

# IRRADIATION: PATH TO A SAFER FOOD SUPPLY IRRADIATION AS AN INTERVENTION STEP IN HACCP\*

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## ABSTRACT

*Treating meat and poultry products with ionizing radiation is an extremely effective method to eliminate both spoilage and foodborne pathogens. The source of the ionizing radiation may be gamma rays from cobalt-60 or cesium-137, machine sources of accelerated electrons of energies up to ten million electron volts (MeV), and x-rays of up to 5 MeV energy. The radiation doses required to control and possibly eliminate such common foodborne pathogens as Campylobacter jejuni, Escherichia coli O157:H7, Listeria monocytogenes, Salmonella, and Staphylococcus aureus; parasites such as Toxoplasma gondi; and food spoilage organisms such as common E. coli and Shewanella putrefaciens are within the dose ranges 1.5 to 3.0 kGy that are currently approved for the irradiation of poultry. A petition is under consideration by the U.S. Food and Drug Administration for approval to irradiate raw, fresh chilled/refrigerated and prefrozen intact and comminuted bovine, porcine, ovine, and equine meat. A maximum dose of 4.5 kGy is requested for raw, fresh chilled/refrigerated meat and of 7 kGy for meat held in the hard frozen state (i.e., -18 °C or lower). These doses are well suited for the control of vegetative bacterial pathogens, but not of bacterial endospores or viruses. The temperature of the product at the time of irradiation may affect the survival of some pathogens. Priority should be given to the irradiation of any ground meat or poultry product intended for consumption by children, the elderly, and by those whose immunity may be compromised and to refrigerated, partially cooked or cooked products, especially if such products are stored and marketed in the refrigerated state. Several contract, commercial irradiation facilities exist, and additional ones are under construction. In addition, innovative on-line radiation sources are under development. The processor needs to consider all the factors, but especially packaging, that are required for adopting irradiation as part of a HACCP plan.*

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Mention of brand or firm names does not constitute an endorsement by the U.S. Department of Agriculture over others of a similar nature not mentioned.

Treating meat and poultry products with ionizing radiation is extremely effective in eliminating both spoilage and foodborne pathogens (Thayer et al., 1996). It does not, however, replace proper sanitation, packaging, refrigeration, distribution, cooking, and serving of the food. The processor also needs to be assured that both distributors and retailers understand that irradiated meats require the same types of handling and refrigeration as any other similar product. Irradiation cannot be used to salvage spoiled products. The source of the ionizing radiation may be gamma rays from cobalt-60 or cesium-137, machine sources of accelerated electrons of energies up to ten million electron volts (MeV), and x-rays of up to 5 MeV energy (FDA, 1990; USDA, 1992). The radiation doses required to control and possibly eliminate such common foodborne pathogens as *Campylobacter jejuni*, *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Salmonella*, and *Staphylococcus aureus*; parasites such as *Toxoplasma gondii*, and food spoilage organisms such as common *E. coli* and *Shewanella putrefaciens* are within the dose ranges 1.5 to 3.0 kGy that are currently approved for the irradiation of poultry (Table 1). The Food and Drug Administration (FDA) is considering a petition submitted by Isomedix Inc. of Whippany, New Jersey, to irradiate raw, fresh chilled/refrigerated and prefrozen intact and comminuted edible tissues of domesticated bovine, porcine, ovine, and equine species that are human food sources. A maximum dose of 4.5 kGy is requested for raw, fresh chilled/refrigerated meat and of 7 kGy for meat held in the hard frozen state (i.e., -18°C or lower). If the petition is approved it will greatly enhance the ability of the meat processor to supply products to the public that are almost certainly free of foodborne pathogens.

The temperature of the product at time of irradiation may alter a pathogen's resistance to radiation. *E. coli* O157:H7, *L. monocytogenes*, and *Salmonella* are typical in that their resistance to radiation is significantly higher in the frozen than in the nonfrozen product (Fig. 1, 2, 3). Increased radiation resistance of foodborne-pathogens at decreased irradiation temperatures is entirely predictable on the basis of the well known fact that reaction rates double with each 10°C increase in temperature. This is especially important in non-frozen products where secondary reactions account for approximately 70% of the radiation-induced lethality. However, this occurs also in the frozen state, as can be seen from the Arrhenius plot of the D-values of *L. monocytogenes* in Fig. 4 and from the plots of the log of the number of surviving colony forming units (CFU) of such organisms as *E. coli* O157:H7 when irradiated at different temperatures (Fig. 1). The hydroxyl radical gradually loses its mobility as the temperature decreases until at approximately -60°C it becomes immobilized and only direct interactions with radiation are involved (Taub, 1979).

