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Food Preservation Using Ionizing Radiation

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I. Introduction

A. Overview

Radiation "refers to a physical phenomenon in which energy travels through space or matter" (Radomyski et al. 1994). Irradiation, as used in food science,

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is the application of this energy to a specific material, such as a food product, with the purpose of increasing storage stability through reduction of microorganisms, elimination of parasites or insects, or blockage of enzyme activity. Irradiation may also be used to reduce the risk of foodborne illness. For preservation of foods, the type of radiation applied is referred to as ionizing radiation because it produces electrically charged ions as the energy interacts with target molecules.

Because of the high penetrating ability of such ions, sources of ionizing radiation for irradiation of food products have included gamma rays, electron beam, and x-rays. Cobalt-60, a radioactive isotope, is the most popular and common gamma-ray source used on food products. Cobalt-60 sources are produced in the shape of metal pencils or rods encased in a stainless steel jacket and as such provide convenience and safety in their use and storage. Electron beams are produced by electrically powered Van de Graaff generators or linear accelerators. Electrons are less penetrating than gamma rays but can be useful for irradiating large volumes of small food items, such as grains or prepackaged meats, by conveyor (Radomyski et al. 1994).

The International System of Units has developed the term gray (Gy) to refer to the quantity of radiation energy absorbed by a material such as a food. In terms of energy, a gray is defined as a "dose of one joule per kilogram of absorbing material" (Radomyski et al. 1994). The relationship between the gray and an earlier unit of absorbed dose, the rad (radiation absorbed dose), is that 1 Gy equals 100 rads.

Investigations of food irradiation over several decades have led to a general consensus regarding the dose requirements for application of radiation to food products. High doses, >10 kGy, are designed to sterilize food; medium doses, 1–10 kGy, exert a pasteurization effect with extension of shelf life; and low doses, <1 kGy, effectively control infestation by parasites and insects and delay senescence in most fresh fruits and sprouting in vegetables (Radomyski et al. 1994).

B. Historical Development

Food irradiation was proposed as a method to destroy microorganisms in food shortly after Roentgen discovered x-rays in 1895 and Becquerel discovered radioactivity in 1896 (Hackwood 1994). As scientists began experimenting with radioactive materials, a practical use for irradiation to destroy the parasite *Trichinella spiralis* in meat was patented by Schwartz in 1921 (Hackwood 1994). In 1930, the French patented the use of food irradiation using x-rays to destroy pathogenic bacteria (Josephson and Peterson 1983). Immediately after World War II, improved ionizing radiation sources became available, and a wide range of food products were subjected to and shown to be preservable by short-term exposure to irradiation (Grodner and Andrews 1991). The Low Temperature Research Station at Cambridge, England (Hackwood 1994) began work on food irradiation in 1948, and in the mid-1950s the U.S. Army Quartermasters Corps

became interested in food irradiation. In May 1953, the Quartermaster General approved a 5-yr, $6 million program for use of ionizing radiation processing to improve the acceptability of military field rations (Josephson and Peterson 1983). Then in 1954, President Eisenhower established the Atoms for Peace policy, calling for international cooperation toward meeting that goal (Hackwood 1994). Under the supervision of the Atomic Energy Commission (AEC), research contracts were negotiated with several food research institutes and universities (Josephson and Peterson 1983). Bacon was the first food in the world approved to be irradiated, approved in 1963 for sterilizing dose levels of 4.5 Mrad (45 kGy). In the same year, the U.S. Food and Drug Administration (USFDA) also granted clearance for irradiating wheat for insect disinfestation and white potatoes to inhibit sprouting (Josephson and Peterson 1983). Between 1963 and 1980, numerous projects were undertaken throughout the world to establish the effectiveness of irradiation processing, the wholesomeness of irradiated foods, and the application of ionizing radiation. These included use of irradiation to reduce the use of certain food additives that may present health risks, such as nitrites and fumigants.

Approval by the USFDA for use of ionizing radiation on food products in the United States has been slow to develop. The U.S. Congress officially classified irradiation as a food additive under the Food, Drug, and Cosmetic Act of 1958. Subsequently, any food product undergoing irradiation treatment was to be tested for wholesomeness. In 1980, both the USFDA and the World Health Organization (WHO) of the United Nations accepted foods irradiated with an average dose as high as 10 kGy as neither presenting any toxicological hazard nor introducing any special nutritional or microbiological problems and thus "safe for human consumption" (Hackwood 1994; Urbain 1989). This declaration allowed for modification of the need for wholesomeness testing only for products exposed to doses >10 kGy.

In 1983, the Codex Alimentarius Commission adopted a revised "General Standard for Irradiated Foods" and a revised "Recommended International Code of Practice for the Operation of Radiation Facilities Used for the Treatment of Foods," which incorporated the main conclusions of the 1980 Joint FAO/IAEA/WHO Expert Committees on the Wholesomeness of Irradiated Foods (Hackwood 1994). As of 1994, 37 countries had approved irradiated foods (Radomyski et al. 1994). The majority of these countries are now using food irradiation to ensure the storage and safety of a variety of food products. In more than 30 years of intense studies, there had been no confirmed evidence of toxic substances produced in low-dose-irradiated food products (IFT 1983a,b).

C. Application to Food Products

There are three approaches to the use of radiation in food products: low doses, up to 1 kGy, to inhibit sprouting and delay fruit ripening; medium doses, 1–10 kGy, for partial destruction of microbial flora, to reduce the risk of food pathogens and to increase shelf life; and high doses, >10 kGy, needed for complete

destruction of microorganisms to achieve sterility of a particular food product. In addition to the three levels of radiation application, the following trade type names have been given to these general ranges, which relate more to the desired function than to the actual dose (Satin 1993).

Radurization refers to treatment of foods with ionizing radiation sufficient to lengthen shelf life by reducing the initial number of spoilage organisms before or immediately after packaging. This amount varies with individual food products because spoilage conditions and storage conditions change with each commodity. Radurization doses are usually considered low dose, <2 kGy.

Radicidation is the irradiation treatment required to sufficiently reduce the level of non-spore-forming pathogens, including parasites, to an undetectable level, thus reducing the risk of foodborne illness to near zero. This level of irradiation is generally considered in the medium range, <5 kGy, and may vary depending on the product and possible suspected pathogens.

Radappertization is the highest level of irradiation processing required to achieve sterility in a food product. This application allows for shelf stability at ambient temperatures much as does "canning" or "aseptic packaging." Doses required for radappertization generally are >10 kGy for most food products (Anderson 1983).

D. Radiobiology

Radiation Chemistry. The characteristic property of high-energy radiation, such as gamma rays, is to cause ionization in the material in which the radiation is absorbed. Atoms or molecules that have gained electronic energy without losing electrons are termed excited (Urbain 1986). These excited atoms or molecules are highly reactive and can cause random chemical changes. When atoms actually lose electrons and become positively charged, they are ionized. Because the ions and excited atoms contain additional energy, they are unstable and thus are reactive.

On exposure to ionizing radiation, random water and organic molecules are altered. Water is ionized and a hydrated electron is produced along or adjacent to the "track" of radiation energy (Silverman 1983).

$$H_2O \rightarrow H_2O^+ + e-$$

In further reactions, the positive water ion and the electron can follow these reactions:

$$H_2O^+ \rightarrow OH. + H+$$

$$\underline{e- + H_2O \rightarrow OH- + H^{\cdot}}$$
$$H_2O \rightarrow H^{\cdot} + OH.$$

Free radicals, atoms, or molecules having at least one unpaired electron formed in solution can then recombine to form hydrogen gas, hydrogen peroxide, or water as follows:

$$2H. \rightarrow H_2$$

$$2\ OH^{\cdot} \rightarrow H_2O_2$$

$$H^{\cdot} + OH. \rightarrow H_2O$$

Other molecules may also be formed. In other portions of the track where diffusion occurs, the radicals may react with solute, and the extent of the reactions is solute concentration dependent (Silverman 1983). In the presence of oxygen, more hydroperoxyl radicals ($HO_2^{\cdot}$) may be formed. The hydrogen peroxide molecule and the hydroperoxyl radical may then act as oxidizing or reducing agents. Acting randomly, ionization products form new compounds and free radicals, which may themselves cause indirect actions by recombining or forming new compounds.

Biological Effects (Direct and Indirect). Radiobiology, the study of the effects of radiation on biological systems, begins at the cellular level where bacteria and the tissue cells of higher organisms display similar responses when exposed to ionizing energy such as gamma rays (Alper 1979a). Primary chemical reactions occur as a direct result of absorber compounds acquiring energy through interaction with radiation (Urbain 1986). Additionally, indirect chemical reactions occur when the primary products of radiation interact with themselves or with other components in the system. Free radicals are common constituents of food systems and are produced by thermal energy as well as radiation energy. Free radicals are highly reactive chemically and can combine with other free molecules, resulting in a variety of different compounds.

Cellular (target cell) damage caused by the direct action of ionizing radiation on a target molecule is a result of energy being transferred within the target molecule itself (Silverman 1983). Indirect effects, in contrast, inactivate the organism by diffusion to, or reaction with, a sensitive target site within the organism. Diffusion distances vary with temperature and density within the system. Another type of effect, termed environmental (Silverman 1983), may be caused by free radicals and other radiolytic compounds formed extracellularly but still lethal to the cell. Reactive species of free radicals cause radiation damage to a biological system by attacking molecules within the cell or through oxidation of cell walls extracellularly. The hydroxyl radical, believed to be the most effective oxidizing agent, can extract a hydrogen atom from deoxyribonucleic acid (DNA), leaving a radical site on the DNA (Johns and Cunningham 1983).

Ionizing radiation can cause a variety of physical and biochemical effects in microorganisms with the primary cellular target being DNA (Josephson and Peterson 1983; Kelner 1955; Silverman 1983; Urbain 1986). Sparrow et al. (1967) correlated the radiosensitivity of 79 organisms, ranging from viruses to higher plants and animals, with their chromosome volume. In this study, the larger the volume of the chromosome, the more sensitive the biological unit was to molecular damage by ionizing radiation. Appreciable differences in radiosensitivity appear more likely to result from the ability of the particular organism

to repair DNA damage (Silverman 1983). Among bacteria, radiation sensitivities are also quite varied. Vegetative bacteria are generally more sensitive than spores because vegetative bacteria are undergoing active growth and contain more water. Gram-negative bacteria are more sensitive than gram-positive bacteria because of differences in cell wall density and enzymatic repair mechanisms.

Bacterial Response. The response of cells or bacteria to radiation exposure has been measured in several ways: survival, growth characteristics, genetic changes, and general functionality. In food science, the cellular response of interest is measured by cell survival from sublethal doses and complete cell death from inactivation doses. When measuring irradiation response of food spoilage bacteria and food pathogens, food scientists generally measure survival of the bacteria under differing environmental conditions (food matrices, temperature, moisture, etc.) following varying radiation exposures.

Survival Curves. The destruction of bacteria during irradiation may be characterized by their survival curves (Silverman 1983). "In a given population of bacteria or microorganisms, as radiation dose is increased, the fraction of survivors becomes smaller" (Urbain 1986). This relationship is obtained by graphing the logarithm of the surviving fraction versus the dose. In the concept of the "target theory," the response of organisms is directly proportional to the dose applied and can be plotted as a straight-line exponential curve. Further, the target theory states that only direct effects can cause cellular damage. However, this theory is not supported by research. In fact, some bacteria exhibit, at low doses, an initial threshold or shoulder on the survival curve, termed convex, sigmoidal, multihit, or multitarget, with the curve becoming exponential at higher doses (Silverman 1983). The third type of survivor plot has been described for "microbial populations that are nonhomogeneous with regard to resistivity" (Silverman 1983). This concave curve demonstrates that less resistant cells are inactivated first, leaving the more resistant cells to survive sublethal doses and to graphically "tail out" at higher doses.

D-Values. Food processing methods have been designed to eliminate specific microorganisms from particular food products. One measure of the effectiveness or efficiency of a particular process application is the D-value. In thermal processing, the D-value (D_{10}) is the time required, at a specific temperature, to reduce the designated microbial population by 90% (1 log). The D-value or irradiation D_{10} is also used to provide an estimate of the dose needed for a similar quantitative effect in radiation processing and to provide an index of the radiation sensitivity of a bacterium (Urbain 1986). An irradiation D-value is usually calculated from the linear portion of the bacterial semilog survival plots; it is the irradiation dose required to reduce the bacterial cell population to 10% of the original (D_{10}). Using linear regression analysis, the D-value = 1/slope of the regression curve.

Irradiation D-values vary among microorganisms depending on their sensitivity to the effects of ionizing radiation, their environment during radiation exposure, and their ability to repair and recover from sublethal damage. Vegetative bacteria are more sensitive to ionizing radiation than bacterial spores; for example, Urbain (1986) reported the following D-values. *Escherichia coli* demonstrated a D-value varying from 0.21 kGy in broth at 5 °C to 0.43 kGy in low-fat ground beef at 5 °C; *Staphylococcus aureus* has known D-values ranging from 0.24 kGy in broth at 5 °C to 1.9 kGy in shrimp (temperature unknown); and *Clostridium botulinum* type E has D-values of 1.2 kGy in beef stew at room temperature.

