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Specific consequences of using WMD: Radioactive contamination of foodstuffs and its potential health effects

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Abstract

The excessive presence of radionuclides in foodstuffs can potentially pose health risks. Under normal conditions, the content of radioactive substances in food is very low, resulting in only a small fraction of the total dose caused by natural radiation. This may be substantially different in the case of radiological accidents or terrorist attacks, resulting in increased levels of radioactivity in the environment, which may contribute significantly to the radioactivity of food. The situation must be monitored to assess the contribution of internal exposure coming from ingesting contaminated food. The paper discusses the occurrence of radioactivity in various foods, including its origin and effect on the total population exposure due to radioactive contamination of the environment following the use of WMDs (Weapons of Mass Destruction). To minimise the potentially harmful consequences of such events, the radioactivity in food has to be controlled. The probability of threats of possible radiological attacks in the contemporary geopolitical situation has recently increased.

KEY WORDS: *Weapons of Mass Destruction, food, radioactive contamination, ingestion, long-term effects, population safety, committed effective dose, Chernobyl, Fukushima.*

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1. Introduction

In everyday life, people are exposed to both natural and artificial radiation sources. Radionuclides are inhaled and ingested through air, food, and water on a daily basis. Most of these radionuclides naturally exist in our environment, though some portion comes from medical and industrial radiation use [1,2]. During nuclear or radiological emergencies, additional radioactive materials can contaminate food. These materials can settle on the surface of foods like vegetables or animal feed from the air, rain, or snow. Over time, radionuclides can migrate from the soil into crops and animals, accumulating in the food supply. Through the contaminated water, radioactive material may reach fish and seafood. Eating food contaminated with radionuclides during such emergencies increases the body's radioactivity, thereby elevating health risks associated with radiation exposure. The level of risk depends on the specific properties of radionuclides ingested and the amount of radioactivity absorbed. The radioactive contamination of the environment may lead to an increase in the radioactivity of foodstuffs. Consequently, this will cause additional exposure to consumers above the radiation background. This is why it is necessary in such situations to pay increased attention to monitoring the content of radioactivity in all products used for the preparation of food.

Ionising radiation, a form of energy released by atoms as electromagnetic waves or particles, is omnipresent. People are constantly exposed to natural sources of radiation, such as soil, water, and vegetation, as well as human-made sources like X-rays or charged particle accelerators during medical examinations and treatment. The contribution to the overall exposure from the medical use of ionising radiation is becoming higher and higher, and now in most industrialised countries, it is comparable with the exposure to all natural radiation sources (around 3 mSv/y). On this occasion, it is worth emphasising the importance of using appropriate quantities and units to quantify radiation exposure [1,2].

Based on the radiation protection philosophy, exposure to people should be kept as low as reasonably achievable and always below the set limits for the population, workers and patients. Another rule of radiation protection is to avoid any emergencies and if they occur, to try to minimise their consequences.

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The regulatory requirements also aim to reduce even small exposure that can result in stochastic health effects. These effects, such as cancer and genetic effects, may occur later with the probability proportional to the dose. Health effects related to the consumption of radioactively contaminated food belong to this category since consuming such food could increase the risks associated with stochastic effects. It is very difficult to epidemiologically detect stochastic effects due to radiation exposure at low doses below the range of 100 to 200 mSv, but the ICRP [3] specifies the standards for radiological protection for low-dose exposures, assuming that effects would appear depending on dose levels (linear dose-response).

Under some circumstances, when the intake of radioactive substances into the body is substantial, deterministic effects may appear, which are also referred to as harmful tissue reactions. They include, for example, skin burns, damage to the lens of the eye, and at very high doses, around (6-10 Gy), the exposed person dies. These effects do not appear below a dose threshold. Above this threshold, the higher the dose, the more severe the effect.

