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Effect of irradiation on vitamins

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Food irradiation is a physical process involving treatment of food with ionising radiation. Its main uses are reduction in spoilage and pathogenic organisms, inhibition of ripening and sprouting processes, and insect disinfestation. Chemical changes in the treated foods are small, and expert committees have concluded that they carry no special nutritional problems. Some vitamins are sensitive to irradiative degradation, however, and opponents of the process have claimed that extensive destruction will occur. Irradiation doses will, however, be limited by organoleptic changes, and maximum levels are being introduced into legislation for specific foods. Examination of the published literature shows that vitamins C and B_1 are the most sensitive water-soluble vitamins, and that E and A are the most sensitive fat-soluble vitamins. Vitamin losses on irradiation of permitted foods in western countries will not be of nutritional importance.

INTRODUCTION

The development of food preservation processes has been driven by the need to extend the shelf-life of foods whilst maintaining their safety. Preservation methods that have long been accepted by consumers, however, frequently have associated disadvantages, in particular adverse changes in organoleptic characteristics and loss of nutrients.

Heat processing, e.g. canning, can cause significant deterioration in the sensory properties of food. Even mild heat treatments such as pasteurisation cause substantial flavour changes in products such as milk. Freezing causes severe textural deterioration in foods such as strawberries. Pickling causes similar severe sensory changes, and is limited to a relatively restricted range of foods. Even more modern minimal processing techniques, such as modified-atmosphere packing and sous-vide cooking, each of which gives relatively small changes in sensory quality, add to product cost and can carry microbiological hazards.

The loss in nutritional value of foods following preservation processes has in recent years been used as a weapon by anti-food industry activists, but criticism of the use of food irradiation has reached extreme levels, to the extent that irradiated foods have been subjected to the description 'nutritionally empty'.

The first part of this review describes the nature of the irradiation process and its uses. The second part deals with the effect of irradiation on vitamins, focusing on the major vitamins of importance in foods that are most likely to be subject to irradiation. More detailed accounts of these topics can be found in the books by Elias & Cohen (1977), Josephson & Peterson (1983), Urbain (1986) and Diehl (1990), and the review by Thayer *et al.* (1991).

THE IRRADIATION PROCESS

Food irradiation is a physical method of processing food using ionising radiation. The processes used for food irradiation have been used for many years for a number of purposes; they continue to be used for applications such as medical diagnosis and therapy, sterilisation of medical supplies and to modify and improve the physical properties of polymeric materials. Irradiation can also be used to decontaminate animal feed and to treat food for hospital patients requiring sterile diets.

Ionising radiation is sufficiently high in energy to remove an electron from water, which is the main component of foods and living organisms, and to create very reactive free radical species. These radicals can react with the DNA of living insects and microorganisms, causing death. The high reactivity of free radicals in aqueous foods results in very short lifetimes, and they can only persist, in low concentrations, in a solid matrix such as bone. Free radicals are naturally present in living tissues, and the chemical changes involving free radical reactions are similar to those found in processes such as autoxidation in fat-containing foods.

Three sources of ionising radiation are used in commercial radiation processing plants. γ-radiation plants

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use a radioactive source, usually ^{60}C, generating γ-radiation with energies of 1·17 and 1·33 MeV. This isotope is produced on irradiation of the non-radioactive ^{59}Co, and is not, as is frequently implied, a by-product of nuclear power. The radioactive source is usually stored in a pool of water when not in use, and is raised into an irradiation chamber for irradiation treatment. The ^{60}Co itself is encapsulated in several layers of stainless steel, and cannot contaminate any material, including food, in the irradiation chamber. A major characteristic of γ-radiation is its high penetrating power, which facilitates its use in treatment of bulk items such as chickens and drums of food.

The second main source of ionising radiation is high-energy electrons from machines. These can be generated in a number of ways, but such machines all have the advantage that they can be switched off when not in use, leaving no radiation hazard. A major limitation of electron beams for food use is their limited penetration depth, up to a maximum of about 8 cm in food. Despite this limitation, electron beam treatment can be used for products such as grain on a conveyor or low-density foods such as ground spices, and it can also be used to remove surface contamination on prepared meals. A consequence of the environmental advantage conferred by the switch-off capability is that such machines are suitable for integrating with a food-processing operation, and a dedicated plant is operating in France for processing mechanically recovered poultry meat.

