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Irradiation as a method for decontaminating food
A review

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Abstract

Despite substantial efforts in avoidance of contamination, an upward trend in the number of outbreaks of foodborne illnesses caused by nonsporeforming pathogenic bacteria are reported in many countries. Good hygienic practices can reduce the level of contamination but the most important pathogens cannot presently be eliminated from most farms nor is it possible to eliminate them by primary processing, particularly from those foods which are sold raw. Several decontamination methods exist but the most versatile treatment among them is the processing with ionizing radiation. Decontamination of food by ionizing radiation is a safe, efficient, environmentally clean and energy efficient process. Irradiation is particularly valuable as an endproduct decontamination procedure. Radiation treatment at doses of 2–7 kGy—depending on condition of irradiation and the food—can effectively eliminate potentially pathogenic nonsporeforming bacteria including both long-time recognized pathogens such as *Salmonella* and *Staphylococcus aureus* as well as emerging or ''new'' pathogens such as *Campylobacter, Listeria monocytogenes* or *Escherichia coli* O157:H7 from suspected food products without affecting sensory, nutritional and technical qualities. Candidates of radiation decontamination are mainly poultry and red meat, egg products, and fishery products. It is a unique feature of radiation decontamination that it can also be performed when the food is in a frozen state. With today's demand for high-quality convenience foods, irradiation in combination with other processes holds a promise for enhancing the safety of many minimally processed foods. Radiation decontamination of dry ingredients, herbs and enzyme preparations with doses of 3–10 kGy proved to be a viable alternative to fumigation with microbicidal gases. Radiation treatment at doses of 0.15–0.7 kGy under specific conditions appears to be feasible also for control of many foodborne parasites, thereby making infested foods safe for human consumption. Microorganisms surviving low- and medium-dose radiation treatment are more sensitive to environmental stresses or subsequent food processing treatments than the microflora of unirradiated products. Radiation treatment is an emerging technology in an increasing number of countries and more-and-more clearances on radiation decontaminated foods are issued or expected to be granted in the near future.

Keywords: Irradiation; Decontamination; Foodborne pathogens

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1. Introduction

Contamination of foods, especially of those of animal origin, with microorganisms, particularly pathogenic nonsporeforming bacteria, parasitic helminths and protozoa is an enormous public health problem and important cause of human suffering all over the world. Pathogenic microorganisms are frequently found also in some food ingredients.

The US Public Health Service estimated that 9000 deaths from 6.5 million to 81 million cases of diarrhoeal diseases occur in the US each year due to pathogenic bacteria such as *Salmonella*, *Campylobacter*, *Escherichia coli* and *Vibrio*, as well as *Toxoplasma gondii* and other parasites (Archer and Kvenberg, 1985; Lee, 1994). Extremely virulent pathogens such as the verotoxin-producing *E. coli* O157:H7 and psychrotrophic pathogenic species including *Listeria monocytogenes*, *Yersinia enterocolitica* and *Aeromonas hydrophyla* raise a special concern (Palumbo, 1986). Besides being a quite serious obstacle to the well-being of populations, contaminated food is the source of tremendous economic losses in relation to medical costs, loss of productivity, loss of business and possible legal action (Todd, 1989a,b; Loaharanu and Murrell, 1994; Buzby et al., 1996). It hampers producers of food as well as processors and traders.

In spite of all past efforts in avoidance of contamination, relatively high percentages of foods of animal origin are contaminated with potentially pathogenic bacteria, resulting in increasing food infections and foodborne illness in many countries (Käferstein, 1992).

Considering the tremendous importance of microbial and parasitic diseases related to foods, food safety should be guaranteed at the retail and possibly at the consumer level and preventive programmes should receive a high priority, including development and implementation of better food processing technologies. Elimination or reduction of foodborne pathogens in foods is especially important to people with compromised immune systems, such as the elderly, AIDS patients and others. While thermal pasteurization of liquid foods is well established and satisfactory as a decontamination treatment of such commodities, it does not suit solid foods and dry ingredients well. The chemical sanitizing procedures have inherent problems concerning residues and environmental pollution. This is where food irradiation among the other intervention alternatives (Corry et al., 1995) comes into the picture. By irradiation, the use of ionising radiations—either gamma rays from radionuclides such as ^{60}Co or ^{137}Cs, or high energy electrons and X-rays produced by machine sources—is meant. In conjunction with good manufacturing practices, its well established safety and freedom from residues create a solid scientific background for implementation of radiation processing of specific food products as an effective means to improve safety of our food supply (WHO, 1994; Diehl, 1995; Wilkinson and Gould, 1996). The simultaneous reduction in number of the nonpathogenic spoilage microflora by the same radiation treatment results in the concomitant extension of nonfrozen (fresh or defrosted) edible/marketable life of radiation decontaminated high-moisture foods (Urbain, 1986). The benefits of irradiation also include the fact that products can be processed in the package, as a terminal treatment, eliminating the possibility of contamination until it is removed from it and ready to be used. Radiation can inactivate organisms in foods that are in the frozen state, without thawing them up.

This paper deals with food items which rate high on the list of commodities where irradiation can be used in order to reduce microbial load, minimize the presence of pathogenic microorganisms, and to control parasite infestation.