In assessing severe radiation levels resulting in deterministic effects, quantities developed for evaluating stochastic effects, such as dose equivalent, equivalent dose, effective dose, committed effective dose and other quantities based on dose equivalent, cannot be used. This refers also to units, where in this case of low exposure, the unit of Sv (sievert) should be used, while for high dose assessment, the units Gy (gray) or Gy-Eq (gray-equivalent) must be applied. This is not always the case; inappropriate use of quantities and units may cause some difficulties in assessing real radiation protection situations.

The information necessary to assess the radioactivity of common foodstuffs was studied from different sources, mainly from scientific papers and some specific reports presenting the results of measurement of radioactivity in various agricultural and other products used for food preparation. The situation is obviously slightly different in various parts of the world. During the last few decades, a visible increase in environmental radioactivity has resulted from some significant nuclear accidents that happened in Chornobyl (1986) and Fukushima (2011).

2. Natural and Artificial Exposure

Radioactivity has existed on Earth naturally since its inception. More recently, humans have introduced artificial radionuclides for various beneficial applications. All radioactive elements in the environment are either naturally occurring or man-made. Humans have always been exposed to natural radiation, with the global average exposure being around 2.4 mSv per year (world average). Since the early 20th century, the use of radioactivity in industry and medicine has resulted in the release of artificial radionuclides into the environment. Fig. 1 illustrates the worldwide average public exposure from various radiation sources, showing that ingestion of naturally occurring radionuclides in food accounts for about 9.6% of the total exposure, approximately 0.23 mSv annually [3].

Several types of exposure to radioactive compounds exist. A distinction is made between radioactive contamination and exposure to ionising radiation. One has distinguished between internal exposure, which is the case of dealing with the impact of contaminated food, and external exposure. In general, internal contamination corresponds to the penetration of radioactive material by incorporation into the body. This can occur through ingestion, inhalation, skin diffusion, or absorption through a contaminated wound.

Everyone is constantly exposed to radiation from natural sources. This natural background radiation is an unavoidable part of our environment, though its levels vary significantly around the world. For instance, people living in granite-rich areas or on mineralised sands experience higher levels of terrestrial radiation, while those at high altitudes are exposed to more cosmic radiation. It is important to consider both external and internal exposure to radiation, as illustrated in Fig. 2 (based on [3]).

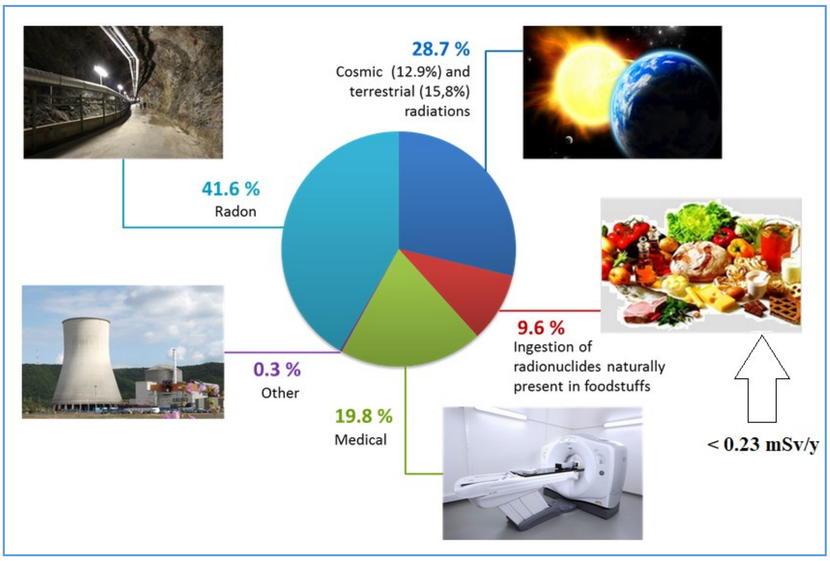

Fig. 1. Main radiation sources contributing on average to the world population.

