A Review

The potential for food irradiation

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Introduction

The two main direct microbiological benefits of applying low dose irradiation to foods are: (1) improvement of food safety—common bacterial pathogens can be killed, thus reducing the risk of food poisoning and (2) extension of shelf-life—numbers of viable spoilage organisms can be reduced resulting in an increased shelf-life.

In many food applications both of these benefits may occur simultaneously as the doses applied to kill pathogens will also be effective against many spoilage organisms. In addition, an indirect benefit can be obtained when irradiation is used instead of chemicals to reduce the microbial load of foods. Spices, for example, can be decontaminated by irradiation rather than by treatment with ethylene oxide.

In the last decade within the UK, changes in lifestyle have led to consumers demanding more convenience and a greater variety in foods. The food industry has responded with a wide range of value-added products and 'ready prepared' meals, particularly suitable for microwave cooking. Chilled, rather than frozen, products are becoming more popular and there is a reduction in the amount of chemical preservatives in food. These measures are designed to give 'fresh and natural' products but some potential microbiological hazards remain. With these trends the increased dependence on refrigeration to preserve foods has led to a greater awareness of food-borne pathogens which can grow at chill temperatures.

A number of these problems could be resolved by the use of low dose irradiation. There may be particular additional advantages if the technique is used in combination with other preservation treatments. This review aims to discuss the benefits and acceptable limitations of the process and the potential which exists for food irradiation in the 1990s.

Improving food safety

In the UK, the number of reported cases of food poisoning continues to rise each year, with the two most important causative organisms being *Campylobacter* and *Salmonella* spp. In the last decade, reported cases of campylobacter infections have continued to increase. The organism is known to cause substantially more human diarrhoeal disease than that caused by salmonella (Dirksen & Flagg 1988). Campylobacter is frequently associated with raw milk, unchlorinated drinking water, undercooked chicken, raw shellfish and mushrooms. *Salmonella* spp. continue to be important causes of infection and are often associated with poultry (Roberts 1988).

Both *Salmonella* and *Campylobacter* spp. are relatively sensitive to irradiation (Table 1). A dose of 2·5 kGy effectively eliminates salmonella from poultry carcasses. The numbers of spoilage organisms are also reduced at this dose level, giving a shelf-life extension of at least 7 d at 3°C (Mulder 1984).

Table 1. Sensitivity of bacteria to irradiation

Organism/strain	D_{10} value (kGy)*	Food	Temperature during irradiation (°C)	Reference
Pseudomonas putida	0·08	Poultry	10	Patterson (1988)
Yersinia enterocolitica	0·10	Beef	18	Tarkowski *et al.* (1984)
Aeromonas hydrophila	0·14	Ground beef	2	Palumbo *et al.* (1986)
Campylobacter jejuni	0·14	Beef	18	Tarkowski *et al.* (1984)
Escherichia coli	0·39	Poultry	10	Patterson (1988)
Staphylococcus aureus	0·42	Poultry	10	Patterson (1988)
Listeria monocytogenes	0·49	Poultry	12	Patterson (1989)
Salmonella typhimurium	0·50	Poultry	10	Patterson (1988)
Moraxella phenylpyruvica	0·86	Poultry	10	Patterson (1988)
Clostridium botulinum type E spores	1·37	Beef stew	Room temp.	Schmidt *et al.* (1962)

* D_{10} = dose required to inactivate 90% of the population.

In recent years, psychrotrophic food-borne pathogens have been of increasing concern. One such organism *Listeria monocytogenes*, can cause various and severe disorders such as septicaemia and meningitis in infants, the elderly and the immunocompromised. Infections in pregnancy can lead to abortion. Soft cheeses have been implicated in listeriosis but the organism has also been isolated from various foods including uncooked poultry and raw vegetables (Pini & Gilbert 1988; Schlech *et al.* 1983). Other psychrotrophic pathogens include *Yersinia enterocolitica* and *Aeromonas hydrophila*. These organisms, in common with most non-spore-forming pathogens, are relatively sensitive to irradiation (Table 1) and doses aimed at removing salmonella from meat and poultry will also eliminate them.

