Food Irradiation's Advantages Will Not Escape Public Attention

The approval by the U.S. Food and Drug Administration of meat irradiation on December 2, 1997 has been universally hailed. Even some advocacy organizations and individuals that formerly opposed the procedure for a variety of reasons have been positive in their responses to this development.

The Scientific Status Summary, prepared by Dr. Dennis Olson for IFT's Expert Panel on Food Safety and Nutrition, that follows is an excellent analysis of the tortuous history and the science that preceded the approval. IFT members and others will benefit from this readable and informative paper. Olson's eminence in the field and his pioneering efforts to provide answers to this and other leading edge technologies are well-known and much respected.

The eagerly awaited approval of this technology by FDA was preceded a few weeks earlier by a meeting organized jointly by the World Health Organization (WHO), the United Nations Food and Agriculture Organization, and the International Atomic Energy Agency. The findings of that meeting were extremely reassuring. The experts concluded that there was no unsafe level of food irradiation. This dramatic statement was emblematic of the already demonstrated scientific fact that food irradiation is eminently safe.

Public acceptance remains something of a conundrum. Why should people accept irradiation of all things medical and not that of foodstuffs? Forty irradiation facilities in the United States (25% of the world's commercial irradiation facilities) sterilize all types of medical equipment including implants, intravenous fluids, instruments, gloves, bandages, gowns, sutures, and drugs. Additionally, foods for the immunocompromised and for astronauts may be legally irradiated.

My prediction is that public acceptance in this country has arrived. This is due to a remarkable concatenation of events including the gradual public recognition of the horrific nature of the *Escherichia coli* O157:H7 syndrome and certain other foodborne diseases, the strong stand of conscience on food irradiation made by the WHO, and the historic FDA approval. Although it has always been fashionable to criticize the FDA, all must admit to the enormous global significance of each and every finding the agency makes. Just during the past five years the heroic approval processes that resulted in the FDA stamp of approval on petitions as diverse as bovine somatotropin (BST), bioengineered foods, and Olestra have markedly transformed public opinion. And the credibility of WHO in scientific veracity is essentially unchallenged. Finally, food safety knowledgability has clearly improved over the past ten years and most Americans now seem to understand that the real threats in the food supply are not things chemical but things microbiological.

Prior to the 1990s, most U.S. citizens generally felt that food safety problems could be handled either by regulation or by antibiotics. But when the government exercised its authority to declare a pathogen illegal and this came to no avail, the lesson was not lost on a goodly number of people. Moreover, the current national debate over antibiotic resistance carries with it the sobering premise that things are so bad it is medically unsound to treat salmonellosis with antibiotics because such therapy will only reduce levels of competitive bacteria thus exacerbating the salmonella infection. Armed with such facts and exercising its collective wisdom some, if not most, of the public has concluded that for food to be truly safe there must be a kill step prior to cooking. The only viable solution to this enigma is irradiation. It is, of course, possible to come to this conclusion with reservations. Cardinal among these reservations is the necessity of providing the public an option via labeling. Others evince the caveat that the public must be educated to comprehend that one cannot treat irradiated foods like one treats Ultra High Temperature (UHT) milk. Notwithstanding this, it must be gainsaid that the primary advantage of food irradiation to the world at large may be shelf life extension which is in most instances doubled.

It is my firm belief that Americans are going eventually to love the idea of irradiated food. Especially when they find out it does not look different, it does not taste different, it will deliver the same nutrients and, most important to most, the same satisfaction. The food scares of the future that will be emblazoned across the front pages of our newspapers will not come from irradiated food but will, predictably, come from non-irradiated food. The miseries of the dairy industry—salmonella, *Brucella*, *Listeria*, and all the other grisly visitors—come from unpasteurized milk and, more and more, unpasteurized cheese. This has not escaped public attention and neither will the food safety advantages of food irradiation. When this becomes ingrained upon the American psyche in 2000 or 2010 or whenever, then the clarion cry of a new breed of consumerists might well be, "What can we do to get more of our food irradiated?"

