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Effects of Ionizing Radiation Treatments on the Microbiological, Nutritional, and Structural Quality of Meats

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Treating fresh or frozen meats with ionizing radiation is an effective method to reduce or eliminate several species of food-borne human pathogens such as *Salmonella*, *Campylobacter*, *Listeria*, *Trichinella*, and *Yersinia*. It is possible to produce high quality, shelf-stable, commercially sterile meats. Irradiation dose, processing temperature, and packaging conditions strongly influence the results of irradiation treatments on both microbiological and nutritional quality of meat. These factors are especially important when irradiating fresh non-frozen meats. Radiation doses up to 3.0 kGy have little effect on the vitamin content, enzyme activity, and structure of refrigerated non-frozen chicken meat, but have very substantial effects on food-borne pathogens. Some vitamins, such as thiamin, are very sensitive to ionizing radiation. Thiamin in pork is not significantly affected by the FDA-approved maximum radiation dose to control *Trichinella*, but at larger doses it is significantly affected.

Treating fresh or frozen meats with ionizing radiation in the form of gamma rays from cobalt-60 or cesium-137, accelerated electrons of 10 MeV or lower energy, or X-rays of less than 5 MeV can reduce the populations or eliminate many food-borne pathogens and extend the shelf life of the product. This manuscript describes the effects of ionizing radiation on the microbiological, nutritional, and structural quality of meat (edible tissue of vertebrate animals) and discusses how and why processing variables may dramatically alter the results of the treatments.

Appropriateness of Technology

The appropriateness of any meat processing technology is determined by its ability to control food-borne pathogens and spoilage microorganisms without adversely affecting the wholesomeness, nutritive value, and organoleptic properties. The technology must also be economically competitive. The effects of ionizing radiation on food-borne pathogens and on the meat itself depend on the absorbed radiation dose, irradiation temperature, irradiation atmosphere, packaging, dose rate, storage time and temperature before cooking and consumption, and cooking method.

Food irradiation cannot substitute for proper food sanitation, packaging, refrigerated storage, and cooking. The primary reason for treating fresh or frozen meat with ionizing radiation is to eliminate food-borne pathogens. Extending shelf life of fresh, non-frozen meats may result, but is secondary in importance. Shelf-stable meats that can be stored at room temperature without refrigeration can be produced. Sterile, refrigerated meats suitable for consumption by immuno-compromised hospital patients may be prepared. Each of these products requires specific processing conditions; ionizing radiation treatments are often self-limiting because of changes in the organoleptic properties of the treated meat at higher dose levels.

The following are recommended as tests of the wholesomeness of irradiated foods (*1*): failure to induce gene mutations in bacteria or in cultured mammalian cells; failure to alter DNA repair in mammalian cells; failure to induce recessive lethal mutations in *Drosophila*; and failure to exhibit evidence of treatment related toxicological effects in 90-day feeding studies with a non-rodent species and a rodent species that include *in utero* exposure of the fetuses to the test material. These tests are inherently different from toxicological tests of food additives because an irradiated meat cannot be included in the diet of test animals in amounts that are greatly in excess of those usually found in the diet without causing toxicity from excessive protein consumption.

All meats are considered to be a good source of high quality protein, and red meats a source of the B-complex vitamins. Tests for the effects of ionizing radiation treatments on the nutritive value of meat may include analyses of amino acids, fatty acids, and vitamins and include the effects of storage time and temperature and cooking on these nutrients in the irradiated product. Gross tests of the food value of the meat, such as for the protein efficiency ratio of the irradiated meat, may reveal subtle changes in the irradiated meat. The treatment may also change the sensory properties of the meat. Some of these, such as texture, color, firmness, softness, juiciness, chewiness, taste, and odor are closely related to possible changes in nutrient value. Enzymatic and ultrastructural studies may be performed to help define the nature of the textural changes in irradiated meats. These sensory changes cannot be too severe or the treated meat will have no economic value.

