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Radionuclide exposure in animals and the public health implications

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Abstract: Living tissues are usually exposed to varying degrees of radiation from natural and manmade radioactive substances. Depending on the type of radiation emitted and rate and dose of absorption, all radioactive substances are potentially hazardous. Previous researches on the biological effects of radiation as well as preventive measures have focused on human subjects, being the most radiosensitive species. However, exposure of animals to ionizing irradiation may negatively influence their production performance, resulting in some level of economic loss. In addition, many food animals may represent a significant pathway for transfer of radionuclides to humans, thereby adding to the exposure burden. The current review aims at evaluating the effects of ionizing radiation on animals as important components of human food chain, and some preventive measures. A proper understanding of radioactivity and the behavior of important radionuclides in livestock animals will serve as an informational tool in livestock management as well as consumers' dietary choices.

Key words: Animals, food chain, public health, ionizing radiation, radionuclides

1. Introduction

Since the formation of the earth, naturally occurring radioactivity has been present as a result of varying concentrations of heavy metals contained in the soil (1). The earth also receives radiation from the sun and other sources located in outer space and these are collectively called cosmic radiation (2). However, cosmic radiations are relatively constant for any particular location although solar flares may cause occasional variations (3). Again, the radionuclide concentration of the soil differs from area to area thus the radiation dose that a person or an animal receives depends on geographical location (4). Every inhabitant of the world has therefore been exposed to small doses of radiation at all times from these natural sources referred to as natural background radiation. In addition to natural radioactivity, manmade sources of radiation exist and include radioactive materials injected into the body either for treatment or medical diagnosis, fallout from nuclear weapons, radiation from consumer products such as paints, and radiation from nuclear power plants (5). All the aforementioned sources can result in either external or internal exposure of living tissue to radiation. Additional sources of internal tissue radiation include tissue-inherent natural radionuclides and radioactive substances present in air, food, or water (6). All radioactive materials are potentially hazardous if absorbed into the body in sufficient quantity. Figure 1 below shows the various sources of routine radiation exposure. Much attention and research focus has been on evaluating the potential consequences of radiation on humans, which are among the most radiosensitive mammalian species. However, many plants and animals that are elements of food chains represent pathways for the transfer of radionuclides to humans and may contribute to human radiation exposure when contaminated (7). This review therefore focuses on radiation exposure of animals as an important component of the human food chain.

2. Sources of radiation in animals

Besides the natural background radiation, animals may be exposed to radiation through accidents at nuclear power plants, medical diagnosis/treatment, and human activities (3). Following the expansion of the nuclear industry and increase in the use of radioactive materials over the last few decades, there has been increase in the concentrations of various pollutants including radioactive substances such as uranium, cadmium, cesium, and cobalt in the environment (8). These radioactive materials eventually circulate through the biosphere and end up in the air, drinking water, vegetables, and grasses (9). Animals are therefore exposed to radioactive substances through environmental contamination and grazing on

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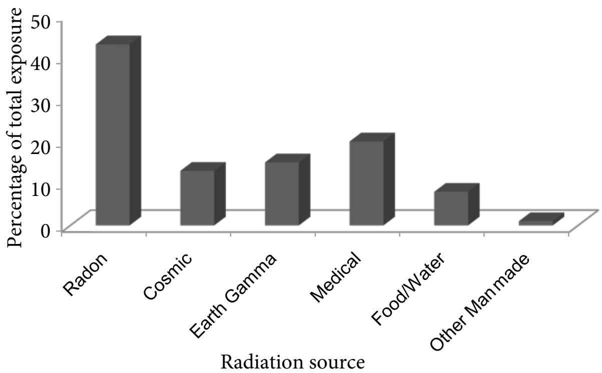

Figure 1. Sources and distribution of average radiation exposure for the world population (59).

