Polish J. of Environ. Stud. Vol. 19, No. 4 (2010), 771-778

Original Research

Accumulation of Uranium (^{234}U and ^{238}U) and Plutonium ($^{239+240}$Pu) in Cervid Tissues and Organs

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Received: 17 December 2009
Accepted: 23 February 2010

Abstract

Livers, kidneys and muscles of large herbivorous animals: the roe deer (*Capreolus capreolus*), red deer, (*Cervus elaphus*) and fallow deer (*Dama dama*), collected in Northern Poland, were the subject of our investigation. The radioactivity concentration of ^{238}U ranged widely between 2.49±0.18 and 69.37±5.45 mBq·kg^{-1} w.w. There was no correlation between the accumulation of uranium and the analyzed tissues and organs. The values of ^{234}U/^{238}U activity ratio in analyzed samples were between 0.61±0.08 and 1.41±0.26, while most of the samples had ratios close to 1. The concentration of $^{239+240}$Pu in the analyzed tissues decreased in the order kidney > muscle tissue > liver. The average radioactivity concentrations of $^{239+240}$Pu ranged between 0.18±0.04 mBq·kg^{-1} ww in muscle and 2.77±0.60 mBq·kg^{-1} ww in kidneys. As statistically checked, the sampling location (ROLP Białystok, Gdańsk, Olsztyn, Szczecin, Szczecinek, Toruń), sex, age, and animal species did not influence the uranium and plutonium concentrations of the analyzed samples.

Keywords: uranium, ^{234}U, ^{238}U, ^{234}U/^{238}U activity ratio, plutonium, $^{239+240}$Pu, bioaccumulation, Cervid, northern Poland

Introduction

Among radionuclides in the environment, alpha emitters have a significant role in the effects connected with the accumulation of these radionuclides in organisms. Natural uranium and man-made plutonium are widespread all over the world, take part in geochemical circulation and accumulate in the food chain. Humans can be the final link of this chain and be vulnerable to accumulating uranium and plutonium in dangerous amounts ($\geq 10^{-12}$ g·g^{-1}) during lifetime exposure [1]. Forests are vulnerable ecosystems. Areas covered in trees are traps for contamination transported in the air [2]. Radionuclides are much more persistent in forest ecosystems than in agricultural land [3].

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Uranium is widely spread in nature, where it occurs in over 160 minerals [4, 5]. Isotopes ^{234}U and ^{238}U occur in the natural uranium decay chain; both are alpha emitters of low radioactivity and radiotoxicity, and the harmful effects of uranium of its high chemical toxicity are comparable to lead [4, 6-9]. The occurrence of uranium in the environment can also result from human activity such as the nuclear energy industry, combustion of fossil fuels, production and use of phosphorous fertilizers, and the utilization of depleted uranium for military purposes [4, 10-14].

In soils, sediments, and waters, metallic uranium corrodes and is transformed into U(VI). In aerobic conditions it occurs as the uranyl ion UO_2^{2+} and this soluble form may be transported into living organisms [4, 8]. After deposition, soluble U(VI) may also be reduced by microorganisms to insoluble U(IV), or be partly washed from the upper soil

layer to deeper layers by infiltration [15]. The average concentrations of ^{238}U in the surface soil layer are about 25 Bq·kg^{-1} dw (2.1 μg·g^{-1} or 10-50 Bq·kg^{-1} dw) [8, 10, 16-18]. Uranium is transported as the UO_2^{2+} ion in a way similar to calcium, with which uranium competes [19]. Resuspension and adhesion of soil particles can enhance the surface contamination of plants with uranium and the resuspension process is the main source of airborne uranium [16, 20, 21].