On a recent national call-in radio program, I was confronted by the hostess in the last minute of the 45 minute show with the dilemma that dozens of people were waiting on the line with questions about food irradiation. I was asked what should the network say to them. In the expediency of the moment, I responded, "Tell them it is safer to irradiate the food than to not irradiate it . . ." That was the last word then and it is the last word now. ●

LESTER M. CRAWFORD, D.V.M., PH.D.
Director, Georgetown Center for Food and Nutrition Policy
Washington, D.C.

Irradiation of Food

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This Scientific Status Summary addresses the current state of scientific knowledge of the technology, with emphasis on muscle foods.

DENNIS G. OLSON

Author Olson, a Professional Member of IFT, is Director, The Utilization Center for Agricultural Products, Iowa State University, 194 Meat Lab, Ames, Iowa 50011.

The Food and Drug Administration's (FDA) approval of irradiation for red meats in December 1997 ended a long chapter in the tumultuous history of an important food safety and preservation technology. Federal acceptance validates what food scientists have long known: that appropriate absorbed doses of radiation effectively kill disease-causing bacteria and delay food spoilage. When irradiated ground beef becomes available, consumers once again may enjoy their hamburgers rare or medium rare. Low doses of radiation can kill at least 99.9% of *Salmonella* in poultry and an even higher percentage of *Escherichia coli* O157:H7 in ground beef.

This summary briefly addresses the remaining questions about food irradiation. In addition, it provides a useful summary of the regulatory history and the current state of scientific knowledge of the technology as applied to food. Federal regulators, food scientists, food processors, and consumers will write the next chapter in the story of irradiation. New challenges awaiting resolution include safely and successfully implementing irradiation in the meat and poultry processing industries; maintaining the quality of raw, irradiated meats; developing packaging suitable for irradiation; developing methods to detect irradiated foods; and educating the public about the wholesomeness of foods made safer by irradiation.

Regulatory Acceptance and Commercial Application

Research on the application of ionizing radiation to food began in earnest in the early 1950s. This processing technology was ready to be commercialized by the late 1950s. In the United States, however, passage of the Food Additives Amendment to the Food, Drug, and Cosmetics Act in 1958 effectively delayed the commercialization of irradiation for three decades. The Food Additives Amendment classified sources of radiation as food additives. The amendment, thus, required an authorizing regulation prescribing safe conditions of use and pre-market review and acceptance by the FDA. The agency has authorized ionizing radiation for several specific food uses, shown in Table 1.

Although irradiation of medical devices and disposables has a long history of use (Derr, 1993), irradiated foods were not produced commercially in the United States until 1992. Radiation is cleared for use on at least one food product in 35 countries, and irradiated foods are commercially available in 28 developing as well as developed countries (IAEA, 1995; Loaharanu, 1996). Spices are the most commonly irradiated food. Other commercially-available irradiated foods include a variety of fruits and vegetables, rice, potatoes, onions, sausage, and dried fish (in Bangladesh only). At least one irradiated muscle food (meat, poultry, and seafood) is cleared for use in 18 countries, including Chile, France, and the Netherlands.

The number of retail outlets offering irradiated foods and the amount of irradiated foods commercially available in the United States has grown slowly. Only four retail stores in the United States continuously offer irradiated foods. Use of irradiated foods has grown slightly faster in the food service sector, primarily in hospitals for reducing the potential for cross contamination in food preparation and for immune-compromised patients

