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FOOD IRRADIATION: BENEFITS AND CONCERNS

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ABSTRACT

The benefits and concerns about treating foods with ionizing radiation are reviewed. Radioactivity cannot be induced in foods by treatment with gamma rays from ^{137}Cs or ^{60}Co , X-ray sources of 5 MeV or lower energy, or electrons of 10 MeV or lower energy. The evidence supports the safety and efficacy of using ionizing radiation for insect disinfestation of grains; dried spices, vegetables and fruits; and fresh fruit. Species and dose dependent phytotoxic and vitamin changes may occur in some fruits at greater doses than currently approved by the U.S. Food and Drug Administration. Irradiation can inactivate protozoan or helminth parasites and significantly decrease the probability of viable food-borne bacterial pathogens in fish, poultry, and red meats. The titers of amino acids, fatty acids, and vitamins of chicken meat sterilized by thermal, electron-beam, or gamma radiation are presented. On the whole, the data support the safety and efficacy of the process.

INTRODUCTION

Ionizing irradiation has been proposed for (1) insect disinfestation of grain; dried spices, vegetables, or fruits; and fresh fruits; (2) inhibition of sprouting in tubers and bulbs; (3) alteration of postharvest ripening and senescence of fruits; (4) inactivation of protozoa or helminths in meats and fish; (5) elimination of spoilage microorganisms from fresh fruits and vegetables; (6) pasteurization or sterilization of dried spices and vegetables; (7) extension of shelf-life of meats, poultry, fish, or shellfish; (8) elimination of bacterial pathogens from meats, poultry, fish, or shellfish; and (9) sterilization of foods and feeds (Thayer 1984). Because ionizing-irradiation treatments have been proposed for virtually every class of fresh and processed food involving vastly different treatment conditions and radiation doses, discussions of the wholesomeness of such products must be categorized by food class, specific nutrient, the intended purpose of the

irradiation treatment, the absorbed dose, and at least some concern for the benefit-to-risk ratio. In this manuscript the benefits of food irradiation in context with the risks that may be associated with the treatment will be discussed.

Four criteria are generally recognized as necessary for an irradiated food to be considered wholesome (Josephson 1983): (1) the absence of induced radioactivity; (2) the absence of viable pathogens or their toxins; (3) the absence of excessive loss of nutrients; and (4) the absence of toxic, mutagenic, or carcinogenic radiolytic products. These criteria, with the exception of induced radioactivity, will be discussed when appropriate for each of the objectives for food irradiation stated above. In addition the following caveats are applicable to food irradiation and should be considered by those using the process: Food irradiation is like any other process in that it can be used properly to accomplish a desirable goal or it can be abused. Food irradiation is not a panacea for all food preservation or food safety problems. Food irradiation cannot, nor is it intended to, replace proper food sanitation, packaging, storage, and preparation.

INDUCED RADIOACTIVITY

Extensive research exists to demonstrate that irradiation of foods with the isotope sources ^{60}Co or ^{137}Cs , X-ray sources of 5.0 MeV or less energy, and accelerated electrons with energies of less than 10 MeV will not induce radioactivity in foods (Becker 1983; Koch and Eisenhower 1967). The absorption of ionizing radiation in the form of high energy neutrons, alpha particles, protons, and photons can induce a wide variety of nuclear reactions in various nuclei; the question of concern, however, is whether such reactions can be induced in foods using the radiation sources, described above, which are approved for use in food treatments. In order for ionizing radiation to induce a nuclear reaction it must be of sufficient energy to excite the atom (threshold energy). Only three nuclides are likely to occur in foods which have threshold energy values permitting reactions with X or γ rays of 5 MeV or less. These are ^2H at 2.23 MeV, ^{17}O at 4.14 MeV, and ^{13}C at 4.95 MeV (Koch and Eisenhower 1967). Each of these forms a stable isotope (^1H , ^{16}O , and ^{12}C , respectively) by emitting a neutron. The neutron fluxes from the reactions with these minor isotopic constituents of foods are low and do not lead to other nuclear reactions in foods. The emissions from either ^{60}Co or ^{137}Cs are of lower energy than these threshold levels. The effective threshold level for the induction of measurable radioactivity in food by electron radiation through bremsstrahlung is 10.5 MeV (Becker 1983).

INSECT DISINFESTATION OF GRAIN AND FLOUR

The use of ionizing-radiation treatments to an absorbed dose of 0.2 to 0.5 kGy (1 kGy = 100 krad) for control of insect infestations of wheat and wheat

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flour from unirradiated wheat was approved by the United States Food and Drug Administration in 1963 (Federal Register 1986b). These regulations were amended to permit the use of food irradiation at doses not exceeding 1 kGy for insect disinfestation in 1986 (Federal Register 1986b). No use has been made of these regulations in the United States; commercial grain irradiation reportedly does take place in Russia (Zakladnoi *et al.* 1982). Even the rather small radiation doses allowed would be effective, as attested by several reviews (Thayer 1985; Tilton and Brower 1983; Tilton and Burditt 1983; Tilton and Brower 1987). Combining ionizing radiation with other insect disinfestation treatments increases their overall effectiveness (Tilton and Burditt 1983; Tilton and Brower 1987). Insects that survive the radiation treatment do not develop resistance to radiation (Tilton and Brower 1987).

