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Nutritional aspects of irradiated food

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Purpose of the review: Food irradiation is a food processing technique that can reduce the microbiological burden of foods and extend shelf life. This review summarises recent literature on the effect of food irradiation on food nutritional content.
Findings: The effect of irradiation on nutritional content depends on the dose of irradiation used, the food matrix and preparation method, while any analysis examining potential effects on population intakes should also consider background adequacy of intake. Macronutrients, such as carbohydrates, proteins and fats, are not sensitive to irradiation, while vitamins vary in their sensitivity, with some being relatively insensitive (vitamins D and K, carotene and most B vitamins) and others being potentially sensitive, but where most populations have more than adequate intakes (vitamins A and E). Thiamin and vitamin C are the most radiation-sensitive vitamins, with some concern about the potential impact of irradiation-induced losses on population adequacy, but the most up-to-date analyses suggest that, at the irradiation doses being used for the main food sources of vitamin C (ie, fruits and vegetables, low doses), the impact on population nutritional status should be small. Similarly thiamin is relatively sensitive to irradiation, and some meats, eg, pork, do make a significant contribution to population intakes, yet there is thought to be little likely impact of food irradiation on population adequacy. A number of agencies with responsibility for nutrition have supported the use of food irradiation, therefore, the impact of food irradiation on population nutritional status would appear to be minimal.
Limitations/implications and directions for future research: Many studies have measured food nutritional content, yet such studies should also consider population nutritional intake to be able to conclude what likely impact any change in food content will have on population adequacy.

Keywords: nutrition; population; irradiation; micronutrient; macronutrient

Abbreviations

DRI	Dietary Reference Intakes
DRV	Dietary Reference Values
RDA	Recommended Dietary Allowance
RNI	Reference Nutrient Intake

Introduction

Food irradiation is a technology that addresses both food quality and safety because of its ability to control spoilage and food borne pathogenic microorganisms without significantly affecting sensory or other organoleptic attributes of the food [1]. Foods are irradiated to provide the same benefits as when they are processed by other technologies such as heat, refrigeration, freezing or chemical treatment, but with no increase in food temperature, no potentially harmful residues, and with the advantage that it can be used to treat packaged food, which will remain safe and protected from microbial contamination after treatment.

After many years of research, technology development and the introduction of national and international standards, more than 60 countries allow irradiation of at least one food or food product [1]. Commercial food irradiation is normally applied in combination with other food processing technologies at radiation doses of less than 10 kilogray (kGy). This degree of irradiation reduces microbiological burden, including disease-carrying bacteria and spoilage organisms, and the many-fold reduction in microorganisms helps prevent illnesses and also makes it possible to keep food longer [2].

The technical aspects of food irradiation are covered elsewhere in other articles in this edition, whilst a detailed consideration of potential target groups for these foods, and the effectiveness of irradiated foods in reducing food-borne illness, regulatory and retailer issues are also dealt with in separate reviews. Finally, the issue of consumer acceptance of irradiated foods is also dealt with elsewhere. A crucial question, prior to the widespread acceptance of irradiated foods by retailers, food supply chain managers and consumers, however, is the effect of food irradiation on nutrition, and the literature relating to this area will be summarised within the current review.

Dietary guidelines to promote health/recommendations for nutrient intakes

Whenever considering the effect of food irradiated food on nutrition, it is important to look both at the levels of a particular nutrient within a food, as well as the likely impact of wide consumption of that food on population nutritional status, and this will require consideration of recommended nutrient

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Table 1: Relative sensitivity of vitamins to irradiation (adapted from [24, 25]).

High sensitivity	Low sensitivity
Vitamin C	Carotene
Vitamin B1 (thiamin)	Vitamin D
Vitamin E	Vitamin K
Vitamin A	*Vitamin B6 (pyridoxine)*
	Vitamin B2 (riboflavin)
	Vitamin B12 (cobalamin)
	Vitamin B3 (niacin)
	Vitamin B9 (folate)
	Pantothenic acid

Water soluble vitamins; fat soluble vitamins

intake guidelines, and also the major dietary or food sources of particular nutrients of interest.