2. Assessment of dose requirements for radiation processing of foods for microbial safety

Since maintaining organoleptic and nutritional quality and keeping costs down are important factors, it is desirable to use the lowest possible doses necessary to achieve desired levels of microbiological and parasite control on a commercial scale. It is important, therefore, to establish the efficacy of the radiation treatment and threshold doses for quality changes. Actually, the exact dose required for each individual application should be established by risk analysis, taking into consideration the contamination level, the hazard involved, the efficacy of the radiation treatment and the fate of critical organisms during manufacturing, storage, distribution and culinary preparation of foods.

Threshold doses at which detectable ''irradiated'' flavours occur in some foods of animal origin are shown in Table 1 (Sudarmadji and Urbain, 1972). The raw foods were irradiated at 5–10°C, and the flavour was determined after cooking the product. Too high a dose of irradiation will also discolour meat. Lipid oxidation during irradiation can be minimized by excluding oxygen and applying antioxidants (Formanek et al., 1996). Dissipation of radiation-induced off-odours or -flavours may occur during the storage and determining optimum packaging conditions and controlling packaging permeability can control, to a certain extent, the sensory changes (Luchsinger et al., 1996; Murano, 1997). Irradiation in the frozen state increases the threshold doses before off-flavour develops (Urbain, 1978). Therefore, irradiation in the frozen state allows use of considerably higher radiation dose levels than those indicated in Table 1. The threshold dose for off-flavour, e.g., in frozen poultry is at least twofold higher compared with chilled poultry (Coleby et al., 1961; Farkas, 1987).

These considerations, together with the experimental data on radiation sensitivity of foodborne nonsporeforming pathogenic bacteria and parasites make it possible to assess the technological feasibility and the processing dose requirement for radiation decontamination of food products. Actual number and percentage of cells that will be killed by irradiation depend on various factors such as the microorganisms, the type of food medium; irradiation temperatures, oxygen presence, and water content (Thayer, 1995a,b; Thayer and Boyd, 1991, 1995; Thayer et al., 1995). Typical published data on radiation resistance of *Salmonella* and other nonsporeforming pathogens in fresh and frozen foods are given in Tables 2 and 3, respectively. D_{10}-values in the tables are radiation doses needed to reduce the number of various organisms in specific foods of interest by a factor of 10.

Campylobacter, *Yersinia* and *Vibrio* spp. have low resistance to ionising radiation, *E. coli* also seems to be quite susceptible, while *Salmonella* serotypes vary in their radiation sensitivity. The D_{10}-values for radiation inactivation of *L. monocytogenes* overlap with the range of resistances of *Salmonella* spp. In summary, irradiation doses suggested to eliminate salmonellae in food would also be sufficient to inactivate all nonsporeforming pathogens listed in Table 2. Comparing Tables 2 and 3, it can be noted that irradiation in the frozen state increases the radiation dose required for control of vegetative bacteria.

Table 1
Threshold doses for some foods of animal origin for an organoleptically detectable ''off-flavour'' (adopted from Sudarmadji and Urbain, 1972)

Food[a]	Threshold dose (kGy)
Turkey	1.50
Pork	1.75
Beef	2.5
Chicken	2.5
Shrimp	2.5
Frog	4.0
Lamb	6.25
Horse	6.50

[a] Irradiated at 5 to 10°C.

3. Foods which are good candidates for radiation decontamination

Food which are good candidates for radiation decontamination are poultry meat/carcasses, egg products, red meats, fishery products, and spices and other dry food ingredients.

3.1. Poultry

Many approaches have been adopted to reduce the incidence of *Salmonella* contamination. These include measures aimed at controlling dissemination of pathogenic bacteria by applying microbiological controls at the stages of poultry breeding, farming, processing and postprocessing (Todd, 1980). Inactivation of potential microbiological pathogens in the endproduct is attractive since it is applied just before retail distribution of the carcasses and spoilage bacteria are also reduced.

Alternative sanitizing procedures in poultry processing operations such as in-plant chlorination, surface heating, spray application of lactic acid on carcasses or a trisodium-phosphate dip may be helpful in reducing the contamination pressure, but

Table 2
D_{10}-values of some nonsporeforming pathogenic bacteria in nonfrozen high-moisture foods