Effects of Irradiation

Irradiation exposes food to a source of ionizing radiation sufficient to create positive and negative charges. The amount of radiation energy absorbed is measured in units of grays (or kilograys, kGy). One gray equals one joule per kilogram. Radiation sources approved for food use are gamma rays (produced by the radioisotopes cobalt-60 or cesium-137), machine generated X-rays (with a maximum energy of 5 million electron volts, MeV), and electrons (with a maximum energy of 10 MeV). Depending on the dose of radiation energy applied, foods may be pasteurized to reduce or eliminate pathogens, or they may be sterilized to eliminate all microorganisms, except for some viruses (Crawford and Ruff, 1996; IFT, 1983). For example, low (up to 1 kGy) to medium doses (1–10 kGy) kill insects and larvae in wheat and wheat flour and destroy pathogenic bacteria and parasites. Low to medium doses also inhibit sprouting of potatoes and other foods and slow the ripening and spoilage of fruit. Higher doses (10–50 kGy) sterilize foods for a variety of uses such as for astronauts during space flight and immune-compromised hospital patients who must have bacteria-free food.

When molecules absorb ionizing energy, they become reactive and form ions or free radicals that react to form stable radiolytic products (Woods and Pikaev, 1994). The Council for Agricultural Science and Technology (CAST, 1989) estimated that a dose of 1 kGy would break fewer than 10 chemical bonds for every ten million bonds present, an extremely small percentage. Cooking, or applying infrared radiation to foods, produces similar changes in chemical bonds.

Even though an extremely small percentage of chemical bonds are broken when a food is irradiated, the effect can be dramatic. For example, breaking bonds in the deoxyribose nucleic acid (DNA) results in the loss of a cell's ability to replicate. A relatively small change in the DNA of a bacterial cell can destroy the cell. The cellular destruction caused by disruption of the genetic material in a living cell is the principal effect of radiation on food (Murano, 1995a), enabling destruction of insects, inactivation of parasites, delaying of ripening, and prevention of sprouting. Ionizing radiation cannot make food radioactive.

Table 1 Applications of Ionizing Radiation Accepted in the U.S. by the Food and Drug Administration

Product	Dose (kGy)	Purpose	Date
Wheat, wheat flour	0.2–0.5	Insect disinfestation	1963
White potatoes	0.05–0.15	Sprout inhibition	1964
Pork	0.3–1.0	Trichinella spiralis control	7/22/85
Enzymes, dehydrated	10 max	Microbial control	4/18/86
Fruit	1 max	Delay maturation, disinfestation	4/18/86
Vegetables, fresh	1 max	Disinfestation	4/18/86
Herbs	30 max	Microbial control	4/18/86
Spices	30 max	Microbial control	4/18/86
Vegetable seasonings	30 max	Microbial control	4/18/86
Poultry, fresh or frozen	3 max	Microbial control	5/2/90
Meat, frozen, packaged[a]	44 min	Sterilization	3/8/95
Animal feed and pet food	2–25	Salmonella control	9/28/95
Meat, uncooked, chilled	4.5 max	Microbial control	12/2/97
Meat, uncooked, frozen	7 max	Microbial control	12/2/97

[a] For meats used solely in the National Aeronautics and Space Administration space flight programs

The physical laws that govern the nature of chemical reactions and the stability of chemical substances are the same whether the enhanced molecular reactivity created by heat energy is supplied by infrared radiation, microwaves, ionizing radiation, or other sources (CAST, 1986). The radiolytic products that form when food is irradiated are generally the same as those that are formed when food is cooked. Investigators developing methods for detecting irradiated foods have identified alkylcyclobutones in some irradiated foods that were not detected in unirradiated samples. These substances may serve as markers for irradiated foods. Despite concerns expressed by those who decry the use of radiation, no unique radiolytic products of toxicological significance have been found in irradiated foods (Crawford and Ruff, 1996).

Wholesomeness

Pauli and Tarantino (1995) prepared a comprehensive review of the information FDA requires to establish the safety of proposed applications of radiation. The agency considers four broad areas: radiological safety, toxicological safety, microbiological safety, and nutritional adequacy (Table 2). With radiological safety, the question is whether radioactivity will be induced in the food. This issue is of no concern for the currently approved radiation sources because their energy is too low to induce radioactivity.