Each of the effects of ionizing radiation on red meat, poultry meat, or food-borne pathogens, whether beneficial or adverse, is predictable from the known chemistry of meat and fundamental principles of radiation chemistry.

Predictability

The initial reaction of ionizing radiation is most likely to occur with water because approximately 70% of both meat and food-borne pathogens are water. The initial reactions occur with an electron, whether the source of the radiation is a photon or an accelerated electron, because photon energies from X-rays of less than 5 MeV or gamma-rays from isotopic sources such as ^{137}Cs or ^{60}Co primarily interact with water through the Compton effect (*2*). When the energy of a photon exceeds the binding energy of an electron, it is ejected and the Compton photon is scattered. A small fraction of the photon energy is converted into the kinetic energy of the freed electron. In water that freed electron becomes solvated very quickly. Klassen (*3*) has described the ionization of water at 25°C by the absorption of 100 eV as follows:

$$4.14\ H_2O = 2.7\ e_{aq}^- + 2.7\ H^+ + 2.87\ OH\cdot$$
$$+\ 0.43\ H_2 + 0.61\ H_2O_2 + 0.026\ HO_2$$

The primary products are the hydrated electron (e_{aq}^-), the proton, and the hydroxyl radical. Lesser but significant amounts of hydrogen and hydrogen peroxide are produced. Enough hydrogen is produced to warrant consideration when canning meats that will be sterilized with ionizing radiation. The maximum radiation dose approved in the United States to eliminate food-borne pathogens from fresh or frozen poultry is 3.0 kGy (*4*). Since 3 kGy equals the absorption of 3 kJ/kg, the amount of energy absorbed by the meat is 1.87 X 10^{16} eV/g. A G value of 2.7 at 25°C indicates that 0.84 nmole of product will be formed in meat that has received 3 kGy of ionizing radiation, and the temperature of the meat will increase 0.72°C. The actual yield of radiolytic products in meat will be much less because of many competing reactions for the active species. Both the temperature and the physical state of the product during irradiation affect the results. These effects cause the G value for formation of the hydrated electron to decrease from 2.7 at 25°C to 0.3 at -5°C (*5*). Oxygen rapidly reacts with both the hydrated electron and the proton, eliminating them from further reactions.

Other than water, protein is the major constituent of meat averaging nearly 21% in beef or chicken meat, with fat varying from 4.6 to 11.0% in beef and from 2.7 to 12.6% in chicken. The principal radiolytic reactions of aqueous solutions of aliphatic amino acids are reductive deamination and decarboxylation. Alanine yields NH_3, pyruvic acid, acetaldehyde, propionic acid, CO_2, H_2, and ethylamine (*6*). Sulfur-containing amino acids are especially sensitive to ionizing radiation. Cysteine can be oxidized to cystine by the hydroxyl radical or it can react with the hydrated electron and produce