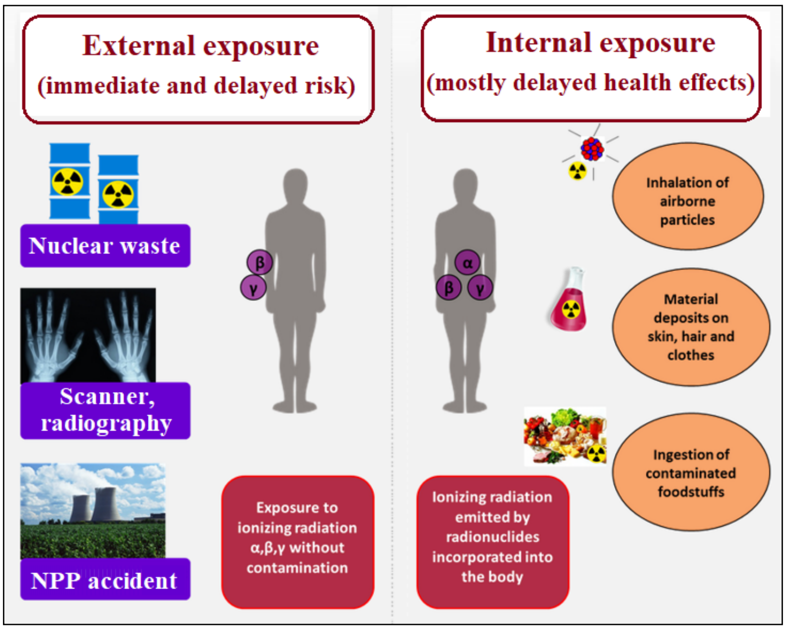

Fig. 2. Schematic view of differences between exposure and contamination. Several types of exposure to radioactive compounds exist. A distinction is made between internal and external radiation exposure (based on [3]).

2.1 Natural Radioactivity

The human body contains small amounts of naturally occurring radioactive materials, primarily derived from radioactive nuclides in the food and air we inhale. These include radionuclides like tritium (3H), carbon-14 (14C), and potassium-40 (40K). About 11% of our radiation exposure is due to these internal radioactive materials, with the majority of this dose coming from the radioactive isotope of potassium. Radionuclides such as 40K and 14C are found in air, water, and soil and become part of our diet and body tissues.

Background radiation largely originates from natural radioactive materials and cosmic rays from space. Continuous exposure to this environmental radiation results in an annual effective dose of about 3 mSv. Radon gas is the most significant source of this background radiation, contributing an average of about 2 mSv per year. Other sources include cosmic radiation, uranium and thorium dissolved in water, and internal radiation.

Besides medical imaging, artificial sources of radiation include construction materials, fuels like gas and coal, smoke detectors, luminous watches, tobacco, certain ceramics, and more. The human body maintains a balance between the radioactivity entering through food and air and the radioactivity exiting the body. Potassium-40 is the major contributor to internal radiation exposure, with natural radionuclides such as 14C also being integrated into our environment and bodies. Background radiation is a continuous exposure primarily due to natural sources like radon gas, which accounts for about 2 mSv per year and includes contributions from artificial sources like building materials and various consumer products [4].

It is evident that natural radionuclides and various harmful elements are inherent components of our surroundings. Geological and geographical factors influence the levels of these substances in the environment. Additionally, human actions like mining, smelting operations, processing phosphate ore, coal ash and industrial discharges, vehicle emissions, atmospheric deposition of particles, utilisation of biosolids, and the use of soil fertilisers can contribute to elevated concentrations of naturally occurring radionuclides and toxic elements in both the environment and food sources. Natural radioactivity in food manifests primarily through three key processes:

a. Uptake: Plant roots absorb radionuclides from the soil.

b. Deposition: Radioactive particles from the air settle on crops.

c. Bioaccumulation: Animals that consume plants, feed, or water with radioactive material accumulated radionuclides.