A third, but less well-developed, radiation source is the use of X-rays generated from bombardment of a metal target by electrons. Although common technology in hospitals, at present it is not used for food treatment because of the low conversion efficiency of electrons to X-rays. X-rays, however, carry the dual advantage of high penetration power and switch-off capability.

The applied irradiation dose is measured in kilograys (kGy), where 1 Gy = 1J/kg. For polymer treatment and medical sterilisation purposes, doses of 25 kGy and above are used, whereas for food irradiation maximum doses of 10 kGy are used. For most food applications, doses considerably lower than this are used.

Applications

At low irradiation doses—of less than 1 kGy—sprouting in products such as potatoes and onions is inhibited, and insect infestation in, for example, grains and citrus fruits, is prevented through sterilisation of the insects and interruption of the breeding cycle. The use of irradiation in either case can eliminate the need for chemical treatments, many of which are now suspected of carrying toxicological hazards and are increasingly facing bans worldwide.

Low irradiation doses can also delay ripening of certain fruits, e.g. mangoes. This application has particular importance in maintaining high quality in imported tropical fruits. This effect is not applicable to all fruits, however, and can also vary with the cultivar type and growing conditions.

At slightly higher doses, of 1–3 kGy, the numbers of spoilage microorganisms present in foods are reduced. Reduction in the normal spoilage microflora can give extension to shelf-life of produce such as soft fruit, meat and fish. Food-poisoning organisms such as *Salmonella, Campylobacter* and *Listeria* are slightly more resistant, but reductions in counts of practical value can be achieved within this dose range. Spores from sporulating bacteria such as *Clostridium botulinum* are much more radiation-resistant, and are unlikely to be affected at practical food irradiation doses. Viruses are highly resistant to irradiation and are unaffected at the highest doses, of 10 kGy, that will be permitted for food.

The sensitivity of microorganisms to irradiation depends on both species and strain, and also on environment, e.g. food type and pH. The resistance also increases at reduced temperatures, and reduction in microbial loading of frozen foods requires doses of up to 7 kGy. Since the primary radiolytic process involves ionisation of water, moisture content is an important environmental factor. For this reason, decontamination of dry spices requires the highest irradiation dose, of 10 kGy. Although the microbial reduction increases with increasing irradiation dose, in practice the maximum dose deliverable is limited by minor changes in food components that can affect the sensory quality of the food.

Changes in food components

A major advantage of irradiation is that the changes that it produces in food components are small. This has resulted in considerable difficulties in establishing methods for detecting irradiation in foods, exacerbated by the fact that most of the changes that do occur are not unique to the use of irradiation. Only recently have methods been developed that can be applied reliably to a restricted range of foods; these are outlined later in this review. Some changes do occur, however, altering the sensory characteristics of the food and also the functional properties of some components. These changes increase with increasing irradiation dose and it is the changes in sensory properties that normally limit the irradiation dose employed.

The changes in sensory properties result mainly from three types of chemical reaction. First, irradiation initiates the normal process of autoxidation of fats, which gives rise to rancid off-flavours. Unsaturated fats are more readily oxidised than saturated fats, although the process can be slowed by eliminating oxygen by, for example, irradiating the food in a vacuum or in a nitrogen atmosphere.

Secondly, irradiation of proteins that have sulphur-containing amino acids causes a slight breakdown in the amino acids, resulting in unpleasant off-flavours. This is particularly prevalent in dairy products. It should be noted, however, that the breakdown is at a very low level, giving no change in nutritional value. In addition, the activity of enzymes is unaffected at normal radiation doses, and the continuing activity limits the achievable shelf-life extension of fruits and vegetables.

Thirdly, irradiation can break high-molecular-weight carbohydrates into smaller units. This process is responsible for the softening of fruits and vegetables through breakdown of cell wall materials, e.g. pectin. The effect depends on a number of factors such as the type, variety and maturity of the fruit. Softening can be a disadvantage, but may be advantageous in increasing juice yield and in reducing the drying and cooking times of dehydrated products.

Other trace components such as essential amino acids, essential fatty acids, minerals and trace elements are unaffected under practical irradiation conditions, although some vitamins, such as vitamin C and vitamin B_1 are partially lost. These latter changes are covered in more detail later in this review.