Bacterium	Product	Temp. (°C)	Atmosphere	D_{10} (kGy)	Ref.
Aeromonas hydrophila	Ground fish	2±1	Air	0.140–0.193	1
		22±1	Air	0.110–0.152	1
Arcobacter butzleri	Ground pork	NS	Vacuum	0.27±0.01	2
Campylobacter jejuni	Ground pork	NS	Vacuum	0.19±0.01	2
	Filet americain	18–20	Micro-aeroph.	0.08–0.11	4
	Ground beef	18–20	Micro-aeroph.	0.14–0.16	4
	Ground beef	0–5	Air	0.161	5
	Ground beef	30±10	Air	0.174	5
	Ground beef (low fat)	4±1	Air	0.175	6
	Ground beef (high fat)	4±1	Air	0.178–0.199	6
	Ground turkey	0–5	Air	0.186	5
	Ground turkey	30±10	Air	0.162	5
E. coli O157:H7	Mech. deboned chicken	0	Air	0.26±0.01	10
	Mech. deboned chicken	0	Vacuum	0.27±0.01	10
	Ground beef	0	Vacuum	0.27±0.03	10
	Ground beef (low fat)	4±1	Air	0.241	6
	Ground beef (high fat)	4±1	Air	0.251	6
Listeria monocytogenes	Minced chicken meat	NS	Air	0.417–0.553	11
	Mech. deboned chicken	2–4	Air	0.27–0.77	12
	Minced pork	10	Air	0.573–0.648	3
	Minced pork	10	CO_2:N_2 (1:3)	0.602–0.709	3
	Ground pork	4	Air	0.422–0.447	18
	Roast beef	NS	Air	0.644±0.061	7
	Gravy	NS	Air	0.599±0.042	7
	Cauliflower (cooked)	NS	Air	0.564±0.055	7
	Potato (cooked)	NS	Air	0.532±0.047	7
	Ground beef (low fat)	4±1	Air	0.578–0.589	13
	Ground beef (high fat)	4±1	Air	0.507–0.574	13
Salmonella anatum	Filet americain	18–20	Air	0.45	4
	Ground beef	18–20	Air	0.67	4
S. enteritidis	Ground beef (low fat)	2	Air	0.69	4
	Whole shell eggs	Room temp.	Air	0.32–0.41	19
S. panama	Filet americain	18–20	Air	0.49	4
	Ground beef	18–20	Air	0.66	4
S. stanley	Filet americain	18–20	Air	0.61	4
	Ground beef	18–20	Air	0.78	4
S. typhimurium	Filet americain	18–20	Air	0.37	4
	Ground beef	18–20	Air	0.55	4
	Ground beef (low fat)	2	Air	0.59	9
	Minced pork	10	Air	0.403–0.860	7
	Minced pork	10	CO_2:N_2 (1:3)	0.394–0.921	7
	Roast beef	NS	Air	0.569±0.067	3
	Gravy	NS	Air	0.416±0.058	3
	Cauliflower (cooked)	NS	Air	0.590±0.075	3
	Potato (cooked)	NS	Air	0.464±0.080	3
	Mech. deboned chicken	20	Air	0.52–0.56	14
	Mech. deboned chicken	20	Vacuum	0.52–0.56	14
	Minced chicken	4	Air	0.436–0.502	8
	Minced chicken	4	CO_2	0.436–0.502	8
	Minced chicken	4	N_2	0.550–0.662	8

Table 2. Continued

Bacterium	Product	Temp. (°C)	Atmosphere	D_{10} (kGy)	Ref.
Salmonella spp.	Ground beef (low fat)	4±1	Air	0.621–0.624	6
	Ground beef (high fat)	4±1	Air	0.618–0.661	6
Shigella dysenteriae	Oysters	5	Air	0.40	16
	Crabmeat	5	Air	0.35	16
S. flexneri	Oysters	5	Air	0.26	16
	Crabmeat	5	Air	0.22	16
S. sonnei	Oysters	5	Air	0.25	16
	Crabmeat	5	Air	0.27	16
Staphylococcus aureus	Minced chicken meat	4	Air	0.419	8
	Minced chicken meat	4	CO_2	0.411	8
	Minced chicken meat	4	Vacuum	0.398	8
	Minced chicken meat	4	N_2	0.371	8
	Roast beef	NS	Air	0.387±0.056	3
	Gravy	NS	Air	0.360±0.043	3
	Cauliflower (cooked)	NS	Air	0.427±0.055	3
	Potato (cooked)	NS	Air	0.424±0.042	3
	Mech. deboned chicken (in buffered peptone)	0	Vacuum	0.26–0.36	10
	Ground beef (low fat)	4±1	Air	0.437–0.453	13
	Ground beef (high fat)	4±1	Air	0.443–0.448	13
	Ground beef (low fat)	2	Air	0.57	9
Vibrio parahaemolyticus	Seawater fish homogen.	24	NS	0.038–0.111	17
	Freshwater fish homog.	24	NS	0.022–0.044	17
	Crabmeat	24	NS	0.053–0.357	17
Yersinia enterocolitica	Filet americain	18–20	Air	0.043–0.080	4
	Ground beef	18–20	Air	0.10–0.21	4
	Ground beef	25	Air	0.196	15
	Minced pork	10	Air	0.164–0.204	3
	Minced pork	10	CO_2:N_2	0.176–0.187	3

NS = not stated. References: 1. Palumbo et al., 1986; 2. Collins et al., 1996; 3. Grant and Patterson, 1992; 4. Tarkowski et al., 1984; 5. Lambert et al., 1992; 6. Clavero et al., 1994; 7. Grant and Patterson, 1991; 8. Patterson, 1988; 9. Maxcy and Tiwary, 1973; 10. Thayer and Boyd, 1992; 11. Patterson, 1989; 12. Huhtanen et al., 1989; 13. Monk et al., 1994; 14. Thayer and Boyd, 1991; 15. El-Zawahry and Rowley, 1979; 16. Quinn et al., 1967; 17. Matches and Liston, 1971; 18. Tarté et al., 1996; 19. Serrano et al., 1997.

their efficiency seem to be more limited as compared to ionising radiation.

