Food Irradiation[1]

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Ionizing radiation can be used to reduce the population of spoilage organisms (radurization) and to kill all nonsporeforming pathogens (radicidation) and all organisms associated with the product (radappertization). In the radurization process, food is exposed to ionizing radiation doses strong enough to reduce microbial or insect populations and thus, delay spoilage. The radicidation process is analogous to pasteurization. Food in hermetically sealed packages is exposed to ionizing radiation in the radappertization process. In practice, the 12D concept is applied and a dose strong enough to reduce the number of *C. botulinum* spores by a factor of 10^{12} is used. This process is analogous to canning.

However, these processes cannot affect the microbial population without affecting the product, also. Some of these effects take place at levels far below what is necessary to eliminate bacterial or fungal populations, and may be considered either harmful or beneficial depending on the purpose of the treatment.

The U.S. Army Natick Laboratory began researching how to sterilize foods by irradiation in 1962, and by 1964, the use of irradiation was approved by the FDA for use on canned bacon, wheat and wheat flour, and white potatoes (to inhibit sprout growth). In 1968, the FDA rescinded its approval of irradiation for canned bacon and denied approval for canned ham, because, according to the FDA, the data showed significant adverse effects in animals fed irradiated feed, and there were major deficiencies in the way some of the experiments were designed and conducted (1).

The FDA, National Academy of Sciences, and Army developed a new protocol for greatly expanded animal feeding studies, which included beef, ham, pork, and chicken (2). The wholesomeness study of beef was started in 1973, and was in progress when a contract with a different company was established in June 1976 to conduct a parallel study with radappertized chicken (2) (Fig. 1). Unfortunately, the company to whom the beef contract had been awarded did not adhere to the protocol and was declared in default by the Army in 1977 (2). The chicken studies proceeded successfully, and the final reports were accepted by the Agricultural Research Service last year. Responsibility for these studies was transferred from the Army to the Department of Agriculture in October 1980.

Sources and Uses

Two types of radiation sources are proposed for food irradiation: electron (charged particle) sources, in which the electrons are restricted to energy values of less than 10 MeV, and isotope sources. The isotope sources proposed for food irradiation are cobalt-60 and cesium-137. The most important interactions of electrons with organic matter involve collisions with other electrons, causing primary ionization deposition of thermal energy and chemical and/or biological changes (3). Nuclear transformations will probably not occur at energies of less than 10.5 MeV, because the threshold energy for nuclear transformations for most atoms in organic matter is greater than 10.5 MeV (4). Because the gamma rays from ^{60}Co or ^{137}Cs are less than the energy levels required to remove either neutrons or protons from nuclei, they cannot generate significant radioactivity induced in organic matter.

The following are examples of the potential applications of food irradiation: 1) radicidation and radurization of spices, fish and shellfish, meat, and poultry; 2) insect disinfestation of grain and fruit; 3) sprout inhibition for potatoes, onions, and garlic; 4) delay of ripening and senescence and control of storage decay in fruits; and 5) radappertization of nonrefrigerated sterilized diets

Experimental chicken sample sterilized by electron irradiation with an average dose of 5.9 Mrad. The package was opened after 4 yr of storage. Note the firm texture of the product after even this length of storage.

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for the military, space program, and immunologically compromised patients; of animal feed; and of moist pet foods.

Spices. Many spices, such as black pepper, caraway, coriander, ginger, marjorana, and tumeric, are highly contaminated by bacteria and fungi. Aerobic plate counts of 80–100 million bacteria and 100–10,000 mold per gram of spice are typical (5). This results in loss of spice, due to spoilage, and possible health hazards, because although only 0.1–1.0% by weight of the spice will be added to a meat product, it will reach an aerobic plate count of 10^5–10^6.