CURRENT USES OF FOOD IRRADIATION WORLDWIDE

Food irradiation has been approved by 36 countries for more than 40 different foods (IAEA, 1989), and by the end of the 1990s about 55 facilities are expected to be in use for food. Many countries, especially in the Third World, are developing food irradiation to reduce the post-harvest food losses that are a fundamental cause of food shortages. Uses include disinfestation of grain, reduced spoilage of tropical fruits and elimination of fruit flies as a disinfestation treatment. East European countries, South American countries and eastern countries are using irradiation to reduce losses of tuber crops such as potatoes, onions and garlic through sprouting inhibition.

A major application of food irradiation in western countries is the reduction of pathogenic bacteria in foods such as chicken, prawns and frog legs. The US Federal Center for Disease Control has estimated that 7000 deaths per year result from foodborne diseases caused by *Salmonella, Campylobacter*, trichinae and other parasites, and that there are 24–81 million cases of foodborne diarrhoeal disease each year.

Irradiation is permitted in Belgium, The Netherlands and France, and over 30 000/year of food are currently being irradiated in these three countries. In one French food plant in Brittany producing mechanically recovered poultry meat, irradiation is used to reduce the risk of Salmonella contamination. Tests had shown that heat processing impaired important functional characteristics of the product, which is incorporated into foods such as sausages and pâtés.

An increasingly important use of irradiation is for decontamination of spices. Spices imported into Western Europe are often heavily contaminated by pathogenic microorganisms, and have been implicated in food-poisoning outbreaks. In a survey of microbial contamination of spices, for example, out of 108 batches of black pepper 97% were contaminated with $>10^5$ bacterial counts/g and 42% were contaminated with $>10^7$ counts/g (Farkas, 1988). In the past, spices have been decontaminated using ethylene oxide treatment, but several countries, including the UK, have now banned this chemical on safety grounds. Perceived consumer resistance to irradiation, however, has driven several companies to develop heat treatments for spices but all result in some loss of important volatiles that does not occur when irradiation is used.

DETECTION OF IRRADIATED FOOD

No simple method has yet been developed for detecting whether food has been irradiated, reflecting the minute chemical changes that occur. Opponents of food irradiation insist that detection methods are needed to protect consumers from the safety hazards that result from the process, despite thirty years of research that have demonstrated the safety of the process.

The chemical changes that occur on irradiation have been described previously, but for the process to carry any validity as a detection method the changes must be unique to irradiation and stable to further processing treatment, including storage. Despite many years' research activity in many countries, only three methods have been developed that show any substantial promise. These methods—electron spin resonance (ESR), thermoluminescence (TL) and detection of lipid breakdown volatiles—have only recently become available for use, and all require specialist expertise.

ESR measures very small concentrations of radicals produced on irradiation of a solid matrix such as bone. As the radicals are effectively immobilised in the matrix, the radicals persist and can be detected some time after irradiation. The method is currently limited to those foods containing bone, such as poultry and fish, but may have some application in other foods containing a solid matrix. Most work has been carried out on irradiation of poultry, and researchers at Queen's University, Belfast, UK, have examined the effect of factors such as sample preparation method, irradiation dose, storage time and storage temperature on the strength of the ESR signal (Stevenson & Gray, 1990). The Belfast workers have also shown that the irradiation dose in French mechanically recovered poultry meat can be determined reliably. The ESR technique requires expensive instrumentation and specialist expertise, which may limit its practical application, but dedicated ESR equipment claimed to need no specialist knowledge is now available.

TL relies on light emission from dried products such as herbs and spices on heating. The method has been investigated extensively and has been proposed as a basis for official testing in Germany, but doubts remain regarding its reliability and the production of some false positives. Recent work has shown that the TL signal is produced from mineral grains present in the foods, and that much stronger signals can be produced from mineral grains separated from the food (Sanderson, 1990). These researchers have proposed that this technique could be extended to fruits and vegetables, which normally have dust adhering. The fact that the TL signal is not associated with the food itself, however, could be regarded as an inherent weakness. Quantitative dose measurement also currently requires a re-irradiation step, again limiting the usefulness of the technique.

The team at Belfast has also developed a method for detecting lipid breakdown products (alkylcyclobutanones and hydrocarbons) from poultry (Stevenson & Gray, 1990). The method has potential uses for all fat-containing foods, and has recently been shown to be suitable for detecting irradiation in eggs.