Recommended doses for radiation processing of frozen poultry are 3–5 kGy, and 1.5–2.5 kGy for chilled poultry. These treatments have been effective in reduction of the most resistant serotype of *Salmonella* by about 3 log-cycles, and *Campylobacter* by a still greater rate (Kampelmacher, 1984). The latter doses can extend the shelf-life of chilled poultry two- to threefold compared with untreated samples (Kiss and Farkas, 1972). The effect of irradiation on the microbial quality of frozen chicken is shown in Table 4 (Prachasitthisakdi et al., 1984). Sensory evaluations in Hungary showed that irradiation of frozen chicken with 3–5 kGy had no effect on the culinary properties of various dishes prepared from chicken (Kiss, 1984).

A process implemented in France is the electron beam processing of frozen blocks of mechanically deboned poultry meat to reduce the risk of salmonellosis (Gallien et al., 1985). A treatment with 4–5 kGy average absorbed dose appears to be adequate for this purpose.

3.2. Egg products

Sensory and functional properties of eggs are relatively radiation sensitive. However, considering that *Salmonella enteritidis* counts in naturally contaminated eggs are very low and do not normally exceed 10-100 colony forming units (CFU)/ml, Serrano et al. (1997) concluded on the basis of their recent studies that a minimal dose of 0.5 kGy would be sufficient to eliminate *S. enteritidis* from the

Table 3
D_{10}-values of some nonsporeforming pathogenic bacteria in frozen foods

Bacterium	Product	Temp. (°C)	Atmosphere	D_{10} (kGy)	Ref.
Aeromonas hydrophila	Shrimp paste	− 20	Vacuum	0.21	1
	Ground fish	− 15±2	Air	0.222–0.340	2
Campylobacter jejuni	Ground beef	− 30	Air	0.315	3
	Ground beef (low fat)	− 16±1	Air	0.235	4
	Ground beef (high fat)	− 16±1	Air	0.178–0.199	4
	Ground turkey	− 30±10	Air	0.293	3
E. coli O157:H7	Ground beef (low fat)	− 16±1	Air	0.39	5
	Ground beef (high fat)	− 16±1	Air	0.307	5
Listeria monocytogenes	Shrimp paste	− 20	Vacuum	0.70	1
	Ground beef (low fat)	− 16±1	Air	0.558–0.610	6
	Ground beef (high fat)	− 16±1	Air	0.524–0.575	6
Salmonella enteritidis	Surface of prawn	− 10±2	Air	0.49	5
S. typhimurium	Mech. deboned chicken	− 20	Air	0.45–0.70	7
	Mech. deboned chicken	− 20	Vacuum	0.48–0.79	7
Salmonella spp.	Ground beef (low fat)	− 16±1	Air	0.756–0.800	4
	Ground beef (high fat)	− 16±1	Air	0.675–0.745	4
Shigella boydii	Precooked peeled shrimp	NS	Air	0.26	9
S. dysenteriae	Precooked peeled shrimp	NS	Air	0.22	9
S. flexneri	Precooked peeled shrimp	NS	Air	0.41	9
S. sonnei	Precooked peeled shrimp	NS	Air	0.25	9
Staphylococcus aureus	Surface of prawn	− 10±1	Air	0.29	5
	Ground beef (low fat)	− 16±1	Air	0.443–0.451	6
	Ground beef (high fat)	− 16±1	Air	0.435–0.448	6
Yersinia enterocolitica	Ground beef	− 30	Air	0.388	9
Vibrio cholerae	Surface of prawn	10±2	Air	0.11	5
V. parahaemolyticus	Shrimp paste	− 20	Vacuum	0.44	1
V. vulnificus	Shrimp paste	− 20	Vacuum	0.30	1

NS = not stated. References: 1. Rashid et al., 1992; 2. Palumbo et al., 1986; 3. Lambert et al., 1992; 4. Clavero et al., 1994; 5. Han et al., 1992; 6. Monk et al., 1994; 7. Thayer and Boyd, 1991; 8. El-Zawahry and Rowley, 1979; 9. Mossel, 1985; 10. Bandekar et al., 1987.

surface of whole eggs, and a dose of 1.5 kGy would be sufficient to eliminate the organism from whole shell eggs and liquid whole eggs without significant adverse effects on the egg quality.

Whereas heat pasteurization of liquid whole egg and egg yolk became well established in the past decades, for bulk frozen eggs and particularly for pasteurizing egg albumen, radiation treatment seems to be well suited (Neal, 1965).

Irradiation of 4–5 kGy does not impair the quality of frozen whole egg or of foods prepared with the irradiated egg product (Ley et al., 1962). The same dose resulted in 6 log-cycles reduction of the mesophilic aerobic counts and reduced coliforms and

Table 4
Effect of ionising radiation on the microbial quality of frozen chicken (Prachasitthisakdi et al., 1984)

Organisms	$\log_{10}$ CFU/g				
	0 kGy	1 kGy	2 kGy	3 kGy	4 kGy
Mesophilic colony count	6.8	5.8	4.6	4.1	3.6
Psychrotrophic colony count	5.8	5.7	4.0	< 2.8	< 1.8
Enterobacteriaceae	5.5	< 2.8	1.0	0.4	− 0.4
Lactobacilli	6.0	4.1	4.2	3.1	< 2.8
Lancefield D streptococci	5.1	3.7	3.9	3.2	> 2.0
Staph. aureus	4.6	2.2	− 0.5	< − 0.5	< − 0.5

Staphylococcus aureus below the detectable level (Kiss, 1985). A radiation dose of 5 kGy gives a 7–8 log reduction in the most radiation resistant *Salmonella* tested in frozen whole eggs (Thornley, 1963).

