Nuclear Radiation

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1 Introduction

Radioactive substances may originate from both natural and man-made sources. Radioactive material in the environment is of potential concern since it may enter the food chain for animals and humans and persist in the environment for a long time. There is thus a risk that both humans and other organisms may be exposed to radiation.

For most people, cosmic radiation and naturally occurring radionuclides in the environment are the primary sources of radiation exposure. For example, the potassium isotope ^{40}K in our bodies (55 Bq/kg fresh weight in the body of an average adult human) gives an annual radiation dose of about 0.2 mSv (effective dose, millisievert) (AMAP 1998), and cosmic radiation leads to average doses that are about twice as high as that due to ^{40}K (although it is enhanced at high altitudes). Inhalation of decay products of radon (^{222}Rn) and thoron (^{220}Rn), often termed "radon daughters," may cause enhanced doses at locations where the geological profile includes these nuclides. Radon daughters emit alpha radiation, so inhalation of these natural radionuclides may potentially cause lung cancer. Exposure to radiation from inhalation of such decay products is generally low in areas with permafrost (as in the Arctic), and where houses are normally built without a basement.

This chapter focuses on radionuclides that are of anthropogenic (or man-made) origin and also briefly considers naturally present radionuclides which are made available for plant and animal uptake as an effect of human activities. The emphasis of the text is on those radionuclides that have the potential to constitute a health risk for animal populations (with a focus on mammals) or enter the human food chain and create a potential health risk for Arctic and Subarctic people. Most of the focus is on

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terrestrial and freshwater systems since radionuclides accumulate in organisms more easily in these systems compared with those in marine environment. Of special concern are those radionuclides that are either absorbed by inhalation or that contaminate vegetation that is eaten by animals including humans.

2 Radionuclides of Concern

Iodine (^{131}I) will be of particular initial concern after there has been radioactive fallout from sources such as nuclear accidents and atmospheric nuclear weapons testing. Iodine-131 (and other less important shorter-lived radioiodine isotopes) can be inhaled with air, thereby entering the lungs, and may be absorbed into the circulatory blood system and then absorbed by the thyroid where it is accumulated as an essential component of several hormones. At high doses, this may cause thyroid cancer as occurred after the Chernobyl accident (IAEA 2006). For grazing animals, ingested ^{131}I is completely absorbed in the gut and readily transferred to milk. There is a potential transfer of ^{131}I to suckling offspring and to humans by consumption of contaminated milk and milk products. Fortunately, ^{131}I is short lived with a physical half-life of 8 days so it disappears relatively fast from the environment. Therefore, after a single contamination event, the potential exposure from this radioisotope largely exists for the first month, and to a much lesser extent the second month after releases and deposition have ceased.

Potential long-term environmental transfer to humans and other animals may occur for radioactive cesium (largely ^{137}Cs, with a physical half-life of 30 years, and ^{134}Cs, with a 2-year half-life), and strontium (^{90}Sr and ^{89}Sr, with half-lives of 28 years and 50 days, respectively). Cesium belongs to the alkali metals (like sodium and potassium), and when present in the diet, it is readily absorbed from the gut and then transferred to body tissues. The highest activity concentrations are found in soft tissue such as muscle, liver, and kidneys (Åhman 1994; Skuterud et al. 2004). Strontium belongs to the same group as calcium (alkaline earth metals) and is mainly accumulated in bone and milk (Stara et al. 1971). Both of these environmentally mobile radionuclides can be transferred from plants to grazing animals and through the food chain to humans and carnivores. While strontium has a long turnover rate in animals and may remain in the body for long, cesium has a relatively short retention time (a short biological half-life). The reduction of radiocesium is thus rather rapid when there is no further intake of contaminated food. The biological half-life may however differ depending on the organism liveweight and organ considered, and there are generally longer biological half-lives in larger organisms (Beresford et al. 2004; Stara et al. 1971).