The main sources of plutonium in the atmosphere are nuclear weapon tests carried out in 1945-62. During this time, about 0.33 PBq ^{238}Pu and 13 PBq $^{239+240}Pu$ were released. A high amount of plutonium was released also during the Chernobyl accident: $3.51 \cdot 10^{13}$ Bq of ^{238}Pu, $7.2 \cdot 10^{13}$ Bq of $^{239+240}Pu$ and $5.5 \cdot 10^{15}$ Bq of ^{241}Pu [14, 15]. Radionuclides fall down on earth as wet and dry fallout. The fallout from the atmosphere varies between 0.05-0.5 kBq·m^{-2} [24]. Due to the consumption of forest products or leaching of radionuclides into groundwater, forests also contribute to the internal human dose. For example, after the accident in the Chernobyl nuclear reactor forest products contained higher accumulations of ^{137}Cs than agricultural products [25-27].

Plutonium in the environment is mostly connected to soil, sediments, or suspended matter [28]. In soil and sediments it is reduced to Pu(IV) and Pu(III), and subsequently associated with the soil structure [29, 30]. 85-90% of plutonium in soil is connected to organic matter, mostly humus [31-36]. The concentrations of plutonium in soil decrease with depth, but in soil particles the concentrations increase with decreasing size [33, 37, 38]. The vertical migration rate of plutonium from global fallout into soil is below 1 cm·year^{-1} and the lowest values are noticed in soils rich in humus (0.1 cm·year^{-1}); in the mineral layer these values can increase to 1.7 cm·year^{-1} [38, 39].

Plutonium $^{239+240}Pu$ concentrations in forest litter from northeastern Poland (Puszcza Augustowska) in 1991 varied from 1.95 Bq·kg^{-1} dw to 6.88 Bq·kg^{-1} dw, of which Chernobyl -derived plutonium represented 64%. Other regions of northeastern Poland were less contaminated and the concentrations varied from 0.07 to 4.40 Bq·kg^{-1} dw [40-42].

Reindeer are exposed to plutonium via food, such as lichens, and 20% of total ingested plutonium is accumulated in their skeleton. In reindeer bones from Novaya Zemlya, $^{239+240}Pu$ concentration was between 0.47-3.5 Bq·kg^{-1} dw (^{238}Pu – 0.07-0.2 Bq·kg^{-1} dw), while in the mandibles it was in the range 40-70 Bq·kg^{-1} dw [42]. In organs of reindeer from Lapland, $^{239+240}Pu$ concentrations varied from 1.48 in muscle, 14.8 in bones, and 22 in kidneys to 185 mBq·kg^{-1} ww in liver and the accumulation did not depend on reindeer age [44, 45]. Among Polish animals, the highest $^{239+240}Pu$ concentration was found in the common vole *Microtus arvalis* (97.5 mBq·kg^{-1} ash). In the skulls of rodents and insectivores from eastern Poland the plutonium concentrations were at least 10 times higher than in big herbivores ($^{239+240}Pu$ 9.6-17.7 mBq·kg^{-1} ash) [42, 46].

The tissues of deer, especially of the roe deer, seem to be good bioindicators of environmental contamination, especially in the case of heavy metals and radionuclides [47, 49]. The tissues accumulate pollutants efficiently in proportion to their amounts present in the environment. Moreover, the physiological and ecological features of the species are well known and the roe deer is widespread. Roe deer occupy small territories, on average below 100 ha in area, due to which they reflect the conditions of a well-defined site [47-49]. Antlers are often used to indicate local contamination, e.g. by lead or strontium ^{90}Sr [42, 50-53]. Moreover, teeth and bones of deer are used to assess fluoride contamination [52, 53].

The aim of this investigation was to assess the level of radioactive contamination of the northern Polish environment and to estimate the potential threat for game meat consumers, which is of importance because of the economical value of game [25, 55, 56]. Moreover, the present study can provide valuable information about the factors influencing the accumulation of uranium and plutonium in the tissues of the examined deer and about the factors determining the transport of these elements in the food-chain.