Salmonellae are the principal microbial problem with dried egg products (ICMSF, 1980). Doses about 6 kGy seem to be adequate for radicidation of dried egg albumen (Thornley, 1963) without impairing its functional and organoleptic properties, while irradiation under aerobic conditions causes off-flavour and radiation-induced undesirable oxidative changes in whole egg powder or egg yolk solids at 3 kGy or higher doses (Katusin-Razem, 1984). A sensorially acceptable dose of 2 kGy would result in 2–3 log-cycles reduction of *Salmonella* contamination (Bomar, 1979). Irradiation of sensitive products in oxygen-free packaging would minimize oxidation (Lebovics et al., 1994), improve flavour retention, and thus improve the feasibility of the radiation treatment.

3.3. Red meats

An outbreak of food-poisoning linked to undercooked hamburgers containing *E. coli* O157:H7 which caused the death of four children and the severe illness of 600 people in the US raised serious doubts about food safety (Lee, 1994). The problem is further emphasised by the fact that treating carcasses with organic acid spray proposed for sanitation can reduce enteric pathogens but has limited efficiency particularly in controlling *E. coli* O157:H7 (Brackett et al., 1994; Cutter and Siracus, 1994; Fu et al., 1994). Thus, irradiation of certain prepackaged meat products such as ground beef, minced meat, and hamburgers may help in controlling meatborne pathogens and parasites. Pathogenic microorganisms and parasites in meat products which are commonly consumed raw, e.g., ''filet americain'', or semicooked are of particular importance.

Experiments in the Netherlands showed that a dose as low as 1 kGy was effective in reducing *Salmonella* up to approximately 2 log-cycles in ''filet americain'' (Kampelmacher, 1984). *Campylobacter jejuni* and *Y. enterocolitica* are even reduced by more than 4 log-cycles with this dose.

A dose range as low as 1–3 kGy can be expected to reduce any *Salmonella* by an overall average 2–3 logs (Beuchat et al., 1993) and be more than adequate for control of *E. coli* O157:H7 and other more radiation sensitive nonsporeforming pathogen on chilled meat cuts or in ground beef (Thayer and Boyd, 1993; Clavero et al., 1994) while at the same time effecting significant shelf-life extension.

3.4. Fishery products

Crustaceans and molluscs as well as frog-legs, originating from polluted aquatic environments, frequently harbour pathogenic microorganisms and pose a public health hazard as shown by a number of disease outbreaks with a high number of persons sickened and with a relatively high mortality rate (Kampelmacher, 1984).

Radiation microbiology studies with fishery products demonstrated that irradiation with doses up to 4 kGy to control pathogens could be very useful with frozen fishery products such as shrimps, prawns and frog-legs (Nerkar and Lewis, 1982; Nouchpramoul, 1985; Ito et al., 1989; Han et al., 1992).

D_{10}-values of *Salmonella* serovariants in artificially contaminated shrimp in Thailand were found to range from 0.3–0.5 kGy for refrigerated samples, and from 0.4–0.6 kGy for frozen samples (Nouchpramoul, 1985).

A radiation dose of 4 kGy resulted in a 3 log-cycles reduction of the aerobic psychrotrophic and mesophilic colony counts of frozen Malaysian shrimps (Prachasitthisakdi et al., 1984). In addition, Enterobacteriaceae, Lancefield D streptococci, and *Staph. aureus* could not be detected in 1 g samples, after application of doses between 2–4 kGy (Table 5).

Vibrio parahaemolyticus has been considered the leading causative agent of bacterial gastroenteritis from eating fishery products in South-East Asia. Sixty per cent of fresh fish obtained from local markets in Bombay, India, was reported as being contaminated with this organism (Lewis, 1983). Nouchpramoul (1985) detected *V. parahaemolyticus* in 85% of fresh or frozen shrimp in Thailand. This organism is quite radiation sensitive. Various strains inoculated into crabmeat and irradiated at a dose of 0.25 kGy caused a 2–5 log-cycles reduction in numbers (Matches and Liston, 1971). Lewis (1983) reported D_{10}-values of 0.04–0.05 kGy in shrimp

Table 5
Effect of ionising radiation on the microbial quality of frozen Malaysian shrimps (Prachasitthisakdi et al., 1984)

Organisms	$\log_{10}$ CFU/g			
	0 kGy	2 kGy	4 kGy	6 kGy
Mesophilic colony count	6.8	4.8	3.3	<2.8
Psychrotrophic colony count	6.2	4.2	<2.8	<2.8
Enterobacteriaceae	3.2	< −0.5	< −0.5	< −0.5
Lactobacilli	5.2	<2.8	<2.8	<2.8
Lancefield D streptococci	4.9	1.0	< −0.5	< −0.5
Staph. aureus	3.5	< −0.5	< −0.5	< −0.5

homogenates. Therefore, a dose as low as 1 kGy is sufficient to eliminate *V. parahaemolyticus* in frozen seafoods.

A dose of 2.5 kGy reduced the number of survivors of four *Shigella* serotypes by more than 6 log-cycles in frozen precooked shrimps in inoculated pack studies.