Sublethal Repair and Recovery. Many forms of damage can contribute to cell death; however, most of the information available at this time indicates that damage to the DNA is most critical (Josephson and Peterson 1983). In addition to direct hits on the DNA, it is possible to have indirect effects from radiolytic products that may cause sublethal damage to cells. Many bacterial cells have demonstrated the ability to block toxic free radicals by enzymatic action such as catalase or peroxidases, while others may repair sublethal damage to metabolic enzymes through DNA activity. The ability to block or bind up harmful free radicals is dependent on the bacterium's general metabolism and may be related to its general vitality and pathogenicity. Virulent stains of bacteria such as *Listeria monocytogenes* produce enzymes that block the action of phagocyte activity during tissue invasion. Farber and Peterkin (1991) discuss the ability of *L. monocytogenes* to produce high concentrations of catalase and superoxide dismutase during active growth. These two enzymes are capable of detoxifying the effects of hydrogen peroxide, superoxide, and hydroxyl radicals (Farber and Peterkin 1991). Activated phagocytes produce these toxic compounds as a defense mechanism to rid the body of invading bacteria. These same compounds—hydrogen peroxide, hydroxyl radicals, and superoxide—are also the major toxic secondary products of the ionization of water and oxygen (Josephson and Peterson 1983; Urbain 1986). Therefore, it is probable that highly virulent bacteria have the same resistance to many radiolytic products that they have to activated phagocytes.

Several researchers have reported the recovery of bacteria following irradiation processing after several days in storage. Andrews and Grodner (1992) reported that 10^7 colony-forming units (cfu)/g of *L. monocytogenes* in crawfish tail meat was able to recover from sublethal irradiation damage. The bacterium was not recovered during subculture immediately following 4-kGy gamma radiation but was recovered after 7 d storage at 4 °C. Juneau (1989) reported similar results when irradiating *L. monocytogenes* in crab meat. Grodner and Gutierrez (1992) presented similar data for *Plesiomonas shigelloides* in shrimp and clams; *P. shigelloides* was not recovered immediately after irradiation with 3 kGy but was recovered after 1–2 wk of ice storage. Josephson and Peterson (1983) discussed the ability of some bacterial cells to quickly rejoin breaks in the DNA, especially under anoxic conditions. These authors suggested the ligase activity

of bacterial cells is active in this repair process. No doubt there are many more molecular processes that allow some bacteria to use enzyme systems actively for repair and recovery in a toxic environment such as that produced directly or indirectly from gamma radiation processing.

E. Factors Affecting Radiation Sensitivity of Bacteria

Water Content. The amount of water present in foods plays a significant role in how readily bacteria respond to exposure to ionizing radiation (Urbain 1986). In an aqueous solution, ionizing radiation first encounters water molecules to form ionized water, hydrated electrons, hydroxyl radicals, etc. These secondary products, in turn, react by combining with other compounds to block normal cell function. When water activity is low, as in dry foods, frozen foods, or foods with high salt and sugar content, the indirect effects of radiolytic products are minimal and the radiation resistance of bacteria is increased. Researchers have demonstrated a direct relationship between water content and rate of inactivation by radiation. For example, Stapleton and Hollaender (1952) showed that reduction of the water content of spores of the fungus *Aspergillus terreus* reduced the fraction of cells inactivated per unit dose, and Bruns and Maxcy (1979) showed a protective effect resulting from lyophilization of *Moraxella* sp. with extension of the shoulder or threshold of response. These researchers also concluded that radiation sensitivity in the dry state was not temperature dependent.

Food Component. Food components other than water also affect the radiation response of bacteria (Urbain 1986). The individual food components actually compete with bacteria for interaction with active radiolytic products that are produced during ionization of water. The degree of complexity of any food matrix is individual, and the application of D_{10} values for an irradiation process must be established for each combination of food product and bacterium of interest, much as in thermal processing methods. Research has supported the idea that food components may offer protection for bacteria. For example, Patterson (1989) found lower D-values for four strains of *L. monocytogenes* irradiated in phosphate buffered saline (D-value range, 0.39–0.46 kGy) when compared with the same bacterial strains irradiated on poultry meat (D-value range, 0.42–0.54 kGy). When Huhtanen et al. (1989) irradiated seven strains of *L. monocytogenes* in culture media and in mechanically deboned chicken meat, their data provided additional support for the protective effect of a food matrix with higher D-values reported for all strains when irradiated in chicken meat (D-value range, 0.41–0.53 kGy) than in BNT (buffered nutrient trypticase soy broth with glucose) culture medium (D-value range, 0.28–0.34 kGy). Farag et al. (1990) reported a significantly higher radiation resistance for *L. monocytogenes* strain CFPDC in dry poultry feed (D-value, 0.44 kGy) than in phosphate buffer (D-value, 0.18) or trypticase soy broth (D-value, 0.21). Comparing irradiation responses of bacteria in different menstruum, whether in culture media or food, has consistently indicated that food matrices offer some protection to bac-

teria. Note that differences in recovery techniques by different researchers may account for some variations in D-values reported from study to study.

pH. The pH of the medium of gamma radiation has been reported to affect free radical formation as it relates to the radiolysis of water and consequently may affect the indirect action (Urbain 1986). Specific studies have reported varying results with different bacteria and whether the bacteria were vegetative cells or spores. Urbain (1986) supported the theory that medium pH influences radiation resistance, based on a study with *C. botulinum* 33A spores. When irradiated with 9 kGy at −50 °C, the spores were most sensitive at a pH of 7 and least sensitive at a pH of 8 or higher. Bridges and Horne (1959) reported that resistance to radiation was greatest at neutral pH with *Staphylococcus aureus* but reported no difference with *Pseudomonas geniculata* vegetative cells or spores of *Bacillus subtilus*. In other research reviewed by Duggan et al. (1963), the consensus of these studies on the effect of menstruum pH on the rate of gamma radiation destruction of bacteria was that the rate of kill was independent of pH. Indirect action of irradiation may be influenced by pH in a food matrix. "The pH effect is a consequence of protonation and deprotonation of various functional groups of the solute molecules and the free radicals" (Josephson and Peterson 1983). It is likely that factors such as temperature and the ability of a particular bacterium to recover from sublethal damage combine to influence the effect of pH on bacterial radiosensitivity.

Oxygen. The presence of oxygen enhances the indirect action of gamma radiation by sensitizing the biological system (Johns and Cunningham 1983), which increases the effectiveness of the radiation damaging processes and thereby lowering D-values (Urbain 1986). The first evidence for a modifying effect of atmospheric conditions on the sensitivity of irradiated microorganisms was presented in the early 1940s (Kelner et al. 1955). Several researchers have since shown increased resistance of microorganisms to gamma radiation by removing oxygen to create a microaerophilic or anaerobic environment. *Serratia marcescens* demonstrated increased sensitivity to x-rays with an increase in oxygen concentration in the irradiation atmosphere (Dewey and Boag 1959). At dosages less than sterilizing level (0.2 kGy), the sensitivity of dry spores, as measured by recovery and vegetative growth, was found to be 1.25 times greater when x-rays were administered in air than when spores were irradiated in the absence of oxygen (Powers and Boag 1959). Epp et al. (1968) reported that electron beam radiation of *E. coli* was most effective under 100% oxygen, with gradually increased resistance as oxygen concentration was reduced. Thornley (1963) found that D_{10} values were approximately threefold higher when various strains of *Salmonella* were irradiated under anoxic conditions as compared with irradiation under aerated conditions.

Temperature. Although the primary effects of irradiation processing (ionization and electronic excitation) are independent of temperature (Urbain 1986),

the role of temperature in the secondary indirect effects has been found to be significant. As temperature decreases, free radical movement throughout the irradiation menstruum also decreases. With less movement at the molecular level, the opportunity for the formation of secondary radiolytic products diminishes. When food irradiation was first introduced to the public as a means of preservation (1947), workers stressed the importance of reducing undesired chemical changes by irradiating foods at temperatures of –40 °C or lower. Other authors have reported no quality protection by using subfreezing temperatures (Josephson and Peterson 1983). Work conducted at the Low Temperature Research Station at Cambridge, MA, provided evidence for quality protection at cryogenic temperatures between –20 °C and –196 °C, but indicated that freezing at temperatures just below 0 °C afforded less sensory protection. For sterilization purposes, freezing to protect the sensory quality and reduce chemical change should be considered (Josephson and Peterson 1983). Ma and Maxy (1981) reported that temperature of irradiation influences the bactericidal effect but that the differential is greater for some bacteria than for others. Matsuyama et al. (1964) reported certain species of bacteria (*Pseudomonas, Streptococcus, E. coli,* and *Alcaligines*) were more sensitive to irradiation at 13 °C than at –79 °C. The D-values of *Streptococcus faecium* were increased from 0.09 to 0.38 when the temperature of irradiation was reduced from 5 °C to –196 °C (Anellis et al. 1973). Bruns and Maxy (1979) noted that the preexponential portion (shoulder) of inactivation curves was longer when *Micrococcus radiodurans* and other typical food spoilage organisms were irradiated at –30 °C than at above freezing temperatures. Ma and Maxy (1981) reported a greater temperature effect in liquid media than with lyophilized media because water was less available in the dry media. Kelner et al. (1955) reported significant reduction in the fraction of cells inactivated per unit dose when *E. coli* was irradiated at –196 °C as compared with ice bath temperatures.

Cell Concentration. Under controlled atmospheric conditions, Bridges and Horne (1959) reported that survival curves for a given microorganism were independent of the initial number of cells. This was supported by previous research (Kelner et al. 1955) in which an apparent protective effect was negated when oxygen was supplemented to a normal atmospheric level. Some researchers have reported that the presence of other microorganisms such as spoilage bacteria or large numbers of a single species of bacteria may provide a protective effect for some of the microorganisms in the medium of irradiation (Anellis et al. 1973; R.M. Grodner, 1992, personal communication, Department of Food Science, Louisiana State University). It is not clear whether this so-called protective effect is real or a product of other changes in the irradiation environment such as oxygen depletion, as mentioned previously.

Dose Rate. "Whether there is any dose-rate effect in bactericidal effect of radiation is controversial" (Hayashi 1991). When bacteria are subjected to sublethal levels of ionizing radiation, some of the damaged biomolecules are repaired

by the action of enzymes. Therefore, Hayashi (1991) suggested that it is reasonable to expect that, in the region of low dose rate, the sensitivity of bacteria would decrease with the decrease in dose rate and the specific bacterial repair ability. Other authors do not support this idea. Urbain (1986) reported that in complex food systems the dose rate is irrelevant and that radical interaction with food components predominates. Urbain (1986) also reported that radiation effects on bacteria, when oxygen is a factor, can be altered by high dose rates where oxygen depletion may reduce the sensitivity. For example, *Serratia marcescens* irradiated with x-rays at a dose rate of 0.02 kGy/min was more sensitive to the radiation than when irradiated at 0.002 kGy/min so long as oxygen was present in the system (Dewey 1969). When the bacteria were irradiated under a 100% nitrogen atmosphere, there was no observable difference in radiosensitivity.

Dose Application. Traditionally, irradiation processing of food products has focused on single-dose application to processed and packaged food products. Another method of radiation application used extensively by radiobiologists to treat cancerous tumor cells has been to administer the radiation doses in partial fractions over a period of time. This application was developed as a method to reduce damage to "good" tissue while effectively denaturing the DNA of the tumor cells. One problem that has occurred in tumor treatment when using split-dose application is that the targeted tumor cells as well as the good tissue cells may be able to repair and subsequently recover from sublethal damage; in some cases these become more resistant to irradiation (Alper 1979b). Fractionated doses of irradiation have also been used in agriculture to control the fertility of boll weevils. Haynes and Smith (1993) irradiated male and female pupae with nine equal doses totaling as much as 80 Gy of gamma irradiation. The weevils were effectively sterilized but not killed by this method.

Multiple-dose application has been used on food products only rarely. Liston and Matches (1968) discussed the use of single and multiple doses in the radiation pasteurization of seafoods both on shipboard and on landing the catch. These researchers applied 0.5-, 1.0-, 2.0-, and 3.0-kGy doses of gamma radiation to fresh, ice-stored fish, at intervals between irradiation doses of 3–17 d, with the purpose of extending the shelf life of iced stored fish until they could be marketed. They concluded that multiple doses were only slightly more effective in extending the shelf life of very fresh fish. From a practical point of view, the authors reported a failure of the double irradiation process to provide effective and sustained reduction of bacterial count in fish of poor quality.