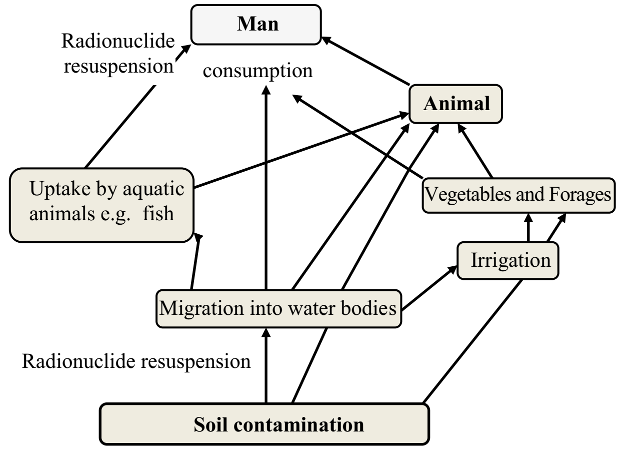

Figure 2. Circulation of radionuclides in the environment.

contaminated forages (10). Human activities, among others, also include the introduction of heavy metals into an animal's environment in the form of rock phosphate fertilizers applied on croplands, application of pesticides to animals or their housing facilities, and use of herbicides (11,12). Rock phosphates, for example, contain high levels of radium, thorium, and uranium that in turn can lead to higher soil, outdoor air, and groundwater content of radon (decay product of uranium).

A study undertaken in Algeria in 2011 to measure radioactivity levels in soil relative to the use of phosphate fertilizers showed that there was a significant increase in radionuclides in the fertilized soils compared with the virgin soils (13). Another study, by Saueia and Mazzilli (14) in Brazil assessing the distribution of natural radionuclides and the use of phosphate fertilizers in agriculture, revealed an increase of up to 0.87 and 7.6 Bq/kg grain and green crops, respectively. Radionuclides accumulated in arable soil can be incorporated metabolically into plants and eventually get transferred into the bodies of animals when contaminated forages are consumed (15). Other indirect sources of radiation result from the use of well (ground) water that contains radon or other radionuclides on animal farms and contamination of ingredients (e.g., bone meal) used for making animal feed (10). Groundwater releases an estimated 500 million curies of radon per annum globally, thus constituting a secondary source of the radionuclide (16). Furthermore, radiation experiments usually target animals as models for radiation rather than protecting them. Figure 2 shows the routes of exposure of animals and circulation of radionuclides in the environment following soil contamination.

3. Cellular effects of radionuclide exposure in animals

Radioactive decay of radionuclides incorporated into animal tissues through inhalation/ingestion results in internal exposure to radiation (3). Whichever way ionizing radiation is delivered, it has the potential to create harmful effects by causing neoplasia and genetic mutations at somatic and germ cell levels, respectively. This is brought about by cellular DNA alteration or damage and interference with metabolic pathways (17). The different types of DNA damage that may be induced by radiation include single-stranded breaks (SSB), double-stranded breaks (DSB), sugar/base modifications, and DNA-protein cross-links (18). Three mechanisms usually involved in DNA damage are genomic instability, indirect DNA ionization by reactive oxygen species, and direct DNA ionization with subsequent chemical alteration of the bases to molecules that are no longer recognized as coding signals (17). The damaged DNA is usually not recognized by the sensory proteins, leading to recruitment of DNA repair enzymes. There is also a simultaneous generation of signals to delay the progression of cell cycle until the damaged DNA is repaired (19). Depending on the type, dose rate, and dose of the radionuclide, attempts to repair the damaged DNA may fail, leading to either cell death or transformation to a malignant state (20) (Figure 3). The biological damage of radionuclide exposure in an animal depends on the distribution and retention of the radionuclide in the body, dose rate and dose of irradiation, the tissue irradiated, and size, age, and physiological status of the animal (21).