Most countries produce their own sets of recommendations concerning the intake of nutrients. They are intended primarily for health professionals who then in turn translate the recommendations into practical advice for the general public, and such advice tends to focus on foods and their major components. This means that dietary guidelines are designed so that a person who follows them is assured of obtaining enough of every nutrient. Nutrient intake recommendations vary between countries, for example, Dietary Reference Intakes (DRI) in the USA and Canada include the calculation of a Recommended Dietary Allowance (RDA), which is an estimate of the daily amounts of each nutrient considered necessary to meet the needs of the majority of healthy people. Values of RDA are given for 14 vitamins and 15 minerals [3]. Values are also given for energy, carbohydrates, essential (n-3 and n-6) fatty acids, protein, dietary fibre, and water, with recommendations being broken down by age and sex, and specific recommendations given for women who are pregnant or lactating. In the UK, Dietary Reference Values (DRV) include a Reference Nutrient Intake (RNI), which is the amount of a nutrient that is sufficient for almost all individuals in a group (about 97%), and habitual intakes above the RNI are almost certain to be adequate [4].

Effect of irradiation on nutritional status of food and nutritional adequacy of populations

The addition of any energy to food can breakdown its nutrients, therefore the effect of irradiation on the nutritional status of food has been examined extensively. Irradiation, like pasteurization, destroys pathogenic bacteria, but irradiation does not substantially raise the temperature of the food being processed, therefore nutrient losses are relatively small and are often substantially less than nutrient losses associated with other methods of preservation, such as canning, drying, and heat pasteurization and sterilization [5-8]. The relative sensitivity of nutrients to irradiation will depend on the food source/matrix, and also accompanying cooking and packaging methods, for example, nutrient losses can be minimized by irradiating food in an oxygen-free environment or in a frozen state [8, 9]. Sensory qualities such as appearance and flavour have been evaluated in laboratory settings [8, 10-13**] and in studies with consumers [12, 13**]. Consumers rate irradiated fruit similarly to non-irradiated fruits in appearance, freshness, and taste [12, 13**]. The effects of irradiation on nutrition will be considered, firstly for macronutrients, and then for micronutrients.

Macronutrients

In general, macronutrients, such as carbohydrates, proteins and fats, are not significantly altered by irradiation at usual doses [14-17]. Similarly, the biological value and digestibility of food proteins or amino acid pattern post-irradiation does not seem to be affected, in chicken [18, 19], mackerel [20], or cod [21]. The good growth observed in various animal species fed different kinds of irradiated feeds supports the conclusion that digestibility and biological value of proteins are not adversely affected by irradiation with doses up to 70 kGy [17, 22].

Individual fatty acids

Analysis of oily fish, wholegrains, poultry and legumes, summarised by the WHO [17], and published since that summary [23], suggests that irradiation of these foods has no or only marginal effects on essential fatty acids.

Micronutrients

The following sections highlights studies that have examined the effect of irradiation on micronutrients (minerals, vitamins, antioxidants, etc).

Minerals

Similarly, minerals (eg, iron, phosphorus and calcium) are also relatively unaffected by irradiation [14-16**].

Vitamins

Although major losses of macronutrients and minerals are not likely to be found under good irradiation practices, some vitamins have been shown to be more sensitive to irradiation [17**]. The relative sensitivities of individual vitamins to irradiation are presented in Table 1. It should be noted that vitamins can be susceptible to any food treatment method, such as heating, with water soluble vitamins being particularly sensitive, but fat soluble vitamins also seem to be sensitive to irradiation.

The actual vitamin loss will also depend on factors such as irradiation dose, food composition, packaging, and processing conditions, such as temperature and presence of oxygen [26**]. Foods are rarely irradiated with doses higher than 10 kGy, to minimise effects on organoleptic changes, and also vitamin losses [26**], therefore attention has focused on the effects on vitamin content at these lower doses.

B vitamins

The effect of irradiation on vitamin content of meat, specifically on B-vitamins, has been extensively reviewed [16**, 17**, 26**]. In 1997 the Food and Drug Administration amended its food additive regulations to allow the use of irradiation to treat refrigerated or frozen uncooked meat, meat by-products and certain meat food products (up to 4.5 kGy for refrigerated products and up to 7.0 kGy for frozen products) to control foodborne pathogens and extend product shelf life. As part of that amendment, the FDA examined the potential effect of such irradiation on nutrients in meat [16**]. Meat is consumed primarily as a source of protein, with red meat, and beef in particular, also being a rich source of minerals such as iron and phosphorus. Meat can also contribute significantly to the dietary intake of B vitamins. Irradiation of meat at relevant doses (as above) had insignificant effects on cobalamin, niacin [27] and pyroxine and pantothenic acid [28]. Another study [29] compared radiation-induced reductions in B vitamin levels in beef, lamb, pork, and turkey, all of which were irradiated at 5°C in the presence of oxygen, conditions which would tend to maximize vitamin loss. Even under such conditions, losses of riboflavin resulting from irradiation were virtually undetectable at radiation doses up to 3 kGy and the losses did not differ significantly between meat types. The average incremental loss of riboflavin at radiation doses above 3 kGy was reported to be 2.5 percent per kGy, which was judged by the authors as insignificant. Other studies have confirmed the stability of riboflavin in meat, fish and shellfish and confirmed its relative insensitivity to irradiation [30-33].