The radiation doses required to inactivate 90% (D_{10}-value) of the colony forming units of 6 common food-borne pathogens associated with meat are presented in Table II. The values for the inactivation range from 0.16 kGy for the vegetative cells of *Campylobacter jejuni* in beef to 3.56 kGy for the inactivation of *Clostridium botulinum* endospores in vacuum-packed enzyme-inactivated chicken meat at a temperature of -30°C. If irradiated chicken were to receive exactly 3.0 kGy then, in theory, the population of the very mild pathogen *A. hydrophila* would decrease by 15.8 logs and the most resistant strain of *Salmonella enteritidis* (*20*) by 3.9 logs. *Salmonella sp.* are a very important potential contaminant of all meats but especially of poultry carcasses (*22*) and have been the subject of many studies for potential uses of food irradiation. The D_{10}-value reported in Table II for *C. botulinum* is a special case in that the value refers to an irradiation temperature of -30°C delivered *in vacuo* to enzyme-inactivated chicken to produce a shelf stable product. A 12D dose of 42.7 kGy is required to assure the elimination *C. botulinum* endospores. The high D_{10}value for *C. botulinum* is the result of the greater resistance of the bacterial endospore to ionizing radiation and the effect of subfreezing temperatures during irradiation. It was noted earlier that the G value for e_{aq} decreases dramatically in ice (*5*). If the lethal action of ionizing radiation were primarily due to direct interaction with the pathogen, we would not expect to find a temperature dependence of the irradiation process nor would we find an effect of irradiation atmosphere on the inactivation process. Thayer and Boyd (*23*) reported highly significant effects for both temperature and atmosphere during irradiation of *Salmonella typhimurium* in mechanically deboned chicken meat over the temperature range of -20 to +20°C. In the presence of air, a dose of gamma radiation of 3 kGy destroyed 4.8 and 6.4 logs of colony-forming units at -20 and +20°C, respectively. Hydroxyl radicals are identified as the major damaging species for the inactivation of *Escherichia coli* ribosomes and tRNA in aerated solutions (*24*). Though data are lacking for other bacterial species, it seems probable that the hydroxyl radical has a major role in their inactivation. This conclusion is supported by the increased resistance to ionizing radiation of many bacterial species at subfreezing temperatures where the mobility and reactivity of free radicals is known to be severely restricted (*25*). Advantage can be taken by the food processor of the decreased mobility of free radicals at subfreezing temperatures to help prevent changes in organoleptic properties and vitamin losses in meats.

Radiation-Sterilized Chicken Meat

Thayer et al. (*26*) reported the results of nutritional, genetic, and toxicological studies of enzyme-inactivated, radiation-sterilized chicken meat. The study included four enzyme-inactivated chicken meat products: 1) a frozen control, 2) a thermally processed product (115.6°C), 3) a gamma-sterilized product, and 4)

Table I. Control of Food-borne Protozoans, Nematodes, and Cestoda by Irradiation

Pathogen	*Radiation Dose to Inactivate* kGy	*Ref.*
Toxoplasma gondii	0.25	11
Trichinella spiralis	0.3	12
Cysticercus bovis	0.4 to 0.6	13
Cysticercus cellulosae	0.4 to 0.6	13

Table II. Control of Food-Borne Bacterial Pathogens by Treatment of Meat with Ionizing Radiation

Pathogen	*Irradiation Temperature* °C	*Substrate*	D_{10}-*Value (kGy)*	*Ref.*
Aeromonas hydrophila	2	Beef	0.14-0.19	16
Campylobacter jejuni	0 - 5	Beef	0.16	17
Clostridium botulinum	-30	Chicken	3.56	18
Listeria monocytogenes	2 - 4	Chicken	0.77	19
Salmonella sp.	2	Chicken	0.38-0.77	20
Staphylococcus aureus	0	Chicken	0.36	21

an electron-sterilized product. The radiation-sterilized products were given a minimum radiation dose of 46 kGy and a maximum of 68 kGy at -25 $\pm$ 15°C with gamma rays from ^{60}Co or 10 MeV electrons. All of the meat was enzyme-inactivated by heating to an internal temperature of 73-80°C. The frozen control, the thermally sterilized product, and the gamma-sterilized meats were vacuum canned. The chicken intended for sterilization by electrons was vacuum packed in laminated foil pouches. The entire study required 230,000 broilers (135,405 kg of enzyme-inactivated meat) and four production runs. Because each product was analyzed chemically for nutrients before use in the animal feeding studies, an unusual opportunity existed to compare the effects of ionizing radiation to freezing and thermal processing. No evidence of genetic toxicity or teratogenic effects was observed when any of the four products was included as 35 or 70% of the diet of mice, hamsters, rats, and rabbits. No treatment-related abnormalities or changes were observed in dogs, rats, or mice fed any of the four test products as 35% of their diet during multigenerational studies (*26*). No treatment effect was found for any amino acid or fatty acid in the four test meats (*27*). No treatment effect was found for the contents of pyridoxine, niacin, pantothenic acid, biotin, choline, vitamin A, vitamin D, and vitamin K. The percentage of thiamin in the thermally processed and gamma-sterilized meats was approximately 32% lower than that in the frozen control. The percentages of riboflavin and folic acid were significantly higher in the electron-sterilized product than in the frozen control. The percentages of vitamin B_{12} were significantly higher in the gamma-sterilized and in the thermally processed meats than in the frozen control meat. Thus, the only identifiable significant adverse change was a decrease in thiamin in the thermally and gamma-processed meats.