Lorenz (1975) reviewed the extensive data on the irradiation of grains and cereal grain products and concluded that studies with rats, mice, pigs, dogs, chickens, and humans had not produced any evidence of significantly decreased nutritional value of grains and cereal grain products even at irradiation doses considerably higher than those recommended for control of insects. Concern was expressed by one reviewer with the proposed US regulations for irradiated foods (Federal Register 1986b) because of reports by Privadarshini and Tulpule (1979) that wheat irradiated at dose levels up to 2.50 kGy showed a dose-dependent susceptibility to aflatoxin production by *Aspergillus parasiticus*. These workers did not claim that irradiation would increase the susceptibility of stored wheat to aflatoxin production. They were investigating production of aflatoxin on wheat that had been irradiated and then sterilized by autoclaving before inoculation. It is well known that irradiation affects both starches and lipids in grains, and indeed the investigators noted a dose-dependent increase of free fatty acid levels in the irradiated wheats. Privadarshini and Tulpule (1979) pointed out that other workers had found that lipids stimulated aflatoxin production. Whether or not increased aflatoxin production might occur during growth of *A. parasiticus* on irradiated as opposed to nonirradiated wheat remains to be tested.

A report by Bhaskaram and Sadasivan (1975) claiming that feeding irradiated wheat to malnourished children caused them to develop polyploid cells generated considerable controversy. This report was the subject of extensive reviews by several different agencies leading to the conclusion that the bulk of these data are mutually contradictory and at variance with well-established knowledge of biology (Kesavan and Sukhatame 1976; Federal Register 1986b). George *et al.* (1976) reported the results of a study of the frequency of polyploid cells in the bone marrow of rats fed irradiated (0.75 kGy) wheat for 1 to 6 weeks. No cytological evidence was found to support a conclusion that eating irradiated wheat resulted in increased polyploidy even when the wheat was fed to the rats within 24 h of irradiation.

One aspect, however, merits further consideration: whether or not combination treatments may aggravate radiation-induced losses of vitamins. Diehl (1981)

obtained results with rolled oats and wheat flour that indicated a more than additive effect on the loss of α -tocopherol and thiamine when irradiated grains are cooked. Rolled oats lost 17.1%, 40%, and 60% of their α -tocopherol when irradiated (1 kGy), baked (30 min at 200°C), or irradiated and baked, respectively. The combined value should have been 57.1%. Wheat flour lost 20%, 5%, and 50% of its thiamine when irradiated (0.35 kGy), cooked (10 min, 100°C), or irradiated and cooked (Diehl 1981). These values are not additive, and the radiation dose is in the range that would be used for insect disinfestation. The wheat flour that was baked 30 min at 200°C following irradiation to 0.35 kGy had no detectable thiamine remaining. Diehl (1981) reported that the loss of α -tocopherol in stored irradiated (1 kGy) rolled oats was greater than that in nonirradiated oats under the same conditions. Diehl (1981) correctly pointed out that these grains would probably not be cooked by themselves, and the presence of other ingredients would alter these results. This comment, however, cannot be applied to the storage of irradiated grains. No significant differences, however, were observed in the thiamine content of irradiated (1.0–10 kGy) and nonirradiated corn flour even after storage for one year (Tobback 1977). Chappel and MacQueen (1970) reported that irradiation had no effect on the levels of thiamine and riboflavin in wheat flour immediately after treatment or after 3 months storage.

INSECT DISINFESTATION OF DRIED SPICES, VEGETABLES, AND FRUITS

Dried spices, vegetables, and fruits are frequently infested with insects and are usually disinfested with methyl bromide. Insects can also be eliminated by irradiation to a maximum dose of 1.0 kGy. The same considerations of effectiveness and wholesomeness apply, plus the fact that the amount of dried spices ingested is a very small proportion of the total diet. If greater doses of radiation are used, the microbial population can be eliminated from these products as described below; and it is in this area that there is much greater interest.

INSECT DISINFESTATION OF FRESH FRUIT

Insects can be completely eliminated from fruit by ionizing irradiation. However, phytotoxic damage to the fruit and vitamin losses will also occur depending primarily on the total absorbed radiation dose. The greatest advantage of ionizing irradiation for insect disinfestation of fruits is that insecticides need not be used at harvest time. The ban on the use of ethylene dibromide (EDB) in the USA coupled with the fruit fly infestations that occurred in California have increased the need for alternative methods of insect disinfestation. Fruits and vegetables