The endospores of spore-forming genera are more resistant to most preservation treatments, including irradiation, than the vegetative cells of these and other pathogens. Spores of *Clostridium* spp. can have D_{10} values an order of magnitude higher than those of vegetative bacteria, and may therefore survive doses of irradiation used to kill vegetative cells. Although the spores are likely to be present in relatively low numbers, concern has been expressed that their survival in irradiated foods could be a potential food poisoning hazard. It has been shown, however, that when poultry skin moistened with poultry exudate was inoculated with *Clostridium botulinum* type E spores and irradiated at 3 kGy, the *Cl. botulinum* survivors could not compete with the natural surviving microflora. At 10°C and 30°C storage, spoilage off-odours were observed before toxin was produced by *Cl. botulinum* type E (Firstenberg-Eden *et al.* 1983). In fish and seafood, *Cl. botulinum* type E spores also have the potential to survive the normal irradiation process and grow and produce toxin at refrigeration temperatures. This has been recognized as a possible hazard and therefore it is recommended that a maximum dose of about 2·5 kGy be applied to these products and storage should be below 5°C. This will give a shelf-life extension but spoilage will occur before toxin is produced (Lewis 1984).

While irradiation is effective in increasing food safety a criticism often levelled against the process is that it is too expensive and therefore cannot be justified on economic grounds. The process is estimated to cost 2–8 US cents per kilogram depending on the product and processing requirements (IAEA 1989). One study has attempted a cost–benefit analysis of food irradiation (Yule *et al.* 1986). The authors used the costs of a hospital outbreak of poultry-borne salmonellosis to estimate the total cost of poultry-borne salmonellosis in Scotland. This was compared with the costs of irradiating poultry as a salmonella control measure. It was concluded that, on the basis of assumptions made in the analysis, the public health benefits could exceed irradiation costs. The benefits obtained by the removal of other food-borne pathogens from poultry or by the irradiation of other foodstuffs were not included in the analysis. These cost–benefit considerations need to be taken into account during discussion of the benefits of food irradiation.

Extension of shelf-life

The majority of meats and related products are irradiated primarily to remove pathogens. This will also give a shelf-life extension as many of the spoilage bacteria such as pseudomonads are very sensitive to irradiation and will be destroyed in the process. Organisms which have been isolated from poultry skin immediately after low dose irradiation (2·5 kGy) include the *Moraxella/ Acinetobacter* group, yeasts and *Lactobacillus* spp. (Hughes & Patterson 1988). During refrigerated storage (4°C and 10°C) of poultry meat, yeasts and Gram-positive non-spore-forming rods such as *Brochothrix thermosphacta* and *Microbacterium* spp. dominated the microflora (Hughes & Patterson 1989).

Irradiation for the sole purpose of shelf-life extension is most applicable to fruits and vegetables although not all products can be treated successfully. Undesirable effects such as colour changes can occur in leafy vegetables and tissue softening occurs in some stone fruits such as peaches after low doses of irradiation. However, a dose of 2 kGy can inhibit mould growth in strawberries and, provided the fruit is kept cool during storage, a shelf-life of greater than 14 d can be obtained compared with 6 d in cold storage without irradiation. Cut vegetables, used as 'soup greens', have been successfully irradiated at doses up to 2 kGy. This delayed bacterial spoilage from 1 to 4 d at 10°C (Langerak & Damen 1978).

The producer may take advantage of the longer shelf-life to expand his market over greater distances. Mushrooms, for example, have a short shelf-life (1–2 d) due to post-harvest changes such as browning, stalk elongation and cap opening. These changes can be minimized and shelf-life increased to 4–7 d by irradiating at 2 kGy and storing at 2°C (M.H. Stevenson, personal communication). The consumer can also benefit by having a longer 'at home' shelf-life. Shopping patterns are changing from multiple shopping visits per week to less frequent buying (once or twice every 14 d). Therefore, the requirement for a longer shelf-life for fresh foods can be met by the irradiation process.