The issue of toxicological safety raises the questions: (1) Is there evidence of adverse toxicological effects that can be attributed to toxic substances produced by irradiating the food? (2) What should be tested? (3) What tests provide useful information? The questions are difficult to address because radiation leads to the absorption of ionizing energy rather than the addition of a substance. The toxicological safety of food additives has traditionally been assessed by animal feeding studies and involves determining the highest dose of a substance that causes no toxicological effects, and the application of safety factors to account for individual variability and uncertainty in extrapolating from animals to humans (Pauli and Tarantino, 1995).

To assess the changes caused in foods by irradiation and recommend toxicological testing requirements for assessing their safety, the FDA formed the Bureau of Foods Irradiated Food Committee (BFIFC). Because no evidence of toxicity attributable to irradiation of food was found, the committee recommended that foods irradiated at doses less than 1 kGy, or foods representing only a very small fraction of the diet, should be exempt from requirements for toxicological testing. FDA then organized a task group to assess animal feeding and mutagenicity studies. The group concluded that toxic effects are not expected from foods irradiated at doses below 1 kGy and concurred with the recommendation of the BFIFC. Because available data were not adequate to evaluate the safety of irradiation of all foods at doses greater than or equal to 1 kGy, the task group also recommended that the agency consider authorizations of the process on a case-by-case basis for foods that are consumed in significant amounts or that are irradiated at higher doses. Hence, the poultry petition that was cleared by FDA in 1990 (9 CFR Part 381) was considered separately because the petition requested radiation dose levels greater than 1 kGy.

With the red meat petition, however, the concept of chemi-generic clearance was used. This concept is that radiation

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chemistry of the constituent components (e.g., water, protein, lipid, carbohydrates) among a food group produces common and predictable stable end-products. Muscle foods, for example, have similar macronutrient composition and, therefore, are expected to yield similar radiolytic products. The database of the toxicological studies completed for the poultry petition can thus be used to address toxicological questions about different meat species and fish. For foods to be irradiated above 1 kGy, FDA's principal interest is with the conditions for food irradiation (temperature, packaging atmosphere, dose range) and their impact on microbiological safety and nutritional adequacy.

The issue of microbiological safety of irradiated foods raises many questions; the two most important are: (1) Can irradiation mutate microorganisms, producing more virulent pathogens? (2) Will irradiation reduce the numbers of spoilage microorganisms, allowing pathogens to grow undetected without competition? FDA does not consider radiation-induced mutation a concern with respect to increased virulence or heat resistance since there is no evidence for such effects. In fact, radiation is much more likely to reduce the virulence of any surviving pathogens (Farkas, 1989). FDA requires evidence that radiation, under realistic conditions, achieves the intended microbiological effect without allowing *Clostridium botulinum* to grow and produce toxin undetected.

The two most important questions of nutritional adequacy of irradiated foods are: (1) Does irradiation result in a significant loss of any nutrient in the food under the proposed conditions of use? (2) Is the food proposed for irradiation an important dietary source of the affected nutrient? Many food processes, like cooking, alter nutrient content much more than irradiation. Trace elements and minerals are not affected by irradiation. Macronutrients such as protein, carbohydrates, and fats are not significantly affected by doses up to 10 kGy. Even with sterilization doses of 50 kGy, macronutrient losses are small and nonspecific (Diehl, 1995; WHO, 1994).

Some vitamins, however, are sensitive to radiation. The amount of vitamin loss due to food irradiation is affected by several factors, including dose, temperature, presence of oxygen, and food type. Generally, radiation at low temperatures in the absence of oxygen reduces any vitamin loss in foods, and storage of irradiated foods in sealed packages at low temperatures also helps prevent future vitamin loss (WHO, 1994).

Table 2 Information Required by the U.S. Food and Drug Administration to Establish the Safety of Irradiated Food

Considerations	Question(s)
[illegible]	[illegible]
[illegible]	[illegible]
	[illegible]
	[illegible]
Microbiological Safety	Can irradiation mutate microorganisms, producing more virulent pathogens?
	Will irradiation reduce the numbers of spoilage microorganisms, allowing pathogens to grow undetected without competition?
Nutritional Adequacy	Does irradiation, under the proposed conditions of use, result in a significant loss of any nutrient in the food?
	Is the food proposed for irradiation an important dietary source of the affected nutrient?