Material and Methods

Kidney, liver, and muscle tissue samples were collected from 28 deer obtained in northern Poland (ROLP Białystok, Gdańsk, Olsztyn, Szczecin, Szczecinek, Toruń) in the 2000/2001, 2001/2002 and 2002/2003 hunting seasons (Fig. 1). All animal carcasses were routinely collected and partly dissected at the wild game purchasing centers localized in the area of study [57]. All obtained samples of kidney, liver, and muscle were used for uranium and plutonium analysis but plutonium in many of the analyzed samples were below the detection limit. From obtained samples, uranium and plutonium was determined in 17 specimens of red deer (*Cervus elaphus*) (9 samples of kidney, 12 samples of muscle, 9 samples of liver), 8 specimens of roe deer (*Capreolus capreolus*) (5 samples of kidney, 3 samples of liver and 1 sample of muscle) and 3 specimens of fallow deer (*Dama dama*) (3 samples of kidney).

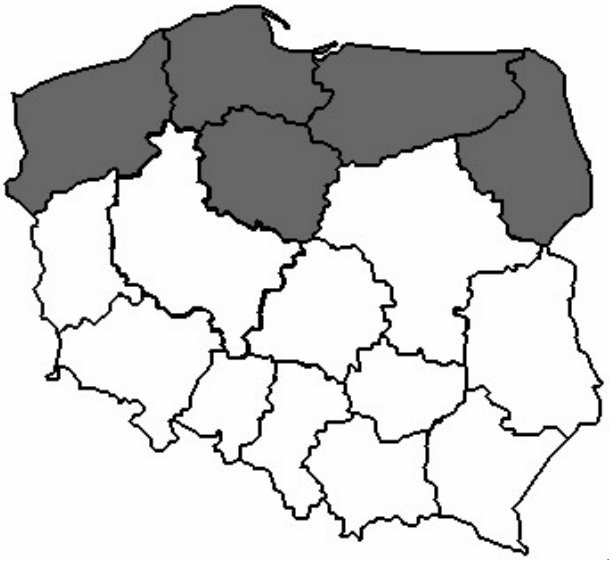

Fig. 1. Map of Poland with regions (in grey) where deer have been sampled.

Table 1. ^{234}U and ^{238}U concentration in tissues and organs of deer from northern Poland.

Tissue	Sample amounts	Minimum and maximum concentrations (mean ± SD) [mBq·kg^{-1} ww]		Mean value of ^{234}U/^{238}U activity ratio
		^{238}U	^{234}U	
Kidney	17	2.49±0.18 – 69.37±5.45 (19.43±17.89)	2.88±0.20 – 42.39±4.35 (16.89±12.73)	0.98±0.23
Liver	6	4.87±0.55 – 50.15±4.89 (17.70±16.93)	6.09±0.62 – 58.34±5.35 (19.79±19.53)	1.14±0.20
Muscle	4	4.01±0.49 – 52.06±5.40 (23.61±21.97)	3.16±0.44 – 69.20±6.32 (26.79±30.33)	0.96±0.26

The fresh samples were weighed, homogenized (Thermomix, Vorwerk, Germany), and digested using 65% HNO_3 with a ^{232}U (about 32.5 mBq) and ^{242}Pu (about 5 mBq) spikes added as yield tracers. The uranium and plutonium analyses were treated as follows: sample mineralization in nitric acid, separation, and purification on ion resins, electrolysis on a steel disc and determination of uranium and plutonium isotope activities by alpha spectrometry. The radiochemical method allows U and Pu determination from the same sample [58-61]. After radiochemical preparation, the activities of uranium (^{234}U, ^{238}U) and plutonium (^{238}Pu, $^{239+240}$Pu) radionuclides were measured separately by alpha spectrometry (Alpha Analyst S470, Canberra Packard, USA) equipped with 12 surface-barrier Si PIPS detectors (300 and 450 mm^2 area each, FWHM=18 keV).

On this basis the values of the ^{238}Pu/$^{239+240}$Pu activity ratio were estimated. The proportion of Chernobyl-derived plutonium F_{Ch} in the total plutonium concentration in analyzed organs and tissues was calculated as follows [44]:

$$F_{Ch} = \frac{R_{obs} - R_n}{R_{Ch} - R_n} = \frac{R_{obs} - 0.04}{0.56}$$

...where R_{obs}, R_n, and R_{Ch} are values of the ^{238}Pu/$^{239+240}$Pu activity ratio in the analyzed material, in total atmospheric fallout before the Chernobyl accident (0.04), and in the moment of the Chernobyl accident (0.6), respectively [2, 44].