4. Effect of radionuclide exposure on animal tissue

Damage caused to various organs and tissues of animals by radionuclides has been evidenced by several animal studies. Abo-Elezz (22) exposed Balady rabbits to direct solar radiation and observed 37.5% mortality after 6 h of continuous exposure. He also noted a decrease in average litter size and weight with increasing exposure to solar radiation. This is an indication that exposure of animals to high degrees of direct solar radiation can reduce

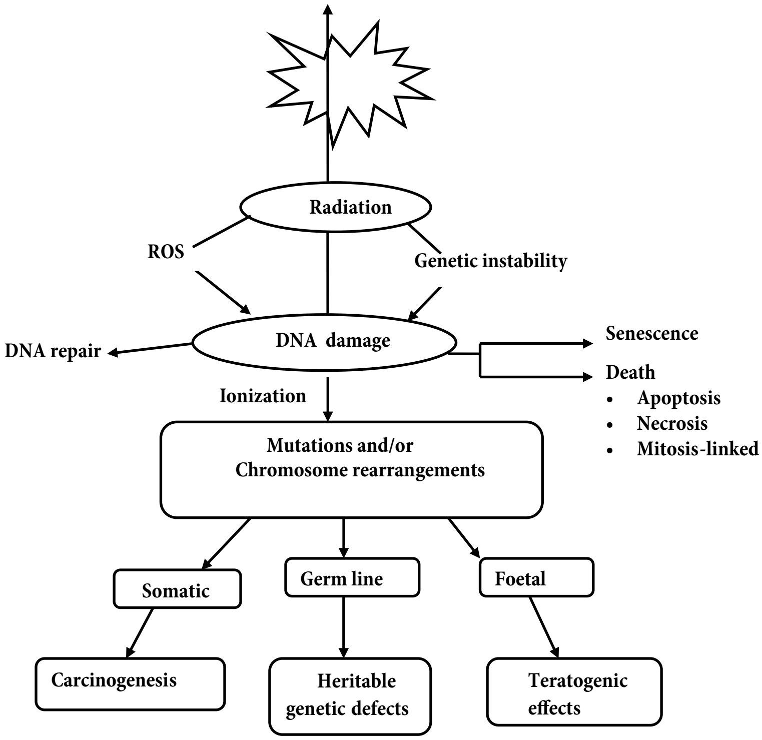

Figure 3. Paradigm for the biological effects of ionizing radiation exposure at cellular level. Adapted from UNSCEAR (60).

production efficiency. External exposure of animals, such as occurs mostly in cases of gamma radiation, may also cause symptoms of diarrhea due to loss of mucosal cells and cerebral syndrome as a result of damage to nerve tissues (8,23). Fallout irradiation may cause skin injury that may appear as thermal burns in exposed animals. Ionizing radiation may also cause clinico-pathologic effects that may include thrombocytopenia (resulting in blood clotting failure) and leucopenia (3). Radiothorium for instance has been shown to induce aggregation and lysis of erythrocytes, with alteration in shape from normal discoid to equinocytic (24). This will obviously result in marked reductions in the number of functional erythrocytes. Intraperitoneal or intramuscular injection of rats with thorium nitrate for 30 days showed the liver, spleen, and skeleton as major sites of thorium accumulation. The radionuclide was also found to localize in the brain, suggesting its ability to cross the blood–brain barrier. Inference from further experimental results indicates the effects of thorium on cholinergic functions associated with neurobehavioral changes (24). Exposure to radon on the other hand induced marked erythropenia and leucopenia in animals due to bone marrow suppression (25). Radon and its decay particles, when inhaled, can also attach to the respiratory epithelium, where its radioactive effects on the lung parenchyma can lead to cancer. Numerous neoplasias were observed in the nasal cavities of animals that inhaled alpha emitters (e.g., radon and uranium) and beta-gamma emitters (e.g., ^{144}Ce and ^{90}Sr), perhaps resulting from continuous irradiation of the nasal epithelium (26). In cases of internal exposure by ingestion of contaminated forage, radioactivity follows the gastrointestinal tract with local irradiation of the gut wall, especially by beta-particles (3).

When radionuclides enter the bloodstream, they may either be distributed throughout the entire body or localized in some selective tissues based on their chemical properties and metabolism. Pellmar et al. (27) implanted adult Sprague Dawley rats with up to 20 depleted uranium alloy pellets in the gastrocnemius muscle for 18 months. They noted significantly elevated uranium concentrations in the kidneys, liver, spleen, brain, serum, tibia, skull, and urine at most time points. Several studies have also shown natural uranium to be a reproductive toxicant in rodents, possibly teratogenic to the developing fetus (28). Furthermore, the chemical and radiological activities of enriched and depleted uranium produced brain oxidative stress and induced negative effects on various behavioral parameters in rats (8). Houpert et al. (29) exposed rats to 4% enriched uranium over a period of 6 weeks and they discovered uranium accumulation in the hippocampus, hypothalamus, and adrenals. They concluded that this exposure is associated with the sleep–wake cycle, affecting the spatial working memory and anxiety in the rodents.