The two available control methods for erradicating bacteria, mold, and insects in spices are fumigation and irradiation. The major fumigants used are ethylene oxide and propylene oxide for bacteria and methyl bromide for insects. Propylene oxide and ethylene oxide have been reported to form chlorohydrins, which are suspected carcinogens in treated spices (6). Molds and yeasts are least resistant to ethylene oxide. Nonspore-forming bacteria and vegetative cells of spore formers are approximately twice as resistant as yeasts and molds, and bacterial spores are approximately 10 times as resistant as vegetative cells. Fumigation with propylene oxide may take as long as seven hours; propylene oxide is only half as effective as ethylene oxide.

Vajdi and Pereira (7) demonstrated by comparative studies that ionizing radiation was more effective than ethylene oxide in eliminating bacterial contamination of spices. The microbial contamination can be reduced to a level of less than 10^3–10^4 per gram by a radiation dose of 0.5–0.8 Mrad, according to Farkis (8). The FDA responded to petitions in 1983 and approved the use of ^{60}Co and ^{137}Cs for applying radiation doses of up to 1 Mrad to reduce or control microbial contamination of spices, natural flavorings, and dehydrated seasonings.

Several researchers reported changes in the flavoring characteristics of spices after irradiation treatments. No significant changes were found in the quality of powdered black pepper at 1 Mrad, but changes were observed at greater doses. Organoleptic studies of white pepper irradiated with doses of up to 4.5 Mrad indicated that the treatment did not significantly alter the taste or odor (8). Josimovic (9) concluded that ionizing radiation doses of up to 5 Mrad on some water-soluble components of pepper and parsley did not cause any distinct qualitative changes, but quantitative changes were observed in irradiated pepper at doses of less than 1 Mrad. This investigation was typical in that the irradiation was at ambiant temperature in the presence of air at a dose rate of 1 Mrad per hour. Thus, the maximum dose required five hours and the minimum, only 15 min. The authors of that study (9) found an increase in hydroxy carbonyls that was dose dependent at up to 2 Mrad. If these changes are significant, studies should be made under controlled atmospheres and, preferably, at cryogenic temperatures. None of the studies considered by Farkas indicated a problem in the wholesomeness of irradiated spices.

The economic feasibility of radiation treatment of spices is supported by several factors (8). Radiation treatments of spices, unlike fumigation treatments, can be automated and run on a continuous basis, and they can be applied to prepacked materials. The treatments, if used to eliminate bacterial pathogens, could be done after packaging and would not need to be a seasonal activity. Because of both their high value and compactness, the spices could be irradiated at an off-site service facility. The demand for decontaminated spices is increasing and may justify a higher price for treated products.

Meat and Poultry. Meat and poultry can also be treated with the radicidation processes. Fortunately, most pathogens, such as *Salmonella typhimurium* and trichinae, are more sensitive to irradiation than are the normal spoilage flora. Exceptions are those that form endospores (eg, *Bacillus sp.* or *Clostridium sp.*), which are much more resistant to ionizing radiation. There is a threshold treatment level above which nonfrozen, vacuum packed products will develop an unacceptable "irradiation flavor." Urbain (10) established these threshold doses at 5–10° C of pork, beef, chicken, and lamb as 175, 250, 250, and 625 krad, respectively; below these doses, a taste panel could not detect changes in flavor in products. These doses extended shelf-life from seven to 21 days when the products were stored at refrigeration temperatures. Irradiation of vacuum packed beef cuts at 200 krad eliminated pseudomonads, *Enterobacteriaceae*, and enterococci, which resulted in a 10-week shelf-life (11).

The use of low doses of ionizing radiation to extend the shelf-life of refrigerated poultry and to reduce the amount of *Salmonellae* was investigated extensively in the Netherlands by Mulder (12) and Mossel (13). Mossel (13) estimated that the most probable effective dose for reducing *Salmonellae* was 400 krad, leading to a reduction of six log cycles. A major concern about such treatments was whether the potential of *Clostridium botulinum* type E spores, if present, to outgrow and produce toxin would be increased by low-dose (300 krad) irradiation treatment (14). Type E, *C. botulinum*, can multiply at temperatures of less than 10° C and thus, might be a threat in a refrigerated product. The results demonstrated that with 300-krad treatment, even under the worst conditions (30° C, vacuum packed), toxin was not detected before characteristic spoilage began by the surviving natural flora. The question of altered competition, however, still must be studied. Other strains of *C. botulinum* and enteropathogenic strains of *Bacillus cereus* need to be included, and the effect of the relative and total populations considered.