The accuracy and precision of plutonium analysis were satisfactory, i.e. precision was less than 7% (1.5-6.4%), as estimated by analysis of the International Atomic Energy Agency standard materials (IAEA-367, IAEA-384, IAEA-414). In the case of uranium analysis the accuracy and precision were 2.2-5.0%. The uranium yield in the samples ranged from 30 to 90%. The chemical yield of plutonium analysis varied from 60% to 90%. The results are also given with standard deviation (SD) calculated for 95% confidence intervals. The detection limits were calculated to be 0.33 mBq for ^{234}U and ^{238}U and at 0.12 mBq for $^{239+240}$Pu [57].

Due to the small number of samples, nonparametric tests were used (Kolmogorov-Smirnoff, Mann-Whitney U-test, Wald-Wolfowitz) and ANOVA Kruskal-Wallis at statistical significance $p<0.05$.

Results and Discussion

^{234}U and ^{238}U

The results of ^{234}U and ^{238}U radioactivity measurements in livers, kidneys and muscles of red deer, roe deer, and fallow deer from northern Poland are given in Table 1 and Fig. 2. Generally, the concentration of ^{238}U in tissues and organs ranged between 2.49±0.18 and 69.37±5.45 mBq·kg^{-1} ww, which corresponds to total uranium concentrations from 0.20±0.01 to 5.64±0.44 µg·kg^{-1} ww. The concentration of ^{234}U varied between 2.88±0.20 and 69.20±6.32 mBq·kg^{-1} ww. The accumulation of ^{234}U and ^{238}U in the deer tissues and organs was independent of age and sex (Kolmogorov-Smirnoff, Mann-Whitney U-test, Wald-Wolfowitz tets at $p<0.05$). Similarly, there was no correlation between the organs or tissues examined and the amount of ^{234}U or ^{238}U accumulated (ANOVA Kryskal-Wallis and frame figures) (Fig. 2).

In the red deer stags, the concentration of ^{238}U increased in the order: muscle < kidney < liver, and in red deer hind in the order kidney < liver < muscle. The concentrations of uranium in tissues of deer from the examined area were higher than these found in human soft tissues. The human body contains about 100 µg of uranium, 7.4 mBq·kg^{-1} in

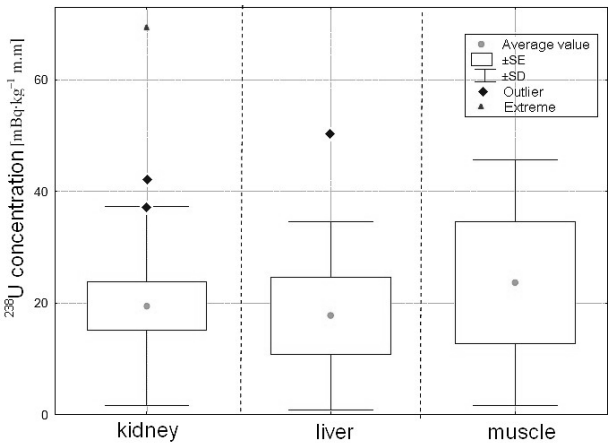

Fig. 2. ^{238}U concentrations in deer tissues and organs.

Table 2. Estimated effective dose in humans caused by the consumption of 1 kg game meat.