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grown in the continental USA can be infested with insects not found in other countries, and the reverse is also true. For example, the Caribbean fruit fly *Anastrepha suspensa* (Loew), which infests grapefruit, and the codling moth *Cydia pomonella* (L.), which infests cherries, are not found in Japan so these products require treatment before they can be imported into Japan (Burditt 1982). Irradiation doses below 1 kGy are effective for the control for codling moths, fruit flies, mango weevils, naval orangeworms, potato tuberworms, spider mites, and scale insects (CAST 1984). Doses of 0.25 kGy are tolerated by most fresh fruits and vegetables with little or no detrimental effect on quality (CAST 1984). Fruits such as apples, cherries, dates, guavas, mangoes, nectarines, papayas, peaches, raspberries, strawberries, and tomatoes suffer little phytotoxic damage (CAST 1984). However, inconsistent or detrimental results have been obtained with products such as avocados, grapefruit, grapes, kumquats, lemons, limes, oranges, pears, peppers, pineapples, and tangerines (CAST 1984). A carefully controlled study of consumer responses to irradiated papayas was recently conducted in California (Bruhn and Noell 1987). The consumer was offered both the traditional double-dipped (in hot water) and the clearly identified irradiated (0.45 kGy) papayas of comparable size and quality. The consumers purchased significantly more of the tree-ripened (irradiated) than the traditional double-dipped products. The consumers also preferred the taste of the irradiated products. Surprisingly, 60–75% of the customers did not realize that pest-control treatments are required before papayas can be brought to the mainland from Hawaii. Jessup *et al.* (1988) reported that a hot benomyl dip in combination with irradiation to 0.75 to 6.0 kGy preserved the quality of mangoes with negligible adverse phytotoxic effects.

CAST (1984) concluded that only negligible losses in niacin, thiamine, riboflavin, and β -carotene in fruits have been attributed to treatments with ionizing radiation. Losses in ascorbic acid, however, varied from 0 to 95% depending upon the commodity, variety, radiation-dose duration, and temperature of storage. Since much of the ascorbic acid is converted to dehydroascorbic acid, which is known to be metabolized by man in the same way as ascorbic acid, nutritional evaluations should consider both forms of the vitamin (Tobback 1977; Kraybill 1982).

When a pure solution of glucose is irradiated a number of products such as formate, acetate, propionate, lactate, acrylate, fumarate, dimethyl fumarate, benzoate, methyl benzoate, and phenyl acetate are formed (Simic 1983). In the presence of oxygen further reactions of the six possible glucose radicals may take place to yield such products as D-gluconic acid, D-glucuronic acid, and glyoxal (Simic 1983). Starch undergoes degradation via splitting of a glycosidic bond (Simic 1983). Irradiated sucrose solutions have produced an abnormal anaphase in bean tips (Bradley *et al.* 1968), decreased carrot tissue culture growth (Holsten *et al.* 1965), and increased *Salmonella typhimurium* revertants (Beyers

et al. 1983). Dicarbonyl sugars are the predominant biologically active compounds formed by irradiation of pure sugar solutions in the presence of oxygen (Beyers *et al.* 1983). These dicarbonyl sugars can be converted to the α , β -unsaturated carbonyl sugars, which are also present in nonirradiated foods (Beyers *et al.* 1983). The yield of these compounds in a fruit rather than in a pure sugar solution would be expected to be much lower. Bradley *et al.* (1968) concluded that the low pH of the irradiated sucrose solution was responsible for the abnormal anaphase formation observed in the study. Mango pulp irradiated to a dose of 20 kGy did not produce a mutagenic effect (Beyers *et al.* 1983); and even when glucosone (2×10^{-3} M) was added to the mango pulp, the number of revertants was significantly reduced. *In vivo* mutagenicity studies (micronucleus test and sister-chromatid exchange) in rats, mice, and Chinese hamsters fed a 100% diet of irradiated dates (1 kGy) and mangoes (0.8 kGy) for 4 days showed no evidence of genetic toxicity (Renner 1982). Ingestion of irradiated (1 kGy) dates by *Drosophila melanogaster* larvae did not produce sex-linked recessive lethals in the germ cells of surviving male flies (Graf and Wurgler 1982). Reproductive studies and chronic toxicity studies with rats fed irradiated dates or mangoes have not demonstrated irradiation-induced toxicity (Tesh 1981; Raltech Scientific Services 1981a,b).

INHIBITION OF SPROUTING IN TUBERS AND BULBS

The use of ionizing irradiation (0.05–0.15 kGy) to inhibit sprouting of white potatoes was approved in the USA in 1964. The only commercial application of the process has been in Japan (Matsuyama and Umeda 1983). Matsuyama and Umeda (1983) reviewed the biological effects, benefits, limits, disadvantages, and applications of ionizing irradiation for sprout inhibition. A minimum dose of 0.02 to 0.03 kGy for onions and 0.03 kGy for potato tubers is required for sprout inhibition, and smaller doses may actually stimulate sprouting (Matsuyama and Umeda 1983). Doses greater than 0.15 kGy may cause significant detrimental effects in both tubers and bulbs (Matsuyama and Umeda 1983). Careful attention as to handling, selection, avoidance of mechanical injury, irradiation during dormancy, and proper storage conditions appear to be essential to avoid discoloration. Neither onions nor potatoes that had received sprout-inhibiting doses of ionizing radiation before storage had significant losses of vitamin C compared with nonirradiated potatoes (Basson 1983). In aqueous solutions ascorbic acid is degraded to dehydroascorbic acid by ionizing radiation (Basson 1983). Matsuyama and Umeda (1983) reviewed several studies in which the percentage of ascorbic acid of the tuber was determined immediately after irradiation and again after storage. At sprout-inhibiting doses approximately 15% of the initial ascorbic acid was lost; however, after prolonged storage the dif-

ferences in ascorbic acid between irradiated and unirradiated potatoes were not significant. Maysuyama and Umeda (1983) concluded that though changes occurred in the free amino acids of potatoes irradiated (0.15 kGy) for sprout inhibition, these changes disappeared during storage. No significant changes were identified in protein-bound amino acids or in the biological value of the protein of irradiated potatoes.