Bananas and Brazil nuts are two well-known instances of naturally occurring radionuclides in food. Bananas contain a small fraction of radioactive potassium, emitting a minute amount of radiation (0.1 µSv per banana). To contextualise, consuming about 100 bananas equals daily exposure to natural radiation in the United States. Brazil nuts, in addition to potassium, contain a trace amount of radium from the soil. It's crucial to differentiate natural radiation in food from food irradiation. The latter is a process employing radiation to prevent foodborne illnesses and spoilage without rendering the food itself radioactive. In a radiological event, animals may ingest radioactive materials, which could pose a risk if consumed by humans. Public guidance on food restrictions would be issued in such scenarios. To safeguard the public, regulatory authorities globally mandate testing for contaminants, including radioactivity, in food. Stringent limits and restrictions on imported foods are set to ensure public safety.

2.2 Artificial Radioactivity

Artificial radioactivity involves converting a stable nucleus into an unstable one by bombarding it with atomic particles like alphas, neutrons, or protons. This phenomenon was first identified by I. Curie and F. Joliot in 1934. Lighter elements such as boron and aluminium can be induced to become radioactive when exposed to radiation like charged particles or neutrons. This process results in the emission of radiation and elementary particles. During the disintegration, the original nucleus is termed the 'parent nucleus,' while the resulting nucleus is called the 'daughter nucleus.' When the atomic projectile collides with the parent nucleus, it triggers the transformation into an unstable nucleus, leading to spontaneous decay and the release of the daughter nucleus along with an ejected particle. The distinctions between natural and artificial radioactivity are outlined in Table 1 (based on [5]).

Table 1.

Main features characterizing natural and artificial radioactivity

Natural radioactivity	Artificial radioactivity
Emission of radiation due to self-disintegration of a nucleus	Emission of radiation due to the disintegration of a nucleus through induced process
Alpha, beta and gamma radiations are emitted	Mostly elementary particles such as alphas, betas, neutrons, positrons, etc. are emitted
It is a spontaneous process	It is an induced process
Exhibited by elements with atomic number more than 83	Exhibited by elements with atomic number less than 83
The process cannot be controlled	This process can be controlled

Many people may not realise that their highest dose comes from their medical examinations. There are some indications that not all medical examinations are fully justified. The responsibility for justification lies with the relevant professions. Relevant medical practitioners need to have special training in radiation protection to take responsibility for justification. The main purpose for justifying all radiologic procedures is to assess the benefits and risks of a requested radiographic procedure and determine whether exposure will continue. Furthermore, justification helps to prevent unnecessary radiation exposure and reduce the chances of harmful effects of ionising radiation. Various studies reported that radiological examinations are not always justified [6], and in some cases, about 50 %r reported radiological examinations were not fully justified [7].

Table 2.

Approximate mean doses relevant to societal low-dose radiation exposures and to low-dose radiation risk estimation (based on [8]):

Exposure specification	Approximate average effective dose (mSv)
Some societally relevant exposures:	
Round-trip flight, New York to London	0.1
Single screening mammogram (breast dose)	3
Single screening mammogram (breast dose)	3/y
Dose (over 70 years) to 0.5 million individuals in rural Ukraine in the vicinity of the Chornobyl accident	14
Dose range over a 20-block radius from a hypothetical nuclear terrorism incident, scenario 1: medical gauge containing cesium	3 - 30
Pediatric CT scan (stomach dose from abdominal scan)	25
Radiation worker exposure limit	20/y
Exposure on the international space station	170/y
Some low-dose epidemiological studies:	
Medical x-rays (breast dose in scoliosis study)	100
Nuclear workers (mean dose from major studies)	20
Individuals diagnostically exposed *in utero*	10

Typical radiological exams produce doses ranging from 3 to 30 mSv. It's clear that high radiation doses (over 100 mSv) significantly increase cancer risk, while the relationship at lower doses is less certain. Epidemiological studies show that the lowest dose of radiation associated with a noticeable increase in cancer risk in humans is about 10–50 mSv for acute exposure and around 50–100 mSv for prolonged exposure.