From Pauli and Tarantino (1995)

Not all vitamins have the same sensitivity to irradiation. For water soluble vitamins, the order of sensitivity is generally: thiamin > ascorbic acid > pyridoxine > riboflavin > folic acid > cobalamin > nicotinic acid. For fat soluble vitamins, the order of sensitivity is generally: vitamin E > carotene > vitamin A > vitamin K > vitamin D (WHO, 1994).

FDA requires that the affected vitamin(s) in the irradiated food are not significant in the overall diet. The nutritional significance of vitamin loss due to irradiation depends on the level of loss and the proportion of the irradiated food in the diet. It is doubtful that any vitamin deficiency would develop from consuming irradiated foods. For example, pork is a major source of thiamin, the most radiation sensitive water-soluble vitamin, but only 2.3% of thiamin in American's diets would be lost if all the pork in the United States were to be irradiated (CAST, 1996).

The most recent World Health Organization (WHO) review of the safety and nutritional adequacy of irradiated foods concluded that food irradiation: (1) will not lead to toxicological changes in the composition of food that would have an adverse effect on human health; (2) will not increase microbiological risk; and (3) will not lead to nutrient losses that would have an adverse effect on the nutritional status of people (WHO, 1994). Furthermore, a meeting of the Food and Agriculture Organization of the United Nations, International Atomic Energy Agency, and the World Health Organization (WHO) concluded on the basis of knowledge derived from over 50 years of research that irradiated foods are safe and wholesome at any radiation dose (WHO, 1997).

Irradiation of Muscle Foods

• Microbiology. As with cooking and thermal processing, higher radiation doses kill greater numbers of bacteria. The D values (decimal reduction, or dose required to destroy 90% of the microorganisms present) of several pathogenic bacteria that may be associated with raw meat and poultry are shown in Table 3. *Salmonella* is the most resistant non-spore forming pathogen, with a D value of about 0.6 kGy. The radiation doses approved for poultry, 1.5–3.0 kGy, would destroy about 99.9% (3 logs) to 99.999% (5 logs) of *Salmonella*. Except for spores of *Clostridium botulinum*, all other

Table 3 D values of some important foodborne pathogens

Pathogen	D values (kGy)	Suspending medium	Irradiation temperature (°C)	References
[illegible]	[illegible]	[illegible]	2	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	2	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

pathogenic bacteria listed in Table 3 would be controlled within this dose range. A minimum dose of 1.5 kGy would destroy at least 6 logs of *E. coli* O157:H7, which has a D value of about 0.24 kGy. Irradiation, therefore, would be extremely effective at eliminating this pathogen, declared an adulterant in ground beef in 1994. The parasites *Toxoplasma gondii* and *Trichinella sprialis* are inactivated at doses of 0.25 kGy (Dubey et al., 1986) and 0.3 kGy (Brake et al., 1985), respectively.

Although the primary objective of irradiation of muscle foods is destruction of pathogenic bacteria, substantial reduction of spoilage microorganisms also occurs. Niemand et al. (1983) reported that levels of aerobic and anaerobic bacteria were reduced by over four logs and almost five logs, respectively, in chilled ground beef irradiated at doses to 2.5 kGy. Shelf life of the ground beef stored at 4°C was extended by nine days, before counts reached seven logs. The refrigerated shelf-life of vacuum-packaged beef sirloin cuts irradiated to 2 kGy more than doubled, from about four weeks for non-irradiated product stored at 0°C to 10 weeks for irradiated product stored at 4°C (Niemand et al., 1981). Lefebvre et al. (1992) reported a three log reduction in psychrotrophic aerobic bacteria in ground beef irradiated at 2.5 kGy. The irradiated ground beef had a shelf-life of ten days before counts reached seven logs compared with the non-irradiated control which lasted only one day.