ALTERATION OF POSTHARVEST RIPENING AND SENESCENCE OF FRUITS

In some cases, the same or slightly greater doses of ionizing radiation that control insect pests will alter the postharvest ripening and senescence of fruits (Akamine and Moy 1983). Examples are the delay of ripening of bananas (0.20 kGy), mangoes (0.10 to 0.25 kGy), and papayas (0.75 kGy) (Akamine and Moy 1983). The shelf-life of sweet cherries can be extended by a 3 kGy radiation dose and that of strawberries by a 2 kGy dose, which greatly inhibits the growth of the principal fungal pathogen (Akamine and Moy 1983). The same discussion of changes in organoleptic properties and vitamins described previously for insect disinfestation is applicable.

INACTIVATION OF PROTOZOA OR HELMINTHS IN MEATS AND FISH

Several meat- and fish-borne parasites of man that are transmitted in raw or improperly cooked meat and fish might be controlled by irradiation. *Toxoplasma gondii*, *Trichinella spiralis*, *Cysticercus bovis*, and *Cysticercus cellulosae* may be especially well suited to control by irradiation. *Toxoplasma gondii* is an intracellular protozoan parasite that can be transmitted to man in improperly cooked beef, mutton, or pork. Recent work by Dubey *et al.* (1986) has provided evidence that radiation doses of 0.25 kGy or greater will inactivate *T. gondii* in pork tissues. The bovine and pork tapeworms, *Cysticercus bovis* and *Cysticercus cellulosae*, respectively, can be rendered incapable of development and presumably incapable of infecting man by low doses of radiation (0.40 to 0.60 kGy) (King and Josephson 1983). *T. spiralis* has received the most extensive study under conditions appropriate for the development of regulations for the use of ionizing radiation for its control. This parasitic nematode causes trichinosis in man and localizes in the muscles of pigs and many wild mammals. Brake *et al.* (1985) found that 0.30 kGy of radiation blocked maturation of *T. spiralis* from infected, split, market-weight hog carcasses when ingested. These data were the basis of the U.S. Food and Drug Administration regulation allowing control of *T. spiralis* in pork carcasses or fresh, nonheat-processed cuts of pork carcasses

by the use of ionizing radiation doses of 0.3 to 1.0 kGy (Federal Register 1986b). A detailed discussion of the food safety considerations made by the U.S. Food and Drug Administration can be found in the Federal Register (1987). The USDA Food Safety Inspection Service requested the Agricultural Research Service to study the effect of ionizing radiation on vitamins of fresh pork and poultry over the anticipated dose ranges and operating conditions for the control of pathogens in these products (Thayer *et al.* 1988). Surprisingly little information was available on vitamin destruction in meat or poultry at doses below 10 kGy. These authors found thiamine losses of 5.6 and 17.6% in pork irradiated to 0.3 or 1.0 kGy, respectively, which includes the radiation dose range approved for trichina control. Losses were not found in the riboflavin, niacin, pyridoxine, and cobalamin in pork irradiated to a dose of 1 kGy (Fox *et al.* 1989).

EXTENSION OF SHELF-LIFE AND ELIMINATION OF BACTERIAL PATHOGENS MEATS, POULTRY, FISH, OR SHELLFISH

The benefits of ionizing radiation for nonsterilizing treatments of red meat, poultry, fish, or shellfish derive both from a food preservation and a safety standpoint. Urbain (1983) reviewed some of his own data for the effect of various doses of gamma radiation on the total plate count of vacuum-packaged beef steaks stored at 40°C. The nonirradiated steaks reached a plate count of $5.6 \times 10^7/g$ after 14 days storage. A dose of 0.5 kGy resulted in a plate count of $3.0 \times 10^7/g$ after 21 days and a dose of 2.5 kGy in a plate count of $9 \times 10^6/g$ after 21 days. It should be noted, however, that he also stated that the threshold dose for identifiable irradiation flavor is 2.5 kGy for beef irradiated at 5 to 10°C. Nickerson *et al.* (1983) provide an example of the extension of shelf-life of haddock fillets with ionizing-radiation treatments and storage under refrigerated conditions. At a refrigeration temperature of 5°C the fillets became organoleptically unacceptable at 16, 31 and 41 days after radiation doses of 0, 1.0 and 2.0 kGy, respectively. Data from Sieling is also cited by Nickerson *et al.* (1983) in which the storage life of cut catfish at 0°C was extended by 16 days with a radiation dose of 2.0 kGy. Several other examples of shelf-life extension by the use of ionizing-radiation treatments of the commodity can be found in the literature.

