have unique effects on quality maintenance (39). However, there have not been many studies examining the combined effect of these two treatments for fresh meat and poultry.

**Beef**

Even though fresh beef in MAP is currently available on the market in Europe, few studies have been done on the effects of MAP and low-dose irradiation in beef. Some early work on irradiation was done in conjunction with a nitrogen gas atmosphere in the package to compare nitrogen with the effects of oxygen. Groninger et al. (23) reported that radiation of ground beef in a nitrogen atmosphere produced an insignificant increase of peroxide and carbonyls, and the destruction of hematin pigments was an approximate function of radiation dose. However, it was reported that irradiation in nitrogen resulted in a significant difference in flavor score compared with the nonirradiated samples (68).

**Pork**

**Shelf life and safety.** When pork chops were packaged in 100% CO_2, 100% N_2, 25% CO_2/75% N_2, 50% CO_2/50% N_2, and 20% CO_2/70% O_2/10% N_2, the gas mixtures were more effective than pure gases for reducing the growth rate of surviving microorganisms at 4°C. However, 100% CO_2 was most effective for controlling microbial growth at 10°C (21). Lambert et al. (39) reported that the numbers of microorganisms were unacceptably high after 10 days at 25°C irrespective of packaging atmosphere for fresh pork irradiated with 1 kGy. Products packaged with 10% O_2/90% N_2 and irradiated with 0.5 kGy had a shelf life of 6 days at 15°C and 21 days at 5°C using 100% N_2 and 1.0 kGy.

An irradiation dose of 1 kGy reduced both psychrotrophic and mesophilic bacterial counts by two log cycles and inactivated most of the species of Enterobacteriaceae in fresh pork packaged in 100% N_2, 10% O_2/90% N_2, or 20% O_2/80% N_2, whereas lactic acid bacteria were largely unaffected (39). The microflora of MAP pork irradiated with 1.75 kGy gamma rays was almost exclusively composed of lactic acid bacteria, predominantly Lactobacillus spp. regardless of gas composition (21). The majority of the strains of lactic acid bacteria were Lactobacillus sake (20). These authors indicated that spoilage of irradiated MAP meat would also be due to lactic acid bacteria.

Grant and Patterson (22) assessed the safety of pork packaged in 25% CO_2/75% N_2 and irradiated with 1.75 kGy at abuse temperatures (10 or 15°C). MAP increased the D_10 values of Salmonella typhimurium NCTC 74, Yersinia enterocolitica NCIMB 10460, and Listeria monocytogenes, but decreased that of Clostridium perfringens. In samples inoculated with 10^3 cells per g, irradiation significantly reduced the numbers of S. typhimurium, E. coli, Y. enterocolitica, and L. monocytogenes, and during storage at 15°C, these pathogens were outgrown by the lactic microflora.

Concerns have been expressed for the safety of MAP foods, especially with the possibility of growth of Clostridium botulinum. Lambert et al. (35) reported that toxin production by C. botulinum was detected after 43 days at 15°C in pork loins packaged in 100% N_2 and irradiated with 1 kGy. After 14 days in irradiated samples packaged in 10% O_2/90% N_2 and 20% O_2/80% N_2, toxin was detected. At 25°C, toxin was detected after 2 days in all treatments. No toxin was found in any of the products at 5°C even after 44 days. With fresh pork loins packaged in various gas mixtures (100% N_2, 20% CO_2/80% N_2, 20% CO_2/20% O_2/60% N_2, and 20% O_2/80% N_2) and irradiated with 1.0 kGy gamma rays, Lambert et al. (37) found that the presence of CO_2 in the package headspace was not a significant factor affecting the time until toxin was first detected from C. botulinum. Irradiation was significant in affecting the lag time until toxin was first detected in treatments with O_2 initially present. These results (35, 37) are different from others, which showed that CO_2 stimulated germination of clostridial spores. In a study on the effect of CO_2 concentration, Lambert et al. (36) indicated that toxin production by C. botulinum occurred faster in pork loins initially packaged with 15 to 30% of CO_2, higher levels of CO_2 (45 to 75%) delayed toxin production. Irradiation dose of 1.0 kGy significantly delayed toxin production in inoculated samples at all levels of CO_2.

As occurred with vacuum-packaged pork and poultry, all samples in MAP generally become spoiled (with off-odors and discoloration) before they become toxic (22, 36, 37). Therefore, the concern for toxin production occurring before spoilage may only be valid if doses above 3 kGy were to be used to irradiate meat (22).

**Sensory quality.** Irradiated pork in a nitrogen atmosphere showed only small increases in peroxides and carbonyls (23). However, it seems to result in differences in flavor. Schultz et al. (68) reported that irradiation resulted in a significant difference in the flavor of ground pork packaged in nitrogen compared with nonirradiated ground pork. The irradiated pork chops with 1.75 kGy of gamma rays either in 25% CO_2/75% N_2 or 50% CO_2/50% N_2 had a distinct irradiation odor initially. The intensity of this odor did not change significantly during storage at 4°C, but the nature of the odor changed with time to become more acceptable (21).