The biological effects of low radiation levels have been studied and debated for over a century. There is no doubt that intermediate and high doses of radiation (>100 mSv), whether acute or prolonged, have harmful effects on humans, including cancer. However, the situation is less clear at lower doses.

Compared to higher radiation exposure, the potential risks associated with lower doses are likely reduced. Extensive epidemiological studies are essential to accurately measure these risks. For instance, if the excess risk is directly proportional to the radiation dose, a sample size of 50,000 would be needed for a 100 mSv exposure and about 5 million for a 10 mSv dose. Essentially, to maintain statistical accuracy and power, the required sample size increases inversely proportional to the square of the dose. This trend reflects a decrease in the signal (radiation risk) to noise (natural background risk) ratio as the dose decreases.

Table 2 provides examples of radiation exposure in various situations, helping to assess and compare risks from radioactive contamination in foods. This data can be used to communicate radiation risks to the public, who often overestimate or underestimate these risks. The complexity of the many quantities used in radiation protection and the unclear definitions and measurements by some radiation monitors (often in Gy or Sv), further complicates this communication. It looks like the current system of radiation protection quantities is too complex and has to be simplified.

3. Overview of radioactivity contamination in some plants and animals

Naturally occurring radioactive elements in the environment are the main source of radiation exposure for humans and other living beings. Human activities, such as using radiation in industry and medicine, coal mining, making phosphorus fertilisers, and managing radioactive waste, affect how radiation spreads in the environment and how much people are exposed to it. Once released, radioactive materials can enter the food chain, taken up by plants or eaten by animals, which become part of human diets. Certain plants like mosses, lichens, and mushrooms can accumulate high levels of radioactive substances and are useful for identifying areas at risk of radiation. They can also indicate air, water, and soil quality. More research is needed to understand how radionuclides move through different parts of the environment and how they end up in food and herbal products that humans consume.

Radiation can be harmful to living tissue when absorbed, so understanding how radionuclides move through the environment and enter the body is important for minimising exposure. Radionuclides can enter the body through ingestion, inhalation, or skin absorption. Food and drinking water contains natural radionuclides from soil and water sources, but these levels are usually low and considered safe for consumption. However, the amount of natural radionuclides in food can vary depending on factors like agricultural practices and environmental conditions. Monitoring radiation levels in food and informing consumers about any potential risks is important. Generally, the radiation dose from natural radionuclides in food is low, contributing about 10% of the total annual radiation dose from all natural sources received by an individual. However, the situation may be completely different when the environment is radioactively contaminated as a result of the use of WMDs [11,12].

In addition to radioactive materials released in the case of the explosion of a “dirty bomb” as one type of “radiological dispersal device (RDD), the use of WMDs such as nuclear bombs can lead to the creation of huge radioactive cloud which can spread and severely contaminated an area of hundreds of square kilometres [13,14].

3.1 Radioactivity in Plants

Plants extract water, nutrients, and minerals from the soil via their roots, and they can also absorb minerals and radionuclides from their environment, which is essential for assessing potential risks to human health. This accumulation of radionuclides in plants acts as a monitoring system in the environment, occurring through two main methods: absorption by plant components such as leaves and shoots or uptake through the roots from the soil. There are three primary pathways through which radioactive materials from the environment reach the edible parts of plants.

Firstly, radioactive materials can directly adhere to the surfaces of edible plant parts from the air, particularly immediately following an accident or release.

Secondly, through a process called translocation, where nutrients or metabolites absorbed by leaves or bark are transported to other parts of the plant, radioactive materials can be transferred to new leaves and fruits.

Thirdly, radioactive materials in the soil can be absorbed by plant roots, especially after the release of radioactive materials into the air ceases. This route is significant for farmland, as radioactive materials absorbed into the soil can be taken up by crops through their roots.