The work by Lemercier et al. (30) demonstrated the ability of uranium to cross the blood–brain barrier in animals.

Similarly, animals that were exposed to very high doses of cesium showed changes in behavior, such as increased or decreased activity. Indeed, studies have shown that administration of cesium chloride to animals triggered stimulant and depressant central nervous system responses (31,32). Changes in preferred nesting sites, and reduced hatchability and fecundity were also observed in birds that lived in the Chernobyl zone and were exposed to chronic ^{137}Cs irradiation (8). Alterations in natural behavioral responses can have severe implications for survival of individuals and of population of some animal species. Yamashiro et al. (33) in their investigation of the effect of a nuclear plant accident on bull testes did not observe any adverse radiation-induced effect following chronic exposure to high doses of $^{134,\,137}$Cs over a period of 10 months. Overall, the highest deposition of ^{137}Cs was found in muscle tissues. Transport of radiocesium between the gastrointestinal tract and body pool was studied in reindeer calves fed lichens. The net exchange of radiocesium between the gastrointestinal tract and body pool was more than four times higher than the amount ingested. It was concluded that radiocesium is rapidly recycled between the gastrointestinal tract and other body pools (34,35). Other animal studies indicated increased risk of cancer following either external or internal exposure to relatively high doses of ^{137}Cs radiation. For instance, intravenous injection of ^{137}Cs in the form of cesium chloride to dogs led to increased risk of all cancers combined in both males and females (31).

Fukuda et al. (36) evaluated gamma-ray emitting artificial radionuclides in multiple organs of cattle located within the evacuation zone of the Fukushima nuclear power plant accident. They detected organ-specific deposition of radionuclides with short half-lives (e.g., ^{110m}Ag and ^{129m}Te) in the liver and kidney, respectively. They also observed higher concentrations of radiocesium in fetal organs than in the corresponding maternal organs. Based on their report, the activity concentration of internally deposited radionuclides is greatly influenced by feeding conditions and geographic setup of the cattle farm. Stricker et al. (37) evaluated the impact of forages grown on phosphatic clays on concentrations of radionuclides in animals and their products. It was noted that concentrations of ^{226}Ra, ^{210}Po, and ^{210}Pb in bones were three orders of magnitude higher than concentrations found in the muscle, suggesting the affinity of these high-risk radionuclides for the skeletal system. Inferences from some reports point to the fact that ^{210}Pb may have some effects on the biokinetics and biodistribution of ^{210}Po in animal tissues. For instance, ^{210}Po produced by the decay of skeletal ^{210}Pb remains in the bones, whereas ^{210}Po produced from soft tissue decay of ^{210}Pb follows typical ^{210}Po biokinetics (38). ^{210}Pb is a radionuclide that is known to have a high skeletal bioaccumulation and it will therefore not be surprising to find accumulation of ^{210}Po in the bones of exposed animals. This is a double whammy because grazing animals in particular are directly affected by consumption of forage/feed contaminated by lead (either airborne or absorbed by plant roots), resulting in impaired erythrogenesis and central nervous system dysfunction (39). Moreover, acute lethal doses of ^{210}Po can cause fatal damage to the bone marrow and severe damage to the kidneys, spleen, and gastrointestinal tract (40).