Other radionuclides that are of potential concern are the naturally occurring isotopes of polonium (^{210}Po) and lead (^{210}Pb) that mainly accumulate in internal organs like kidney and liver. These radionuclides have a high radiotoxicity and are a potential health risk even at low activity concentrations. In addition, radionuclides such as technetium (^{99}Tc), iodine (^{129}I), americium (^{241}Am), and several plutonium

(Pu) isotopes are emitted into waters around reprocessing plants, thereby entering mainly marine environments.

3 Sources of Radioactivity

Man-made sources of radioactivity are related to either military activities or the production of nuclear power (including local use of radioisotope thermoelectric generators for production of electricity in remote places or energy for use in machinery such as that used in submarines) (AMAP 2010). Most of the man-made radioactive material presently found in Arctic and Subarctic regions derives from atmospheric nuclear weapon testing after the Second World War, the Chernobyl accident in 1986, and the releases from reprocessing plants in the Northern Hemisphere. In addition, there are local sources linked to industrial or military facilities in the Arctic, which may potentially release radionuclides to the environment (AMAP 2010).

Aboveground nuclear bomb testing mainly took place from 1945 to 1960, with additional fewer tests up to about 1980. Many of these tests were made at the USSR test site on Novaya Zemlya in the Arctic Sea. The nuclear weapon testing (NWT) released radioactive isotopes of cesium (^{137}Cs) and strontium (^{90}Sr) high into the atmosphere and stratosphere. These emissions were gradually deposited over subsequent decades after the releases, mainly in a circumpolar belt between the 30° and 60° N latitudes (Langham 1961; UNSCEAR 2000). Most of the radioactive material was deposited with rain or snow, and the highest depositions are, therefore, located in areas with high precipitation (Pálsson et al. 2013).

The accident in the Soviet nuclear power plant in Chernobyl, Ukraine, in 1986, caused substantial releases of several radionuclides ejected upward to 1–10 km in the atmosphere. Subsequent radioactive fallout from the accident was recorded in most European countries (Wilson et al. 1998). Radioactive cesium (^{137}Cs and ^{134}Cs), strontium (^{90}Sr and ^{89}Sr), and iodine (^{131}I) were transported long distances and deposited mainly with precipitation (rain and snow), creating a highly uneven pattern of ground deposition over large areas (Wright et al. 1999). Cesium isotopes dominated the fallout, and ground deposition of ^{137}Cs reached 200 kBq/m^2 in some locations in Scandinavia, just south of the Arctic Circle. As an effect of the prevailing winds after the accident, ground depositions in Arctic Russia were considerably lower (up to 1 kBq/m^2 on the Kola peninsula and declining further east).

The more recent accident at the Fukushima Daiichi nuclear power plant in Japan, 2011, was caused by an earthquake and subsequent tsunami. Although radioisotopes of iodine, cesium, and plutonium were detectable in large areas of the Northern Hemisphere, the global release of radionuclides from Fukushima was too low to cause concern for human or animal health outside Japan, with less than 1% of the total release from Fukushima estimated to be deposited in the Arctic region (above latitude 67°N) (Thakur et al. 2013). Nevertheless, radiocesium from the accident was

detected, for instance, in Finland (Koivurova et al. 2015) at very low levels (c.1 Bq of ^{137}Cs per m^2).

Releases of radionuclides from reprocessing plants (e.g., Sellafield in the UK and La Hauge in France) are entering marine environments and include nuclides like ^{99}Tc, ^{129}I, ^{241}Am, several plutonium (Pu) isotopes, and also some ^{137}Cs and ^{90}Sr (AMAP 2010). In the Russian Arctic, there is also operational release of various radionuclides from nuclear power plants (e.g., Kola and Bilibino) and other industry.