The radiation resistance of microorganisms may be lower if they are irradiated in the presence of oxygen because peroxides may be produced. This is readily demonstrable when bacteria are irradiated in buffer, but it is much more difficult to demonstrate an oxygen dependence when they are irradiated on meat, especially if that meat is finely divided. There are at least three reasons why this should be the case: Only very small doses of radiation are required to reduce the normal oxygen levels present in meat through diffusion to zero, so even with oxygen-permeable packaging the radiolytic reactions occurring are largely anoxic (Taub, 1979). Secondly, the normal respiration of fresh meat will reduce the content of oxygen greatly within a ground product. Lastly, a meat matrix

competes with the bacteria for the free radicals generated from the radiolysis of water; this does not occur in a buffer.

Other physical, physiological, and environmental factors such as size, the presence of additives, and the growth stage of a bacterium may alter radiation resistance. By far the most significant of these factors is the great radiation resistance of the bacterial endospore compared to that of its vegetative cell. Because the relative amount of DNA per cell mass is much greater during the log phase of growth when the cells are rapidly dividing, log-phase cells are much more sensitive to radiation than are vegetative cells. These factors are readily demonstrated by the responses of log-phase cells, stationary-phase cells, and endospores of *Bacillus cereus* to radiation (Fig. 5). The increased sensitivity of the log-phase cell is probably much less important, assuming that the product will be properly refrigerated before and during irradiation. The physical factor of size in the case of virus particles, along with their relatively simple structure, results in high radiation resistance. Examples are the hepatitis A virus and rotavirus in clams with D-values of 2.0 and 2.4 kGy (Mallet et al., 1991). Sullivan et al., (1971) found that the radiation resistance of thirty viruses in Eagle's essential medium ranged from 3.9 to 5.3 kGy. Lasta et al., (1992), however, reported that the hoof and mouth disease virus can be inactivated in beef by combining a 15 kGy radiation dose with mild heating at 78°C for 20 min. The implication of this discovery is that the process of radiation sterilization of enzyme inactivated meats, such as are used by U.S. astronauts, would also eliminate the hoof and mouth disease virus. An extreme is the prion particle associated with spongiform encephalopathy (mad cow disease), which is classified, in part, by its extreme resistance to both heat and ionizing radiation. I am unaware of any studies of the combination of irradiation and heating on the prion. The lower the amount of water, not necessarily water activity, in a food the greater the resistance of any foodborne pathogens to radiation (Thayer et al., 1995a). Some food additives, especially antioxidants, are noted for their ability to scavenge free radicals and may, therefore, protect the pathogen from secondary radiolytic reactions. Radiation doses limited to a maximum of 4.5 kGy, thus, are well suited for the control of vegetative cell bacteria, but not for the control of bacterial endospores or of viruses.

Many published studies indicate that if bacteria are in different substrates or even on different meat or poultry products that substantial differences may exist in their radiation resistance. Thayer et al., (1990) documented differences in the radiation resistance of various serovars of *Salmonella*. Well-defined reasons exist, as described above, that explain increased radiation sensitivity in buffers or high radiation resistance in the dry state. It is considerably more difficult to explain statistically significant differences in radiation resistance when bacteria are present on various meats. Thayer et al., (1995b) theorized that since most meats are more similar than different, it was possible that the reported differences in radiation resistance associated with different meats might be explained by experimental differences rather than by chemical differences in the meats. To test this hypothesis the radiation resistance of *E. coli* O157:H7, *L. monocytogenes*, *S. aureus*, and *Salmonella* were determined on beef, lamb, pork, turkey breast, and turkey leg meat. Mixtures of at least three strains or isolates of each pathogen were used in these studies. In three replicate studies conducted at different times, the bacteria were cultivated under identical conditions, the same cuts of meat were used, and the surviving-colony forming units of bacteria were estimated using identical

methodology. The radiation resistances of *E. coli* O157:H7 and *L. monocytogenes* did not change when measured on the five different meats (Table 2). The radiation resistance of *Salmonella* was identical on all meats except pork. The radiation resistance of *S. aureus* was very similar, though not identical, on these meats. The hypothesis was recently stretched considerably further by comparing the radiation resistance of *Salmonella* and *S. aureus* on exotic high-value meats from unrelated classes of animals, namely, bison (bovine), ostrich (ratite), alligator (reptile), and caiman (reptile). The results were the same as above in that there were no significant differences in radiation resistance associated with the meat. The significance of these studies is that both regulators and processors can consider predictions of radiation sensitivity obtained with any of these meats to be extrapolatable within limits to other meats. One does not have to test every possible combination of meat or poultry with every known pathogen.