Sample	U isotope	Mean value [μSv]	Minimum [μSv]	Maximum [μSv]
Kidney	^{238}U	$0.88 \cdot 10^{-3}$	$0.11 \cdot 10^{-3}$	$3.12 \cdot 10^{-3}$
	^{234}U	$0.83 \cdot 10^{-3}$	$0.14 \cdot 10^{-3}$	$2.08 \cdot 10^{-3}$
Liver	^{238}U	$0.78 \cdot 10^{-3}$	$0.22 \cdot 10^{-3}$	$2.26 \cdot 10^{-3}$
	^{234}U	$0.97 \cdot 10^{-3}$	$0.30 \cdot 10^{-3}$	$2.86 \cdot 10^{-3}$
Muscle	^{238}U	$1.06 \cdot 10^{-3}$	$0.18 \cdot 10^{-3}$	$2.34 \cdot 10^{-3}$
	^{234}U	$1.31 \cdot 10^{-3}$	$0.16 \cdot 10^{-3}$	$3.39 \cdot 10^{-3}$

soft tissues and 0.148 Bq·kg^{-1} in bones [4, 12, 16]. The kidneys of the deer contained on average 19.43±17.89 mBq·kg^{-1} ww of ^{238}U and 16.89±12.73 mBq·kg^{-1} ww of ^{234}U. In Poland the content of ^{238}U in beef is about 5.63 mBq·kg^{-1} ww. In pork, poultry and eggs the concentrations are about 0.62-1.78 mBq·kg^{-1} ww [62]. These values are similar to the minimal values found in tissues and organs of the analyzed deer from northern Poland. It may denote that wild ruminants could accumulate uranium more efficiently than non-ruminants and domestic ruminants. It is possible that the longer food retention time in the alimentary tracts of ruminants enhances the efficiency of absorption of uranium and deteriorates the efficiency of removal, for example, in faeces. Wild ruminants also consume more plants with high amounts of uranium (i.e. cereal) or mushrooms – compared to domestic animals [62]. Mushrooms from north-eastern Poland can concentrate ^{238}U at levels as high as 15-270 mBq·kg^{-1} dw [46]. ^{238}U concentration in the most commonly consumed species, such as the cep (*Boletus edulis*), bay bolete (*Xerocomus badius*), parasol mushroom (*Macrolepiota procera*), fleecy milk-cap (*Lactarius vellereus*) and honey mushroom (*Armillaria mellea*) was estimated to be between 15 and 240 mBq·kg^{-1}, and the value of ^{234}U/^{238}U activity ratio was close to 1. The highest uranium concentration was observed in the parasol mushroom (270±90 mBq·kg^{-1} dw) [46]. The higher content of uranium in the food of wild ruminants could result in higher transfer factors of U into the organism, because when uranium absorption becomes more efficient, the high amounts of uranium can handicap kidney function and the efficiency of uranium removal with urine [63].

The uranium content in tissues of reindeer depends on the amounts of radionuclides in water and the plants consumed rather than on the lichens eaten. The uranium concentration in the liver and bones of reindeer was 0.037 Bq·kg^{-1} ww [16]. The transfer factor of ^{238}U from lichens to liver and bones of reindeer amounts to 0.07 year^{-1} and 0.08 year^{-1}, respectively. In Lapland the uranium concentration was estimated to be between 0.2 Bq·kg^{-1} ww for ^{234}U and ^{238}U and 0.007 Bq·kg^{-1} ww for ^{235}U in star reindeer lichen (*Cladonia alpestris*) [16]. In dense-flowered cordgrass (*Spartina densiflora*) in Spain the ^{238}U content is between 2.16-42.6 mBq·g^{-1} dw and the value of ^{234}U/^{238}U activity ratio is 1.073, while values of bioaccumulation factor for ^{234}U and ^{238}U are 0.02-0.27 [18].

The values of ^{234}U/^{238}U activity ratio were 0.61±0.08–1.42±0.28 for kidney, between 0.81±0.21–1.41±0.26 for liver and 0.76±0.07–1.33±0.18 for muscle (Table 1). For the remaining samples the values were generally close to 1. ^{234}U/^{238}U activity ratio in mushrooms from Poland is close to 1 [46] and in the various food products from the Wałbrzych region 1.16±0.21 [62]. The content of uranium in the analyzed deer tissues and organs did not correlate with the amount of ^{210}Po determined previously for deer (r_s= 0.12, $p<0.05$) [57].