Enhanced release of naturally occurring radionuclides may be produced by anthropogenic activities such as mining, oil extraction, and the use of geothermal energy. The radionuclides of concern for these sources belong to either the natural uranium (^{238}U) or thorium (^{232}Th) decay series. Radionuclides belonging to these series have been detected in many living organisms in the Arctic (AMAP 2010). The radionuclides of most concern are ^{210}Po and ^{210}Pb because of their relatively high radiotoxicity, thereby constituting a potential health risk even at low activity concentrations.

4 Contamination of Animals of Concern for the Human Food Chain

4.1 Radionuclides in Terrestrial Environments

Radioactive fallout affects both agricultural food products and food derived from natural ecosystems. Research on the fallout from NWT and from the Chernobyl accident demonstrated that natural and seminatural food chains, together with freshwater systems, are associated with relatively high risk of significant transfer of some radionuclides to humans over a longer timescale (Calmon et al. 2009; Howard et al. 1996). The transfer of radioactive cesium (^{137}Cs) and strontium (^{90}Sr) from lichen to reindeer and caribou (subspecies of *Rangifer tarandus*), and hence to humans, was identified during the 1960s, generating research in North America (Hanson 1967; Holleman et al. 1971), Fennoscandia (Hvinden and Lillegraven 1961; Salo and Miettinen 1964; Svensson and Lidén 1965), and USSR (Nevstrueva et al. 1967; Ramzaev et al. 1970). After the Chernobyl accident in 1986, this food chain gained extensive attention, primarily in Fennoscandia, where reindeer herding is a traditional occupation among the indigenous Sámi population and where parts of the reindeer ranges were contaminated by substantial fallout that was many times higher than that from the previous NWT fallout (De Cort et al. 1998).

Lichens have no roots, but absorb nutrients, including contaminants, directly from air and precipitation (Tuominen and Jaakkola 1973). Reindeer and caribou are particularly vulnerable to radioactive contamination which is because lichens often form a large part of their diet. Close agreement between the measured activity of ^{137}C per m^2 in the lichen carpet and the deposition per m^2 showed that most of deposited radiocesium is captured by ground lichens in places where they cover the ground surface (Svensson and Lidén 1965). Lichens are long-lived and grow slowly; therefore, contaminants remain in the lichen carpet for many years. Consequently,

the intake of radionuclides will be exceptionally high for reindeer and caribou, especially in winter when lichens often dominate their diet (Åhman and White 2018). Since meat from reindeer and caribou is a staple food for many indigenous populations in the Arctic and Subarctic, the radiation doses to these people may be much higher than those of people residing in other temperate areas.

Radioactive substances are transferred from fallout to vegetation to reindeer/caribou and other terrestrial species that are consumed by humans. High, long-lasting, contamination with radiocesium has been reported in wild animals such as moose (*Alces alces*), roe deer (*Capreolus capreolus*), Arctic hare (*Lepus arcticus*), and game birds from areas contaminated by the Chernobyl fallout (Howard et al. 1996; Johanson 1994). Much of the vegetation in natural environments, where these herbivores feed, effectively absorb radiocesium, which also seem to persist longer in most natural environments than in agricultural systems (Howard et al. 1996; Pröhl et al. 2006). The specific role of fruit bodies from fungi (mushrooms) was early recognized as responsible for transfer of radiocesium to white-tailed deer (Johnson and Nayfield 1970), and the transfer of radionuclides from soil via consumed fungi to herbivores was further emphasized after the Chernobyl accident (e.g., Avila et al. 1999; Hove et al. 1990).

The NWT fallout was deposited over many years and distributed over the northern hemisphere (relative to the amount of precipitation). In contrast, the fallout from the Chernobyl accident was a 10-day emission into the atmosphere, and the subsequent deposition on terrestrial and aquatic sources was highly heterogeneous even at a local level. Pooled samples from herds of caribou and reindeer at several sites in North America during 1962–1969 showed ^{137}Cs activity concentrations up to 2000–3000 Bq/kg fw (fresh weight) in the meat, with maximum values in caribou of 6000 Bq/kg (Macdonald et al. 2007). There was a trend of increasing ^{137}Cs activity concentration in caribou and reindeer from west to east, correlating with the precipitation density and in accordance with models by Wright et al. (1999). Activity concentrations of ^{137}Cs similar to those reported by Macdonald et al. (2007) were recorded in Fennoscandian reindeer (Rissanen and Rahola 1990; Westerlund et al. 1987), while some herds in Alaska (O'Hara et al. 1999) and Greenland (Aarkrog et al. 2000) were less affected.