Other proposed detection methods based, for example, on hydroxylation of aromatic rings have yet to exhibit the uniqueness and reliability that will be required for control and enforcement purposes. Methods based on changes to DNA may have the most general applicability, but require much more development.

CURRENT LEGISLATION

Food irradiation was legalised in the UK at the start of 1991 as part of the new Food Safety Act. In June 1989 the Minister accepted the Report of a Working Party of Officials of the Agriculture and Health Department on controls appropriate for introduction of irradiation in the UK.

This development is the culmination of a process initiated by the recommendation of the Joint FAO/IAEA/WHO Expert Committee (1981) that the irradiation of food up to an overall average dose of 10 kGy presented no toxicological hazard and introduced no special nutritional or microbiological hazard. The following year the UK Government set up the Advisory Committee on Irradiated and Novel Foods (ACINF) to examine relevant scientific data on the safety and wholesomeness of irradiated food. The Committee reported in 1986, broadly endorsing the JECFI recommendations (ACINF, 1986).

The control of food irradiation is covered in The Food (Control of Irradiation) Regulations 1990. These regulations define the process conditions, the foods to which the process may be applied, the purposes for which food irradiation may be used and the purposes for which food irradiation may be used and the conditions that must be satisfied for granting irradiation licences. Foods that will be cleared for irradiation, and the maximum permitted doses, are shown in Table 1.

Table 1. Foods permitted for irradiation in the UK

Food type	Irradiation dose (kGy)
Fruits	2
Vegetables	1
Cereals	1
Bulbs and tubers	0·2
Spices and condiments	10
Fish and shellfish	3
Poultry	7

Irradiation of these items may only be carried out for the following purposes:

(1) elimination or reduction of pathogenic organisms;

(2) retardation of decay processes and destruction of spoilage organisms;

(3) reduction of waste from premature ripening, germination or sprouting and

(4) disinfestation of plants and plant products from organisms.

The position within the EC is less clear, but the harmonisation of EC policies in 1993 will, in theory, see trade in irradiated foods throughout the EC. A Commission Proposal is currently being debated in the European Parliament. The Proposal covers those foods that are already irradiated by EC countries, and is meeting opposition from the environmentalist lobby, which seeks to permit only irradiation of spices. Under the conditions of the Treaty of Rome, however, prohibition of trade in irradiated food will not be possible in 1993 and it is probable that an approach similar to that taken by the UK will eventually be adopted.

IRRADIATION, FOOD SAFETY AND THE CONSUMER

The technical possibilities of food irradiation will only be realised if the process is to be accepted by consumers. There has been strong resistance in the UK to processes that are associated with nuclear industry, in contrast to experiences in France and Belgium where the nuclear industry has a higher level of acceptance and where food irradiation is not a contentious issue.

In the UK, reliable scientific information has often been ignored or distorted in irresponsible statements made by pressure groups, and subsequent media reports have had a disproportionate effect on public opinion. Despite the claims of its critics, food irradiation has been one of the most thoroughly researched food preservation processes in the past 40 years, and this research is continuing at establishments such as the Leatherhead Food Research Association, Leatherhead, Surrey, UK.

Whilst there is evidence that the public now accepts that irradiation does not make food radioactive, the myths of excessive nutrient destruction and generation of toxic chemicals continue to give rise to considerable concern. There remain fears that irradiation will be used to clean up food with high microbial levels, although such food would show other clear signs of deterioration, such as visible spoilage and off-odours. Companies producing food that is subsequently treated by irradiation would also be expected to conform to good manufacturing practice procedures, but failures can occur in the most tightly controlled operations and irradiation would then offer an effective insurance policy.

The industry must recognise that the fears and suspicions of the consumer, whilst not logical, are real and will not disappear overnight. The development of detection methods should help serve to reassure consumers that the process is not being misused.

IRRADIATION OF VITAMINS IN FOODS

Much of the research work on the effect of irradiation on nutrients was carried out in the 1950s and 1960s as part of programmes investigating sterilisation processes at doses considerably greater than 10 kGy. In addition, there has been natural scientific curiosity in investigating effects at unrealistically high doses. An unfortunate consequence of this has been to give the activists an opportunity to quote data out of context. It is therefore important to remember that no food will be irradiated at doses greater than 10 kGy, and that most foods will receive doses much lower than this. In addition, the drive to use lower irradiation doses, perhaps in combination with other mild preservation treatments, as a means of minimising organoleptic changes will also minimise any effect on vitamins.