The microbiological safety of irradiated foods is, to a very large extent, affected by the same factors which interact with any other food processing technology. Those factors are the types and numbers of potentially pathogenic microorganisms; the relative resistance to ionizing radiation of the pathogen(s) compared with those of the normal microbial flora; the abilities of these pathogens to compete with the food's normal microbial flora following irradiation treatment;

the radiation dose; the irradiation temperature; the atmosphere; the presence of food additives; the nature of the food itself (its pH, water content, surface area, and composition); the possible interaction of the radiation treatment with any other processing treatment; and packaging of the treated product (Thayer *et al.* 1986). The sequence in which the product has become contaminated with the potential pathogen is also obviously important as contamination following irradiation reduces competition from the natural flora. Four factors must be considered when the doses of ionizing radiation are insufficient to sterilize the product: (1) What dose of ionizing radiation will be required to sufficiently reduce the population of the pathogen(s) of concern so that it will no longer be of concern? (2) Will the natural flora of the product be so altered by the ionizing radiation that even a few vegetative cells or endospores of a potential pathogen may be able to grow or to produce toxin under abuse conditions because of the absence of competition? (3) Is it probable that a radiation-resistant mutant of a pathogenic microorganism might be introduced into the food chain? (4) Is it probable that treating the food with ionizing radiation might produce a mutant strain more pathogenic than the parent strain or might result in greater toxin production?

The answer to the first two questions depends on the type of food product, the presence or absence of any food additives, the use of processing treatments other than irradiation, the pathogen of concern, and the packaging and storage of the product. It is extremely unlikely that most food products will contain more than 1,000 vegetative cells or endospores of a human pathogen per gram of food before the product is obviously spoiled from growth of normal spoilage microorganisms. Thus, treatments that reduce the pathogen population by 10^3 to 10^6 generally should be microbiologically safe. Radiation doses necessary for a 10^3 reduction in the population of bacterial vegetative cells are not conducive to uninhibited growth of the pathogen because of the much greater numbers of the natural microbial population. However, few published studies have tested this concept. Adequate data exist on salmonellae as contaminants of fresh or frozen poultry to conclude that the limiting factors for the irradiation of this product are more organoleptic than microbiological (Mulder *et al.* 1977; Mossel 1977). Food irradiation is appropriate for the control of *Aeromonas hydrophila* (Palumbo *et al.* 1986) *Campylobacter jejuni* (Lambert and Maxcy 1984) and *Lysteria monocytogenes* (Huhtanen *et al.* 1989). Two recent studies concluded that there is no increased probability of growth and toxin production of *Clostridium botulinum* types A, B, and E on chicken skin following a 0.3 kGy radiation dose (Dezfulian and Bartlett 1987; Firstenberg-Eden *et al.* 1982). The possibility of the presence of *C. botulinum* type E on fish requires that it be stored below 3.3°C after irradiation treatment (CAST 1986).

The use of ionizing radiation to ensure the microbiological safety of processed meats was reviewed by Thayer *et al.* (1986). Because the organism of concern

is, in this case, *C. botulinum*, whose endospores are extremely resistant to radiation, great care must be used in evaluating attempts to substitute irradiation for additives such as salt or nitrite in the preparation of processed meats. Unfortunately, several studies have indicated that irradiation of some processed meat products at doses of less than 10 kGy may not be beneficial and, in some cases, may result in decreased safety especially where there is an attempt to substitute the irradiation treatment for all or part of the nitrite or sodium chloride that would normally be used in such products (Anellis *et al.* 1977a; Huhtanen *et al.* 1986; Rowley *et al.* 1983). However, the use of 2.5% NaCl together with 0, 5, or 10 kGy inhibited *C. botulinum* toxin formation in inoculated turkey frankfurters for 4, 30, and 40 days, respectively, when incubated at 27°C (Barbut *et al.* 1987). The use of NaCl was markedly more effective than KCl or MgCl₂.

It is highly unlikely that radiation-resistant mutant strains of pathogens will be introduced into the food chain (Maxcy 1983; Mossel 1977; CAST 1986).

The wholesomeness of meat, poultry, fish, and shellfish products irradiated either to extend shelf-life or to control pathogens was reviewed (Brynjolfsson 1985; CAST 1986; JECFI 1980; Thayer 1987). One of the objections to the consumption of irradiated foods is that ionizing radiation produces free radicals and that their subsequent ingestion in the food may cause toxic effects (Federal Register 1986b). At least in the case of meats, fish, and poultry this does not seem to be a valid concern since it has been demonstrated that free radicals generated in beef muscle proteins by irradiation to 50 kGy at -40°C decayed within 8 h at -10°C and completely disappeared upon thawing (Taub *et al.* 1978). These results would be expected because of the water content of these commodities. Admittedly some dry products might retain free radicals for a considerable period of time, but few, if any, of these products would be consumed in the dry state. Feeding studies conducted by Renner and Reichelt (1973) specifically to determine if there were any effects from the ingestion of a diet containing a high concentration of free radicals from irradiated (45 kGy) milk powder did not reveal such effects in a 3-year multi-generation study with 716 rats.