In contrast, the Chernobyl fallout resulted in huge variations between regions and sites (several orders of magnitude within a plant or animal species). For example, only moderate elevations (around a doubling) of activity concentrations of ^{137}Cs were recorded in reindeer from the northernmost parts of Norway and Sweden, while reindeer in the southern and central parts of the reindeer herding area were heavily affected (Skuterud and Thørring 2012; Åhman et al. 2001). Activity concentrations of ^{137}Cs in reindeer meat reached around 80,000 Bq/kg fw in the most affected parts in Sweden (Åhman and Åhman 1994), and highest values at about 150,000 Bq/kg fw were recorded for individual reindeer in Norway (Strand et al. 1992). The Finnish reindeer herding area was less affected, with activity concentrations of ^{137}Cs up to around 2000 Bq/kg fw, except for the Halla area in the southeastern corner of the Finnish reindeer herding area, with up to 16,000 Bq/kg fw in reindeer meat (Rissanen and Rahola 1990).

A smaller increase in the activity concentrations of radiocesium was observed in North American caribou after the Chernobyl accident, adding around 100 Bq ^{137}Cs/kg to the remaining contamination from NWT (Macdonald et al. 2007). The "old" ^{137}Cs from NWT, however, still dominated in these animals (on average 80% of total ^{137}Cs).

In 2020, 34 years after the accident, significant levels of radiocesium from Chernobyl still persisted in parts of the reindeer ecosystem in both Norway (Komperød et al. 2017) and Sweden (Åhman and Wiklund 2019). The radiocesium activity concentration in animal tissues reflects that in the diet within a few weeks due to a fairly short biological half-life, and changes in activity concentrations in reindeer are soon to follow that of the forage (Åhman and Åhman 1994). Few reindeer carcasses, however, presently exceed the standard maximum values for sale (3000 Bq/kg in Norway and 1500 Bq/kg in Sweden). In areas where there is possibility that values reindeer will exceed the limit, they are either fed uncontaminated feed to decontaminate the meat for some weeks prior to slaughter or slaughtered in a different season when they have grazed on less contaminated pastures which will then be reflected in the radiocesium activity concentration in the meat (Åhman 1999; Mehli et al. 2000).

Strontium-90 radionuclide has also received attention with respect to human health. The behavior of strontium is very similar to that of its close analogue, calcium. Therefore, the uptake and metabolism of calcium are sometimes expressed in relation to Ca in living organisms. Persson (1971) reported activity concentrations of ^{90}Sr in relation to Ca at 37 Bq/g Ca in bone (recalculated to Bq from original values in pCi) and 6 Bq/g Ca in muscle from Swedish reindeer in 1965. Because muscle, in contrast to bone (and also antlers), contains little Ca, the levels of Sr will be several times lower in muscle compared with bone. Consequently, Hanson et al. (1967) reported activity concentrations of ^{90}Sr between 1173 and 2582 Bq/kg dw (dry weight) in bone, and only about 0.1–1.6 Bq/kg fw in muscle, from Alaskan caribou after the NWT fallout.