As expected, if oxygen is included in MAP, the sensory quality usually deteriorates. Lambert et al. (38) showed that with pork loins packaged in 100% N_2 and 20% O_2/80% N_2, and irradiated with 1.0 kGy, autooxidation of fat was accelerated if oxygen was present during or after irradiation. TBA values from samples packaged in 20% O_2 also were higher than those from 100% N_2-packaged samples. It was again noticed that irradiated samples packaged in 20% O_2 had a strong off-odor compared with nonirradiated samples whereas N_2-packaged samples showed no difference.

Grant and Patterson (21) reported that the MAP pork
irradiated with 1.75 kGy was significantly pinker than unirradiated pork. An atmosphere containing 25% CO₂/75% N₂ was better for maintaining the color of pork chops than one containing 50% CO₂/50% N₂. An increase in red color of irradiated pork in a nitrogen atmosphere has also been observed (23). Lambert et al. (38) indicated that oxygen, irradiation, and storage temperature affected Hunter “L”, “a”, and “b” values of MAP pork loins irradiated with 1.0 kGy. However, they could not define clearly the changes in a values (redness), which is the most important factor in meat color. Irradiated samples in the package containing oxygen became more discolored during storage at 5°C than 100% N₂-packaged ones.

Irradiation increased exudate loss from MAP pork but did not affect the pH. The increased exudate loss may have resulted from a change in the secondary and tertiary structure of protein, influencing the water-holding capacity of muscle tissue (38).

In terms of sensory quality, the shelf life of pork was extended from 9 to 26 days at 5°C and from <2 to 2 days at 25°C by irradiation with 1 kGy in 100% N₂ (38).

Poultry. As in the case of beef, there have not been many reports for poultry concerning the effect of irradiation in conjunction with MAP.

Ingram and Thornley (31) reported that when minced whole chicken meat packaged under nitrogen was irradiated with up to 0.25 Mrad (2.5 kGy) of cathode rays, the storage life at 5°C increased progressively with the dose of irradiation. Little change occurred during 3 weeks in samples irradiated with 0.25 Mrad (2.5 kGy). Patterson (56) studied the sensitivity of seven bacterial species inoculated on sterile poultry meat and irradiated under various atmospheres. 

*Streptococcus faecalis* and *Staphylococcus aureus* were not affected by the kind of atmosphere and *Salmonella typhimurium* was more resistant under N₂. The sensitivity of the *Lactobacillus* spp. and *Moraxella phenylpyruvica* to irradiation was significantly increased under CO₂. *Escherichia coli* was more sensitive to irradiation under N₂. *Pseudomonas putida* was more resistant to irradiation under CO₂. Grant and Patterson (29) reported that the majority of the strains of lactic acid bacteria that survived the irradiation of chicken under 100% CO₂ were *Lactobacillus sake*.

Irradiation of chicken in a nitrogen atmosphere resulted in low concentration of peroxides and carbonyls (23). When minced chicken meat packaged in nitrogen was irradiated with increasing doses of electron beams at room temperature, the threshold for detection of off-flavor was about 0.25 Mrad (2.5 kGy) (27).

Radiation of chicken in a nitrogen atmosphere was reported to produce a bright oxymyoglobin pink coloration (23) or a pinkish transparent appearance (25).

**EFFECTS OF IRRADIATION ON PACKAGING MATERIALS**

Because most meat and poultry products are packaged before irradiation treatment, the packaging materials are subjected to various irradiation doses as well. The barrier properties required for most products mean that the packag-
have been done for either beef or poultry. For pork, less than 3 kGy of gamma rays irradiation has been suggested to suppress toxin production by Clostridium botulinum and extend shelf life. If oxygen is included in MAP, the sensory quality is likely to deteriorate in irradiated pork. A gas mixture of 25% CO\(_2\)/75% N\(_2\) has been recommended for acceptable flavor and color in pork irradiated with 1.75 kGy.

It is important to remember that foods are consumed for both good nutrition and eating pleasure. Consequently, the sensory quality of foods deserves as much attention as safety. This is currently one of the major challenges to successful marketing of irradiated meat and poultry. It is clear that shelf life and safety can be improved by irradiation treatment, but sensory changes sometimes occur. Vacuum and MA packaging result in better sensory quality for irradiated fresh meat and poultry, but the best combination of conditions for retaining sensory quality is not clearly established. Further, work relative to the effects of irradiation on packaging materials is also important for the implications this has for product quality changes. Considering these facts, more studies on the combined effect of irradiation and vacuum and MA packaging relative to the quality characteristics of fresh meat and poultry are necessary and should be initiated to clarify the best practical application of these technologies.

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REFERENCES