It is not known whether use of fractioned doses will alter the overall sensitivity of bacterial cells. It is possible that direct damage to bacterial chromosomes from an initial dose could be of such a nature as to sensitize the cells to irradiation damage, with a subsequent increase in the overall radiosensitivity of a bacterium. Damage from the indirect effects of irradiation administered in sublethal doses would be expected to be minimal in bacterial populations equipped biochemically to repair damage as it occurs. Unlike mammalian cells, bacteria have

not been shown to develop increased resistance on exposure to sublethal doses. Huhtanen et al. (1989) reported that *L. monocytogenes* cells selected from colonies of subcultured survivors of sublethal irradiation exposure were no more radiation resistant or radiation sensitive than the parent culture. Liston and Matches (1968) indicated that irradiation sensitization of spoilage flora bacteria may have occurred when survivors of an initial irradiation were subsequently irradiated after several days storage. These authors believed that increased sensitivity resulted from the microbial flora moving into a stage of active reproduction. More recently, Andrews and Grodner (in manuscript) reported variations in the radiosensitivity of *L. monocytogenes* exposed to split doses of radiation that may be more temperature related. At −80 °C, split dose was not significantly ($p < .01$) different than single dose. However, at 22 °C (room temperature, RT), *Listeria* was more radiosensitive to split doses at 1- and 2-hr intervals between doses than with a single dose or with intervals of 0.25 and 0.5 hr between fractions.

As part of Good Manufacturing Practices, federal guidelines (FSIS 1992a,b) for application of irradiation to food products prohibit its use on spoiled or old products with the purpose of improving quality. The purpose of irradiation application is to extend good quality factors for a longer period of time or to reduce the risk of pathogenic bacteria, if present. Reapplication of irradiation or multiple application of irradiation to food products after being marketed has been prohibited by ASTM (1994) and FAO/IAEA/WHO (1977, 1981). However, it is permissible to interrupt an irradiation process for short intervals as long as the product remains within the irradiation facility under proper storage conditions (H. Everett, 1994, personal communication, Executive Vice President, Food Technology Services, Inc.).

II. Fruits and Vegetables

Since the end of World War II, scientists have expended considerable effort investigating irradiation of fruits and vegetables, resulting in very few practical applications. Much of this work involved attempts to increase the shelf life of fresh produce by controlling spoilage microorganisms or the senescence enzyme systems. Several reviews have concerned the feasibility of irradiating fruits and vegetables for this purpose (Akamine and Moy 1983; Anonymous 1961; Brownell 1961; Kader 1986; Maxie and Abdel-Kader 1966; Maxie and Sommer 1965; Maxie et. al. 1971; Romani 1966; Rowley and Brynjolfsson 1980; Sommer and Mitchell 1986). In general, only a very limited number of these crops would benefit from irradiation. In many cases, spoilage actually increased with radiation treatment when compared to normal refrigeration. At least two factors have limited the usefulness of irradiation in fruit and vegetable crops: quality degradation and treatment costs.

Unlike other foods, fresh fruits and vegetables are actively respiring living tissues and, if high quality is desired, must remain so until consumed. With the exception of refrigeration (sometimes combined with chemical preservatives),

all other preservation techniques, including heat and irradiation, significantly decreases the quality of fruits and vegetables to less than that at harvest. To maintain high quality in these foods, the preservation process must not destroy a significant number of cells within the plant material. Unfortunately, for most produce the irradiation dosages required to inhibit or destroy spoilage rots and catabolic enzymes are usually more than enough to cause significant injury to the plant tissue with consequential degradation of quality (Sommer and Fortlage 1966). Table 1 (from Maxie et al. 1971) clearly illustrates the problem of using irradiation for control of microbial spoilage.

Application of irradiation has been attempted commercially for strawberries, grapefruit, and oranges (Marcotte 1992; Pszczola 1992). The irradiation/controlled atmosphere (CA) treatment (30–100 krad/10% CO_2) of strawberries was apparently successful in moderately extending shelf life above that of a CA-only treatment. Maxie and Sommer (1965) indicated that shelf life of strawberries could be extended about 1 wk at 5 °C using a 3-kGy treatment.

Treatment of blueberries was not successful (Miller et al. 1994). One of the most obvious quality changes that occurs is softening, which in many cases is unacceptable. Consumers expect most fresh fruits and vegetables to be crisp or firm. The damage caused by irradiation is believed to be from alteration of cell membranes, which causes loss of turgor, and to changes in cell wall components, such as pectin, which then allow cell movement (Maxie and Abdel-Kader 1966; Maxie and Sommer 1968). Other problems include interference with normal ripening, development of off-flavors and aromas, and increased susceptibility to posttreatment decay. There are currently other methods to control microbial storage that do not cause as much crop damage and are less costly.

Table 1. Relationship between dosages (kGy) causing quality damage and inhibiting storage rots.

Commodity	Maximum estimated tolerable dose of crop	Minimum estimated dose required for control
Apricots	50	200
Asparagus	15	5–10
Boysenberries	100	200
Lemons/limes	25	150–200
Nectarines	100	200
Oranges	200	200
Peaches	100	200
Raspberries	100	200
Strawberries	200	200
Table grapes	25–50	1000
Tomatoes	100–150	>300

Adapted from Maxie et al. (1971).

The use of irradiation for inhibition of ripening and sprouting has been more promising because dosages are not as high and damage is less. Ripening of bananas was successfully inhibited by irradiation using 30–35 krad (Maxie et al. 1968, 1971; Thomas 1986). Likewise, research has indicated that ripening in mangoes, papayas, sweet cherries, and apricots could be inhibited in a similar manner (Abdel-Kader et al. 1968; Akamine and Moy 1983; Larrigaudiere et al. 1991; Lee et al. 1968). Irradiation with low doses (0.05–0.15 kGy) has been successfully used to suppress sprouting in potato, onion, garlic, carrot, sweet potato, yam, turnip, sugar beet, table beet, Jerusalem artichoke, and ginger (El-Oksh et al. 1971; Kwon et al. 1985; Matsuyama and Umeda 1983; Paull et al. 1988; Thomas 1984a,b). Irradiation (0.15 kGy) for sprout suppression has been approved by many countries and is in commercial use. Nevertheless, the use of irradiation for inhibition of ripening and sprouting must compete with lower cost chemical alternatives.

The cost of irradiation of fruits and vegetables is arguably the most important limiting factor preventing widespread adoption. Most fruits and vegetables are low-value crops, unlike meat and seafood; that is, the net value of each individual food unit is very low. Compounding the problem is the manner in which fruits and vegetables are grown in the U.S. Although there are some concentrated growing areas, crops are often grown on small acreages distributed over a wide area, which increases the cost of transportation at the grower level. Because of their highly perishable nature, when harvested most fruits and vegetables must be treated and transported immediately to reduce quality loss. The harvested produce usually passes through small local packing houses that consolidate the fresh material for shipment to larger distribution centers. Each packing house usually handles only a few items. Unlike other commodities, there is rarely a single large facility that handles all produce from a region, which severely limits the economic advantage of using a single irradiating facility. A further limiting economic factor is the price consumers are willing to pay for fresh produce in the U.S., which is significantly less than for meat and seafood. With an upper limit for retail price, the margin available to accommodate postharvest treatment costs is narrow, and there are many other cheaper methods to lengthen shelf life in lieu of irradiation.

Although irradiating fruits and vegetables for shelf-life extension appears to be economically unattractive, a more promising use may be insect deinfestation (Blalock et al. 1966; Burkitt 1982; Moy et al. 1983; Moy 1985; Sommer and Mitchell 1986; Tilton and Burkitt 1983). When fresh commodities are imported or moved interstate, there is always a danger of including noxious insect pests with the crop. Numerous introductions of insect pests into pestfree growing regions have been caused by inadvertent transport of infested crops. Quarantine of produce has become a significant problem. Highly perishable fresh produce cannot be held indefinitely without seriously degrading quality, if an insect infestation is suspected, however, there is little alternative but to quarantine. Gaseous fumigants previously were routinely used to eliminate insect pests from agricultural commodities. Control of these insects is becoming more important

because some of the fumigants (e.g., ethylene dibromide) are no longer approved for this use and other methods, such as chilling and hot-water treatment, are damaging in their own right. In 1988, the USFDA granted approval for use of irradiation on fruits and vegetables at doses not to exceed 1 kGy (100 krad). For many fruits and some vegetables, dosages at this level or lower do not cause substantial loss of food quality. The potential for using irradiation to control insects in fruits and vegetables appears good because there are fewer low-cost alternative treatments in contrast with its use to extend shelf life. Additionally, in the case of imported produce, the cost of irradiation can be spread over high volumes of many different crops passing through a single port facility.

In summary, irradiation does not appear to be a cure-all for shelf life extension in fresh fruits and vegetables; cost and quality damage preclude general use. There may be some economic benefit in using irradiation for control of senescence in a few crops, but again wide usage cannot be expected. It appears that the most likely use of irradiation in fruits and vegetables is as an insect control for those commodities for which there is no effective alternative method.

III. Grains

The principal employment of ionizing energy on grains and grain products has been for control of insect infestation. Initial research before World War II was not productive because the sources of the energy were not strong enough (Hilchey 1957). Nelson (1962, 1967) discussed revived interest in the use of radionuclides in the 1950s. Generally, the doses of ionizing energy required to control insects in grains and grain products are less than 1 kGy. In 1963, the USFDA granted one of its first approvals for the use of ionizing energy on food when it endorsed its use for disinfestation of wheat and wheat products.

Although the fumigants and other insecticides presently employed to control insects in stored grains are effective when properly used, the development of resistance by certain insects and residues on the grains have been of concern (Champ and Dyte 1976). Ionizing energy offers an alternative to these treatments and could become the method of choice, should approval for use of chemical treatments be withdrawn. Ionizing energy leaves no residue, and development of resistance by insects is not a problem. The USSR began using accelerated electrons for large-scale processing of grain imported through Odessa in 1980 (Farkas 1988).

Doses of ionizing energy exceeding 2 kGy can also reduce the number of microorganisms in grains and grain products and extend their storage life. Higher doses have been shown to reduce the cooking time of legumes and to affect the baking quality of wheat flour. Treating wheat flour with ionizing energy has been found to increase the loaf size of bread baked from formulas containing only small amounts of added sugars. The ionizing energy breaks down some of the long-chain starch molecules to short-chain molecules that are more readily metabolized by yeasts to produce carbon dioxide and water. The result is greater porosity of the bread because of the greater amount of carbon

dioxide produced. However, bread formulas containing more sugar resulted in smaller loaves when the flour was treated with ionizing energy than when loaves were made with untreated flour. The decrease in volume appeared to be a result of the ionizing energy effect on splitting some of the molecules of the gluten proteins that give dough its tough, elastic quality (Lee 1959; Lorenz 1975).

Grains and grain products usually are stored in large quantities. As a result, special handling methods are required to ensure that all parts of these commodities receive doses of ionizing energy within the desired range. The technique that has been suggested for use with accelerated electrons is moving the grain past the accelerator at high speed in an airstream; however, this source has little penetration power. A factor to consider for using this method is that some kernels become cracked or broken. Airstream transport is not needed if x-rays and gamma rays are used because their penetrating power is greater. The large lots of grain involved in world trade, however, are almost invariably moved from shore to ship and vice versa by blowing the grain through tunnels. All three sources of ionizing energy thus could be applied with such transport.

Cogburn et al. (1972) attributed a major portion of the control of insects during exposure to gamma rays to movement of the grain in the air stream. Adem et al. (1978) found that gamma rays from cobalt-60 were more effective than accelerated electrons against pupae and adults of two species of insects in stored grain. At doses of 0.15 or 0.25 kGy, the two forms of ionizing energy were equally effective in preventing the development and emergence of the two insect species.

A major problem in disinfecting commodities of insects is the fact that many species may be present and the dose of ionizing energy employed must consequently be great enough to sterilize or kill the most resistant species. Tilton and Brower (1973, 1987) tested more than 30 species of insect pests of stored products for radiosensitivity using techniques yielding results that are comparable among species. They found that the most resistant beetles are six- to sevenfold more resistant than the least resistant of the beetles tested. Both males and females reproduced after exposure to 0.3 kGy of ionizing energy.

Temperature modifies the effects of ionizing energy on insects by affecting the metabolic state of the insects (Tilton and Brower 1983). Tilton and Brower (1985) found that when certain insects in stored wheat were treated with relatively low doses of ionized energy, infrared energy, or microwave energy, combinations of the latter two sources of energy with ionized energy produced somewhat greater mortality than the sum of the treatments applied individually. The beneficial effect of the combined treatments on insect kill was great enough to reduce the total cost of the disinfestation to less than the cost required for control by the use of ionizing energy alone.

Several studies have determined that the nature of the gases in the atmosphere and the atmospheric pressure affect the sensitivity of insects to ionizing energy (Baumhover 1963; Clark and Herr 1955; Langley and Maly 1971; O'Brien and Wolfe 1964; Ohinata et al. 1977; Smittle 1967; Tilton and Vardell 1982). In general, these studies have shown that the sensitivity is decreased

when the supply of atmospheric oxygen is decreased by evacuation or substitution of other gases. Thus, it appears unlikely that any technique involving an oxygen deficiency will result in improved control of insects by ionizing energy. Studies to determine the nutrient stability of irradiated grains have suggested that the doses employed have few if any detrimental effects on the retention of some nutrients (Table 2). Research has recently been conducted on the utilization of gamma radiation to reduce the cooking time of brown rice, especially because brown rice is known to contain more nutritive value than milled rice.