In Japan potatoes are irradiated to a maximum of 0·15 kGy to inhibit sprouting. China also permits low dose irradiation of onions and garlic for the same purpose. At present, the widespread use of irradiation to control sprouting is limited due to the high cost of the treatment compared with the use of chemicals. However, with the trend for reduced use of chemicals, irradiation may become a more attractive option in the future.

Use of combination treatments

The aim of combination treatments, when applied to foods, is the enhancement of preservative action and/or reduction in the severity of one or all of the treatments. The use of combination treatments by the food industry is not novel. Nitrite and mild heat treatment are used to control growth and toxin production by *Cl. botulinum* in canned meats. Sugars such as sucrose are used with a heat treatment in the making of fruit preserves and condensed milk.

Irradiation in combination with some other treatments is also effective and this approach could be where further and perhaps major benefits of the process will eventually be seen. For example, it has been shown that irradiation can not only kill micro-organisms but also lower the resistance of survivors to some other preservation treatments. An irradiation dose of 2·32 kGy sensitized clostridial spores to subsequent heat treatment (Morgan & Reed 1954) and it has been proposed that this combination could be of value in heat-treated spiced meats (Kiss & Farkas 1981). Spices often contain large numbers of bacterial endospores and doses greater than 10 kGy would be required for sterilization. In the USA doses up to 30 kGy are permitted for the treatment of spices. However, doses below 5 kGy would be sufficient to sensitize the spores to heat and improve the microbial quality. This would result in a substantial reduction in the heat treatment required for seasoned food. The heat process needed to produce commercial sterility in canned luncheon meat can be reduced from an F_0 of 4·7 to 3·4 if irradiated spices are used. This reduction in heating gives better product quality and a saving in energy (Kiss *et al.* 1978). Further work is needed to investigate how the sensitizing effect of irradiation on the spores persists during storage under various conditions prior to heat treatment.

Low dose irradiation, followed by chill storage, can successfully eliminate pathogens and extend the shelf-life of poultry and pork. A combination of modified atmosphere packaging (MAP) followed by irradiation and refrigeration storage has proved to be an even more effective method for extending shelf-life. Modified atmosphere packaging is already used in conjunction with chill storage to extend the shelf-life of some meats and vegetables. Studies have shown that some bacteria in poultry meat, including *Moraxella phenylpyruvica* and *Lactobacillus* sp. were more sensitive to irradiation when the treatment was carried out under vacuum or in 100% carbon dioxide (Patterson 1988). Similar results with lactobacilli were obtained when beef was irradiated (Hastings *et al.* 1986).

During refrigerated storage of pork irradiated to a dose of 1·75 kGy the growth of surviving bacteria was reduced in packs containing 25% CO_2 : 75% N_2 compared with air (Fig. 1). Sensory analysis showed that this atmosphere also gave the most acceptable product, in terms of colour and odour, during storage over a 17 d period.

Combination treatments involving hot water dipping followed by low dose irradiation have been proposed to improve the quality of some fruits and vegetables. Irradiation can inhibit sprouting of white potatoes at doses of 0·1 kGy but spoilage due to microbial rot can occur with the high ambient temperatures (25–35°C) common in tropical countries. A reduction of microbial spoilage can be achieved by first heating the potatoes in water at 85°C for 10 min. Similarly, a combination of hot water dipping (55°C for 5 min) followed by a dose of 0·75 kGy has been found to improve the quality of mangoes by controlling the fungal decay, delaying ripening and inactivating the mango weevil (Urbain 1986).