Consideration of the effect of irradiation on vitamins depends on the specific vitamin, the food type and the conditions of irradiation, as well as on the relative contribution of the food in question to the dietary intake of the vitamin. For this reason, the FDA and others have focused on thiamine [16**], as thiamine is one of the vitamins most susceptible to radiation, and pork is a relatively large contributor to dietary thiamine intake (estimated at 9% within the American diet [16**, 27]). Losses in thiamine levels in different meats were detectable at all irradiation doses tested and differed among the meat types tested, but the range was fairly narrow: from a low of 8 percent loss per kGy in lamb to a high of 16 percent loss per kGy in beef. The incremental thiamine loss in pork was approximately 11 percent per kGy above 3 kGy when irradiated at 5°C in the presence of oxygen, and these results were consistent with previous studies, with losses ranging from approximately 10 to 50 percent over a dose range of 0.6 to 7.3 kGy [summarised in 16**, 27]. The highest losses occurred when meat was irradiated non-frozen and/or in the presence of oxygen. Irradiation of meat is, however, likely to be carried out on pre-packaged products, packed under vacuum or reduced oxygen levels and shipped either refrigerated or frozen [16**]. Irradiation of food in the frozen state (or at reduced temperatures) and under reduced oxygen levels tends to minimize vitamin losses [14]. Whether food is irradiated before or after cooking also seems to affect the thiamine losses [34], while new packaging techniques, for example modified atmosphere packaging, also seem to have favourable effects on meat quality when combined with irradiation [35]. Pretreatments, such as marinading prior to irradiation, seem to enhance the ability of irradiation to reduce bacterial growth, and also help to preserve sensory quality [36]. Thus, irradiation of most meat will be likely to result in thiamine losses that are less than 50 percent [16**]. The FDA used the worst case scenario of 50 percent and concluded that average thiamine intake would still be above the RDA, using data on quantities of these food items consumed from the second National Health and Nutrition Examination Survey in the USA. Therefore the FDA concluded at that time that meat irradiation would not result in an adverse effect on the dietary intake of thiamine, or other B-vitamins (eg, riboflavin, niacin, cobalamin) and that, along with little evidence of detrimental effects on minerals or protein quality, that meat irradiation would not have an adverse impact on the nutritional adequacy of a person's diet [16**, 27].

Fat soluble vitamins – vitamins A, D, E and K

The most important sources of vitamins A and E in the human diet (milk, butter and cheese for vitamin A and margarine, butter and vegetable fats and oils for vitamin E) are either unlikely to be considered for commercial irradiation, or are low risk in terms of microbiological hazard. Therefore even though vitamin E seems to be relatively radiation sensitive, and vitamin A somewhat less so [17**, 23, 26**], the widespread use of irradiation would be unlikely to have any effect on population intakes and the likelihood of individuals achieving adequate status. Vitamin D is less radiation sensitive than vitamin A, and increases in some forms of vitamin D post-irradiation in certain foods, eg, mushrooms (see below) have been reported. Similarly, vitamin K seems to be radiation insensitive [17**, 26**].

Antioxidants and other vitamins – vitamin C and carotenes

The effect of irradiation on the main micronutrients found in fruits and vegetables, ie, vitamin C, folic acid and carotenes, has been comprehensively reviewed [17**, 25**, 26**, 37]. As the effect of irradiation at higher doses seems to have marked effects on organoleptic properties of fruits and vegetables, particularly firmness [25**], doses used tend to be low, at around a maximum of 1 kGy [25**]. A recent review, conducted by Food Standards Australia and New Zealand, has focused on nutrient losses at these doses, firstly observing extensive natural variation in the nutrient composition of individual fruit and vegetable types, with the major sources of variation being cultivar, season, growing location and degree of ripeness, while post-harvest storage and processing also contribute to variation. For example, concentrations of vitamin C and carotene can vary ten-fold between cultivars [25**]. Doses of irradiation up to 1 kGy had no effect on carotene levels in fruit and vegetables, did not decrease vitamin C levels in the majority of fruits and vegetables, and seemed to have little effect on other non-vitamin bioactive compounds [25**]. Vitamin C did decrease in some cultivars of some fruits, but the vitamin C content in these cases remained within the range of natural variation, and, within the context, of usual dietary population intakes, irradiation was not considered likely to have an impact on the adequacy of local population intakes [25**]. The authors considered irradiation to have no more detrimental effect on vitamin C content of fruit, than that which occurs under normal growing, storage and handling conditions [25**]. The report did, however, recommend that vitamin C levels in irradiated fruits and vegetables continued to be measured, to monitor effects, but that further analysis was not required for carotenes [25**].