Care is needed in interpreting the contradictory literature data for other reasons. Many of the results are from investigation of pure solution chemistry, whereas food components appear to have a protective effect (Diehl, 1990). Vitamin analysis of foods immediately after irradiation can underestimate losses that subsequently occur on storage. Further losses can also occur on subsequent cooking, although this is not always true; for example, structural changes in dry legumes can reduce cooking times and improve vitamin retention (Sreenivasan, 1974).

Water-soluble vitamins

Vitamin B_1, thiamin

The major sources of thiamin are whole grains, nuts and beans, but, in the Western diet, meat can be a significant source.

Vitamin B_1 is the most radiation-sensitive of the water-soluble vitamins. Table 2 shows the effect of irradiation dose and temperature on losses from chicken meat (Hanis *et al.*, 1989). Increasing loss of vitamins is seen with increasing radiation dose, the losses reducing at the lower irradiation temperature. Similar losses have been found in other meats and fish. The beneficial effect of low temperature is maintained on prolonged storage and after cooking.

Table 2. Effect of irradiation dose and irradiation temperature on vitamin B_1 loss from chicken meat[a]

	Percentage loss relative to non-irradiated control	
Dose (kGy)	10°C	−15°C
0·5	0	0
1·0	18·8	11·2
2·5	29·1	22·4
5·0	43·6	28·0
10·0	57·3	44·8

[a] From Hanis *et al.* (1989), permission requested.

Losses on irradiation of whole grain are small, but increase in the milled product. These losses can be minimised by exclusion of oxygen during irradiation and storage.

It should be noted that vitamin B_1 is even more sensitive to heat than to irradiation. For example, pork and beef sterilised by irradiation retain much more vitamin B_1 than canned meats sterilised thermally (Josephson *et al.*, 1978).

Vitamin C

The main sources of vitamin C in the Western diet are fruits and vegetables, including potatoes. Total vitamin C activity is the sum of ascorbic acid (AA) and dehydroascorbic acid (DHAA) activity. Freshly harvested produce contains mostly AA and many workers only determine AA as a measure of vitamin C. However, both the ratio of AA to DHAA and the sum of AA and DHAA can change significantly during storage and processing. Some reports on the effects of irradiation of vitamin C appear to be conflicting because some refer to AA only whilst others refer to AA plus DHAA. Since irradiation of fruit and vegetables will be limited to 2 kGy, effects on vitamin C at higher doses are irrelevant.

Concentrations of AA and total vitamin C in potatoes decrease over the first few months after harvest, and this decline is greater in irradiated potatoes. The faster decline is without practical significance, however. The purpose of irradiating potatoes is long-term storage. After periods of around 6 months, irradiated potatoes can have higher AA and vitamin C contents than the controls (Diehl *et al.*, 1991). No loss in vitamin C has been found in onions and garlic at sprout inhibition doses. Studies of citrus fruits irradiated at doses up to 1 kGy have shown no significant losses.

Changes in ascorbic acid on irradiation are probably due to metabolic changes in plant tissue rather than chemically induced changes (Wilkinson, 1985).

Vitamin B_2, riboflavin

The major sources of vitamin B_2 are liver, meat and dairy products. Dairy products are unsuitable for irradiation owing to the ready development of off-flavours. In spite of this sensitivity, however, irradiation of dairy products at doses up to 40 kGy can be carried out without development of off-flavours provided the process is carried out at low temperatures (−78°C) and under a nitrogen atmosphere (Dong *et al.*, 1989).

No losses in vitamin B_2 were found in pork chops and chicken breasts irradiated at temperatures between −20° and +20°C at doses up to 6·6 kGy. Some irradiated samples showed increased vitamin B_2 concentrations of up to 25%. Increased concentrations of several vitamins in various foods have been reported. This may reflect a true increase by the radiation-induced conversion of precursors to the active vitamin, although the possibility that irradiation improves the efficiency of the extraction procedures preceding the analysis must also be considered.