Insect Infestation. The highly toxic fumigants currently used for insect infestation may be the best reason for investigating the use of ionizing radiation and other innovative techniques that do not use toxic materials, such as heat, cold, impact, aspiration, and microwave.

Tilton and Burditt discussed in a recent review (8) results of treating grains with ionizing radiation on insect disinfestation, and in a critical review, Lorenz summarized the literature up to 1975 on irradiation effects on grains (15). According to Tilton and Burditt, the large number of insect species which may be present in a commodity mandates that an effective dose of irradiation must kill or sterilize the most resistant species present. They also found that the sensitivity of any species can be affected by age, sex, strain, food, temperature, type of radiation, and dose rate (8). Differences among the *Coleoptera*, for example, were substantial; a sterilizing dose for both males and females of *Callosobruchus maculatus* was 7 krad, but both males and females of *Palorus subdepressus* were able to reproduce after doses of 130 krad. In general, Tilton and Burditt found that females were more sensitive than were males. The *Lepidoptera* were more resistant to gamma radiation than were the *Coleoptera*. The dose for sterilization for the Indian meal moth, *Plodia interpunctella* (Hübner), exceeded 100 krad. Tilton and Burditt concluded that a dose of 50 krad would control beetles and immature moths.

Combining gamma radiation with other treatments, such as infrared or microwave, are synergistic. Tilton and Burditt reported that treatments of the lesser grain borer, *Rhyzopertha dominica*, with gamma or infrared radiation produced 54 and 55% population reductions, respectively, but when both treatments were used, regardless of the order, a 93% reduction was obtained. The expected reduction was 79%. Similar results were obtained with microwave and gamma irradiation treatments.

Research shows that insects decrease their food consumption after gamma irradiation. Brower and Tilton (16) irradiated adults of the rice weevil, *Sitophilus oryzae* (L.), and the lesser grain borer, *Rhyzopertha dominica* (F.), with 2.5, 5, 10, 25, or 50 krad, and placed them on uninfested wheat. The amount of wheat consumed by the adults and their progeny was much less than that consumed by the controls. Dosage levels of 25 krads reduced feeding by the rice weevil to less than 3% and by the lesser grain borer to less than 11%. During a five-week period, wheat consumption was reduced by 90 and 97%, respectively, for the rice weevil and lesser grain borer. Similar results were reported for the red flour beetle and granary weevil.

The wholesomeness of irradiated grains was established at greater doses than those used for insect disinfestation. Studies with mammals and other animals did not indicate significantly decreased nutritional value or induced toxicity. One negative aspect that needs to be considered is the possible effects of higher radiation doses necessary to control fungal infestation.

Lorenz (15) summarized several studies of the effects of irradiation on the quality of grain and grain milling fractions. Possible effects of irradiation at doses of more than 50 krad include decreased germination, starch damage, changes in dough mixing times, increased water absorption, adverse changes in bread and cake flour, and negative changes in the rate of staling. None of the studies, however, considered the well-defined effects of temperature and atmosphere during the irradiation process. Lorenz concluded that large-scale application of irradiation of cereal grains was unlikely in the United States because of economics, adverse effects of doses sufficient to control fungi, and the ready availability of excellent fumigants. This may change, though, because of increased public concern over the use of fumigants and because of improved design of electron sources.

The ban on the use of EDB and recent fruit fly infestations in California have greatly increased the need for an alternative method of disinfestation treatment for fruits, also. The program for the eradication of the Mediterranean fruit fly (*Ceratitis capitata* - Wiedemann) in California is estimated to have cost more than $40 million (17). Fruits and vegetables grown in the United States are infested with insects not found in other countries. The Caribbean fruit fly, *Anastrepha suspensa* (Loew), which may infest grapefruit in this country, and the codling moth, *Cydia pomonella* (L.), which may infest U.S. cherries, are not found in Japan. As a result, Japan requires that citrus and cherries imported from the United States be treated to eliminate these pests.