The relative proportion of radiostrontium compared with other radionuclides was lower in the Chernobyl fallout than in the fallout from NWT, and therefore it was regarded as a minor problem for human health compared with radiocesium. Strontium-90 was, however, detectable in bone from reindeer in one of the most contaminated reindeer herding districts in Norway (Vågå) in 1988–1989, with average activity concentrations of 1810 Bq/kg dw (Staaland et al. 1991), thus similar to that measured after the NWT fallout. Most of the strontium detected in reindeer bone and antlers from Vågå seemed to originate from the Chernobyl fallout. The ^{90}Sr activity concentrations in bone and antlers collected from both the same site and a more northerly reindeer herding district in 2000–2002 had ^{90}Sr activity concentrations ranging from about 2 to 4 Bq/g Ca, which corresponds to around 300–900 Bq/kg dw in bone or antler tissue (Skuterud et al. 2005b).

Radionuclides in samples from muskox and caribou, collected from 1998 to 2000 from the Aleutian Islands, Alaska, were reported by Hong et al. (2011). Muskox (four animals) had ^{137}Cs and ^{90}Sr activity concentrations in muscle at 5.33–20.4 and 0.28–0.36 Bq/kg fw, respectively. Bone from the same animals contained 36–64 Bq/

kg dw of ^{90}Sr. Cs-137 activity concentrations in caribou, sampled from July to early September, were lower (1–8 Bq/kg fw) than those in muskox, while those of ^{90}Sr in bone were higher (76–154 Bq/kg dw). Lower amounts of ^{137}Cs in caribou than in muskox would be expected at this time of year, because caribou mainly feed on vascular plants. In contrast, due to long biological half-lives, strontium in bone reflects intake over a longer time period and is probably affected by intake during the previous seasons.

The content of several radionuclides from the uranium series in caribou from areas around uranium mines was studied in northern Canada (Thomas and Gates 1999). The highest activity concentrations of ^{226}Ra, ^{210}Pb, and ^{210}Po were in bone with mean values of 72, 669, and 367 Bq/kg fw, respectively. Activity concentrations of ^{226}Ra were much lower in all soft tissues (less than 3% of that in bone), whereas ^{210}Pb and ^{210}Po activity concentrations were relatively high in liver (154 and 286 Bq/kg, respectively) and kidney (169 and 159 Bq/kg, respectively) and low in muscle (1.1 and 12.4 Bq/kg, respectively).

The radionuclide activity concentrations in living organisms in relation to deposition density can differ considerably between species. The relation between deposition and contamination of living organisms is often expressed as aggregated transfer factor "T_{ag}" (m^2/kg), denoting the activity concentration (Bq/kg) in an organism or tissue relative to fallout per area unit (Bq/m^2). Typical T_{ag} values for ^{137}Cs in reindeer in Sweden in the first year after the Chernobyl fallout were around 1 m^2/kg fw in winter and 0.025 m^2/kg in summer (Åhman and Åhman 1990), which can be compared to values for moose around 0.01 m^2/kg fw (Calmon et al. 2009; Howard et al. 1996). Higher T_{ag} values have been reported for Arctic hare (0.03 m^2/kg fw) than for brown hare (*Lepus europaeus*, up to 0.008 m^2/kg), probably reflecting their habitat, as the brown hare is commonly found in agricultural landscapes, while Arctic hare is found in forest and on tundra. T_{ag} values for game birds have been reported to be i 0.01–0.02 m^2/kg (Calmon et al. 2009; Howard et al. 1996).

For reindeer and caribou, which mainly eat lichens in winter and vascular plants in summer, the change in diet, and thus radiocesium intake, creates a pronounced seasonal variation, enhanced by a shorter biological half-life in summer compared to winter (Holleman et al. 1971). Radiocesium activity concentrations in the body of reindeer and caribou are thus typically high in winter and low in summer (Eikelmann et al. 1990; Hanson and Palmer 1965; Åhman and Åhman 1994). However, since the Chernobyl accident, the magnitude of the variation has declined with time (Skuterud et al. 2005a) as radiocesium is lost from the lichens by weathering (or the lichens are eaten by reindeer) and transported into the soil, eventually becoming available for root uptake by vascular plants and, thereby, more evenly distributed in the environment. Seasonal patterns in ^{137}Cs activity concentrations in reindeer may, therefore, gradually change with occasional peaks in autumn if there is a high abundance of fungi (Hove et al. 1990), which has been observed, for instance, for roe deer (Avila et al. 1999).