Cod fillets irradiated in crushed ice at doses of 6 kGy and stored at this temperature for 7 days had 7% less vitamin B_2 than non-irradiated controls, both raw and after cooking (Kennedy & Ley, 1971). Chicken meat irradiated to 5 kGy at 10 and –15°C lost 18·4% and 9·2% of its vitamin C, respectively (Hanis *et al.*, 1989).

Vitamin B_5, niacin

The main sources of niacin are liver, meat and fish, and numerous studies of the effect of irradiation have been reported.

In pork chops irradiated at different temperatures at doses of up to 5 kGy, no loss of niacin was observed; a loss of 15% was noted after irradiation to 6·65 kGy at 0°C. Chicken breast showed no consistent effect of irradiation under the same conditions (Fox *et al.*, 1989). No change or slight increases of niacin in fish muscle were observed when ground mackerel and cod fillets were irradiated at 0°C at doses of up to 10 kGy (Underdal *et al.*, 1976).

Bread prepared from wheat flour irradiated at a dose of 0·5 or 5 kGy contained more niacin than bread made from non-irradiated flour. Similar doses had no significant effect on the concentration of niacin in wheat, maize, mung beans and chick peas (Khattak & Klopfenstein, 1989).

Vitamin B_6, pyridoxine

Pyridoxine is present in a wide range of foods in the diet, including meats, grains, pulses, fruits and vegetables.

Most irradiation studies have focused on the effect of doses greater than 10 kGy (e.g. Richardson *et al.*, 1961), and have indicated that the sensitivity is less than that of thiamin and closer to that of riboflavin. Fewer studies have been carried out at doses below 10 kGy, but losses appear to be low, ranging from zero in wheat, irradiated at doses up to 2 kGy and stored for 3 months (Kennedy, 1965), to 13% and 16% in cod and mackerel, respectively, irradiated at a dose of 1 kGy (Underdal *et al.*, 1976).

Vitamin B_{10}, biotin

The best sources of biotin are yeast, liver, soya, rice and eggs, but it is also present in meat, fruits and vegetables.

Work at sterilisation doses has shown little or no loss of this vitamin. Irradiation of wheat to 2 kGy gave a loss of 10% after 3 months storage (Thayer *et al.*, 1991).

Choline

No losses in choline have been reported in the few studies reported (Diehl *et al.*, 1991).

Vitamin B_{12}, cobalamin

Meat, particularly liver, is the main source of this vitamin, and studies have shown that it is fairly stable to irradiation. Pork irradiated to a dose of 6·65 kGy showed no losses (Fox *et al.*, 1989), and no losses were found in other studies on clams, haddock and chicken meat.

Folic acid

Vegetables such as broccoli and spinach are good sources of folic acid, as is liver. The radiation chemistry has been complicated by uncertainties regarding the nature of the biologically active compounds and their analysis (Diehl *et al.*, 1991), and additional work has been suggested (Joint FAO/IAEA/WHO Expert Committee, 1981). Little work has been published subsequently, but there are indications that some components are sensitive at doses of 25 kGy whilst others are unaffected at this high dose.

Pantothenic acid

Pantothenic acid is distributed widely in many foods, for example yeast, liver, egg yolk, milk and nuts. Studies have shown that there are no losses in a wide range of foods irradiated at doses of 10 kGy and above (Thayer *et al.*, 1991).

Fat-soluble vitamins

Vitamin E, α-tocopherol

Vitamin E is the most radiation-sensitive of the fat-soluble vitamins, but since the main sources of the vitamin are oils and dairy products, none of which will be suitable for irradiation on account of their sensitivity to off-flavour development, any effects will be of no nutritional relevance.

It has been pointed out (Diehl *et al.*, 1991) that the sensitivity depends on the presence of oxygen. For example, losses on irradiation of rolled oats at 1 kGy and storage for 6 months were reduced from 44% on storage in air to 16% on storage under nitrogen. Losses were also greater for produce with large surface area.

Vitamin A, retinol

Vitamin A is present in a wide range of foods, but the main sources are dairy products and eggs, none of which will be suitable for irradiation.

An additional source of importance is liver. When pork liver was irradiated to 5 kGy at 0°C it contained 4% less vitamin A than the non-irradiated control after one week and 13% less after 4 weeks. Calf liver sausage showed losses of 10% and 18% respectively, under the same conditions (Diehl *et al.*, 1991). Studies on powdered whole egg showed that losses could be reduced substantially by irradiation under vacuum at low temperature.