Lambert et al. (1992) found that pork loin slices packaged under nitrogen and irradiated to 1 kGy had a 26-day shelf-life (21 days more than the control) stored at 5°C. Thayer et al. (1993) found that uninoculated ground pork, irradiated at 1.9 kGy, had no surviving bacteria when stored at 2°C for up to 35 days.

The predominant food spoilage organisms are Gram-negative psychrotrophic microorganisms that are very susceptible to radiation (Monk et al., 1995). Several researchers have shown that irradiation of food at doses of at least 1 kGy virtually eliminate Gram-negative microorganisms, but has a much smaller effect on Gram-positive lactic acid-producing microorganisms (Dempster, 1985; Ehioba et al., 1988; Lambert et al., 1992; Mattison et al., 1986; Niemand et al., 1983; Thayer et al., 1993). *Pseudomonas* species and *Enterobacteriaceae*, common spoilage bacteria, are easily eliminated even with low doses of radiation. However, in all of these studies at doses in the range of 1–5 kGy, Gram-positive microorganisms survived and caused spoilage after prolonged refrigerated storage.

• Quality. Irradiation may affect the quality of meat by processes other than those attributable to microorganisms. Radiation dose, dose rate, temperature and atmosphere during irradiation, and temperature and atmosphere during storage can all affect the outcome of specific foods (Thayer, 1990). Radiolytic products can cause oxidation of myoglobin and fat, leading to discoloration and rancidity or other off-odor or off-flavor compounds (Murano, 1995b). Ozone, a strong oxidizer, is produced from oxygen during food irradiation and may oxidize myoglobin, causing a bleaching discoloration.

Some scientists have observed that irradiated raw meat developed an off-odor compared with the non-irradiated control (Lefebvre et al., 1994; Lynch et al., 1991). Sudarmadji and Urbain (1972) reported that the threshold dose for irradiation odor ranged from 1.5 kGy for turkey to 6.25 kGy for lamb. Niemand et al. (1981) reported that an irradiation odor was detected but not objectionable in raw beef irradiated at low dose. Cooking appears to reduce or eliminate any irradiation-induced odor (Kropf et al., 1995; Luchsinger et al., 1996). Odor resulting from irradiation may thus be important only in raw meat. Further investigation would enable full characterization of irradiation-induced odor and better understanding of the conditions that affect its development.

Irradiation can also cause some color changes in meat, that are greatly influenced by the packaging environment. For example, irradiated vacuum packaged meat can develop a fairly stable brighter red or pink color in pork, beef, and turkey breasts (Lebepe et al., 1990; Lynch et al., 1991; Niemand et al., 1983). In the presence of oxygen, however, irradiation can cause discoloration. Grant and Patterson (1991) observed discoloration in pork irradiated in the presence of oxygen. Irradiation of frozen grass prawns at 10 kGy reduced levels of polyunsaturated fatty acids ($C_{20:5}$ and $C_{22:6}$) by 25–32%, possibly due to oxidation and decomposition of lipids into volatile compounds (Hau et al., 1992). The threshold dose for development of irradiation flavor in the frozen grass prawns was 4.5 kGy.

The extent of chemical changes that occur in the frozen state is less than that in non-frozen food due to decreased mobility of free radicals. With less mobility in the frozen state, free radicals tend to recombine to form the original substances rather than diffuse through the food and react with other food components (Taub et al., 1979). Irradiating foods at appropriate doses and under certain conditions, such as in a reduced oxygen or oxygen-free atmosphere, packaging, and the frozen state, can minimize or avoid the development of objectionable off-odors and flavors. Irradiated meat will be successful in the market place only if consumers are satisfied with its sensory quality.

• Packaging. To obtain the full benefit from the potential to reduce levels of microorganisms, eliminate pathogens, and prevent cross-contamination, muscle foods should be packaged before irra-

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diation. Irradiation of packaging film may result in evolution of gases, such as hydrogen, and production of low-molecular weight hydrocarbons and halogenated polymers (Kilcast, 1990). The impact of irradiation on the packaging material itself must, therefore, be considered (Lee et al., 1996).