Despite its high nutritional content, demand for brown rice has been limited because of its longer cooking time, instability during storage, strong bran flavor, and undesirable texture. Studies have been conducted to produce quick-cooking brown rice that involved such physical methods as fissuring, soaking, cooking, drying (Luh et al. 1980; McCabe 1976; Roberts 1972; Roberts et al. 1980), and chemical treatments (Cox and Cox 1975; Smith et al. 1985); some have reported that gamma irradiation reduced cooking time in legumes and rice (El Saadany et al. 1979; Rao and Vakil 1985). Sabularse et al. (1991) reported that gamma irradiation at doses of 1 and 2 kGy on brown rice varieties Mars, Lemont, and

Table 2. Nutrient stability of irradiated grains.

Grain	Dose (kGy)	Nutrient	Retention (%)
Wheat	0.2–2	Thiamine	90[a]
		Riboflavin	90
		Niacin	90
Wheat flour	0.3–0.5	Thiamine	100[b]
		Riboflavin	100
		Niacin	100
		Pyridoxine	100
Corn	0.25–3	Protein content	100[c]
		Protein quality	100
		Vitamins	100
Sorghum millet	0.2	Amino acids	100[d]
		Vitamin B_1	100
		Vitamin B_{12}	100
		Niacin	100
		Pantothenic acid	100
Rolled oats	1 (nitrogen)	Vitamin E	95[e]
	1 (air)	Vitamin E	44
Brown rice	1–2	Thiamine	100
		Riboflavin	100

[a]Vakil et al. (1973).
[b]Josephson et al. (1977).
[c]Murray (1983).
[d]Diehl (1979a,b).
[e]Douglas et al. (1996).

Tebonnet influenced cooking quality. Cooking times were reduced, and increases in water uptake and amount of starch in residual cooking liquid with increasing dose levels were evident. Results suggested that starch may be the major component in the rice kernel affected by gamma irradiation. Sabularse et al. (1992) also reported the effects of the irradiation of brown rice on solids that leached into the cooking water, on moisture within the grain, amylose content, peak viscosity, setback values, and final viscosity.

Liuzzo et al. (1996) reported that brown rice irradiated at 1 and 2 kGy and stored for 3 mon under ambient conditions resulted in significant decreases in lipase activity and fatty acids concentration, suggesting a possibility for extension of shelf life before rancidity develops. Douglas et al. (1996) found that irradiation of two varieties of brown rice (Mars and Lemmont, medium and long grain, respectively) at 1 and 2 kGy of cobalt-60 irradiation did not affect the thiamin and riboflavin concentrations (see Table 2). Simultaneous sensory determinations during a 6-mon storage period indicated that the 2-kGy level affected the sensory quality of both varieties. However, quality of the 1-kGy-irradiated rice was not significantly affected. These results and those of Liuzzo et al. (1996) suggested that irradiation is capable of extending the shelf life of brown rice.

IV. Spices

The International Trade Center UNCTAD/GATT (1982) defined spices as one of the various strongly flavored or aromatic substances of vegetable origin obtained from tropical and other plants, commonly used as condiments or employed for other purposes on account of their fragrance and preservative qualities. Spices can be divided into "true spices" such as pepper, cinnamon, and cloves, which are of tropical origin; herbs such as basil, marjoram, and oregano, which usually originate from leafy plants of temperate zones; and spice seeds (mustard, celery, anise, etc.) that may be from either tropical or temperate regions (Farkas 1988). The major spice-exporting countries include Brazil, China, India, Pakistan, Malaysia, Madagascar, Indonesia, and Mexico. The largest markets for spices are the U.S. and the European Economic Community.

Spices are widely used in food preparation at home and in the food industry. As the demand for convenience foods increased, the industrial use of spices increased accordingly, especially in meat, fish, bakery, and vegetable products. The widespread use of spices in convenience foods has led to increasing concern about their effect on the shelf life and wholesomeness of these foods. Spices often contain excessive molds and bacteria, which may induce food spoilage and constitute a health hazard for the consumer. The high bacterial load of spices is generally attributed to the endogenous soil and plant microbial population and to contamination during harvesting, handling, and transportation (Farkas 1988; Juri et al. 1986). In tropical regions, during drying, sorting, and storing of spices under high humidity and elevated temperatures fungi and insect larvae may grow and multiply on the spices. Thus, insect infestation, mold

growth, and bacterial contamination are major problems that jeopardize subsequent use of spices for food, pharmaceutical, and cosmetic applications. Of special concern is the possible contamination of food by aflatoxin-producing microorganisms such as *Aspergillus* spp. and pathogenic bacteria like *Salmonella* originating from contaminated spices.

Applicable decontamination methods are, therefore, of considerable concern from economic, public health, and environmental aspects. In many countries, both fumigation with ethylene oxide and heat sterilization have been tried with varying degrees of success. The fumigation of spices with ethyl bromide for disinfestation and ethylene oxide for destroying microbes are relatively effective but have inherent disadvantages (Razem et al. 1988). The fumigation process generates chemical residues that may represent a significant health hazard for both handlers and consumers; hence, its use is banned by many countries. Additionally, fumigation may cause reduction of solubility and loss of sensory characteristics (Onyenekwe and Ogbadu 1995). Fumigation is also known to be a time-demanding process. Further, the delicate flavor and aroma compounds of spices are very sensitive to the process of decontamination. Excessive heating of spices may cause loss of volatiles and the production of off-flavors and odors. Washing, on the other hand, decreases the microbial load of spices but induces changes in sensory characteristics, thereby yielding a product of inferior quality (Juri et al. 1986; Onyenekwe and Ogbadu 1995; Sharma et al. 1989).

Given the inherent disadvantages associated with heat treatment and fumigation, researchers are focusing their efforts on finding methods that effectively decontaminate spices without altering their delicate flavor or posing health hazards to processors and consumers. Results so far have shown that treatment of spices with ionizing radiation ensures their sterilization without leaving harmful residual and does not induce sensory changes. Irradiation of spices is a relatively easy and cost-effective process. Furthermore, the product can be sterilized in plastic pouches, preventing posttreatment recontamination.

The preservative effect of irradiation results from its ability to inactivate food spoilage organisms including bacteria, molds, and yeast. Irradiation also destroys disease-causing organisms such as worms and insect pests that damage food in storage (WHO 1988). The effect of radiation may, however, be beneficial or deleterious depending on the dose used. In the case of spices, the maximum allowable radiation dose is 30 kGy for dry spice (CFR 1993). However, the majority of researchers agree that a radiation dose as high as 10 kGy is sufficient to eliminate deleterious microbial flora of spices without causing alteration of their sensory characteristics. Andrews et al. (1995c) reported a reduction of extractable flavor components in ground ginger, but sensory scores were similar for treated and untreated ginger. Other researchers have shown similar results: Onyenekwe and Ogbadu (1995), red chili pepper; Piggott and Othman (1993), black pepper; and Farkas (1988), allspice, oregano, thyme, paprika, celery seed, red pepper, black pepper, garlic powder, and basil. Tables 3 and 4 show bacterial and fungal loads of selected spices as well as the effectiveness of ionizing radiation in reducing these numbers.

Table 3. Total viable bacterial (log_{10}/g) cell counts in untreated and irradiated spices.

Spice	Untreated (log_{10}/g)	5 kGy	10 kGy
Basil[a]	4.4–6.5	—	3.0
Cardamom[a]	4.1–6.3	2.5	—
Celery seed[a,b]	5.6	3.6–4.0	<1
Cinnamon[c]	3.3	2.1	<1
Clove[a]	2.9–5.5	1.6–2.3	<1
Garlic powder[a]	4.7–5.9	1.3–3.8	2.3
Ginger[d]	8	—	1
Marjoram[e]	3.6	—	<1
Nutmeg[c]	4.6	2.7	<1
Oregano[b]	4.5	2	<1
Paprika[b]	7	5	<1
Parsley[a]	3.3–6.9	3	<1
Black pepper[f]	7.7	4.9	<2
Red pepper[g]	6.6	4.2	1.5
Red pepper[h]	7.2	3.5	<1
White pepper[f]	6.7	5	2
Tumeric[i]	4.3–6.5	—	<1–2

[a]Farkas (1988).
[b]Vajdi and Pereira (1973).
[c]Sharma et al. (1984).
[d]Andrews et al. (1995c).
[e]Farag et al. (1995).
[f]Juri et al. (1986).
[g]Munasiri et al. (1987).
[h]Onyenekwe and Ogbadu (1995).
[i]Sharma et al. (1989).

Munasiri et al. (1987) investigated the effect of gamma irradiation on the storage stability of black pepper, chili, turmeric, coriander, and curry powder. These authors concluded that bacterial counts decreased continuously in all samples irradiated with 5 kGy during 6-mon storage. They attributed such a continuous decrease of microbial counts to the inability of microorganisms to sustain the radiation damage under poor restorative conditions in dry samples. In the same study, these authors reported zero microorganism counts in samples treated with 10 and 12.5 kGy during 6-mon storage. Similar results were obtained by Onyenekwe and Ogbadu (1995), who reported zero microbial counts in red pepper irradiated with 10 kGy and stored for 9 mon.

In conclusion, treatment of spices with irradiation doses up to 10 kGy significantly extended their shelf life without causing any significant change in their sensory or chemical quality. Furthermore, extended animal feeding studies showed no toxicological or mutagenic effect associated with the consumption

Table 4. Mold counts (log_{10}/g) in untreated and irradiated spices.

Spice	Untreated	5 kGy	10 kGy
Basil[a]	2.6	—	<1
Cardamom[a]	3.1	<1	—
Celery seed[a]	2.3	—	<1
Cinnamon[b]	2.5	<1	<1
Clove[b]	3.0	<1	<1
Garlic powder[a]	2.5–3.9	<2	<1
Ginger[c]	4.3	—	<1
Marjoram[c]	3.8	—	<1
Nutmeg[b]	4.0	<1	<1
Oregano[a]	3.3–4.0	<1	—
Paprika[a]	2.2–5.7	<1	—
Parsley[a]	2.3	<2	—
Black pepper[d]	3.5–3.7	<1	—
Red pepper[e,f]	5.8–6.3	<2	<1
White pepper[d]	2.4–4.2	—	<1
Tumeric[e]	3.1	<1	<1

[a]Farkas (1988).
[b]Sharma et al. (1984).
[c]Farag et al. (1995).
[d]Juri et al. (1986).
[e]Munasiri et al. (1987).
[f]Onyenekwe and Ogbadu (1995).

of food treated with such gamma irradiation doses (Vakil et al. 1973). The use of irradiation doses higher than 10 kGy was found to sterilize spices but may cause undesirable changes in their sensory and chemical characteristics.

V. Dairy Products

Milk was the first dairy product to be subjected to irradiation during the 1930s. Ultraviolet (UV) light was used to increase the vitamin D activity of milk; its effect is similar to the action of sunlight on plants or human skin. By 1935, there were approximately 35 million consumers of irradiated milk in North America (Satin 1993). Benefits of increased vitamin D were considered to outweigh the reported loss of vitamin B and C. As vitamin D became cheaper, its addition to milk replaced the use of UV irradiation.

Since World War II, the use of gamma irradiation on foods has increased to include many food commodities. Irradiated dairy products, however, have not been well received because of the development of off-flavors, off-colors, and off-odors, even at low doses (<1 kGy). A dose of 45 kGy applied to fluid milk at 5 °C produces a brown color and a strong caramelized flavor (Urbain 1986). When freezing temperatures are used during irradiation, discoloration and cara-

melization are kept to a minimum; however, other bitter flavors may result. Hashisaka et al. (1989) reported very high irradiation D-values (16.8 and 24.4 kGy) for treatment of *Listeria monocytogenes* in mozzarella cheese and ice cream, respectively, at –78 °C. Doses of 1.5 kGy have been shown to produce minimal sensory changes but may not effectively rid cheese or other dairy products of potential pathogens such as *L. monocytogenes*.

VI. Red Meats

A. Microbial Safety

Animals from which red meat and meat products are derived can harbor microbial contaminants from various sources. Bacteria and other microorganisms can be found in the skin, hair, hooves, gastrointestinal tract, urogenital tract, respiratory tract, and milk ducts of most animals (Ray 1996). The number and type of contaminants depend on the location, with numbers reaching as much as bacteria per gram of tissue. Pathogenic organisms in the intestinal tract, such as salmonellae, campylobacters, *Yersinia enterocolitica, L. monocytogenes*, and pathogenic serotypes of *E. coli* are easily transferred to the muscle tissue of the animal during slaughter, dehairing, and similar processing operations. In addition, other pathogens, as well as spoilage organisms, can contaminate the meat through contact with unclean surfaces, contaminated air and water, and food handlers (Ray 1996). Animal carcasses usually contain 1–3 log bacterial cells per square inch of outside surface. The levels in ground meat are usually 4–5 log, while those in whole cuts are about 1–2 log less (Silliker 1980). Of these, pathogenic organisms usually do not exceed 500 cells per gram, with fewer than 100 cells often being present.