A visual representation of these pathways is in Fig. 3, based on information provided [9].

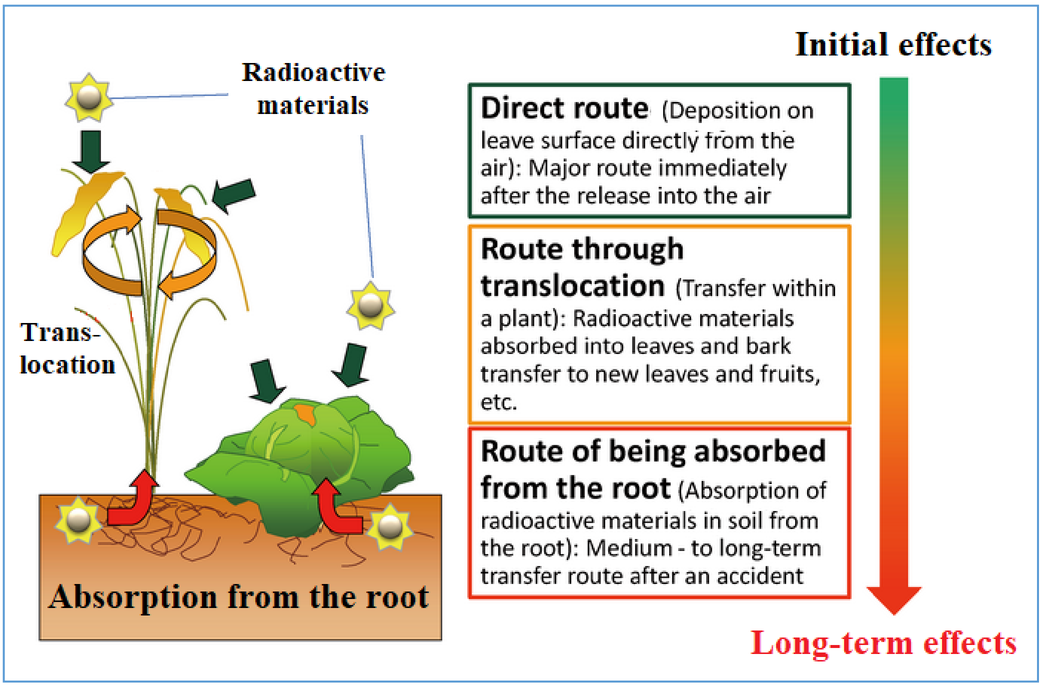

Fig. 3. Main pathways of transferring radioactive materials to plants

One commonly overlooked source of natural radiation stems from bananas, which possess higher levels of 40K due to their naturally occurring potassium content. Additionally, many fertilisers used in tobacco cultivation contain varying levels of natural radioactivity. Tobacco plants are known to accumulate natural radionuclides, particularly 238U. Phosphate fertilisers, found to have elevated radioactivity, can contribute to increased radioactivity in soil and tobacco leaves. This poses significant radiological risks for tobacco consumers, whether through snuffing or smoking, resulting in effective doses surpassing those received annually by the general public from inhaling natural radionuclides. The study suggests that the use of phosphate fertilisers amplifies natural radioactivity in soil, affecting its uptake by tobacco plants. The activity concentrations of various radionuclides in fresh produce can correlate with the annual effective dose. However, these values may vary depending on factors such as location and region. The content of some important radionuclides in specific samples is given in Fig. 3.

Table 3.