Materials used to package foods before irradiation must be accepted for such use by the FDA. Acceptable materials are listed in 21 CFR 179.45. Any co-extruded or laminate multicomponent films, commonly used for packaging non-irradiated muscle foods, must be accepted by FDA before use in food irradiation.

At radiation doses accepted for food, only low-molecular weight polymers and gases have the potential for migrating into the product and influencing product quality. Taint-transfer problems, for example, have been observed when the commonly used fresh meat overwrap polyvinylchloride (PVC) was irradiated at 3.9 kGy (Kilcast, 1990). PVC, however, is not accepted by FDA for use in food irradiation. Antioxidants used in packaging films may also be significantly degraded, although migration of antioxidants into the food product has not been observed (Buchalla et al., 1993).

The suitability for food irradiation of new types of polymeric packaging material, including co-extrudates and multilayer laminates requires further investigation. In addition, additives, adhesives, and printing materials should also be screened (Kilcast, 1990). Determination of the threshold level of migration of film components, resins, and additives is required to expand the availability of FDA-approved polymeric films. With FDA approval of individual film components, film manufacturers would be able to develop film structures that would have defacto FDA approval without having to petition for approval of each new film structure.

Detection of Irradiated Foods

Development of food irradiation detection methods, useful for regulatory compliance purposes, is an active area of investigation. Stevenson (1992) reviewed progress of several methods. Detection methods would likely accelerate approval of additional food irradiation applications and would enhance international trade of irradiated foods.

Because there are no major chemical, physical, or sensory changes in irradiated foods, detection methods must focus on minute changes. Glidewell et al. (1993) prepared a comprehensive review of over 200 references relating to detection methods for irradiated foods. Generally, detection methods focus on chemical, physical, histological, morphological, and biological changes in the foods.

Lipids and DNA are particularly sensitive to ionizing radiation. Crone et al. (1992) detected 2-alkyl-cyclobutone, a cyclic compound formed from fatty acids in irradiated but not cooked lipid-containing foods. An interlaboratory comparison of the cyclobutone method correctly identified, with no false positives, 99% of 134 samples (ADMIT, 1994). Detection of hydrocarbons from irradiated lipid-rich foods is also a promising detection method. In an interlaboratory comparison of irradiated and non-irradiated chicken, 93% of 239 samples were correctly identified. False negative results occurred only in samples irradiated at 0.5 kGy (ADMIT, 1994).

DNA base damage, single-strand and double-strand DNA breaks, and crosslinking between bases are the main effects of irradiation. Detection and quantification of these DNA changes hold some promise for determining that an uncooked food has been irradiated. Further development is needed to distinguish irradiation-induced DNA changes from those caused by other processing treatments (Stevenson, 1992).

Techniques for detecting measurable changes in physical properties of foods, such as cell membrane damage, hold potential. Detection methods for membrane damage include measurement of electrical impedance, viscosity, electric potential, electron spin resonance, and thermal and near-infrared analysis (WHO, 1994). Hayashi (1988) reported that electrical impedance may be effective in determining irradiation of potatoes. Electron spin resonance appears effective for detecting irradiated bone-containing food and possibly shellfish (Derosiers, 1989; Gray and Stevenson, 1989).

Thermoluminescence (TL) has been successfully used to identify over 20 irradiated spices (Heide and Bögl, 1990). Sanderson (1991) demonstrated that contaminated minerals in spices are responsible for their TL. The use of TL for field crops, such as vegetables, fruits, and grains would be possible, as they all contain some minerals (WHO, 1994).

Changes in cell structures due to irradiation may be measurable by histological and morphological methods. Measuring the percentage germination of viable seed in fruits and the microscopic changes in cell structure could indicate whether the food has been irradiated. Because such measurements can take from days to weeks to complete, the methods may be impractical.