Foodborne illness is a problem that has received increased attention in the U.S. in recent years from consumers, the food industry, the government, and academia. In the U.S., an average of 479 outbreaks of foodborne illness were reported each year from 1983 to 1987, involving 18,336 individuals. Of those cases in which the disease agent was identified as either bacterial, fungal, parasitical, or viral, 90% were attributed to bacteria (Bean et al. 1990). Of the food types associated with confirmed outbreaks during this period, red meats consisted of 14%, with salmonellae being the predominant cause of the outbreaks (Bean and Griffin 1990). This figure may not appear significant, but if we consider that 19% of the total outbreaks for that period involved multiple foods and that 40% involved unknown foods, 14% for red meats represents the largest portion of outbreaks ascribed to any specific food group.

In recent years, a number of bacteria, viruses, and parasites have emerged as foodborne pathogens, resulting in numerous outbreaks. A recent example is the outbreak of more than 9,500 cases of hemorrhagic colitis in Japan from the consumption of undercooked or raw meats and organs contaminated with verotoxigenic strains of *E. coli* (NIH Japan 1996). Smith and Fratamico (1995) postulated that genetic changes in microorganisms, resulting in increased virulence, plus changes in social attitudes and eating habits, changes in food production

and distribution systems, increased numbers of immunocompromised persons in the population, and improved methods of pathogen detection have contributed to the emergence or recognition, as well as the persistence, of foodborne pathogens.

The methods that are used to prevent outbreaks of foodborne illness from consumption of red meats are surprisingly simple. They are based on three principles: (1) preventing the initial contamination of the product by proper sanitation of contact surfaces, following good food handling practices as part of a Hazard Analysis Critical Control Points (HACCP) system; (2) slowing or minimizing the growth of microorganisms already present in the food, usually by refrigeration or freezing; and (3) eliminating or reducing the number of contaminants by some form of processing. Following Good Manufacturing Practices (GMP) in conjunction with a HACCP system is imperative for manufacturers to control contamination. The HACCP system is also aided by the introduction of intervention strategies along the processing line. These may include washes with hot water (Reagan et al. 1996; Smith and Graham 1978), steam (Dorsa et al. 1996), and organic acid dips or washes (Hardin et al. 1995).

There are some concerns associated with washing and decontamination procedures for removal of feces, whether by hot water, steam, vacuum, or organic acid. The most significant is the fact that less than complete decontamination and possible spreading of contamination to previously uncontaminated areas through carriage of bacteria in liquid runoff has been shown to occur during washing. Reductions in bacterial contaminants achieved on the slaughter floor do not guarantee that the subprimal cuts derived from these carcasses will have few contaminants. Prasai et al. (1991) showed that acid-treated beef carcasses sprayed after dehiding and evisceration decreased in total contaminants from 3.9 to 1.6 log. However, beef loins obtained from those carcasses had counts of 4.8 log only 3 d after fabrication.

Irradiation of pork has been available since 1985 (USDA 1985) when its use was approved at a dose range of 0.3 to 1.0 kGy. The purpose was to destroy larvae of the parasite *Trichinella spiralis*. However, today we recognize the need to eliminate bacterial pathogens, which requires that higher doses be applied. Regarding other meats, there is currently no approval for the use of this technology on beef, lamb, or veal. A petition has been submitted to the USFDA (FDA 1994) asking for approval of irradiation of red meats at medium doses, including pork, in both fresh and frozen states. Specifically, irradiation of fresh, intact, and comminuted beef, pork, lamb, and veal is requested at doses between 1.5 and 4.5 kGy. For frozen meats (−18 °C), the petition asks that the irradiation dose be 2–3 kGy as a minimum and 7.0 kGy as a maximum. Aerobic as well as vacuum and modified-atmosphere packaging is requested with the ultimate goal of eliminating foodborne pathogens such as *Salmonella*. Several pathogenic organisms of concern can contaminate red meats; some are pyschrotrophic, or able to grow at refrigeration temperatures. Given that merchants and consumers rely on refrigeration as an important control step to maintain the safety of such products, it would be beneficial if pathogens such as *L. monocytogenes* that

grow at low temperatures could be eliminated. Irradiation sensitivities of foodborne pathogens vary greatly, however (Table 5).

The organism *E. coli* O157 : H7 has been implicated in several outbreaks of foodborne illness in which contaminated, undercooked ground beef patties were the vehicles of infection (Doyle 1991). Irradiation sensitivities of *E. coli* and other mesophilic gram-negative bacteria are also presented in Table 5. As the leading cause of diarrhea in the world (Harris et al. 1986), *Campylobacter* is

Table 5. D_{10} Values of foodborne pathogens found in red meat.

Microorganism	Meat product	D_{10} value/kGy
Listeria monocytogenes	Ground beef[a]	0.31–0.61
	Beef steaks[b]	0.50–0.60
	Pork[c]	>0.61
	Ground pork[d]	0.42–0.45
	Minced pork[e]	0.71
	Roast beef[f]	0.70
Aeromonas hydrophila	Ground beef[g]	1.04–1.89
Yersinia enterocolitica	Ground beef[h]	0.04–0.08
	Minced pork[e]	0.16–0.20
Escherichia coli 0157:H7	Ground beef[i]	0.25–0.31
	Beef steak, ground beef[b]	0.30–0.40
Salmonella spp.	Ground beef[h,e]	0.38–0.92
	Roast beef[e]	0.37–0.70
Campylobacter jejuni	Ground beef[j]	0.16–0.32
	Pork loin[c]	<0.30
Bacillus cereus (spores)	Ground beef and pork[k]	2.61–2.78
Clostridium sporogenes (spores)	Beef fat[l]	6.2–6.4
	Pork fat[l]	7.4–8.2
Clostridium botulinum (spores Type A&B)	Canned cured ham[m]	0.61–2.42
Clostridium perfringens (spores)	Minced pork[e]	1.5–2.5

[a]Monk et al. (1994).
[b]Fu et al. (1995a).
[c]Lebepe et al. (1990).
[d]Tarté et al. (1996).
[e]Grant and Peterson (1991a).
[f]Grant and Peterson (1992).
[g]Palumbo et al. (1986).
[h]Tarkowshi et al. (1984a).
[i]Clavero et al. (1994).
[j]Lambert and Maxcy (1984).
[k]Thayer and Boyd (1994).
[l]Shamsuzzaman and Lucht (1993).
[m]Anellis et al. (1972).

unique in that studies have shown that it is fairly sensitive to irradiation when compared with many other pathogens (Table 5).

A foodborne pathogen not usually studied in relation with irradiation is *Staphylococcus aureus*, mainly because it is thought to be a contaminant associated with food handlers and not one that is indicative of fecal contamination of red meats (Trantner 1991). Grant and Patterson (1992) found D_{10} values for this organism ranging from 0.25 to 0.43 kGy in roast beef, which are similar to those found by Monk et al. (1994), 0.44–0.45 kGy, in ground beef. Grant et al. (1993), reporting the susceptibility of *S. aureus* to irradiation in roast beef and in the subsequent toxin production of survivors during storage, found that irradiation at 2 kGy resulted in a 3–4 log reduction of cells that began as an inoculum of 10^6 per gram. Production of toxin A was delayed by irradiation, with no toxin being detected after 7 d at 15 °C, compared with toxin detection in the nonirradiated control at 2 d of storage. When the storage temperature was 22 °C, toxin A could be detected, although barely, in irradiated samples at 2 d, compared with 1 d for unirradiated samples.

No discussion of this topic would be complete without including the work that has been carried out to eliminate or reduce the number of spore-forming bacteria in meats, especially the pathogens. *Bacillus cereus* is one organism responsible for several outbreaks of foodborne illness from consumption of starchy foods such as rice and pasta as well as red meats (Gilbert 1979). The D_{10} value of the spores was reported by Thayer and Boyd (1994) (Table 5).

Some work has been done to determine the irradiation doses necessary to eliminate other types of organisms from red meats, such as parasites and viruses. Verster et al. (1977) showed that a dose of 0.14 kGy was not sufficient to prevent evagination of cysticerci belonging to the pork tapeworm *Taenia solium*. However, evagination was adversely affected 6 d after irradiation, rendering the cysticerci noninfective. Cysticerci exposed to 0.12 kGy were found to be infective to hamsters but could not maintain themselves indefinitely, compared with the unirradiated controls. In addition, the worms from irradiated cysticerci did not increase in size, compared with tapeworms from controls, which grew considerably.

Irradiation of pork infected with the parasite *Trichinella spiralis* was carried out by Brake et al. (1985), who showed that a dose of 0.15–0.30 kGy blocked maturation of ingested larvae and prevented production of larval progeny. These investigators could not detect any viable trichina during subsequent storage. Regarding viruses, Lasta et al. (1992) reported that irradiation at 15 or 25 kGy was not sufficient to inactivate foot-and-mouth disease virus. However, irradiation at 15 kGy combined with heat treatment at 78 °C for 20 min completely inactivated the virus in bovine tissues. This can be explained by examining the work of Sullivan et al. (1973), who found D_{10} values ranging from 6.8 to 7.5 kGy for Coxsackie virus in ground beef. Assuming some similarities between these two types of viruses, it is clear that a dose of 25 kGy would only inactivate 3–4 log, which may not be sufficient to eliminate all viral particles from the meat.

One of the important benefits of meat irradiation is the extension of shelf life, which is economical for both merchants and consumers because losses from spoilage are minimized. In a study by Niemand et al. (1983), irradiation of beef at 2.5 kGy reduced the total population of aerobic bacteria by 4.4 log, of which 3.4 log were identified as lactic acid bacteria. Irradiation at this dose also resulted in reduction in the population of total anaerobes by 4.8 log/g. The pseudomonads, members of the family Enterobacteriaceae, and *Brochothrix thermosphacta* were completely eliminated and could not be detected during storage.

Shelf-life extension by irradiation can also be attained in processed meat products, such as luncheon meats (Table 6). In a study involving pork (Mattison et al. 1986), irradiation of loins at 0.01 kGy significantly reduced the number of mesophiles and psychrotrophic spoilage organisms, with the total number of bacteria being 2.0 log lower in irradiated samples than in controls.

Lebepe et al. (1990) reported a reduction in aerobic and anaerobic counts in pork, with lactobacilli being the organism group least affected, after irradiation of pork loins at 3.0 kGy. Spoilage began after 91 d during refrigerated storage, compared with 35 d in nonirradiated controls. Ehioba et al. (1987) identified the microbial flora of ground pork irradiated at 1.0 kGy, finding that the microflora shifted from gram-negative to gram-positive organisms after irradiation. Shelf life was 9 d for nonirradiated controls and 11 d for irradiated samples. Grant and Patterson (1991b) performed a detailed taxonomic study of survivors in pork irradiated at 1.75 kGy, identifying the majority of isolates as *Lactobacillus sake*. Fu et al. (1995b) reported a decrease in total aerobic counts in ham of 6 or 5 log, depending on whether the product was pumped with brine.

The influence that medium composition may have on irradiation susceptibility of microorganisms is not well understood, but radiation-induced changes in the chemistry of the media, may cause different patterns of radical formation.

Table 6. Shelf-life extension of irradiated red meat.

Meat product	Dose (kGy)	Untreated shelf life (d)	Irradiated shelf life (d)
Beef[a]	2.5	2–3	9
Beef top round[b]	2.0	8–11	28
Beef burgers[c]	1.54	8–10	26–28
Beef cuts[a]	2.0	1X	2X
Beef cuts irradiated under vacuum[a]	2.0		70
Corned beef[d]	4.0	14–21	35
Lamb, whole and minced[e]	2.5	7	28–35

[a]Niemand et al. (1983).
[b]Rodriquez et al. (1993).
[c]Dempster et al. (1985).
[d]Willis et al. (1987).
[e]Paul et al. (1990).

Shamsuzzaman and Lucht (1993) reported higher D_{10} values for *Clostridium sporogenes* in pork fat compared with beef fat (see Table 5). Similar differences were seen with *Yersinia enterocolitica* in filet americain and in ground beef. It has been speculated that fat content may play a role in these differences, because the level of fat in filet americain is much higher than that in ground beef. However, a study by Clavero et al. (1994) showed that irradiation of ground beef did not result in significant differences in D_{10} value, according to fat content, for *Staphylococcus aureus, E. coli* O157 : H7, *Listeria monocytogenes*, or *Salmonella typhimurium* at refrigeration temperatures.