Examples of the activity concentration in Bq/kg of Ra-226, Pb-210, Th-232 and K-30 in some vegetables and fruits, including annual effective dose (based on [10]):

Samples	Ra-226	Pb-210	Th-232	K-40	Consumption kg/y	Effective dose µSv/y
Vegetables						
Tomato	ND	0.03	0.02	93.0	4.2	0.082
Potatos	ND	0.07	0.06	131.7	23.9	17.53
Carrot	0.29	ND*	0.05	126.2	3.7	3.0
Lettuce	0.18	ND	ND	59.8	0.6	0.25
Cabbage	0.21	ND	0.24	76.8	0.96	0.48
Pepper	0.01	0.07	0.07	52.3	0.1	0.03
Onion	0.25	0.44	ND	79.7	24.2	15.1
Fruits						
Apple	0.09	0.13	0.01	26.7	6.9	1.42
Orange	0.35	0.22	0.04	64.6	8.1	41.3
Banana	0.30	0.39	ND	197/6	10.6	14.0
Strawberry	0.05	0.08	0.02	52.6	9.58	3.25
Figs	0.05	0.01	0.10	37.3	0.68	0.161

ND* - is not detected

3.2 Radioactivity in animals

Similar to plants, we must consider scenarios where animals could be exposed to radiation from two main sources: the natural background radiation in their environment and radioactive contamination caused by human activities, such as accidents, terrorism, or sabotage involving radionuclides. When humans consume meat from contaminated animals, they face additional exposure to ingested radionuclides. Animal products play a crucial role in transferring radionuclides through the food chain to humans, with grazing animals being a major pathway for contamination acquired from plants. Various factors, including the metabolic characteristics of specific nuclides and agricultural practices, influence the extent of radionuclide exposure in farm animals, affecting their health and leading to higher contamination levels compared to the human populations consuming them.

As in the case of plants, we have to consider circumstances where we expect the contamination of animals from two major sources of radioactivity: background of natural radioactivity in the environment and radioactive contamination as a result of the use of radionuclides in many areas of human work and the consequences of accidents or other intentional interference, for example, terrorist attacks or sabotage. People consuming meat from contaminated animals receive some additional exposure from radionuclides if ingested. Animal products play a crucial role in the food chain as a pathway for radionuclides to reach the human population. Grazing animals effectively accumulates contamination from plants, serving as a significant link. Various factors, including the metabolic properties of specific nuclides and farming practices, influence the extent of farm ***animal exposure to radionuclides***. This exposure impacts the well-being of animals, resulting in higher body burdens compared to the human populations relying on them.

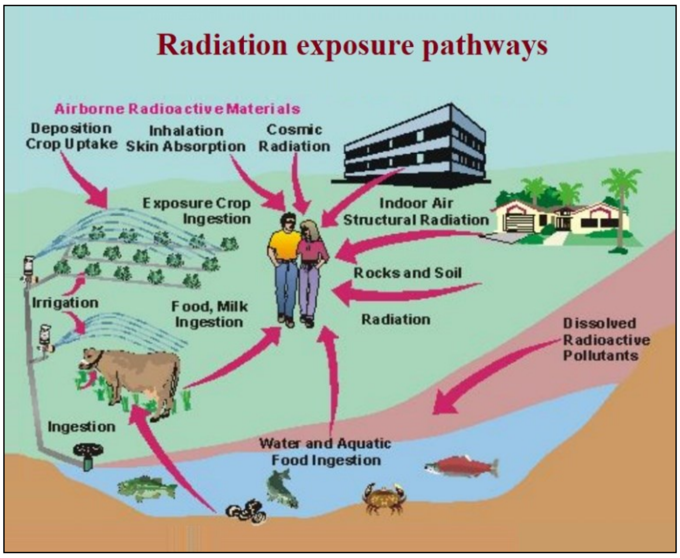

Fig. 4. Pathways of natural radioactivity into food (based on [15]).

All types of food contain natural radionuclides that are transferred from the soil to crops and from water to fish in bodies of water like rivers, lakes, and seas. The levels of natural radionuclides in food and drinking water are typically very low and do not pose a significant risk to human health. The illustration of some important factors affecting radiation protection pathways, which include how radioactivity can be transferred from animals to people, is shown in Fig. 4.