Concern has been expressed that peroxides and hydroperoxides might be formed in irradiated foods (Federal Register 1986b). Many food processing technologies also produce peroxides and hydroperoxides, and their chemistry has been extensively studied (Nawar 1983). There is no evidence to suggest that irradiated foods would be metabolized differently than other foods containing such products. Gower and Wills (1986) reported that the peroxide value of irradiated (3 kGy) herring flesh increased to 516% of the preirradiation value and that benzopyrene was oxidized. Since benzopyrene must be oxidized to be mutagenic or carcinogenic, this observation may be significant where irradiation of fatty fish is considered. A 90-day feeding study with 60 Wistar rats consuming

irradiated dried mackerel did not, however, reveal any treatment-related effect (Nadkarni 1980).

Fox *et al.* (1989) studied the effects of gamma irradiation (0–6.65 kGy) on the thiamine, riboflavin, niacin, pyridoxine, and cobalamin in pork chops and on the thiamine, niacin, and riboflavin of chicken breasts. Irradiation temperatures of -20 , -10 , 0 , $+10$, and $+20^{\circ}\text{C}$ and both cooked and raw products were investigated. The irradiated pork lost 17.5% of its thiamine at 0°C and 1.0 kGy and 65.6% at 0°C and 6.65 kGy compared to that of the nonirradiated pork. Significant losses were not observed for the other vitamins. By comparison, cooked chicken that was irradiated to 6.65 kGy and then cooked lost 36.9% of its thiamine.

STERILIZATION OF FOODS

If the objective of the irradiation treatment is a shelf-stable (sterile) product, then the radiation dose necessary for a 12-log reduction in the number of viable cells or endospores of the most resistant pathogen, which is usually considered to be *C. botulinum*, is determined for the product as it will be used. The 12D values for a given food produced under defined conditions can readily, if laboriously, be determined by inoculated pack studies; several such values have been determined. Typical of these were 42 kGy for enzyme-inactivated chicken (Anellis *et al.* 1977b) and 41.2 kGy for beef irradiated *in vacuo* at -30°C (Anellis *et al.* 1979). High quality shelf-stable meat products have been produced (Thayer *et al.* 1987; Wierbicki 1985; CAST 1986).

Foods are unlikely to be subjected to doses of ionizing radiation greater than 60 kGy for a number of reasons. That dose is greater than required for a 12-decimal reduction of *C. botulinum* in chicken meat irradiated *in vacuo* at -30°C . Secondly, such doses can produce highly undesirable organoleptic changes if the product is not vacuum packaged and deep frozen at the time of irradiation.

In 1976 extensive nutritional, genetic, teratogenic, and multigeneration feeding studies of chicken meat sterilized by ionizing-radiation treatments were initiated by the U.S. Army by contract to Reltech Scientific Services of St. Louis, Missouri. In 1980 the responsibility for this contract was transferred to the Agricultural Research Service. Because large amounts (135,405 kg) of chicken were required for the study an unusual opportunity now exists for the comparison of nutrients in chicken meat preserved by four different techniques. The chicken meat for these studies was enzyme inactivated by heating to an internal temperature of 73 – 80°C and vacuum packaged prior to further processing in cans or in 26 mm thick slices in laminated foil packages in the case of the electron-irradiated product. The frozen control chicken (FC) was stored frozen, the thermally processed chicken (TP) was heated to an internal temperature of 115.6°C

($F_0 = 6$), the gamma-irradiated chicken (GAM) and the electron-irradiated chicken (ELE) were sterilized by gamma radiation from ^{60}Co or by 10 MeV electrons to an absorbed dose of 45 to 60 kGy at $-25^\circ\text{C} \pm 15^\circ\text{C}$. Complete processing details were described by Thayer *et al.* 1987; and Wierbicki 1985. Analytical methods were described by Black *et al.* 1987. The chicken was purchased and processed in three separate lots during the study. Nutrients in each lot of the four products were analyzed for nutrients both immediately after processing and during storage. In Tables 1–3 the values for individual analyses of each lot are abstracted from the appendices of the study reports (Black *et al.* 1983), and the treatment means are reported for each nutrient. Data from the analyses of the four treatment products were subjected to analysis of variance using a randomized complete block design and the SAS GLM procedure. Dunnett's test was used to identify significant differences from the FC. All statements of significance were at the $p = 0.05$ level (SAS 1987).

The percentages of amino acids in the TP, ELE, and GAM meats were not different from those of the FC meat (Table 1). Even cysteine and methionine, which might be expected to have greater sensitivity to ionizing radiation, were unaltered.

In Table 2 the analytical values for fatty acids, crude fat, peroxide, and thiobarbituric acid (TBA) for each of the four processed chicken meats used in the study are presented. No significant differences were detected in the means for the percentages of the individual fatty acids, free fatty acid, crude fat, and peroxide, in the TP, GAM, and ELE meats from those of the FC meat. The TBA values of the TP and GAM meat differed from that of the FC meat.

In Table 3 the percentages of each vitamin in the four processed chicken meats are presented. The percentages of thiamine in both the TP and GAM meats were significantly different (lower) from that of the FC meat. The percentages of riboflavin and folic acid in the ELE meat were significantly higher than in the FC meat. There was a higher percentage of vitamin B₁₂ in the TP and GAM meats than in the FC meat. The percentage of no other vitamin in the GAM, ELE, or TP chicken meats differed from that found in the FC chicken meat.