What products might benefit the most from application of ionizing irradiation as part of a HACCP program, and at what point in a production line do you apply it? There are obviously many possible answers to these questions and many depend upon industrial constraints. What I am about to suggest is based primarily on where I think the greatest potential benefits to health can be obtained. I am not including possible increases in shelf life because that is an economic issue. A company may or may not benefit from an increase in the shelf life of its products. It is unlikely that all meat and poultry products will ever be irradiated; rather, irradiated meat and poultry will be chosen by customers who desire or require a greater degree of food safety, and by food service establishments to protect children and other high-risk consumers from foodborne pathogens. This process should be targeted to products that have high risk either because they contain components that inherently have a substantial possibility of contamination and/or will be consumed by children, by the elderly, by the immunocompromised, and by persons who would prefer to have less risk in their lives. Irradiation of poultry meat, either ground or whole, would seem to be a good idea based on the USDA, Food Safety and Inspection Service national microbiological survey that indicates that the prevalence of broiler chicken carcasses contaminated with *C. jejuni/coli* was 88.2%, with *S. aureus* 64%, with *Clostridium perfringens* 42.9%, with *Salmonella* 20%, and with *L. monocytogenes* 15%. The prevalence of ground chicken samples contaminated with *C. perfringens* was 50.6%, with *S. aureus* 90%, with *L. monocytogenes* 41.1%, with *C. jejuni/coli* 59.8%, and with *Salmonella* 44.6%. At least one firm is now supplying irradiated chicken to hospitals and nursing homes and finding good acceptance of that product. Another obvious target is hamburger, primarily, though not exclusively, because of the risk posed by possible presence of *E. coli* O157:H7. Even though this organism is extremely rare and rather easily killed by proper cooking, its virulence is extremely high. Japan experienced a severe epidemic of infections caused by *E. coli* O157:H7 during 1996.

Irradiation of very large volumes of ground beef required by food service chains may be difficult to accomplish with existing irradiation facilities. This is complicated further by the costs associated with the shipment of products to contract irradiators. Some of these problems may be solved by meat processors building their own radiation plants or by the use of some innovative on-line irradiation systems that are under development. However, before I leave this area of discussion, that there are at least 40 commercial contract irradiators in operation around the U.S.A., and their ability to process products such as hamburger is significant. For example, let us assume for the moment

that we have established a target dose of approximately 3 kGy with a minimum dose of 1.5 kGy and a maximum dose of 4.5 kGy. If the dose rate is 0.11 kGy/min, then the irradiation time per load will be 27.3 min. Further, since these conditions will allow a max/min dose ratio of 3:1, full pallet loads can be processed. Considering that a pallet of hamburger weighs approximately 1,333 pounds, that some plants have carriers with a capacity of two pallets, and that usually 9 carriers will be present in the irradiator at one time, then, 52,734 pounds of hamburger can be irradiated per hour. The actual amount that can be processed will depend on several factors besides the dose rate, such as the bulk density and uniformity of the load, the source strength and configuration, whether the irradiator is batch or continuous operation, the type of carriers used, loading times, and down times. Ideally, irradiators will be specifically designed for the processing of a particular product, such as hamburger. Even on-line, single pallet, self-contained irradiators that are currently under development should have a daily production capability in excess of 53,000 pounds.

Pre-cooked or partially pre-cooked products, especially those foods that are refrigerated rather than frozen, and that require only minimal heating before consumption, merit serious consideration of irradiation as a HACCP intervention step. The pathogen of special concern with such products is *L. monocytogenes* because of the potential for contamination before packaging and its ability to multiply at refrigeration temperatures.

In spite of the great potential for irradiation to serve as an intervention step, the processor must start planning to use the process well in advance of its actual application. Not only is there the consideration of when and how to irradiate, but also the possible effects of irradiation on sensory properties as well as the interactions of packaging. Further, one cannot assume that the packaging materials currently in use are compatible with ionizing radiation nor that they are approved by the FDA for this purpose. In some cases data on extractives may have to be obtained and submitted to the FDA in order to obtain approval of a particular packaging material. It should be noted, however, that major packaging suppliers have stated that upon sufficient demand, materials meeting the current regulation and having the desired physical properties can be produced. Packaging, however, has been a significant problem for those currently processing poultry.