So far as the effect of food ingredients is concerned, addition of sodium acid pyrophosphate (SAPP) at the 0.4% level added 2 d to the shelf life of pork inoculated with spoilage organisms and irradiated at 1.0 kGy, in addition to a shelf life extension of 1.5 d from irradiation alone (Ehioba et al. 1987). However, the additive had no effect on the naturally occurring microflora in uninoculated samples. Firstenberg-Eden et al. (1980) showed that 0.75% NaCl and 0.375% sodium tripolyphosphate in minced beef had no effect on the radiation resistance of *Moraxella-Acinetobacter cells*. Niemand et al. (1983) determined that irradiation at 2.5 kGy, and addition of lactic acid to achieve a pH in minced beef of 5.0 together with irradiation, resulted in significant shelf life extension. The product spoiled after 7 d in unirradiated controls and 11 d in beef treated with lactic acid alone. Samples treated by irradiation had counts not exceeding 4.0 log at those same time intervals, while samples treated by both lactic acid and irradiation had counts <2.0 log.

Huhtanen et al. (1986) reported that irradiation at 1.9 kGy of comminuted bacon containing 0.75% sugar increased the rate of toxin production by *C. botulinum* during subsequent storage compared with nonirradiated controls. It is thought that in the nonirradiated samples the added sugar provided a source of nutrients for the microflora organisms, thus lowering the pH, which inhibited toxin production by *C. botulinum*. Irradiation eliminated most of the microflora, preventing the formation of acids, which enabled the pathogen to germinate and produce toxin. It should be noted that irradiation at a higher dose (15 kGy) resulted in toxin-free bacon for the 8-wk incubation period.

Szczawinski et al. (1989) showed that irradiation of cured ground pork at doses up to 9.0 kGy and containing 50 mg/kg of nitrite reduced the nitrite level and increased the probability of toxin production by *C. botulinum*. This could be avoided if the irradiated samples contained at least 100 mg/kg of added nitrite. However, if the dose was greater than 10 kGy, the residual nitrite was reduced considerably by the irradiation treatment, resulting in outgrowth and toxin production by the pathogen. Thus, it is important for additives to be applied in the right amounts and that irradiation processing be carried out at the appropriate dose to optimize inhibition of *C. botulinum*.

B. Quality of Irradiated Meat

Objective Quality. The possible effect of irradiation on cooking losses and thiobarbituric acid (TBA) values (a measure of lipid oxidation) was investigated

by Mattison et al. (1986). They found that vacuum-packaged pork loins irradiated at 1.0 kGy showed no significant differences in cooking loss, raw TBA values, and cooked TBA values when compared with nonirradiated controls. In fact, the raw TBA values were below detectable levels of rancidity throughout the 14 d of refrigerated storage. Lebepe et al. (1990) also found no change in TBA values in vacuum-packaged pork loins irradiated at 3.0 kGy until day 27 of refrigerated storage. After that time, TBA values of irradiated samples continued to increase slowly, while those of the controls decreased after 34 d, probably caused by the metabolism of the malonaldehyde reagent by spoilage bacteria in the controls. The pH of the samples did not change significantly during storage. Color measurement by the Hunter method revealed significant differences in the degree of lightness and yellowness, with higher values in irradiated compared to nonirradiated samples, but only after 42 d of storage. In a similar study, Fu et al. (1995b) observed no significant differences in pH or TBA values during storage between pork chops irradiated at 2.0 kGy and controls. In addition, no differences were observed between hams irradiated at 1.8 kGy and controls.

Total volatile basic nitrogen (TVBN) was measured in lamb meat irradiated at 1.0 kGy and 2.5 kGy as a measure of off-odor development (Paul et al. 1990). Unirradiated controls reached levels of 35 mg% within 2 wk of storage, while samples irradiated at 1.0 kGy showed the same level after 4 wk. Samples irradiated at the higher dose never reached that level, showing values of less than 20 mg% after 5 wk of storage. In studies involving beef, Dempster et al. (1985) reported a decrease in pH of vacuum-packaged beef burgers, with nonirradiated controls reaching a pH of 5.25 in 7 d of storage, compared with 14 d for meat irradiated at 1.54 kGy. No significant difference was observed in Hunter color values nor in levels of volatile fatty acids between controls and irradiated samples. However, irradiation had an initial effect on peroxide value (a measure of lipid oxidation) immediately after irradiation, but all the samples showed similar peroxide values after 8 d of storage. Fu et al. (1995a) showed no significant difference in the pH or Hunter color values in vacuum-packaged beef steaks and ground beef irradiated at up to 2.0 kGy, when compared with controls. TBA values increased for all samples after 7 d of storage.

Sensory Quality. In evaluating the quality of irradiated meats by sensory panel, two types of tests are usually conducted. One is the triangle test in which the panelists are given three samples, two of which are identical. They are asked to taste the samples and determine which of the three is different from the rest. Of the three samples, two could be nonirradiated controls and the third an irradiated sample, or vice versa. This test is designed to determine whether subjects can detect a difference between irradiated and nonirradiated food. Statistical probability tables are used to determine how many panelists of the total number must correctly select the sample that is different to conclude that this sample was significantly different from the other two.

The other is a descriptive analysis test in which the panelists are asked to rank irradiated and nonirradiated samples according to attributes such as flavor,

texture, juiciness, and aftertaste. Anchor words are used to help the panelist describe a specific attribute. For instance, anchor words for juiciness may consist of "dry" versus "moist," and anchor words for texture may consist of "tender" versus "chewy." A 15-cm horizontal line is drawn for each attribute on a score card, and the anchor words are placed on each end of the line for a specific attribute. The panelists are asked to draw a vertical slash at the point along the 15-cm line between two anchor words that best describes the attribute of the sample being tasted. The distance between the beginning of the line and the vertical slash is measured, and the number is used to determine whether significant differences exist between samples. Other methods for sensory analysis include a numerical ranking from 1 to 10, or a similar scale, to denote acceptability of specific attributes.

In a study by Dempster et al. (1985), trained panelists were asked to rank raw beef burgers irradiated under vacuum at 1.03 kGy or 1.54 kGy according to surface and interior color and intensity of off-odors. On a scale from 1 to 6, 1 being "poor" and 6 being "excellent," panelists detected no difference in surface or interior color between irradiated samples and controls up to 11 d after irradiation. On day 15, interior color of the irradiated samples had a higher number, denoting a ranking closer to "excellent," compared with nonirradiated controls, probably because of spoilage of the controls by this time of refrigerated storage. Samples irradiated at 1.54 kGy developed no detectable spoilage odor during storage, while some spoilage odor was detected in samples irradiated at 1.03 kGy by day 15 of refrigerated storage. By comparison, the unirradiated control developed spoilage odors by day 4 of storage. Irradiated samples did show a discernible odor immediately after irradiation, but it dissipated after exposure to air. The authors speculated that hydrogen sulfide was probably one of the components of this undesirable odor.

Fu et al. (1995a) conducted sensory evaluation of raw beef steaks and ground beef after irradiation to 2.0 kGy. They found no color difference between controls and irradiated samples. However, some panelists detected off-odors in irradiated samples, which quickly dissipated on opening the packages. Similar findings were reported by these investigators (Fu et al. 1995b) with irradiated pork chops. No color differences were detected by the panelists from among all the samples, yet off-odors were detected in irradiated pork chops after irradiation. Just as in other studies, these odors dissipated after opening of the package.

Rodríguez et al. (1993) reported that trained panelists did not detect development of irradiation odor on beef top round irradiated at 2.0 kGy. Niemand et al. (1981) also evaluated vacuum-packaged beef irradiated at 2.0 kGy for sensory quality. The irradiated samples had significantly higher rankings (were deemed closer to excellent) throughout the storage period for appearance and odor compared with unirradiated controls. It is not clear why some studies noted that off-odors develop while other studies conducted with the same product and dose showed no such development. The fact that the off-odors quickly dissipate after opening may provide an answer, because in some studies panelists may be eval-

uating the meat some time after the package is opened, allowing for dissipation of volatile compounds responsible for the odor notes.

In a study done with lamb meat (Paul et al. 1990), the sensory scores for odor were within the acceptable range (score of at least 5 on a scale from 1 to 10) in meat irradiated at 2.5 kGy after 5 wk of storage. These values could not be compared with refrigerated unirradiated controls, because the latter had spoiled much earlier. Irradiated samples were compared with frozen unirradiated controls and found to be indistinguishable from these. In the study by Fu et al. (1995b), ham irradiated to 2.0 kGy showed no off-odors, pointing to the possible effect of product composition and ingredients in preventing the formation of these odors, when compared with fresh pork and beef. However, irradiation of corned beef (a cooked, cured product) by Wills et al. (1987) at 1.0, 2.0, or 4.0 kGy showed an increase in off-odors with an increase in dose. Significant differences were detected between unirradiated controls and samples irradiated at 2.0 and 4.0 kGy immediately after irradiation. Upon storage at refrigeration temperatures, acceptability of the unirradiated meat declined, falling below the values for irradiated samples after 2 wk of storage.

The effect of product composition on sensory quality of irradiated meat can be seen in a study by Tarkowski et al. (1984a) conducted with filet americain (raw ground beef with a mayonnaise sauce). These authors found that irradiation at 1.0 kGy resulted in more panelists preferring the unirradiated samples, describing these as "more spicy," "more body," "good taste," and "more fresh." However, when the beef was irradiated before mixing with the mayonnaise sauce and then served to panelists, the resulting product did not differ from the unirradiated samples. Thus, avoiding the influence that lipid can have on the overall taste of irradiated meats can result in a product that is indistinguishable from the unirradiated control. Luchsinger et al. (1996a) showed that sensory evaluation of cooked pork chops after irradiation under vacuum at 2.5 kGy showed no difference between irradiated and control samples for overall acceptance, meatiness, freshness, tenderness, and juiciness.

Effect of Processing Parameters. As for the microbiological quality of irradiated meats, processing parameters such as temperature, atmosphere, and product composition can play a role in the quality of the product. These parameters can be optimized to minimize the amount of oxygen radicals that are produced by irradiation, which can have an impact on lipid oxidation and off-odor development.

Temperature. Niemand et al. (1981) conducted a sensory evaluation of beef cuts irradiated at 2.0 kGy at both 25 °C and 2 °C. They found irradiated samples processed at the higher temperature scored equally well with unirradiated controls in terms of tenderness and juiciness. However, the irradiated samples had lower acceptability in terms of taste and odor than controls. A second experiment was conducted, with the temperature of irradiation maintained at 2 °C. In terms of aroma and taste, these samples had a lower score at week 2 of storage

than unirradiated controls, an equal score at week 4, and a higher score at week 8 than controls, pointing to the benefits that low temperatures can have on the quality of irradiated fresh meat.

Atmosphere. Packaging atmospheres containing 25% CO_2/75% N_2 maintained the uncooked color and odor of pork chops irradiated at 1.75 kGy more effectively than 50%CO_2/50% N_2 (Grant and Patterson 1991c). In another study (Lambert et al. 1991a), there was no significant difference in the color or odor of fresh pork irradiated at 1.0 kGy under an initial 15% CO_2/75% N_2 atmosphere, when compared with controls. However, when the gas concentration was 30% CO_2/70% N_2, irradiated samples retained acceptable color and odor up to 21 d, compared with 7 d for controls. Lambert et al. (1991b) also reported that irradiation under a packaging atmosphere containing 20% O_2/80% N_2 resulted in a significant delay in the time of rejection of irradiated fresh pork during refrigerated storage (14 d), when compared with unirradiated controls packaged in the same atmosphere (7 d). No significant difference in time of rejection of color and odor of the product was observed between irradiated and unirradiated samples packaged in atmospheres containing $O_2/CO_2/N_2$ mixtures of 20 : 20 : 60 or CO_2/N_2 mixtures of 20 : 80.

Fu et al. (1995a) showed that irradiation of beef steaks at 1.5 kGy caused no significant difference in color when compared with controls whether the product was irradiated under vacuum or air. Differences were detected in odor compared with unirradiated controls, however, regardless of packaging atmosphere. It is evident from these studies that optimum quality can be achieved by irradiating fresh meats packaged in atmospheres containing O_2 and N_2 gas, or a mixture of these with CO_2, so long as the concentration of the latter is at least 30%. Packaging under vacuum affords some benefits in terms of color acceptability, but off-odors do develop, although these dissipate quickly on opening of the package.

Luchsinger et al. (1996b) showed that irradiation of frozen ground beef patties in air had detrimental effects on oxidative rancidity and display color. Vacuum packaging enabled patties to be displayed up to 21 d with minimal changes in color and oxidative rancidity. Murano et al. (1995) attempted to address the issue of off-odor development by comparing the sensory quality of ground beef patties irradiated and stored in air or under vacuum and samples irradiated under vacuum but immediately stored in air. When samples were served 1 d after refrigerated storage, panelists could only detect a significant difference between samples irradiated and stored in air or under vacuum when compared with unirradiated controls. Samples irradiated under vacuum but stored in air were indistinguishable from controls. This suggested that dissipation of off-odors or flavors caused by irradiation occurred during the storage period in air. When samples were served to panelists after 7 d of storage, there was no significant difference in acceptability between irradiated samples and controls, regardless of whether they were stored in air or under vacuum, suggesting a quenching effect or inactivation of off-odor and off-flavor notes within the product during the storage period.