Potential new uses of food irradiation

Foods or food ingredients are irradiated by about 30 pilot or industrial irradiators in 23 countries worldwide, as shown in Table 2 (Loaharanu 1989). A particular reason for irradiation has been identified for each product and research has shown the process to be successful without causing problems with changes in texture, flavour and odour. With increasing interest in combination treatments, there is potential for the problems of adverse organoleptic changes to be overcome and foods previously regarded as unsuitable for irradiation could be successfully treated. Dairy products, for example, are generally thought to be unsuitable as off-odours and flavours develop even at very low doses (Jones & Jelen 1988). However, it has been reported that Camembert cheese made from unpasteurized milk can be successfully irradiated to reduce pathogens such as listeria and salmonella provided conditions of storage temperature and ripening are carefully controlled (Langley 1988). Radappertization (sterilization by irradiation) of frozen dairy desserts, using doses of 40 kGy at −76°C has been investigated for immunocompromised patients. Hashisaka *et al.* (1988) have suggested that off-odours and flavours could be masked by the addition of strong flavours such as peppermint to give a more acceptable product.

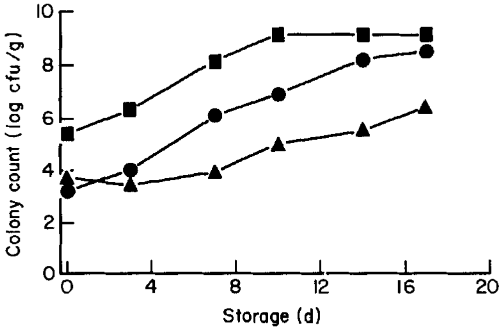

Fig. 1. Effect of modified atmosphere packaging and irradiation on the bacterial count of pork chops stored at 4°C. ■, Packed in air and unirradiated; ●, packed in air and irradiated (1·75 kGy); ▲, packed in 25 : 75 CO_2 : N_2 and irradiated (1·75 kGy). Results are the average of two replicates. Least significant difference between treatments (5% level) = 0·77.

Table 2. Countries with commercial irradiation facilities available, under construction or planned for food processing (April 1989) (Loaharanu 1989)

Country	Location (starting date for food irradiation)	Products
Argentina	Buenos Aires (1986)	Spices, spinach, cocoa powder
Bangladesh	Chittagong (expected completion: end of 1989)	Potatoes, onions, dried fish, pulses, frozen seafood, frogs legs
Belgium	Fleurus (1981)	Spices, dehydrated vegetables, deep-frozen foods, including seafood
Brazil	Sao Paulo (1985)	Spices, dehydrated vegetables
Canada	Laval (1989)	Spices
Chile	Santiago (1983)	Spices, dehydrated vegetables, onions, potatoes, chicken
China	Chengdu (1978) Shanghai (1986) Zhengzhou (1986) Nanjing (1987) Jinan (1987) Lanzhou (1988) Beijing (1988) Tienjin (1988) Daqing (1988)	Potatoes, garlic, apples, spices, onions, Chinese sausage, Chinese wine
Cote d'Ivoire	Abidjan (expected completion: late 1989)	Yams, cocoa beans
Cuba	Havana (1987)	Potatoes, onions, beans
Denmark	Riso (1986)	Spices
Finland	Ilomantsi (1986)	Spices
France	Lyon (1982)	Spices
	Paris (1986)	Spices, poultry
	Nice (1986)	Spices, vegetable seasonings
	Vannes (1987)	Poultry (frozen deboned chicken)
	Marseille (1989)	Spices, vegetable seasonings
	Avignon	
	Bretagne	
	Orsay	
	Orleans	
	Vendee	
German Dem. Rep.	Zwenkau (1983)	Onions, garlic
	Queis (1986)	Onions
	Schonebeck (1986)	Enzyme preparation
Hungary	Budapest (1982)	Spices, onions, wine cork
	Budapest	
India	Cochin Nasik	Spices, onions
Indonesia	Pasar Jumat (1988)	Spices
Israel	Yavne (1986)	Spices
	Yavne	
Italy	Fucine	
Japan	Hokkaido (1973)	Potatoes
Korea, Rep.	Seoul (1986)	Garlic powder
	Seoul	
Malaysia	Kuala Lumpur	
Netherlands	Wageningen (1978)	Spices
	Ede (1983)	Spices, frozen products, poultry, dehydrated vegetables, rice, egg powder, packaging material
Norway	Kjeller (1982)	Spices
Pakistan	Lahore	
Phillippines	Quezon City (expected completion: 1989)	
Poland	Warsaw	
	Poznan	
	Przysucha	
South Africa	Pretoria (1968)	Potatoes, onions
	Pretoria (1971)	Fruits
	Pretoria (1980)	Spices, meat, fish, chicken
	Tzaneen (1981)	Fruits, spices, onions, potatoes
	Kempton Park (1981)	Processed products
	Mulnerton (1986)	Fruits, spices, potatoes, onions vegetables
Thailand	Bangkok (1971)	Onions, fermented pork sausages
	Patumthani (1989)	
USSR	Bogucharovo (1960)	Potatoes, onions, cereals, fresh and dried fruit and vegetables, meat and meat products, poultry
	Odessa (1983)	Grains
USA	Rockaway	Spices
	New York (1984)	
	Whippany	Spices
	New Jersey (1984)	
	Irvine, California (1984)	Spices
	Washington	
	Iowa	
	Oklahoma	
	Hawaii	
	Florida	
Viet Nam	Hanoi (expected completion: end of 1989)	
Yugoslavia	Zagreb (1985)	Black pepper
	Belgrade (1986)	Spices