Variable results are found in the literature on the sensorial acceptability of irradiated crustaceans, probably because of variable experimental conditions and because sensory quality as compared to that of untreated control may depend very much on the time elapsed between irradiation and sensory testing. For example, Rhodes (1964) reported that raw prawn, treated with 3 kGy of ionising radiation, had a slight ''irradiation'' odour but was normal in appearance while Coleby and Shewan (1965) stated that the maximum permissible dose of ionising radiation for raw shrimps is approximately 9 kGy. After a shipping test, fresh unshelled shrimps treated with 2 kGy of ionising radiation were judged to be slightly better in consumer-type testing than unirradiated samples (Novak et al., 1968; Nickerson et al., 1983). In experiments in Thailand, gamma radiation with 2.2 kGy did not significantly ($P > 0.05$) affect the colour, flavour and texture, but had an effect ($P < 0.05$) on odour. A difference in acceptance of irradiated shrimp was noted among consumers at various localities (Nouchpramoul, 1985).

Regarding frog-legs, Indonesian studies (Tambunan, 1985) demonstrated that a combination of washing in chlorinated water, freezing and irradiation at a dose between 3–6 kGy eliminated *Salmonella* from the product.

A radiation dose of 1 kGy is adequate to eliminate *Vibrio vulnificus* in oysters (Mallett et al., 1991).

3.5. Spices and other dry ingredients

A major concern of food processors is to assure that the microbial load of ingredients and processing aids does not contribute to spoilage of food and does not diminish its microbial safety. Spices and dried vegetables or herbal teas may not be suitable substrates for the growth or long survival of salmonellae or other nonsporeforming pathogenic bacteria, nevertheless, occasional *Salmonella* contamination is a reality (Bockemühl and Wohlers, 1984; Bruchmann, 1995). The microbiological quality of the so-called instant soups which need not be boiled before consumption, is of particular importance. If the reconstituted product is held warm, particularly between 30–50°C, eventual pathogens may grow to levels that will cause illness.

Radiation decontamination of spices and many other dry food ingredients is a viable alternative to less effective, or toxicologically suspicious other decontamination processes, and it has a great application potential both in developing and the industrialized countries (Farkas, 1988). In addition to strict hygiene in preparation, radiation decontamination of spices, herbs, enzyme preparations and other dry ingredients with doses of 3–10 kGy proved to be a reliable method for improving microbiological safety of such products (Farkas, 1988). The effect of irradiation on the microbial counts of black pepper, one of the most highly contaminated spices, is shown in Table 6.

The use of irradiation instead of ethylene oxide to ensure hygienic quality of spices and dry vegetable seasonings has increased in the last 10 years especially because of the banning of ethylene oxide in the European Community. While there are other compet-

Table 6
Effect of ionising radiation on the microbial quality of black pepper (Soedarman et al., 1984)

Organisms	$\log_{10}$ CFU/g 0 kGy	2 kGy	4 kGy	6 kGy	8 kGy	10 kGy
Aerobic mesophilic colony count	8.0	6.2	5.2	3.9	2.1	< 1.8
Aerobic mesophilic spore count						
surviving 1 min at 80°C	7.7	6.5	4.7	3.0	1.8	< 1.8
surviving 20 min at 100°C	6.0	2.9	0.2	–	–	–
Anaerobic mesophilic spore count						
surviving 1 min at 80°C	7.5	6.1	3.1	< 1.8	< 1.8	< 1.8
surviving 20 min at 100°C	5.9	< 2.8	< 1.8	< 1.8	< 1.8	< 1.8
Enterobacteriaceae	4.7	2.8	1.7	1.1	< − 0.5	–
Lancefield D streptococci	4.9	1.7	0.4	< − 0.5	–	–
Moulds	4.6	< 1.8	–	–	–	–

ing processes such as various thermal treatments and extrusion, irradiation offers a broader spectrum for application for sanitizing dry ingredients, often at a more competitive cost.

4. Parasite disinfestation of foods of animal origin

Irradiation of carcasses could be used under specific conditions as an effective alternative for preventing diseases caused by some meatborne parasites such as cysticerci, trichinella larvae and toxoplasma cysts.

Radiation effects on parasitic protozoa and helminths are associated with loss of infectivity, loss of pathogenicity, interruption or prevention of completion of life cycle, and death of the parasite. Relatively high doses (4–6 kGy) are required to kill foodborne parasites. Objectionable sensory changes would be induced at these dose levels in raw foods which carry the parasites (Urbain, 1978). However, much lower doses are adequate to prevent reproduction and maturation resulting in loss of infectivity (Table 7).

Gamma irradiation of *Trichinella spiralis*-infected pork with a dose of 0.15–0.30 kGy made the parasite sexually sterile and blocked the maturation of ingested larvae in the hosts gut (Sivinski, 1985a,b). Neither the age of the encysted muscle, nor the oxygen tension in the meat, affect significantly the radiosensitivity. The data indicate that a radiation dose of 0.3 kGy can provide a substantial margin of safety for human consumption of infested meat. The US FDA consequently approved the use of irradiation to control *T. spiralis* in pork at a minimum absorbed dose of 0.3 kGy and not to exceed 1.0 kGy (F.D.A., 1985). Feasibility studies of pork irradiation in commercial operations have shown the process to be technically, and economically feasible in the USA (Sivinski, 1985b). Similarly, irradiation at 0.3–0.7 kGy renders *T. gondii* protozoa nonviable (Dubey and Thayer, 1994).