Vitamins

The results obtained with a sterilization dose administered to chicken meat at subfreezing temperature can be compared to those obtained with radiation doses of less than 10 kGy administered to non-frozen chicken. Fox et al. (*28*) investigated the effects of ionizing radiation treatments (0, to 6.65 kGy) at temperatures from -20 to +20°C on the content of niacin, riboflavin, and thiamin in chicken breasts and of cobalamin, niacin, pyridoxine, riboflavin, and thiamin in pork chops. Chicken breasts irradiated to 3.0 or 6.65 kGy at 0°C and then cooked had thiamin losses of 8.6 and 36.9%, respectively, when compared to unirradiated cooked chicken breasts. The 8.6% loss at the maximum dose currently approved for the poultry irradiation is not significant from a nutritional standpoint, because chicken contributes only 0.53% of the total thiamin in the American diet (*29*). The loss of thiamin in chicken irradiated in air at 0°C to a dose of 6.65 kGy (*28*) was slightly larger than that of the chicken meat treated *in vacuo* to a radiation dose of between 46 to 68 kGy at -25$\pm$15C (*27*). The increased loss can be attributed to a large extent to the difference in irradiation temperature. At doses of 3 kGy or less there was no loss of either niacin or riboflavin from irradiated chicken (*28*). De Groot et al. (*30*) also found no significant changes in nutritive value or in the vitamin content of chicken meat irradiated to 0, 3, and 6 kGy. Large variations in values were noted between samples, and the temperature of irradiation was not stated. Fox et al. (*28*) reported that when pork chops were irradiated to 1.0 kGy at 0°C and then cooked, there was a 17.5% loss of thiamin. These authors concluded that if all pork produced in the United States were to be irradiated, which is extremely unlikely, the American diet would lose about 1.5% of its thiamin, since pork contributes about 8.78% to total thiamin consumption (*29*). In contrast to the minor loss of thiamin at a dose of 1 kGy, pork chops irradiated to 6.65 kGy at 0°C lost 65.5% of their thiamin content when cooked. The reason for the large difference in the rates of thiamin loss in irradiated pork and chicken is currently under study.

Sensory Panel Tests

Klinger et al. (*31*) reported that extensive taste panel tests of chicken breast meat or leg meat irradiated to 3.7 kGy and cooked by boiling in water showed no loss in sensory quality immediately after treatment. The sensory quality of the irradiated chicken deteriorated during refrigerated storage over a period of 3 to 4 weeks. Irradiated chicken breast meat was acceptable for about three weeks; however, quality of unirradiated chicken was retained for only about four days during chilled storage.

Meat Enzyme Activity

Lakritz et al. (*32*) reported that radiation doses of less than 10 kGy (at 0 to 4°C) produced minimal changes in the micro structure of bovine longissimus dorsi muscle. At doses of 30 kGy or higher, myofibril fragmentation and decreased tensile strength were noted. Lakritz and Maerker (*33*) reported reductions of 8% and 42% in the activities of lysosomal enzymes and acid phosphatase of irradiated (10 kGy) bovine longissimus dorsi muscle tissue.

Conclusion

Knowledge of radiation chemistry and meat chemistry allows us to predict the effects of irradiation treatments on both meat and its accompanying microflora. Predictably, higher temperatures of irradiation correspond with greater destruction of structure, nutrients, and microflora. Inhibition of the movement of free radicals by freezing the meat prior to irradiation greatly reduces secondary reactions and provides better nutrient retention. Bacterial pathogens, however, can still be killed by direct action of the ionizing radiation, producing high quality, sterile meats.

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