Long-term decline of radionuclides in the environment, and thus in vegetation and animals, occurs through a number of processes. The most obvious is radioactive

decay, which differs for each radioisotope (resulting in physical half-lives discussed earlier in this chapter). There is also an often quoted "ecological half-life" that describes how fast a radionuclide is made unavailable for uptake by animals though a number of processes in the ecosystem and "effective half-life" that describes the combined decline of a radionuclide from an organism or a system that takes into account the physical decay rate of the isotope (Howard et al. 1996). A more rapid reduction of radiocesium activity concentrations in reindeer was observed during the first 10 years after the Chernobyl accident (with effective half-lives at 2–5 years) compared with later years. The early decline to a large extent followed that of lichens (Skuterud et al. 2005a, 2009; Åhman 2007). The decline during latter years approached that of the physical half-life of ^{137}Cs of 30 years.

4.2 Freshwater Systems

The contamination of fish in freshwater systems after radioactive fallout will depend on several factors. For example, lakes that get most of their water from surrounding (contaminated) wetland catchments will receive more contaminants than those that mainly receive water from direct precipitation. In fish, there is often an accumulation with trophic level, so that piscivore fish (fish that feed on other fish) have higher ^{137}Cs activity concentrations than herbivore and planktivore fish (Ishii et al. 2020; Sundbom et al. 2003). After a single deposition event (such as the Chernobyl accident), there will be a delay before maximum contamination of fish is reached. Measurements in three Swedish lakes after the Chernobyl accident showed that, depending on lake and fish species, it took from 56 to 806 days for ^{137}Cs in fish to reach maximum ^{137}Cs activity concentrations (Sundbom et al. 2003). The decline of ^{137}Cs also differed considerably between lakes, but after 10 years, the lakes seemed to have reached a steady state, and the decline of ^{137}Cs activity concentrations in fish was then dominated by physical decay (30 y half-life). Aggregated transfer factors (^{137}Cs activity concentration in fish divided by deposition per m^2) near to steady-state conditions for roach (*Rutilus rutilus*, an omnivore fish) in these lakes varied between 0.0025 and 0.04 m^2/kg. Cs-137 activity concentrations for large perch (*Perca fluviatilis*, a piscivore) were three to six times higher than in roach.

4.3 Radionuclides in the Marine Environment

Radionuclides that have been released to the ocean from nuclear fuel reprocessing plants are partially transported with currents to Arctic waters. Radionuclides that have been deposited with precipitation (e.g., ^{137}Cs and ^{90}Sr) are also dispersed with currents and eventually reach stable, low, mean concentration in seawater (AMAP 2010). Radionuclides are accumulated by marine organisms such as marine fish, seabirds, seals, and wales in Arctic waters. However, the activity concentrations have generally been very low due to large dilution effects.

Several species of marine fish collected around the Arctic and Subarctic had consistently low ^{137}Cs activity concentrations. The highest ^{137}Cs activity concentrations of up to 3 Bq/kg fw were recorded during the 1960s. Marine fish collected in the Barents Sea and from waters along the Norwegian coast in 2005 (NRPA 2007) had activity concentrations that were well below 1 Bq/kg fw. Fish from waters close to the Teriberka settlement in Russia (Kola Penninsula) were below 0.5 Bq/kg fw for both ^{137}Cs and ^{90}Sr, and up to 1.6 Bq/kg fw for ^{239,240}Pu (AMAP 2010).

Nevertheless, consumption of seafood may contribute to the radiation dose of humans, depending on the diet. Considering both natural radionuclides and those of anthropogenic origin, and based on recent national dietary surveys, Komperød and Skuterud (2018) concluded that fish and shellfish were currently the most important dietary components contributing to the effective radiation dose received by the general population in Norway. The total effective dose was still low (on average 0.42 mSv) and predominantly caused by the naturally occurring radionuclides.