Can gamma or electron irradiation of fruit be used as an effective quarantine treatment without substantially decreasing the quality of the product? The use of irradiation was proposed in the United States by Balock et al (18) in 1956, and studies are still being done. Burditt statistically reexamined data for the effect of gamma radiation on the melon fly, the Oriental fruit fly, and the Mediterranean fruit fly (17). The LD-95 dose required to prevent eggs from hatching in each case directly depended on their age. For the Mediterranean fruit fly, the LD-95 dose was 1.1–115.4 krad for eggs 0 and 45 hr old, respectively. However, the calculated dose required to kill 99.99% of the adults was 3.4 krad for two-day-old eggs, 3.5 krad for six-day-old larvae, 2.5 krad for one-day-old pupae, and 128.8 krad for 10-day-old pupae. Using dosage-mortality curves for adult emergence, Burditt concluded that a 13-krad dose would kill 99.99% of the Mediterranean fruit flies infesting papayas. Fesüs et al (19) concluded that the Mediterranean fruit flies infesting oranges could be controlled with doses of 40–60 krad without harming the product.

The phytotoxicity of gamma or electron radiation to fruit makes irradiation treatments doubtful as a method for preventing mold growth—with some exceptions. Burditt et al (20) reported that grapefruit treated with 25–60 krad had increased skin pitting, scald, decay, and, in some treatments, significant taste changes. Moy and Nagai (21) reported that papaya could be irradiated to 100 krad without any adverse effects on its sensory and nutrient quality, although some delay in ripening was noted. The chemical changes associated with irradiation of subtropical fruits was described by Beyers et al (4), who noted that the presence of oxygen had a marked influence on the mutagenic response of irradiated sugar solutions. Strawberries irradiated with 200 krad to control fungal spoilage are marketed successfully in South Africa.

Radurization and Radicidation of Fish and Shellfish. Nickerson, Ricciardello, and Ronsivalli (8) reviewed the radurization and radicidation of fish and shellfish and reached the following conclusions: Low-dose radiation preservation of seafoods would expand the fresh-seafood market, stabilize supply and demand of the products, and stabilize the quality of the products. Using ionizing radiation to preserve seafood does not degrade the nutritional quality more than it is degraded by preserving by heat. Neither carcinogenicity nor toxicity was reported in feeding tests with seafoods. Unless it can be absolutely guaranteed that the irradiated product will be held under conditions that preclude outgrowth of *Clostridium botulinum*, a radiation dose that would ensure normal spoilage must be used to precede toxin production. The use of ionizing radiation at the optimum dose for the species (100–250 krad) can be used advantageously to extend the storage life of marine fish species by approximately one week over that of unirradiated fish. The treatment of fresh-water fish with ionizing radiation may be less advantageous than that of marine species. The storage life of King and Dungeness crab and unshelled shrimp can be extended by ionizing radiation. Crustacean products should be held at temperatures near freezing following irradiation treatment. The treatment of oysters with radiation of 200 krad extended the shelf-life to 21–28 days when the product was stored at 0.6°C. Higher storage temperatures were very deleterious to the storage life of radiation-treated shucked clams or oysters.

Radappertization of Nonrefrigerated Sterilized Diets. The toxicology study of irradiation sterilized chicken initiated by the U.S. Army in 1976 (22) was one of the most comprehensive studies of a food product ever undertaken, requiring approximately 300,000 lb of chicken. This study was really 20 separate studies, conducted to examine the nutritional and toxicological properties of the irradiation sterilized chicken. Other studies were done to establish the 12-D dose, the radiolytic changes in the chicken, and the properties of the packaging materials.