Irradiation of beef contaminated with *Cysticercus bovis* by a dose of 0.4 kGy would prevent development of this parasite in the human host (King and Josephson, 1983). Verster et al. (1977) suggest that pork carcasses infested with *Cysticercus cellulosae (Taenia solium* in man) might be fit for human consumption after irradiation with doses of 0.2–0.6 kGy.

Although doses that would kill the larvae of the parasitic nematode, *Anisakis*, in salted herring were reported to be high (higher than 6–10 kGy) (Van Mameren and Houwing, 1968), further experiments should be undertaken to determine what sublethal dose might render the larvae noninfectious or nonpathogenic. As far as organoleptic changes are concerned, inconsistent results are published in the literature on herring. Rhodes (1964) reported that irradiation treatment up to the 10 kGy level was found to have no effect on the appearance or odour of herring vacuum-packed in oxygen-impermeable wraps. Coleby and Shewan (1965) stated that the maximum permissible dose of ionising radiation for kippered herring (lightly salted and lightly smoked) is approximately 9 kGy. On the other hand, Bismarck herring treated with ionising radiation at

Table 7
The effect of irradiation on parasites (adopted from Wilkinson and Gould, 1996)

Parasite	Mode of infection	Dose (kGy)	Effect of irradiation
Parasites in fish and crustacea			
Angiostrongylus cantonensis	Parasitic worm found in uncooked molluses, shellfish	2	Minimum effective dose
Anisakis spp.	Nematode is ingested if fish is eaten raw or slightly salted	2–10	Reduces infectivity of larvae
Chlonorchis spp.	Chinese liver fluke, occurs in raw fish	0.15	In vitro minimum effective dose
Gnathostoma spinigerum	Parasitic worm found in raw, undercooked or fermented fish	7	Reduces worm recovery rate in mice
Opistorchis viverrini	Liver fluke found in contaminated raw, pickled or smoked fish	0.1	In vitro minimum effective dose
Paragonimus spp.	Larasitic worm found in crabs and crayfish in Asia	0.1	In vitro minimum effective dose
Parasites in meat			
Cysticercus bovis (*Taenia saginata*, in meat)	Tapeworm found in uncooked or undercooked beef, causes taeniasis	0.3	Preliminary minimum effective dose
Cysticercus cellulosae (*Taenia saginata*, in meat)	Tapeworm found in pork	0.3	Preliminary minimum effective dose
Toxoplasma gondii	Consumption of undercooked meat or poultry; or in contact with infected animals	0.7	Minimum effective dose for fresh pork
Trichinella spiralis	Nematode occurs in raw or inadequately cooked pork	0.3 0.3–1	Minimum effective dose FDA permitted dose to control trichina in pork

levels above 0.75 kGy was found by Wittfagel (1965) to have an off-flavour.

Investigations in Thailand demonstrated that low dose irradiation of freshwater fish can prevent infectivity of metacercariae of liver fluke (*Opistorchis viverrini*) when such fish are prepared into popular local dishes made from raw or semiprocessed fish (Bhaibulaya, 1985). At 0.5 kGy, the metacercariae could not develop in hamsters and caused no infection in their livers.

In summary, one can safely assume that controlling microbial pathogens in nonfrozen flesh food with minimum doses of at least 1 kGy should also control infectious parasites that might be present.

5. Radiation injury and increased sensitivity of the residual microflora surviving radiation treatment

Radiation injury-related extended lag-time of growth of surviving bacteria until cells resume active division and multiplication has been demonstrated by several recent studies (e.g. Patterson et al., 1993; Grant et al., 1993a,b; Farkas et al., 1996).

Sublethal damage to microorganisms taking place during irradiation can increase their sensitivity to environmental stress factors and other injurious agents and synergistic effects of irradiation and certain processes applied in food technology can be encountered (Szczawinska, 1983). For example, salmonellae, which survived irradiation of artificially inoculated meat (with a dose of 1–3 kGy) died slightly faster during storage of meat at 0–2°C and showed retarded growth during storage at 8–10°C compared to an unirradiated control. Similarly, salmonellae irradiated with a dose of 1 kGy were sensitized against curing salts ($NaNO_2$ and NaCl) in meat (Szczawinska et al., 1984; Szczawinski et al., 1985).

The surviving microbial flora of ingredients treated with a ‘‘pasteurizing’’ dose of radiation has been proven to be sensitized to further antimicrobial actions and certain environmental effects (Campbell-Platt and Grandison, 1990; Farkas, 1990) The survivors have lower heat resistance (as shown also in Table 6) and salt-tolerance, and they are more demanding as regards their pH-, moisture- and growth–temperature requirements than the microorganisms of untreated ingredients (Farkas et al., 1973, 1995; Farkas and Andrássy, 1985).