Determining the ratio of viable to total (viable and dead) bacteria on a food using aerobic plate count and the direct epifluorescent filter technique could determine if the food has been irradiated (WHO, 1994). The technique becomes limited, however, if the initial contamination before irradiation is very low, radiation dose is very low, or the food was irradiated to delay ripening rather than to pasteurize. Differences in radiation sensitivity of Gram-negative bacteria and Gram-positive bacteria may be useful. If a large number of Gram-positive bacteria, which are not as sensitive to irradiation as Gram-negative bacteria, are found on a food concurrent with a very low number of Gram-negative bacteria, it is likely that the food has been irradiated. The assumption would have to be made, however, that the initial bacterial contamination on the food is a normal mix of Gram-negative and Gram-positive microorganisms.

In summary, there are several promising techniques to screen and detect a few irradiated foods. No one technique is likely to be applicable to all food materials. Methods likely to become internationally accepted protocols are hydrocarbon and cyclobutone for lipid-containing foods, electron spin resonance for bone-containing food, and thermoluminescence for foods containing silicate minerals. Considerably more collaborative work is necessary to develop universally accepted methods for detecting irradiated foods of all types.

Labeling

Prior to the passage of FDA reform legislation (Public Law 105-115) in November 1997, irradiated foods at the wholesale level were required to bear either the phrase "Treated by irradiation, do not irradiate again" or "Treated with radiation, do not irradiate again." At the retail level, food labels were required to bear the international radura symbol along with either of the statements "treated with radiation" or "treated by irradiation." The regulation for these labeling requirements (FDA, 1986), issued by FDA under its statutory authority within the Federal Food Drug and Cosmetic Act, permitted additional statements about the purpose of the treatment process and the type of radiation used in the treatment. The food provisions of the 1997 FDA reform legislation directed the agency to review its labeling rule and, as appropriate, revise it so that the disclosure statement is not more prominent than the declaration of ingredients. The radura symbol was not excluded as a means of making an irradiation disclosure.

Consumer Acceptance

Irradiated foods marketed in numerous countries were judged superior by consumers and have sold well (Bruhn, 1995). The successful sale of these products, although limited to four stores in the United States, shows that consumers will accept irradiated food. Large segments of the population, however, have not had the opportunity to purchase these foods. Communication with consumers is believed to be critical for expansion of irradiated food markets. Consumer acceptance of irradiated food increases when consumers are provided with information about specific advantages of the radiation process (CAST, 1996).

A survey conducted by Resurreccion et al. (1995) showed that 72% of responders were aware of irradiation, but 87.5% of those did not know much about it. Survey participants expressed less concern about food irradiation than food additives, pesticide residues, animal drug residues, growth hormones, and bacteria. Risks to workers and the environment were among the top concerns expressed about irradiation. Further, Resurreccion et al. (1995) found that 45% of the consumers would buy irradiated food, 19% would not buy it, and the others were undecided. Bruhn (1995) reported that the number of consumers concerned about the safety of irradiated food decreased from 42% to 35% in the last six years and was less than the number concerned about pesticide residues, microbiological contamination, and other food-related issues. Shin et al. (1992) reported that consumers were willing to pay up to $0.81 per meal, more than 10-fold greater than the cost of irradiating food (Morrison, 1989), to avoid foodborne illness.

Summary

Irradiation of food can effectively reduce or eliminate pathogens and spoilage microorganisms while maintaining wholesomeness and sensory quality. Selection of appropriate treatment conditions can minimize or prevent objectionable changes in food quality. Methods to detect foods that have been irradiated are becoming internationally accepted. When informed of the benefits of irradiation, consumers are willing to purchase irradiated foods, even at higher cost.

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The Society for Food Science and Technology

221 N. LaSalle St., Ste. 300, Chicago, IL 60601-1291 USA
Tel. 312-782-8424 • Fax: 312-782-8348
E-mail: info@ift.org • URL: http://www.ift.org

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