Samples of muscle, liver, and kidney in several species of seabirds (*Rissa tridactyla*, *Uria lomvia*, *Larus hyperboreus*, *Fulmarus glacialis*, and *Alle alle*) from Svalbard have been analyzed for ^{137}Cs, ^{210}Po, and ^{210}Pb (NRPA 2007). Only low ^{137}Cs activity concentrations were found in these birds (up to about 0.2 Bq/kg fw, but mostly below the detection limit). The highest activity concentrations of ^{210}Po in muscle (on average 14 Bq/kg fw) were found in little auks, while that of ^{210}Pb in muscle were negligible for all species. Both ^{210}Po and ^{210}Pb had the highest activity concentrations in kidney, with an average 6 Bq ^{210}Pb/kg fw in Northern fulmar (*Fulmarus glacialis*), and Bq ^{210}Po /kg fw in the kidney of Brunnich's guillemot (*Uria lomvia*).

Seals (*Pinnipedia*) and wales (*Cetacea*) are top predators in the Arctic marine food chain and are therefore vulnerable to accumulation of contaminants. Seals and wales from Greenland and wales from the Faroe Islands (organs not specified) have been measured for ^{137}Cs from 1960 and onward (AMAP 2010). Activity concentrations declined from generally only between 1 and 10 Bq/kg fw in the late 1960s and stabilized below 1 Bq/kg fw from about 1980 onward. Polonium-210 and ^{210}Pb have been measured in organs from grey seal (*Halichoerus grypus*) from the Baltic Sea and ringed seal (*Pusa hispida*) from Svalbard in 2003 and 2004 (AMAP 2010). Activity concentrations of ^{210}Po in muscle ranged from 3 to 28 Bq/kg fw for ^{210}Po, and 0.14 to 0.45 for ^{210}Pb. Considerably higher amounts were found in kidney and liver from the same animals (up to 215 Bq/kg fw for ^{210}Po and 2 Bq/kg fw for ^{210}Pb).

Activity concentrations of several radionuclides in muscle and other tissue from seals collected in the Canadian Arctic in 2014 have been reported by Chen et al. (2017). Activity concentrations were low, for ^{137}Cs (0.1–0.4 Bq/kg fw) and for ^{210}Pb and ^{226}Ra (mostly below detection limit of 0.3 Bq/kg fw). Higher activity concentrations were found for ^{210}Po (12–39 Bq/kg fw in muscle and 102–396 Bq/kg fw in liver) and ^{40}K (range 50–80 Bq/kg fw). The data for ^{137}Cs and ^{210}Po were similar to those reported for seal and walrus from the Bering Sea in 1996.

4.4 Exposure of Animals and Humans and the Related Health Risks

Intake of food with elevated levels of radioactive substances may involve a health risk for animals, including humans. A general recommendation for humans from international authorities (ICRP 2007) is that the added radiation dose caused by intake of contaminated food products should not exceed 1 mSv per year. This dose limit is reached at different intake rates depending on radioisotope. For ^{137}Cs, the dose is obtained at an intake of about 75,000 Bq (ICRP 1993), while the same dose is reached at an intake of about 36,000 Bq ^{90}Sr, or an intake of only 800 Bq ^{210}Po.