In terms of occurrence, animals can be affected by radioactivity through their flesh, skeletal structures, dairy products, and eggs. When fresh radioactive substances enter a cow's system, certain elements like iodine, molybdenum, strontium, and barium can be found in their milk. Iodine is especially critical, and if grazing fields have been exposed to radioactive fallout, cows should be transitioned to stored feed. Studies indicate that chicken eggs can accumulate significant levels of radioactive elements, with iodine-131 uptake accounting for up to 8% of daily intake. The yolk might contain 20-50 times more radioactivity than the egg whites. Importantly, promptly washing eggs laid during early fallout can eliminate a considerable portion of radioactivity from the shell.

Various radioactive elements accumulate in different tissues. Muscle tissue is particularly significant in the food chain of many nations, with more extensive data available compared to other accumulating tissues.

Following the Chernobyl nuclear disaster, there were notably elevated levels of 137Cs and 134Cs activity in the muscle tissue of ruminant animals within a few weeks, prompting intensive monitoring of meat from cattle, goats, sheep, reindeer, game, and fish. Numerous countries have reported data on the transfer of radiocaesium to different animals post-Chernobyl. There's notably more data available for beef than any other livestock. The transfer of radiocaesium to meat exceeds that to milk. Animals raised for meat production in contaminated areas cannot be sampled as quickly as dairy animals. The development of equipment suitable for real-time monitoring of animals in these regions was crucial in managing the situation and devising appropriate remediation strategies.

4. Conclusion

Living tissues often encounter varying levels of radiation from natural and human-made sources. The potential dangers of radioactive materials depend on factors like the type of radiation, absorption rate, type of organs exposed, and the overall exposure received in terms of effective dose. Given their heightened sensitivity, research on the biological effects of radiation and preventative measures has primarily focused on humans. It is essential to note that many animal-based foods can transmit radionuclides to humans, potentially increasing exposure levels. While typically low, this exposure can become significant during emergencies with large releases of radioactivity. Hence, it is vital to assess radiation effects on animals, which are crucial in the human food chain, and implement preventive measures. Understanding radioactivity and how key radionuclides behave in livestock and plants is valuable for management and consumer decision-making.

Under normal circumstances, natural radionuclide levels in food, water and air are generally low and safe for human consumption. Food consumption contributes about 10% to an individual's average radiation exposure from all natural sources. However, natural radionuclide concentrations vary widely within food categories like vegetables, fruits, meat, and fish. Thus, monitoring and informing consumers about radioactivity levels in food is essential. Most countries have food monitoring programmes aimed at monitoring natural radionuclides; these programmes primarily focus on artificial radionuclides from sources like nuclear power plants, radiation accidents, or nuclear weapons tests.

The global average effective dose from ingested radionuclides is relatively low (about 0.3 mSv/y) compared to the acclaimed public reference dose of 1 mSv/y. Monitoring suggests a low health risk from radioactivity in food intake. However, ongoing assessment remains crucial, especially in accidents leading to heavy pollution in affected areas. Such contamination can lead to increased radioactive concentrations in food from contaminated plants and animals consumed by people.

The analysis of the recent monitoring and measurement results of radioactive concentration in the most commonly used food has shown some increase in its radioactivity. The situation may be quite different in the areas close to the places where radioactive materials were released in significant amounts. In some locations, radioactivity in plants, water, fruit, and animal meat may be so high that national law and other regulations prohibit or substantially limit their use. On some occasions, the approach of relevant authorities was too strict and not fully justified and supported by scientific analysis.

The presented assessment of the radioactivity in various foodstuffs contributing to the exposure of consumers is important for better selection of all relevant factors which have to be continuously monitored and assessed in order to reduce the impact of contaminated nutriments to the overall exposure to the population. This process has to continue in the future where we may expect some new sources of radioactive contamination of the environment which may also affect content of radioactivity in various foodstuffs. Therefore, it is necessary to pay systematic attention to the level of radioactive concentration in all products and materials used for the preparation of food.

Acknowledgments

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