Further studies in animals revealed that ^{210}Po accumulates in the reproductive and hemopoietic systems and probably transfers from the mother to the embryo/fetus, causing critical cells to suffer damage as a result of its alpha particles (41). This fetal exposure could cause failure of implantation, fetal miscarriage, or major malfunctions (42). Although the studies by Haines et al. (43) suggested the placenta as a barrier against the movement of ^{210}Po from mother to fetus in rats, Paquet et al. (44) found that approximately 0.7%–1% of ^{210}Po injected into pregnant baboons at 5 months was present in the fetus 7 days later. Analysis of data from fall-out irradiation suggests that radiation exposure in local territories about 1480 kBq/m^2 superimposed by other environmental factors does have an impact on animal health (45). The summary of these radionuclide effects is that when animals are constantly exposed to radiation through air, feed, water, and other manmade sources, their performance is impaired and the survivability of their species become stressed and threatened. The estimated survival rate of different livestock species from short-term external gamma radiation doses is shown in Figure 4.

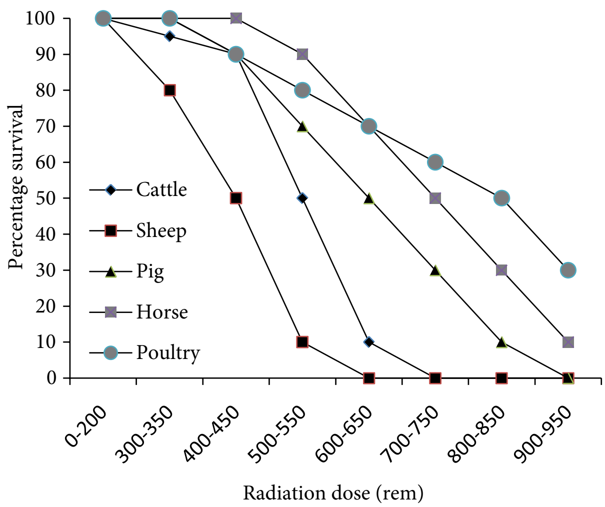

Figure 4. Estimated survival of livestock from short-term external gamma radiation doses. Adapted from Berger et al. (61).

5. Public health effects of animal exposure to ionizing irradiation

The bioaccumulation of some important radionuclides in specific tissues/organs of animals of food chain significance, and their level of absorption from the gastrointestinal tract can constitute a public health threat. In some developed countries, farm livestock provide about 40% of food energy, 67% of protein, and 75% calcium in the diet of the people. Exposure of livestock animals to ionizing irradiation can be a significant pathway to human exposure through consumption of contaminated animal products (46). This is due to the fact that grazing livestock are effective collectors of radionuclide contaminants from vegetation. Several important pathways for the transfer of radionuclides to the human diet involve animal food chains such as milk, eggs, meat, and fish (7). For instance, some important radionuclides such as ^{137}Cs, ^{131}I, and ^{90}Sr are readily transferred from animal fodder to the milk. In addition, ^{90}Sr is transferred to the bones together with the congeneric calcium, whereas ^{137}Cs is preferentially transferred to soft tissues, especially muscle, with its congener potassium (7,35). Iodine, on the other hand, is completely absorbed in the animal's gastrointestinal tract and concentrates in the thyroid, from where it is effectively transferred to milk and eggs (47). Caribou, fish, and seafood are important pathways for the transfer of ^{210}Po in the human diet. The biological half-life of ^{210}Po in humans as determined by its retention from the consumption of shellfish was 40 days, and more than 100 days from the consumption of caribou meat (48,49). Although ^{131}I has a relatively short half-life of a few weeks, the half-life of ^{137}Cs is up to 30 years and it can remain in the environment for a long time (9). The biological half-life of a radionuclide is defined as the time taken for its activity concentration in tissues, milk, or eggs to decline by half of its initial value after cessation of feeding contaminated diet (50).

Consumption of radionuclide-contaminated food will increase the amount of radioactivity inside a person and therefore increase internal exposure to radiation. For example, a year-old child that consumes 0.5 L of milk contaminated with 100 Bq/L of ^{131}I will have 0.009 mSv additional exposure (9). This may possibly increase the health risks associated with radiation exposure. The harmful effects of radionuclides arise mainly from tissue radiation as a result of radioactive decay and this in turn increases cancer risk (51). The degree of harm to human health depends on the type of radionuclides involved, amount ingested, and duration of exposure. For instance, ^{210}Po, an alpha-particle emitter, is one of the most toxic substances known because of its intense radioactivity and is therefore classified as a Group I human carcinogen (42,52). Concentrations as low as 1 µg have an activity of 1.66×10^8 Bq, and acute lethal doses may cause severe damage to the bone marrow, kidneys, spleen, digestive tract, and reproductive system (40,41). The preference therefore of important radionuclides for certain organs/tissues for bioaccumulation may serve as an informational tool in making dietary choices, in which case, consumption of organs that tend to accumulate radionuclides may be avoided. The transfer of radionuclides to animal products is usually quantified using the transfer coefficient (2). The transfer coefficients, half-life, and gastrointestinal absorption of some important radionuclides in animal products are shown in the Table.