The intelligent use of food irradiation, that is, the controlled application of the technology at doses sufficient to eliminate most pathogens, is a viable alternative in the effort to improve the safety of red meats. That irradiation can successfully render red meats safe by means of its effect on bacterial pathogens is beyond question. Research should now be concentrated on determining additional ways in which quality changes of these products will be minimized.

VII. Poultry Meat

Commercially processed broilers and turkeys are recognized as significant vehicles of foodborne salmonellosis and campylobacteriosis. Field and plant surveys on the prevalence of *Salmonella* spp. and *Campylobacter jejuni* and studies undertaken by the U.S. Department of Agriculture (USDA) applying U.S. Public Health Services (USPHS) Centers for Disease Control data suggest that as many as 2 million cases of salmonellosis occur annually in the U.S. population. Based on epidemiological studies, 90% of the cases were attributed to contaminated food, including poultry meat (Bokany et al. 1990; Wray 1994), beef, egg products (St. Louis et al. 1988), raw vegetables and nonpasteurized milk and derivatives. The prevalence of human salmonellosis in the U.S. increased fivefold from 4 to 19 cases/100,000 during the 20-yr period ending in 1985 (Wasserman 1985).

A study of causes of foodborne bacterial infection conducted during the late 1970s showed that inadequate cooking, improper cooling, defects in food handling, or a combination of these factors was responsible for 80% of the cases that were investigated. A disturbing trend is that a high proportion of food-related infection is associated with consumption of meals outside the home. This emphasizes the need for improved surveillance and handling procedures in institutional kitchens and commercial food establishments (Todd 1985). Chicken and turkey are regarded as being the primary source for 12% of cases of salmonellosis (Cohen and Blake 1977) and 50% of *Campylobacter* infections (Shane and Montrose 1985a) in the U.S.

Preharvest control of foodborne infections derived from poultry has been advanced by the WHO and the USDA as an approach to reducing the level of contamination entering processing plants (Schmitz 1993). Biosecurity at the live-bird level may prevent introduction of *Salmonella* spp. and *C. jejuni* into breeder and growout facilities housing broilers (Wierup 1991) and turkeys (Pomeroy et al. 1989). Control of rodents, wild birds (Rollins 1991), and flies (Shane et al. 1985b) may reduce infection.

Salmonella spp. is frequently introduced into flocks through contaminated feed (MacKenzie and Bains 1976), although effective pelleting will reduce the prevalence of infection (Haggblom 1994). Competitive exclusion cultures lower intestinal colonization by *Salmonella* (Goren et al. 1988) and *Campylobacter* (Mulder and Bolder 1991). Immunization of broilers with *Salmonella* bacterins has not been successful, but live vaccines based on transposon-engineered mutants of *S. typhimurium* stimulate antibody production in recipients (Barrow

1991). Combined live attenuated *S. typhimurium* and inactivated *S. enteritidis* vaccines have proven effective in suppressing ovarian colonization and vertical egg transmission of *S. enteritidis* in laying hens in Europe (Veilitz et al. 1996).

Based on current knowledge, there is no immediate prospect of eliminating foodborne bacterial pathogens from floor-reared commercial broilers and turkeys. Reduction of fecal contamination entering processing plants is accomplished by withholding feed from broiler flocks for 8–10 hr before slaughter together with appropriate decontamination of transport coops and modules. Multiphase scalding and upgrading on-line washing stations may reduce carcass contamination. Although experimental application of chemical disinfectants for immersion decontamination of poultry carcasses shows promise (Yogasundram et al. 1987), the process will be subject to practical and regulatory restraints. Concentrations of chlorine, acetic acid, succinate, and lactic acid that reduce levels of *Salmonella* spp. and *C. jejuni* on poultry meat also produce undesirable sensory changes and damage equipment. The potential carcinogenic activity of organohalides may restrict application of hyperchlorination of immersion tanks and sprays. In addition to *Salmonella* spp. and *C. jejuni*, which are well-recognized foodborne pathogens of poultry meat, the industry should also evaluate the possible role of *Aeromonas hydrophila* (Barnhart et al. 1989), *L. monocytogenes* (Bailey et al. 1989), and *E. coli* (Russell 1996) in contaminated value-added products.

The benefits of radiation pasteurization (radicidation) at levels ranging from 2 to 8 kGy have been widely publicized by responsible scientists (ACSH 1988; Steele and Engel 1992; WHO 1986). The specific problems relating to foodborne infection of poultry meat and the technical and biological limitations on preharvest and processing control predicate the application of radiation to achieve acceptable levels of safety. International cooperation in the field of food irradiation is coordinated by the International Project in the Field of Food Irradiation (IFIP), which is organized jointly by the Organization for Economic Cooperation and Development (OECD), the United Nations Food and Agricultural Organization (FAO), and the International Atomic Energy Agency (IAEA). The IFIP, financed by 23 participating nations, is concerned primarily with demonstrating the wholesomeness of irradiated food through the activities of research units in the Federal Republic of Germany, U.S., and Holland. The 1976 meeting of the Expert Committee on Wholesomeness of Irradiated Food evaluated research on safety and confirmed that chicken and other fruit and cereal products exposed to 10 kGy were unconditionally safe for human consumption.

A petition to amend 21 CFR 179.26, to allow irradiation of poultry products to reduce contamination with *Salmonella* spp., *Campylobacter* spp., and *Yersinia* spp. was filed by the Food Safety and Inspection Service of the U.S. Department of Agriculture (USDA-FSIS) with the USFDA on November 19, 1986. Based on published studies, the USFDA approved irradiation of whole carcasses and poultry portions in 1990 at a level ranging from a 1.5-kGy minimum dose to a maximum of 3.0 kGy. The USDA-FSIS was empowered to develop appropriate regulations relating to operating procedures, controls, and

labeling. The USDA-FSIS poultry regulations for irradiation make provision for approval and registration of plants, operating procedures, quality control, packaging, labeling, and inspection. In accordance with the original FSIS petition, poultry, including chickens, turkeys, and ducks, would be irradiated in the fresh or frozen uncooked form, as whole carcasses, portions, ground, hand-boned, and skinless poultry, and mechanically separated poultry products. The regulations do not permit irradiation of cooked or smoked poultry products or poultry that has been combined with other ingredients. Freestanding plants may be licensed to irradiate poultry products or units may be combined with existing primary or secondary poultry processing facilities, consistent with USDA-FSIS regulations and policy. It is axiomatic that all poultry subjected to irradiation should be derived from a USDA-approved plant.

The proposed regulations specify air-permeable packaging, and the design and durability of materials is mandated. Multilayer packaging, suitable for poultry, should exclude moisture and microorganisms but permit entry of oxygen, which will inhibit the possible proliferation of *C. botulinum.* The effectiveness of irradiation in destroying aerobic pathogens on poultry meat was promoted by Idziak and Incze (1968), and subsequent progress was reviewed by Giddings and Marcotte (1991). A 10^7 reduction in *Salmonella* spp. can be achieved in poultry meat at a dose of 4.75 kGy (Licciardello et al. 1968). Mechanically separated turkey meat is commercially processed in France by the Guyomarch Company using electron beam technology at a minimum dose of 3 kGy; 10-kg, 5.5-cm-thick frozen (−18 °C), compressed product is subjected to a double-pass process to eliminate *Salmonella.* Other aerobic pathogens including *L. monocytogenes* (Huhtanen et al. 1986) and *C. jejuni* (Yogasundram et al. 1987) are destroyed at dose levels of 2 kGy. Because slightly higher levels of irradiation may be required for frozen products, a petition will be submitted to the USFDA to raise the maximum dose from 3 to 7 kGy.

Despite the distorted, misleading publicity by opponents of food irradiation, there is no evidence of widespread consumer rejection of irradiated poultry. Giddings and Marcotte (1991) have reviewed studies on consumer attitudes as determined in surveys and test marketing in Israel, the U.S., and Canada. Generally, consumers are ignorant of either the advantages of irradiation, the differences between sterilization and pasteurization, or the inherent wholesomeness and nutritional value of radurized and radicidized poultry. Studies have demonstrated consumer concern for microbiological and chemical contaminants and nonhealthful components of food (Anonymous 1987). Approval of irradiation by the USFDA in 1990 and the subsequent FSIS regulations in 1992 allowed Vindicator Inc. (now Food Technology Service Inc.) of Mulberry, FL, operators of a cobalt-60 multiproduct contract plant, to irradiate a consignment of broilers that were marketed by Nation's Pride Distributors (Pszczola 1993). Consumer acceptance was based on rapid sale of radiation-pasteurized product displayed alongside conventional chilled chicken.

A structured trial conducted at the University of Georgia involving 126 subjects simulated supermarket purchase of irradiation-processed raw chicken (Has-

him et al. 1995) Education was considered the motivator for acceptance of radiation-pasteurized breast and thigh portions. A slide program was demonstrated to be more effective than point-of-sale posters or labeling to influence demand. Of the informed consumers in the study, 84% considered irradiation necessary to reduce risk of foodborne infection from chicken, especially for non-home-prepared meals. Almost half the subjects were willing to pay a 5% premium for irradiated product. Following home-use testing, approximately 85% of the participants considered the organoleptic qualities of cooked irradiated chicken to be superior to the conventional product.

Economic realities and the technical superiority of irradiation for specific poultry products will ultimately lead to the acceptance of the process. Responsible, scientifically valid opinions will prevail and will overshadow the distortions and exaggerations of opponents of food irradiation.

VIII. Seafood

Research conducted on seafood products since the mid-1950s has shown ionizing radiation to have a positive effect on maintaining the quality and freshness of seafoods. The advantages of using ionizing radiation as a processing method are twofold: first, it will reduce or eliminate 90%–95% of the microorganisms responsible for spoilage and subsequently will extend the fresh-storage shelf life; second, this same low dose of irradiation has the ability to reduce or eliminate specific pathogenic bacteria (Grodner and Andrews 1991). Fresh shrimp held on ice normally maintain good quality for up to 7 d, but by irradiating shrimp at low dosage (1.5 kGy) it is possible to extend fresh quality for an additional 7–10 d. Grodner and Hinton (1987) reported that the lethality for vegetative cells of *E. coli* and pathogens such as *Vibrio* spp. have been reduced to undetectable levels ($<10^1$) after treatment with a 1-kGy dosage or less of gamma rays, depending on the specific seafood tested.

A. Irradiation Effect on Microorganisms

Ionizing radiation destroys most microorganisms by lethal damage to nuclear DNA. Species of microorganisms differ in their resistance to ionizing radiation. Sensitivity variations may even occur among strains of the same species. Gram-negative bacteria are generally considered more sensitive than gram-positive species; consequently, many of the typical seafood spoilage bacteria are among the least resistant. Each species of bacteria, as well as the particular seafood substrate with which one is concerned, should be examined on an individual basis. For example, there is great variation among the different *Salmonella* seros in different seafoods. Gram-positive bacteria such as *Staphlycoccus aureus, Micrococcus, Bacillus*, and *Clostridium* are among the more irradiation-resistant genera. Viruses, in general, are extremely resistant to irradiation. Fish parasites also require a fairly high dosage to be inactivated.

B. Spoilage Organisms

Seafood quality is determined by subjective sensory judgment of the consumer. In addition, microbiologists often use aerobic plate counts (APCs) as an objective measurement. This method, although imprecise, can relate to sensory quality. The microbial flora of freshly caught fish and shellfish naturally reflects that of their environment. The predominant bacterial flora of freshly caught fish or shellfish are the *Pseudomonas* groups, which frequently compose 60% of the total flora. Other microbial species implicated in spoilage of fresh-caught marine fish include species of *Micrococcus, Flavobacterium*, and *Crytophaga* with *Corynebacterium, Vibrio, Bacillus, Proteus*, and yeasts (Josephson and Peterson 1983).

In ice-stored fish and shellfish, gamma irradiation below 2 kGy has increased shelf life approximately 7–10 d over the normal shelf life of the specific species involved. This increase results mainly from reduction of the original number of microorganisms, especially the spoilage, immediately after low-dose exposure to gamma irradiation. These results are well documented and can be found in the following specific examples: fillets of fish such as Bombay duck, rohu, cod, haddock, mullet, and catfish, when irradiated with a 1-kGy dose of gamma irradiation and stored on ice, have been found to maintain good quality with a shelf life extension of 7–15 d beyond that of nonirradiated samples (Baldrati et al. 1974; Bhatacharya et al. 1978; Karnop and Antonacopoulos 1977; Oosterhuis 1976; Przybylski et al. 1989; Savagon 1975). Shark and ray fillets steam-cooked after irradiation (1–5 kGy) and irradiated raw (1 kGy) were evaluated to 40 d; analysis of irradiated raw samples showed that irradiation did not extend the shelf life beyond the 10 d observed for control samples because of changes in quality resulting from formation of ammonia.