Earlier reports suggested losses of ascorbic acid in potatoes and other vitamin C-containing foods, due to a shift of ascorbic acid to dehydroascorbic acid, but this is no longer considered valid as they failed to consider that dehydroascorbic acid also has vitamin activity [38, 39], therefore it has been recommended that total ascorbic acid is reported as a more reliable indicator of post-irradiation vitamin C [25**].

Very recent publications have examined the effect of irradiation on specific classes of fruits and vegetables, including mushrooms [40], raspberries [41], strawberries [42] and chestnuts

[43]. The short shelf life of mushrooms is an obstacle to their distribution, therefore irradiation to prolong shelf life is appealing. Effects of irradiation may depend to some extent on species, but irradiation at low doses seems to have little effect on protein and sugar content of mushrooms, data are more conflicting for vitamin C and polyphenols, whilst irradiation of mushrooms may offer an effective method of increasing vitamin D content [40]. Irradiation of raspberries was associated with an increase in total phenolic content with increasing radiation doses and a decrease with storage time [41], with the same trend being noticed for storage time for antioxidant capacity, and, certainly, no reduction in antioxidant capacity and phenolic content of raspberries was observed after irradiation. A very comprehensive study of the effects of irradiation on the nutritional profile of strawberries demonstrated no effect on nutritional content up to 1 kGy, with some losses in vitamin C at 2, 2.5 and 3 kGy (mean vitamin C ranging from 36.7-41.0 mg/100g compared to control levels of 49.7 mg/100g immediately after irradiation) [42]. For all other measures, including beta-carotene, sugars, protein, energy and fibre, no significant effects were observed at any dose [42]. After 14 days cold storage, vitamin C levels were similar in irradiated strawberries versus controls [42]. Finally, for chestnuts, compared to other food processes (curing, roasting or boiling) which also cause changes in nutritional composition, gamma irradiation seemed not to affect the nutritional value and individual nutrients (eg, sugars, starch and fatty acids) in chestnuts, whereas the storage time did [43]. Antioxidant concentration of tocopherols and phenolics seemed to be unaffected, and antioxidant activity was preserved or even enhanced compared with non-irradiated samples [43].

Effect of irradiation on specific products

Other recent studies have focused on very specific products. One such study examined the effect of combining preservatives with irradiation on the shelf life of raw sugar cane juice, indicating that combined processing methods can be effective, and observing no significant effects on nutritional composition, including flavonoid content [44]. In another study from the same group, a nutrient-rich nasogastric liquid feed formulation was developed for patients vulnerable to infection. Due to its high water content and high nutrient density, the shelf life was only a few hours, which restricted distribution of this product. Irradiation at 2.5-10 kGy reduced the microbiological load to non-detectable levels, and increased shelf life to one month with no effect on organoleptic properties. Nutrition quality, as measured by total carbohydrates, fibre, protein, energy, vitamins A and C, and calcium, iron and zinc content, were unaffected [45]. Development of such a product indicates the potential for innovative irradiated food products developed for specific target groups, which is dealt with in more detail in a separate review (Narvaiz, current issue).

Estimates of effects of inclusion of irradiated foods on adequacy of population nutrient intakes

While many studies have examined the nutritional content of specific foods post-irradiation, few studies have examined the likely effect of any nutrient losses on overall diet quality, and population nutrient intake. Narvaiz and Ladomery examined the likely effect of commercial food irradiation on population vitamin intakes in Argentina [46]. Using FAO data, they examined the per capita intake of foods likely to be irradiated, recorded the vitamin content of these food products, calculated the likely vitamin losses from these foods treated under good irradiation practices, and estimated the likely impact of vitamin losses, given national recommended dietary intake (recommended daily allowance (RDA) levels. Vitamins considered were A, B1, B2, B6, B10, B12, C, D, E, niacin, folic and pantothenic acids. For the majority of these vitamins, the authors concluded that average vitamin intakes would still exceed the RDA and that, therefore, no adverse impact would be expected. An exception was folic acid, where the data on losses due to irradiation were incomplete, and where population intakes in Argentina seemed low. A further analysis also suggested that the dietary supply of vitamin D was lower than the RDA, however, this was not surprising given the major contribution of synthesis via UV exposure to status, and therefore should not be a problem for the Argentinean population in terms of adequate status [47**]. As described above, vitamin D is relatively radio-resistant.