6. Measures for reducing radionuclide contamination in animals and their products

Countermeasures aimed at reducing radionuclide contamination of food animals and their products usually involve treatment of land used for growing fodder crops or grazing, changes in animal management regime, administration of binding agents or analogues to animals, and delayed animal slaughter (53). Some adjustments

Table. Characteristics and transfer coefficients of important radionuclides of food chain significance.

Radio nuclide	Transfer coefficients (F)					GI Abs. (%)	t½
	Milk	Beef	Pork	Chicken	Eggs		
^{131}I	5.4E-3	6.7E-3	4.1E-2	8.7E-3	2.4	100	8.021 d
^{137}Cs	4.6E-3	2.2E-2	2.0E-1	2.7	4.0E-1	100	30 y
^{90}Sr	1.3E-3	1.3E-3	2.5E-3	2.0E-2	4.9E-1	30	28.7 y
^{210}Po	2.1E-4	9.9E-4	N/A	2.4	3.1	50	138.38 d
^{210}Pb	1.9E-4	7.0E-4	N/A	N/A	N/A	10	22.3 y

d = days; y = years; N/A = not available; Source: Howard et al. (49)

that can be made in animal management systems include permanent housing and provision of uncontaminated feedstuff (particularly in exposure situations resulting from a nuclear accident), pasture management (e.g., growing of forage species with low potential for radionuclide uptake), and selective grazing (54). Administration of binding or chelating agents to animals aims at reducing gut uptake of radionuclides. Agents such as ammonium-ironhexacyanoferrate and zeolites added to the diet of animals have been effective in reducing radiocesium from the gut (55). Hence, in Norway for example, ammonium-ironhexacyanoferrate has been incorporated into saltlicks and rumen boli for administration to free-ranging animals (56). Similarly, supplementation of animal's diets with a strontium analogue, calcium, reduces the activity concentration of radiostrontium in milk (55). Although administration of stable iodine to animals has been proposed as a countermeasure for radioiodine concentration in milk, there is the concern that the level of concentration of stable iodine in milk may then be raised above recommended levels (57). Delayed slaughtering of animals is another effective measure for truncating the movement of radionuclides up the food chain, particularly when combined with provision of uncontaminated feed (53).

7. Measures for reducing radionuclide transfer from animal products to consumers

Radionuclide monitoring of animal-derived products, a ban on contaminated food, consumer dietary advice (avoiding foods that accumulate radionuclides), and food processing are all measures employed to reduce human radiation exposure through consumption of animal products (55). Food processing is effective in reducing radionuclide concentrations in foods although the retention factor depends on the processing procedure (7). Drying foods, for instance, tends to increase the radionuclide concentration compared with boiling (58). In dairy products, radionuclides are retained less in cream than in other milk products, whereas the concentration of ^{90}Sr in cheese is 5–10 times higher than that in milk as a result of the precipitation process in cheese production. Butter, however, contains none of the radionuclides found in milk (7).

8. Conclusion

The effects of ionizing radiation on exposed animals as evidenced by damage caused to various organs and tissues of such animals indicate that ionizing radiation can greatly impair the performance efficiency of animals, depending on the source, dose, and duration of exposure. Most important is the bioaccumulation of some important radionuclides in preferred animal tissues/organs, leading to contamination of products for human consumption. These two scenarios clearly demonstrate the need to protect livestock animals as much as possible from exposure to ionizing radiation through proper housing and management. Systems should also be put in place to monitor radionuclides in major food commodities in order to reduce human exposure to radiation through consumption of animal products.

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