On the basis of ample evidence of the increased sensitivity of radiation survivors, there is plenty of scope for investigating combined effects (Farkas, 1990; Farkas and Andrássy, 1993, 1996). With today's demand for high-quality convenience foods, irradiation as a nonthermal treatment which does not affect the fresh state holds promise in combination with other techniques for enhancing the safety of many minimally processed, extended shelf-life chilled products (Farkas et al., 1997). Combination treatments have been proposed as a means of enhancing the preservative effect of irradiation (Vas, 1981; Thayer et al., 1991). One of the possibilities is using modified atmosphere packaging (MAP) in conjunction with low-dose irradiation to reduce the numbers of spoilage and pathogenic microorganisms by irradiation and suppress the growth of surviving microorganisms during storage by MAP (Patterson, 1988; Grant and Patterson, 1991; Zhao et al., 1996).

6. Limitations of food irradiation

Food irradiation is not a panacea for all food problems. Besides economic and logistic factors, and opposition based on psychological perception problems due to lack of public knowledge on wholesomeness of irradiated food (Bruhn, 1995; Resurreccion et al., 1995), sensory changes frequently constitute a dose limitation (Urbain, 1982). Irradiation at subfreezing temperatures can reduce off-flavour formation; for either technical or economic reasons, however, some foods cannot be frozen. Certain results cannot be secured through irradiation, and in these circumstances it is inapplicable. For example, at doses within the practical limits, irradiation does not inactivate viruses, enzymes and microbial toxins. Irradiation has no persistent effect, thus, postirradiation contamination must be prevented to secure the microbial benefit of the radiation treatment.

7. Status of legislation and future needs

The safety and effectiveness of irradiation as a method of food processing/preservation have been recognized by the Codex Alimentarius Commission when it adopted a Codex General Standard for Irradiated Foods (C.A.C., 1994) and the increasing numbers of national clearances on food irradiation are recorded in the data base of the Food Preserva-

Table 8
Clearances for microbial control of poultry by ionising radiation (adapted from a data collection of the IAEA)

Country	Item	Date (year)	Dose max. (kGy)
Bangladesh	Chicken	1983	7
Brazil	Poultry	1985	7
Chile	Chicken	1985	7
China	Chicken (spiced)	1994	8
Costa Rica	Chicken	1994	7
Croatia	Poultry (fresh)	1994	3
	Poultry (frozen)	1994	7
France	Chicken	1990	5
	Chicken meat (mech. separated)	1985	5
Israel	Poultry	1987	7
Mexico	Chicken (fresh or frozen) and chicken products	1995	7
Netherlands	Poultry	1992	10.5
Pakistan	Poultry (fresh, frozen)	1996	5
South Africa	Poultry	1989	10
Syria	Chicken	1986	7
Thailand	Chicken	1986	7
United Kingdom	Poultry	1991	7
USA	Poultry (fresh or frozen)	1992	3
	Poultry meat	1992	3
	Red meats (fresh)	1997	4.5
	Red meats (frozen)	1997	7

tion Section of the Joint FAO/IAEA Division in Vienna. The data base shows that radiation decontamination is an emerging technology in numerous countries. For example, Table 8 lists only the clearances for microbial control of poultry by ionizing radiation from a long list of approvals from this data collection. As another example of progress, the FAO/IAEA database records 32 countries where unconditional or conditional clearances have been issued until the end of 1996 for radiation decontamination of spices and herbs. Regarding other applications, e.g., the US FDA approved irradiation sterilization of frozen, packaged meats for use in NASA's space flight programme (F.D.A., 1995) and the same agency recently approved a petition from industry to allow radiation pasteurisation of nonfrozen red meats with a maximum dose of 4.5 kGy, and of frozen red meats with a maximum dose of 7.0 kGy (F.D.A., 1997). A petition to the FDA and USDA to approve low-dose irradiation (0.6 to 1.5 kGy) to control *Salmonella* infections in fresh whole eggs in intact shells is pending (Thayer et al., 1996). Thus, proper regulatory action and socioeconomic feasibility can produce a major radiation application area in the food field, following the well established record of the application of radiation treatment to sterilize disposable medical products for hospital and home health care.

Although food irradiation cannot provide the sole answer to foodborne illnesses, analogous with heat pasteurization of milk, it would prevent a lot of infections from specific solid foods, and thereby, would enhance the microbial safety of important segments of food supply with relatively low costs compared to the costs caused by foodborne disease. Therefore, being a feasible technology serving the fight against foodborne illness, the practical implementation of radiation processing should not be blocked. Food exporting countries find it frequently difficult to permit the radiation decontamination of foods even for inland use as long as their main trading partners do not accept such commodities. Nevertheless, in some 15 countries where marketing tests have been conducted with full treatment labelling, no real consumer aversion against irradiated food was noted (Loaharanu, 1993), e.g., when irradiated chickens were sold some time ago in the USA (A.D.A., 1996). Proper information about the safety and benefits of irradiated foods could increase the level of understanding and acceptance of irradiated products by consumers (Bruhn, 1995; Resurreccion et al., 1995). It is important that the WHO (WHO, 1994) and several respected nonprofit organizations such as the American Medical Association (A.M.A., 1993), the American Dietetic Association (A.D.A., 1996), the Institute of Food Technologists, and the Council for Agricultural Science and Technology in the USA (Thayer et al., 1996) have a positive attitude towards processing of food by irradiation for safety. At the same time, it has to be always emphasized that, like other intervention strategies, irradiation must be applied as part of a total sanitation program. The benefits of irradiation should never be considered as an excuse for poor quality or for poor handling and storage conditions, i.e., as a substitute for good manufacturing and hygienic practices.

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