Josephson (1983) reported that beef that received a radiation dose of 47 to 71 kGy was not significantly different from beef preserved by freezing or thermal processing ($F_0 = 5.8$) based upon the concentrations of 18 amino acids. Thayer *et al.* (1987) reported that the protein efficiency ratios for the chicken meat used in the Raltech Scientific Services toxicological study were not affected adversely by any of the three methods of processing. Skala *et al.* (1987) reported retention values relative to frozen reference samples for thiamine of 26, 66, and 22% and for pyridoxine of 50, 62, and 83% respectively, in γ - and electron-sterilized and thermally processed chicken, respectively. Thiamine retention levels of 23, 44, and 21% were reported by Skala *et al.* (1987) for the γ -, electron-irradiated,

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TABLE 1.
AMINO ACID CONTENTS (% PROTEIN) OF FROZEN CONTROL,
THERMALLY-, γ -, AND ELECTRON-STERILIZED CHICKEN

Amino Acid	Process			
	FC	TP	GAM	ELE
Alanine	5.76	5.72	5.84	5.85
Arginine	6.24	6.17	6.37	6.38
Aspartic acid	8.94	7.98	8.98	8.84
Cysteine	0.91	0.82	0.96	0.93
Glutamic acid	14.33	14.20	14.19	14.17
Glycine	5.83	5.78	5.96	5.87
Histidine	4.05	4.06	4.21	4.36
Hydroxy proline	0.28	0.28	0.27	0.28
Isoleucine	4.51	4.58	4.70	4.67
Leucine	7.53	7.51	7.69	7.64
Lysine	8.34	8.31	8.55	8.49
Methionine	2.52	2.52	2.48	2.57
Phenylalanine	3.78	3.70	3.74	3.79
Proline	4.02	4.33	4.45	4.34
Serine	3.72	3.66	3.73	3.60
Threonine	4.11	4.12	4.14	3.94
Tryptophan	1.16	1.20	1.25	1.20
Tyrosine	3.38	3.30	3.34	3.22
Valine	4.79	4.86	5.02	4.93

FC: Enzyme inactivated frozen control-chicken.

TP: Thermally processed chicken.

GAM: Gamma-irradiated chicken ^{60}Co , 46-68 kGy at $-25\pm 15^\circ\text{C}$.

ELE: Electron-irradiated chicken 10 MeV electrons, 45-68 kGy at $-25\pm 15^\circ\text{C}$.

and thermally sterilized beef. The retention values reported for both thiamine and pyridoxine in electron-irradiated meats were markedly lower than the values found by Raltech. Skala *et al.* (1987) tested these meats for the presence of either anti-thiamine or anti-pyridoxine activities by analysis of transketolase, aspartate aminotransferase and alanine aminotransferase in erythrocytes and found no consistent evidence of antivitamin activity.

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TABLE 2.
FATTY ACIDS, CRUDE FAT, PEROXIDE, AND TBA OF FROZEN,
THERMALLY-PROCESSED, γ -IRRADIATED, AND ELECTRON-IRRADIATED
ENZYME INACTIVATED CHICKEN

Constituent	process			
	FC	TP	GAM	ELE
Arachidic Acid (%-Fat)	1.47	1.46	2.06	1.20
Gadoleic Acid (%-Fat)	0.59	0.60	0.61	0.56
Lauric Acid (%-Fat)	0.37	0.31	0.23	0.32
Linoleic Acid (%-Fat)	20.26	20.63	19.85	20.15
Linolenic Acid (%-Fat)	1.48	1.48	1.48	1.30
Myristic Acid (%-Fat)	0.91	0.93	0.95	1.06
Oleic Acid (%-Fat)	40.80	40.05	40.86	39.81
Palmitic Acid (%-Fat)	21.69	21.67	21.72	22.33
Palmitoleic Acid (%-Fat)	6.93	7.07	6.91	6.68
Pentadecanoic Acid (%-Fat)	0.39	0.44	0.40	0.49
Stearic Acid (%-Fat)	6.32	6.37	6.48	6.98
Free Fatty Acids (%-Fat)	0.63	1.07	0.87	0.97
Crude Fat (%-Dry Weight)	37.22	36.84	37.30	36.61
Peroxide (meq/kg)	1.62	1.83	1.12	1.54
Thiobarbituric acid (TBA) (ppm-Dry Weight)	11.78	0.77	5.58	6.97

FC: Enzyme inactivated frozen control-chicken.

TP: Thermally processed chicken.

GAM: Gamma-irradiated chicken ^{60}Co , 46-68 kGy at $-25\pm 15^\circ\text{C}$.

ELE: Electron-irradiated chicken 10 MeV electrons, 45-68 kGy at $-25\pm 15^\circ\text{C}$.