Most dose estimates for populations in general (not for doses achieved from occupation or, e.g., medical treatment) have been carried out for ^{137}Cs, since this is the radionuclide that has entered the human food chain worldwide. For example, the total dose commitment from ^{137}Cs from NWT fallout has been estimated to be 0.19 mSv for an average person living within the northern hemisphere (UNSCEAR 1982). Doses to persons with special food habits, like reindeer herders or caribou hunters, may be considerably higher. The annual dose for a male reindeer herder in Finland during the 1960s was estimated to be 1.2 mSv (Miettinen et al. 1963), and whole-body measurements of reindeer herders in Sweden during the same period gave estimated annual doses around 1 mSv (Falk et al. 1991). An integrated dose at 18 mSv was assessed (based on whole-body monitoring) for an average reindeer herder in Northern Norway during 1950–2010 (Skuterud and Thorring 2015). This means that herders have received higher dose than recommended during several years. Nevertheless, such doses are too low to be expected to significantly affect the risk for cancer (the most likely effect). Similarly, no measurable differences in the frequency of cancer between reindeer herders and the average population have been recorded (Haldorsen and Tynes 2005; Hassler et al. 2008; Kurttio et al. 2010; Tynes and Haldorsen 2007), although Kurttio et al. (2010) suggest that there are some indications, however ambiguous, of raised cancer risk due to elevated radiation doses during childhood.

Despite the high local fallout after the Chernobyl accident, radiation doses to humans have not generally been higher than that after the NWT, even in the most exposed groups. The effective dose during 50 years to a reindeer herder in the most contaminated areas of Norway has been estimated to be 27 mSv (Skuterud and Thørring 2012), which is on average 0.5 mSv/year. Lifetime doses between 4 and 8 mSv were estimated for members of hunter families in the most contaminated areas of Sweden (Tondel et al. 2017). Countermeasures and dietary recommendations limited the intake of highly contaminated food products, and thus the radiation dose to humans (Skuterud and Thørring 2012; Åhman 1999). Meat from game and reindeer, freshwater fish, and wild berries and mushrooms were identified as food products of concern. Countermeasures, such as changing the timing of hunting and reindeer slaughter, clean feeding of reindeer before slaughter, and the use of cesium binders in salt licks or factory-made feeds, were commonly used to reduce radiocesium activity concentrations in animals (Beresford et al. 2016). These

measures considerably reduced the radiation dose to humans in Sweden and other countries after the Chernobyl accident (Rääf et al. 2006).

4.5 Radiation Exposure of Wildlife

The importance of protecting both humans and other organism in the environment has been increasingly recognized during the last decades (see, e.g., Howard et al. 2010; ICRP 2014; Pentreath 1999). Transfer factors and dose conversion factors have been presented for a range of radionuclides and living organisms (UNSCEAR 2008). These can be used to estimate expected radiation doses and risk for harm to defined groups of wildlife. Specific reference organisms have been suggested for Arctic environments (Hosseini et al. 2005), based on ecological niche, radiosensitivity, and exposure to radioactive contamination. Proposed representative mammals have been identified for different types of environment. These were seals for the marine system, mink for freshwater systems, and lemmings and voles, reindeer/caribou and foxes for terrestrial environments.

Different dose limits have been suggested by various authors and organizations. Howard et al. (2010) suggested using 10 μGy/h (absorbed dose, micro gray per hour) as a limit below which there is little risk of harm to wild organisms, while above this limit, further assessment is needed to find out if there is a potential risk.

Possible effects of radiation for reindeer were investigated in Norway after the Chernobyl accident by Roed and Jacobsen (1995). The authors did not find any differences between reindeer herds in the pattern of chromosome aberrations (an indicator of damage) that could be attributed to the exposure to radiation. However, in a herd from the area with the highest ground radiocesium deposition, calves born during the spring of 1986, when the accident happened, had significantly more aberrations than expected compared with reindeer born in other years, suggesting a negative effect of radiation exposure to the newborn calves.

5 Summary and Conclusions

There are a number of sources that have released radioactive material into Arctic and Subarctic ecosystems. The resulting radionuclide activity concentrations in animals are, however, generally low, with the exception of reindeer, certain wildlife species and freshwater fish in some areas. The highest contamination of food products for humans was caused by the Chernobyl accident in 1986. However, countermeasures and dietary restrictions and recommendations limited the intake of contaminated food by Arctic and Subarctic populations. No adverse effects of radiation on animal or human health, such as increased frequency of cancer, have been demonstrated in Arctic regions.

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