Combined steaming and irradiation extended shelf life to 30–35 d (Ghadi and Lewis 1978). Whole redfish and haddock irradiated at 0.01 kGy with an on-board x-ray facility showed no marked sensory differences between irradiated and nonirradiated samples during the first 16 d of iced storage (Ehlermann and Reinacher 1979). However, after 16 d, the irradiated samples occasionally were scored higher than the nonirradiated ones for sensory quality. The microbial quality of the irradiated samples was improved with a marked reduction in spoilage microorganisms. Another study comparing cooking and irradiation processing of fresh horse mackerel fillets demonstrated that the combined effect of 2 kGy and 5 min of steam cooking at 176 °–185 °F (80 °–85 °C) increased the shelf life to 5–8 wk compared with only 2 wk for the uncooked, irradiated samples and only 3 wk for the cooked, nonirradiated samples. Increasing the cooking time to 15 min extended the shelf life for nonirradiated samples to 4 wk and that of the irradiated samples to 11 wk (Sasayama and Amano 1970). Irradiation of fresh mackerel at 1, 1.5, and 2.5 kGy of gamma irradiation maintained fresh quality for 8, 14, and 35 d, respectively, beyond the storage life of nonirradiated mackerel (Baldrati et al. 1978; Bhattacharya et al. 1978). Fresh whole and filleted hake were gamma irradiated at 7.1 kGy and monitored for sensory quality by an experienced taste panel. This level of irradiation achieved

a 6-d shelf life extension in both forms of the hake. Improvements were attributed to marked reductions in the levels of *Pseudomonas* and other spoilage bacteria (Avery and Lamprecht 1988).

Gamma irradiation of fresh crab meat and shrimp at 1, 1.5, or 2.5 kGy demonstrated that the storage life of these products was significantly extended when followed with refrigerated storage (Chen et al. in manuscript; Houwing 1976; Loaharanu 1973). Total bacterial counts of $<5 \times 105$ after 60 d of storage were reported in fresh and frozen grass shrimp when processed with 4.5 kGy of gamma irradiation (Yeh and Hau 1983) and maintained under refrigerated storage.

C. Pathogenic Microorganisms

Research with gamma irradiation has focused primarily on low-dose pasteurization of fish and shellfish. This historical approach was fostered by the U.S. Atomic Energy Commission, which chose to work primarily with pasteurization dose levels on fresh seafood products. The principal reason that pasteurization levels were chosen was that dosages close to or above 10 kGy will definitely affect the original sensory and physical qualities of seafood, which would remove these from the fresh seafood market. Advantages of low-dose pasteurization included control or elimination of many pathogens and parasites as well as increase the shelf life of these fresh seafoods by at least 1 wk.

Pathogenic bacteria find their way into seafood products in different ways. The pathogens of primary concern are bacteria that are found naturally in the marine environment, which include the various *Vibrio* species, *Aeromonas* spp., and *C. botulinum* type E. In general, *Vibrio* species are relatively sensitive to low-dose gamma irradiation. Table 7 demonstrates the sensitivity of *Vibrio chol-*

Table 7. Response of *Vibrio cholera* to low-dose ionizing radiation in seafood products.

Product	Dose (kGy)	Log_{10} cfu/g
Shrimp[a]	0 (control)	7.0
	0.5	2.0
	1.0	Negative
Crabmeat[b]	0 (control)	7.0
	0.25	3.0
	0.50	Negative
	1.00	Negative
Crayfish[b]	0 (control)	7.0
	0.25	5.5
	0.50	3.5
	1.0	Negative

cfu, colony-forming units
[a]Hinton (1983).
[b]Grodner and Hinton (1988).

era in shrimp, crabmeat, and crawfish. Other *Vibrio* species have been shown to be even more sensitive to low-dose irradiation than *V. cholera.* Twenty-seven strains of *V. parahaemolyticus* suspended in seawater were irradiated with 0–0.4 kGy.

All strains were reduced 4–7 log from the original 10^7 cfu/mL. In fish homogenate made with seawater, the organisms were more resistant and were reduced only 2.7–6.1 log. In most cases complete destruction was obtained with 0.3–0.4 kGy (Matches and Liston 1971). Fresh Gulf shrimp inoculated with 10^7 cfu/g of *V. parahaemolyticus* (sero 05 : 17) strain 116 were reduced to 0 cfu/g immediately following a 0.3-kGy dose of gamma irradiation. At lower dosages of 0.05, 0.1, 0.15, and 0.25 kGy, respectively, 10^3 cfu/g of *Vibrio* spp. survived as long as 3 wk when ice-stored at 32 °F (0 °C). Fresh Gulf oysters demonstrated a similar response, with 0 cfu/g recovered after a 0.3-kGy dosage and survival of 10^3 cfu/g *V. parahaemolyticus* for 1 wk at the lower doses (Lewis 1986).

Vibrio vulnificus, which has been implicated in wound infections and intestinal infections of persons with compromised immune systems, has also been studied. Fresh Gulf shrimp and crabmeat were inoculated with 10^6 cfu/g of *V. vulnificus* strain 1008H and irradiated with 0.15, 0.25, and 0.35 kGy, respectively. The counts per gram were reduced to below detectable levels immediately with the 0.35-kGy dose and reduced by approximately 4 log when treated with 0.15- and 0.25-kGy doses, but they survived in shrimp stored on ice for 7 d and in crabmeat 21 d before being reduced to nondetectable levels at the lower doses (Watson 1987).

A study by Palumbo et al. (1986) examined the radiation resistance of *Aeromonas hydrophilia*, a psychrotropic pathogen of emerging importance. The results of the study indicated that a pasteurizing dose of ionizing radiation of 1.5 kGy is sufficient to destroy *A. hydrophilia* in concentrations of or less than 10^5 cfu/g when present in retail fresh fish such as bluefish. *Clostridium botulinum* type E has always been a potential problem for the seafood processor because it is found naturally in the coastal environment and can produce *Botulinum* toxin under ideal storage conditions. Spores of this bacterium inoculated at 10^3 and 10^4 spores/g into fresh Gulf coast shrimp and irradiated at a dose of 1.5 kGy produced no toxin during 31-d iced (32 °F or 0 °C) storage. However, when the same inoculation treatment and irradiation at 1.5-, 2-, 3-, and 5-kGy dosages were given to shrimp stored at 42.8 °F (6 °C), botulin toxin was found to be produced in all samples after 7 d. In those treated with 5 kGy, toxin production occurred only after 30-d storage. *Clostridium botulinum* spores in oysters were only slightly more sensitive, with toxin recovered only after 30 d in iced samples treated with irradiation of 1.5–5 kGy (Jimes 1967).

Seafood may become exposed to some human intestinal pathogenic bacteria if sewage wastewater occurs in their growing environment. Of greatest concern here are species of *Salmonella, E. coli, Streptococcus faecalis*, and *Shigella.* Only a few strains of *Salmonella* have been treated and studied with gamma radiation to date. *Salmonella typhimurium*, when inoculated into Louisiana Gulf oysters that were then stored on ice up to 14 d, was not recovered immediately

following 2-kGy gamma irradiation (Richard 1966). Underdal and Rossebo (1972) recommended a dosage of 13 kGy when attempting to reduce *Salmonella senftenberg* in Norwegian fish meal by 10^8 cfu/g even though the initial number of viable *Salmonella* seldom exceeded 1 cfu/g of commercial fish meal.

Escherichia coli, the most common bacteria of the human gut, is often used as an indicator for the possible presence of human intestinal pathogens. Shrimp and oysters inoculated with *E. coli* up to 10^4 cfu/g and gamma irradiated with as much as 2 kGy demonstrated the bacterium's ability to survive: 5% survival at 1 kGy and 0.1% at 2 kGy (Lee 1966). It would appear that a dosage >2 kGy would be required for the complete (0 cfu/g) elimination of *E. coli* in these seafood products. *Streptococcus faecalis* also appears to require >2 kGy. Gulf shrimp and oysters were treated with 1- and 2-kGy dosages of gamma irradiation after inoculation with *S. faecalis* 10^6 cfu/g and stored on ice. The number of cfu/g recovered after 14 d was reduced by 4 log following the 1-kGy treatment and by 5 log following 2-kGy (Dietrich 1968).

Another major concern of seafood processing plants is the introduction of bacteria through personnel handling. One major concern is coagulase-positive *Staphylococcus aureus*, which is capable of producing food-poisoning toxins. *Staphylococcus aureus*, coagulase-positive (ATCC9664) was inoculated into fresh Gulf shrimp, irradiated with 1 kGy of gamma irradiation, and stored on ice for 21 d. Although the cfu counts were reduced by 4 log from 10^5 immediately, coagulase enzyme and *Staphylococcus* counts remained at or below 10^1 cfu/g during the 21-d storage period on ice (Kendall 1969). Another study has shown that *Staphylococcus* in dried and smoked mackerel required as much as 5-kGy to be inactivated. The sensory evaluations in this study indicated irradiation at the 5-kGy level did not affect the quality of these food products (Gonzalez et al. 1981). Several bacteria have recently emerged as potential public health concerns. Studies of *L. monocytogenes* (Andrews and Grodner in manuscript; Andrews et al. 1995b) indicate this bacteria to be fairly resistant to irradiation treatment. Viable cells remained after 2-kGy irradiation following inoculation of crabmeat with 10^7 cfu/mL (Juneau 1989).

Accumulation of viruses in shellfish is a major concern in the seafood industry, especially that causing hepatitis A. In the winter of 1996–1997, the Norwalk virus emerged as a major viral contaminant in shellfish-growing areas that had been illegally exposed to improperly treated sewage from offshore rigs or ship discharge. Irradiation is not seen, at this time, as a promising method for elimination of these pathogens from shellfish. Very little work has been published on the effects of irradiation on virus particles, but what has been published is not encouraging. In a typical study (Girolamo et al. 1969), West Coast oysters were contaminated with *Poliovirus* by natural uptake from water by direct inoculation of the digestive tract. Viruses were accumulated rapidly. Irradiation with 0.5, 1, 1.5, 2, 3, and 5 kGy was relatively ineffective as a means of inactivation of viruses in these shellfish. Inactivation of pathogenic viruses in fish and shellfish requires doses that are too high to be usable or even generate interest for this usage by the food industry (Josephson and Peterson 1983; Urbain 1986).

There is currently almost no information on the use of irradiation to inactivate parasites carried by marine and freshwater fish and shellfish. *Anisakis* and related genera are found in fish and have recently become more obvious to the public with the popularity of sushi. Thus, this parasite has been implicated as a human pathogen of recent but real concern. *Anisakis* larvae in lightly salted (5%) herring fillets were only partially inactivated (44% survival) by a dose of 6 kGy. It appears that this dosage or larger would be needed to inactivate this parasite completely. Irradiation at this high dosage produces an unacceptable flavor in the herring (Van Mameren et al. 1969). Other seafood parasites have not been investigated to any great extent for elimination with gamma irradiation.

In spite of the extended research reported in this area during the past 30 yr, approval by the USFDA is still pending. There is no question that the USFDA will eventually give its permission for low-dose pasteurization of seafoods with radioisotopes or electron beam. This method of processing, when used properly, can protect the consumer from many microorganisms of public health concern. In addition, this process maintains the fresh sensory qualities and nutritional value, with an increased shelf life of seafood, while being a proven safe and effective treatment. Irradiation processing of seafood in the U.S. should be permitted in the near future.

Summary

Irradiation processing has been researched extensively and is now in use worldwide for many food commodities. Irradiation has been successfully used to reduce pathogenic bacteria, eliminate parasites, decrease postharvest sprouting, and extend the shelf life of fresh perishable foods. Although food irradiation is widely accepted in world food markets, U.S. markets have been slower to accept the idea of irradiated food products.

For fruits and vegetables, irradiation is not a cure for shelf life problems; cost and quality problems damage preclude its general use. It appears that the most likely use of irradiation in fruits and vegetables is as an insect control in those commodities for which there is no effective alternative method. For grains such as rice and wheat, irradiation has been used primarily to control insect infestation when insects have been shown to develop resistance to the traditional fumigation methods. Treatment of spices with irradiation doses of 10 kGy has proved to extend shelf life without causing significant changes in sensory or chemical quality. Higher doses that effectively sterilize spices, however, may cause undesirable chemical and sensorial changes. For meat, especially red meat, irradiation is considered a viable alternative in the effort to improve the safety of meat products. With time, the authors believe that economic realities and the technical superiority of irradiation for specific poultry products will lead to public acceptance of the process. Irradiation of seafood products is still being considered for approval by the USFDA, although it is currently used in Asian and European markets, especially for shrimp. It is our belief that scientifically based research in food irradiation and the positive results thereof will also prove

economical in the twenty-first century. As we move to a more peaceful world with reduced threat of nuclear holocaust, these valid opinions will prevail and will overshadow the distortions and misinformation generated by the opponents of irradiation.

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