Radappertized foods for general use are less likely to be accepted as an alternative to thermally processed shelf-stable products. The high doses involved (greater than 25 kGy) can cause undesirable organoleptic changes, so the foods are usually treated in a frozen state to minimize these effects. Some preheating is also usually required to inactivate viruses and enzymes. It has been reported that bacon can be successfully treated with 30 kGy without freezing so that the amount of nitrite normally added to control the growth of *Cl. botulinum* can be greatly reduced to the levels necessary to give the colour and flavour of cured meats (Wierbicki 1981). This dose is greater than the 10 kGy limit suggested by the WHO/FAO/IAEA but if concern over nitrite and nitrosamines in foods is justified this could make irradiation more attractive in the future.

Irradiation may be beneficial in increasing the safety and shelf-life of the wide variety of value-added foods such as ready prepared cooked meals and breaded products. Many are sold chilled rather than frozen and an extended shelf-life and 'guaranteed absence' of pathogens would be an advantage. Further studies are required to determine optimum irradiation doses, storage temperature effects on sensory properties and whether or not irradiation in combination with other preservation treatment would be beneficial. It is also necessary to critically assess the economic benefits, in addition to the microbiological advantages, of using the process.

Summary

It has been recognized for many years that irradiation can remove spoilage organisms and pathogens from foods thereby extending shelf-life and reducing the risk of food poisoning. Shelf-life extension is of benefit to the food processor as the market can expand in terms of both variety and supply distance. The consumer also has the advantage of a longer 'at home' shelf-life which is in keeping with the trend for less frequent shopping rather than the daily purchasing of fresh foods.

Combination treatments is the area where irradiation shows the greatest potential. Successful combinations will enhance the preservative action and/or reduce the severity of one or all of the treatments. This should give better product quality without reducing food safety. Combination treatments which show promise include irradiation with mild heat treatment, with MAP or with curing salts. Such treatments would be of value in increasing the quality of fruits, vegetables and meats. The increasing variety of refrigerated foods, including value-added and ready prepared products could also be treated in this way. In addition to shelf-life extension, psychrotrophic pathogens such as listeria and yersinia would be killed along with mesophilic pathogens like salmonella. More foods traditionally regarded as unsuitable for irradiation may be successfully treated if correct processing conditions are used. Camembert cheese, made from unpasteurized milk, can be irradiated to kill pathogens, provided the storage temperature and ripening are carefully controlled.

Further work, including sensory evaluation studies, is required to optimize combination treatments for irradiated foods and to investigate the microbiological implications and economics of these procedures.

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