Protovitamin A, β-carotene

β-Carotene and other carotenoids are present in green and red vegetables and yellow and red fruits, and can be converted into vitamin A in the human body. The effects of irradiation have been studied extensively, and the results differ considerably in different produce.

Losses of up to 50% have been found in potatoes irradiated at 0·1 kGy and stored for 6 months (Janave & Thomas, 1979), whilst no effects have been found with mandarins and pineapples irradiated at 2·45 kGy (Agneessens *et al.*, 1989). Irradiation of mangoes and papayas with a dose of 2 kGy had no effect on carotenoids, whilst freezing and frozen storage for 3 months caused losses of 30% and canning caused a 90% loss in papayas (Beyers & Thomas, 1979). Irradiation of wheat flour with 1 kGy caused very small losses of 2–7% (Tipples & Norris, 1965), whilst irradiation of paprika to 5 kGy caused no losses on storage for 250 days (Farkas *et al.*, 1973).

Vitamin K

Green, leafy vegetables are important sources of vitamin K, together with liver and eggs and dairy produce. The vitamin is also synthesised by bacteria in the human gut, however, and therefore most humans, with the exception of newborn babies and patients treated with antibiotics, are largely not dependent on their diet for the supply of vitamin K. The stability of the vitamin is extremely high in vegetables, although some losses have been found in beef at high irradiation doses.

Vitamin D

The main sources of vitamin D in the diet are fish and fish oils. Few studies have been reported on the stability of vitamin D in foods, but it has been found that in general stability is high, approaching that of vitamins A and E.

A general summary of the radiation sensitivity of vitamins in food is shown in Table 3.

IMPLICATIONS FOR FOOD IRRADIATION IN THE UK

The most immediate application of food irradiation in the UK is as an alternative to ethylene oxide for decontaminating spices and herbs, although spices are not generally perceived by consumers as a high-risk food ingredient. The Isotron plant at Swindon, UK was licensed during 1992 to irradiate over 50 spices. As these ingredients do not contribute significant quantities of vitamins to the diet, irradiation does not introduce any nutritional concerns.

Subsequent applications are less certain. The use of irradiation for treating poultry would be an effective means of reducing the risk of *Salmonella* contamination producing food poisoning, although at the doses needed to avoid flavour changes, *Salmonella* would not be completely eradicated. It is probable that this will be the second important food category to be irradiated in the UK, possibly along with shellfish, and although some vitamin B_1 losses may occur, these would be of similar magnitude to those occurring on other forms of processing and would be of no nutritional significance.

Table 3. Summary: radiation sensitivity of vitamins in food

High	Medium	Low
C (AA + DHAA)	β-carotene	D
B_1 (thiamin)	K (in meat)	K (in vegetables)
E (α-tocopherol)		B_2 (riboflavin)
A (retinol)		B_6 (pyridoxine)
		B_{12} (cobalamin)
		B_5 (niacin)
		Folic acid
		Pantothenic acid
		B_{10} (biotin)
		Choline

Irradiation of fruits and vegetables, including potatoes, may give some slight reduction of vitamin C, but at the permitted doses these will be small in relation to the natural variation in vitamin C content. In addition, it is probable that many published studies have overestimated the loss in vitamin C through neglecting the conversion of ascorbic acid to dehydroascorbic acid. Irradiation of grain is unlikely to be of importance in the UK.

Although the above arguments have referred specifically to the UK, these would change little if applied to the diet in other Western countries. A major reason for this lies in the wide distribution of nutrients in the western diet, and the low level of dependence on any single food class. It is conceivable, however, that small segments of the population may have extreme dietary dependence on a smaller range of foods, and if these foods were to be irradiated, nutrient intake would require monitoring. Indeed, the ACINF report from the UK specifically stated that, whilst nutritional losses from irradiation were not significant in the diet as a whole, monitoring of the effect of irradiation on nutrient intake should take place.

The implications for irradiation outside western countries are less clear, but the Joint FAO/IAEA/WHO Expert Committee (1981) have again recognised that irradiation does not carry any special nutritional problems. Whilst the more restricted dietary variety in Third World countries may amplify the nutritional significance of vitamin loss, it can be argued that in these countries the main concern is access to any food, and that irradiation is an important weapon in reducing the more serious problem of food losses and consequent hunger or starvation.

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