The perspective of international agencies with the responsibility for health

The FAO/IAEA/WHO Expert committee on Food Irradiation concluded already in its report of 1981 that "...irradiation of foods up to an overall average dose of 10 kGy introduces no special nutritional or microbiological problems" [48*], and these relevant specialised agencies of the UN support the use of irradiated food. The nutritional adequacy of foods at higher doses (25-60 kGy) was later confirmed by an FAO/IAEA/WHO Study Group on High Dose Irradiation [17**, 49]. Similarly the Scientific Committee on Food of the European Commission concluded that foods irradiated with appropriate technologies are both safe and nutritionally adequate [50–54], although, other than an EU-wide approval for irradiation of "dried aromatic herbs, spices and vegetable seasonings", individual national regulations apply. A Codex General Standard for Irradiated Foods and a Recommended International Code for Practice for Radiation Processing of Food have been developed [55]. As stated above, more than 60 countries have regulations allowing food irradiation of at least one product.

The perspective of national agencies with the responsibility for nutrition

The American Dietetic Association, who have a responsibility to educate consumers on issues related to food and nutrition, have considered the evidence for food irradiation and concluded that food irradiation is one way to enhance the safety and quality of the food supply, encouraging government, food manufacturers, food commodity groups, and qualified dietetic professionals to continue working together in educating consumers about this technology [13**]. The ADA recommended expanded education for the public and good retailers, with health professionals working with food industry representatives to present accurate information about irradiation to the public [13**].

The Food Standards Agency, responsible for food safety within the UK has stated that, in terms of the effect of food irradiation on nutritional content "All food preservation techniques cause chemical changes in food – that is how they work. The changes caused by food irradiation (for example the production of free radicals) are similar in nature and extent to those caused by other preservation techniques, such as cooking, canning and pasteurisation. There may be some vitamin loss but this would occur with any other preservation technique or even just long-term storage. There is no evidence that any of the changes caused by food irradiation pose a risk to the health of consumers." [56]. Similarly the FDA, in a factsheet on food irradiation state that "Irradiation does not make foods radioactive, compromise nutritional quality, or noticeably change the taste, texture, or appearance of food." [57].

The European Food Safety Authority (both the Panel on Biological Hazards (BIOHAZ Panel) and the Panel on Food Contact Materials, Enzymes, Flavourings and Processing Aids (CEF)), in 2011, considered the safety of irradiation of certain food products [58]. Their published scientific opinions did not, however, comment on the nutritional value of irradiated foods [58], as no new data had emerged on the changes in levels of macro or micronutrient levels following irradiation of foods, since the Scientific Committee on Food had previously commented on this [54].

Conclusion

Food irradiation is a food processing technique that can reduce the microbiological burden of foods and extend shelf life. The effect of such irradiation on nutritional content has been examined and depends on the particular nutrient, and food matrix, the dose of irradiation used and other aspects of preparation (cooking, packaging, etc.), while to assess the importance of any losses on population intake levels requires consideration of nutrient intake guidelines, major food sources of the particular nutrient and adequacy of population intakes. Macronutrients such as carbohydrates, proteins and fats and minerals do not seem to be sensitive to irradiation, while vitamins vary in their sensitivity to irradiation, with some being relatively insensitive (vitamins D and K, carotene and most B vitamins) and others being potentially sensitive, but where most populations have more than adequate intakes (vitamins A and E). Thiamin and vitamin C have been the focus as the most radiation-sensitive vitamins, but the most up to date analyses suggest that vitamin C change is no more than would be expected as part of natural variation and, at the doses being used for the main food sources of vitamin C (ie, fruits and vegetables, low doses of irradiation), the impact on population nutritional status should be low. Similarly thiamin is relatively sensitive to irradiation and some meats (eg, pork) do make a major contribution to population intakes, yet measured impact on population adequacy is not thought to be major. Given these conclusions, accompanied by support of major agencies with responsibility for nutrition, the impact of food irradiation on population nutritional status would appear to be minimal.

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