Irradiation could be a valuable intervention step in a HACCP program.

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Table 1. Dose required to make 90% of bacteria or 100% of protozoans non-viable.

Pathogen or spoilage organism	Dose kGy	Substrate	Reference
<i>Bacillus cereus</i> endospore	2.78 ± 0.17	beef	Thayer and Boyd, 1994
<i>Campylobacter jejuni</i>	0.16 to 0.20	beef	Lambert and Maxcy, 1984
<i>Clostridium botulinum</i> endospore	3.58 @ -30°C	beef	Anellis et al., 1975
<i>Escherichia coli</i> O157:H7	0.27 ± 0.03	beef	Thayer and Boyd, 1993
<i>Listeria monocytogenes</i>	0.45 ± 0.03	beef	Thayer et al., 1995b
<i>Salmonella</i> species <sup>a</sup>	0.70 ± 0.04	beef	Thayer et al., 1995b
<i>Shewanella putrefaciens</i>	0.17 ± 0.01	beef	Thayer and Boyd, 1996
<i>Staphylococcus aureus</i>	0.46 ± 0.02	beef	Thayer et al., 1995b
<i>Toxoplasma gondii</i>	0.25	brain	Dubey et al. 1996

<sup>a</sup>*Salmonella* species: *S. dublin*, *S. enteritidis*, *S. newport*, *S. senftenberg*, and *S. typhimurium*.

Table 2. Effect of suspending meat on gamma radiation D-values at 5°C for foodborne pathogens<sup>a</sup>.

Pathogen	Beef	Lamb	Pork	Turkey Breast	Turkey Leg
	D(kGy)±SE <sup>b</sup>	D(kGy)±SE	D(kGy)±SE	D(kGy)±SE	D(kGy)±SE
<i>Escherichia coli</i> O157:H7	0.30 ± 0.02	0.32 ± 0.02	0.30 ± 0.01	0.30 ± 0.01	0.29 ± 0.04
<i>Listeria monocytogenes</i>	0.45 ± 0.03	0.47 ± 0.04	0.48 ± 0.02	0.50 ± 0.03	0.47 ± 0.03
<i>Salmonella spp.</i> <sup>c</sup>	0.70 ± 0.04	0.67 ± 0.04	0.51 ± 0.03	0.71 ± 0.04	0.71 ± 0.04
<i>Staphylococcus aureus</i>	0.46 ± 0.02	0.40 ± 0.03	0.43 ± 0.02	0.45 ± 0.03	0.46 ± 0.05

<sup>a</sup>Adapted from Thayer et al., 1995b.

<sup>b</sup>SE = standard error.

<sup>c</sup>*Salmonella spp.* = *S. dublin*, *S. enteritidis*, *S. newport*, *S. senftenberg*, and *S. typhimurium*.

## FIGURE CAPTIONS

- Figure 1. Response of *E. coli* O157:H7 in finely ground lean beef to a dose of 1.5 kGy when irradiated in vacuo at temperatures of -60 to +15°C. Note that in this and Fig 1, 2, 3, and 5 that the results are presented as the log of (population surviving divided by the original untreated population). Thus, the results indicate the reduction in the population produced by the treatment. Adapted from Thayer and Boyd, 1993.
- Figure 2. Response of *L. monocytogenes* on ground beef following a gamma radiation dose of 2.0 kGy when irradiated in vacuo at temperatures of -60 to +15°C. Adapted from Thayer and Boyd, 1995.
- Figure 3. Predicted survival of *S. typhimurium* on mechanically deboned chicken meat gamma irradiated within the temperature range of -20 to +20°C. Adapted from Thayer and Boyd, 1991.
- Figure 4. Log D-values for *L. monocytogenes* on beef treated with gamma radiation as related to 1/T (absolute temperature). Adapted from Thayer and Boyd, 1995.
- Figure 5. Gamma radiation survival curves on mechanically deboned chicken meat for *B. cereus* ATCC 33018 log-phase vegetative cells (□), stationary-phase vegetative cells (●), and endospores (Δ). The dashed lines around each regression line represent the 95% confidence limits. Adapted from Thayer and Boyd, 1994.