The toxicology studies can be separated into three general classes: teratology studies; chronic toxicity, oncogenicity, and multigeneration reproductive studies; and genetic studies. The studies used five diets: 100% basal; 35% enzyme-inactivated chicken, stored frozen; 35% thermally sterilized chicken; 35% gamma ray radappertized enzyme-inactivated chicken; and 35% electron-radappertized enzyme-inactivated chicken. The average dose for the radappertized samples was 5.9 Mrad.

Teratology studies were conducted with mice, hamsters, rats, and rabbits. The general conclusion that may be drawn from all four studies is that none of the processed chicken meats produced a teratogenic response when fed to pregnant animals.

A planned two-year chronic toxicity, oncogenicity, and multigeneration study of groups of Sprague Dawley rats fed the five experimental diets was aborted at the 39th week because of a high incidence of neonatal death. Although the cause of death was attributed to lack of lactation, the lactation problem was not linked to any of the chicken diets. None of the five diets produced remarkable toxicological effects on rats or their reproductive capacity.

Beagle dogs were exposed to the same test and control diets *in utero*. These continued until death or sacrifice at 36 months postweaning for females and 40 months postweaning for males. As the F_0 females attained sexual maturity, they were bred on successive estrus periods to produce as many litters as possible before the end of the study. Offspring were selected from the F_1 generation litters at weaning for continued feeding until six months of age. No overt signs of toxicity attributable to diet were observed in any of the experimental groups. Male F_0 dogs fed the gamma-irradiated chicken diet had significantly lower body weights through adulthood than did dogs fed the frozen control diet. This conclusion, however, is obscured by the fact that the dogs in the F_0 group were considered obese. The group of F_0 females fed the gamma-irradiated diet had comparatively greater fecundity than did dogs on other diets. No treatment-related abnormalities or changes were observed.

CD-1 mice were also exposed to the test and control diets *in utero*. These continued until death or scheduled termination. The chronic feeding study was continued for 24 months postweaning. Three generations of mice were studied. No differences were reported in fertility, fecundity, stillbirth incidence, or birth-to-weaning survival in groups of mice fed gamma- (G group) or electron- (E group) irradiated chicken, compared to the frozen control, but the fertility of the mice fed the thermally processed chicken decreased. The study scientists, from Ralston Purina (22), concluded that, "Survival of both sexes in Group G was significantly reduced, at least in certain subgroups, compared to the controls. Group G had the highest incidence of several tumors among those discussed. In particular, the results on alveologenic tumor incidence cannot be summarily dismissed as an artifact resulting from differential survival rates. Also, many of the lesions which occurred infrequently and for which statistical analyses could not be performed, were often found most frequently in the G group." Other scientists, from Tracor Jitco, Inc., who examined this 10,328-page report in detail, did not agree with the significance attributed to these findings by the Ralston Purina scientists. In general, they concluded that an inappropriate statistical procedure was used, and this was exaggerated further by an increased rate of death in the G females that could not be linked to any specific lesion.

The genetic studies resulted in the following conclusions. The manner in which the chicken meat was processed had no effect on the response to known mutagens in the Ames test. Based on the breeding performance by sons of treated male mice and examination of testicular cells, no evidence of chromosome damage was noted after feeding the chicken diets to mice. No dominant lethal effects were observed in mice whose diet consisted of 35% chicken. None of the processed chicken meats were mutagenic, based on the sex-linked recessive lethal study of *Drosophila melanogaster*; a positive control of 100 ppm TRIS (2,3-dibromopropyl) phosphate gave a significant response. There was, however, an unexplained significant reduction in the production of offspring in cultures of *D. melanogaster* reared on gamma-irradiated chicken. This response was dose-related and could not be overcome by adding vitamin supplements. A similar, but much lower, response occurred in cultures reared on the frozen chicken control.

Conclusion

Irradiation processing of foods can produce many potential benefits, but it is not a panacea or a process free from concern. On balance, the studies of radappertized chicken conducted by the U.S. Army and various contractors strongly support the process's safety, but there are some potentially serious adverse results, which must be considered when the FDA examines these studies.

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