The results of the toxicology studies of the radiation-sterilized chicken meat used by Raltech Scientific Services were reported by Thayer *et al.* (1987). No evidence of genetic toxicity or teratogenic effect in mice, hamsters, rats, and

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TABLE 3.
VITAMIN CONTENTS OF FROZEN, THERMALLY-PROCESSED, γ -IRRADIATED,
AND ELECTRON-IRRADIATED ENZYME-INACTIVATED CHICKEN

Vitamin	Process			
	FC	TP	GAM	ELE
Thiamine-HCl, ppm	2.31	1.53	1.57	1.98
Riboflavin, ppm	4.32	4.60	4.46	4.90
Pyridoxine, ppm	7.26	7.62	5.32	6.70
Niacin, Bound, ppm	218.6	220.9	209.8	212.1
Niacin, Chemical, ppm	212.9	213.9	197.9	208.2
Pantothenic Acid, ppm	24.0	21.8	23.5	24.9
Biotin, ppm	0.093	0.097	0.098	0.103
Folic Acid, ppm	0.83	1.22	1.26	1.47
Choline, ppm	952.4	1219	1096	1001
Vitamine A, IU/kg	2716	2340	2270	2270
Vitamine D, IU/kg	375.1	342.8	354.0	466.1
Vitamin K, ppm	1.29	1.01	0.81	0.85
Vitamin B ₁₂ , ppm	0.0083	0.0164	0.0137	0.0088

Vitamin concentrations are reported on a dry weight basis.

FC: Enzyme inactivated frozen control-chicken.

TP: Thermally processed chicken.

GAM: Gamma-irradiated chicken ⁶⁰Co, 46-68 kGy at -25±15°C.

ELE: Electron-irradiated chicken 10 MeV electrons, 45-68 kGy at -25±15°C.

rabbits was reported even though teratogenic studies included diets incorporating up to 70% (dry weight) of the test meats in the diets. It was concluded that processing of the chicken (frozen, thermal-processed, γ -sterilized, electron-sterilized) did not affect the response of the Salmonella-microsomal mutagenicity test to known mutagens. No evidence of sex-linked recessive lethal mutations in *Drosophila melanogaster* was produced by ingestion of any of the four pro-

cessed chicken meats. Diets containing each of the four processed chicken meats supported the growth of beagles to maturity; and no overt signs of diet-related toxicity, oncogenicity, or reproductive toxicity were observed. No evidence of treatment-related abnormalities or changes during the multigeneration study with CD-1 mice was observed. Virgin female mice fed γ -irradiated chicken meat had a significantly poorer survival rate than those fed any of the other diets. However, because this occurred in only one sex group, and no consistent disease or group of diseases, either neoplastic or nonneoplastic, was associated with this group of mice, the results cannot be considered to be treatment related. One other result was obtained in this study that remains unexplained. There was a highly significant reduction in the hatchability of eggs of *D. melanogaster* reared on γ -irradiated chicken meat during the test for sex-linked recessive lethal mutations. This result is of unknown significance, but mammalian data from reproductive tests in the study did not demonstrate any consistent patterns indicative of a positive reproductive effect. Thayer *et al.* (1987) concluded that, "These nutritional, genetic, and toxicological studies did not provide definitive evidence of toxicological effect in mammals due to ingestion of chicken meat sterilized by ionizing radiation." Other recent feeding studies were reviewed by CAST (1986).

STERILIZATION OF FEEDS

There has been much interest in the pasteurization or sterilization of feeds for many years (Ley *et al.* 1969). Toxicologists have been unable to provide test animals with sterile feeds, other than by autoclaving; and many pathogens are apparently introduced to domestic animals, such as poultry, through their feed. Irradiation provides a much less destructive method of preparing either pasteurized or sterile feeds. Numerous feeding studies have been conducted with irradiated feedstuffs with generally good results. The reader is referred to an excellent review by Conning (1983) and to the proceedings of an Advisory Group Meeting on the "Decontamination of Animal Feeds by Irradiation" (IAEA 1979). The U.S. Food and Drug Administration recently approved the irradiation of bagged complete diets for laboratory animals (mice, rats, and hamsters) to an absorbed dose not to exceed 25 kGy for the purpose of microbial disinfestation (Federal Register 1986a).

IDENTIFICATION OF IRRADIATED FOODS

Regulatory agencies need methods for the detection of foods which have been irradiated in order to allow enforcement of any national prohibition for irradiation of specific foods, the requirement for proper labeling of such foods, and for the

control of limitations imposed on the process. Because ionizing radiation adds nothing to the product and few, if any, unique radiolytic products are produced in the foods, regulation will be most dependent on in-plant dosimetry and labeling, although several methods to detect irradiated foods are ready for international testing at this time (Bögl 1987). Some of the more promising of these are thermo- and chemiluminescence of spices, cytological examination of sprouts of tubers and bulbs, impedance measurements of potatoes, formation of hyphae in tissue culture by nonirradiated mushrooms but not by the irradiated mushroom tissue, and identification of specific volatiles produced by the irradiation of fatty acids. Several other methods are under investigation, such as the measurement of free radicals in bone and shell by electron spin resonance spectroscopy, the identification of o-tyrosine formed from phenylalanine during irradiation, and changes in DNA. Several of the developmental methods currently require very advanced instrumental techniques and until further simplified would be unsuitable for general use by regulatory agencies.

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