To assess the risk for consumers of game meat, the committed effective dose was calculated based on the values established by the National Atomic Energy Agency (Poland) (1997). The estimated results are presented in Table 2. The average annual consumption of game meat in Poland is about 0.08 kg per capita [64]. Assuming that game meat corresponds to deer meat, it can be calculated that it would be a source of effective doses of $0.88 \cdot 10^{-5}$–$24.96 \cdot 10^{-5}$ μSv (from decay of ^{238}U) and $1.12 \cdot 10^{-5}$–$27.12 \cdot 10^{-5}$ μSv (from decay of ^{234}U), yielding together $2 \cdot 10^{-5}$–$52 \cdot 10^{-5}$ μSv. This accounts only for $1.86 \cdot 10^{-5}$% of the effective dose from all natural sources in Poland, about 2.8 mSv [65].

The average intake of uranium with food in Europe is about 4.4-16 Bq for ^{238}U [7, 66], in the region of Wałbrzych (Poland) the daily intake with food is about 17.7 mBq for ^{238}U and 30.2 mBq for ^{234}U [62]. Based on uranium concentrations in deer organs and tissues, the annual human intake of ^{238}U and ^{234}U to would be 0.20-5.54 mBq. This equals approximately 0.13% of total ^{238}U intake of an average European person. This indicates that uranium in tissues of deer from northern Poland presents no radiological risk for consumers.

$^{239+240}$Pu

The results of ^{238}Pu and $^{239+240}$Pu measurements in deer livers, kidneys, and muscle from northern Poland are presented in Table 3. The activities of plutonium in many of the analyzed samples were below the detection limit. These data are similar to or slightly lower than the $^{239+240}$Pu concentrations measured from deer bones by Mietelski et al. [41].

The ^{238}Pu/$^{239+240}$Pu activity ratios and the results of the Chernobyl plutonium contribution are presented in Table 4. The Chernobyl plutonium contribution varied from 44% to 82% in kidneys, 64-68% in livers and 91% in muscles, indicating the significant impact of the Chernobyl accident on the north Poland environment and on plutonium transport in the ecosystem. A significant amount of ^{238}Pu in the tissues and organs could be caused by the higher mobility of ^{238}Pu than $^{239+240}$Pu in Chernobyl plutonium, compared to global fallout [37, 39, 42, 67]. The big fraction of Chernobyl plutonium in the analyzed deer could also be caused by its high concentrations in plants that are an important part of the deer diet: berries (*Vaccinium* spp.), tree bark, and needles [68]. In leaves of the blueberry (*Vaccinium myrtillus*) from Poland, the $^{239+240}$Pu concentrations varied from 3.4 to 11 mBq·kg^{-1} dw. In leaves of the lingonberry (*Vaccinium vitis-*

Table 3. ^{238}Pu and $^{239+240}Pu$ concentration in tissues and organs of deer from northern Poland.

Tissue	Sample amounts	Minimum and maximum concentrations (mean value ± SD) [mBq·kg^{-1} ww]	
		^{238}Pu	$^{239+240}Pu$
Kidney	18	0.43±0.11– 1.32±0.34 (0.88±0.63)	0.60±0.27 – 2.77±0.60 (1.62±0.89)
Liver	12	0.26±0.13 – 0.46±0.09 (0.36±0.14)	0.33±0.06 – 1.11±0.21 (0.60±0.32)
Muscle	13	(0.21±0.05)	0.18±0.04 – 1.60±0.16 (0.56±0.59)

Table 4. $^{238}Pu/^{239+240}Pu$ activity ratios and the estimated contribution of Chernobyl-derived plutonium in the tissues and organs of deer from northern Poland.

No.	Tissue	$^{238}Pu/^{239+240}Pu$ activity ratio	Chernobyl plutonium [%]
1	Red deer muscle	0.55 ± 0.17	91
2	Red deer kidney	0.50 ± 0.17	82
3	Red deer liver	0.42 ± 0.25	68
4	Red deer liver	0.40 ± 0.25	64
5	Roe deer kidney	0.29 ± 0.57	44

Table 5. Transfer factors (TF) of plutonium isotopes for particular links in the trophic chain.

Trophic relation	Transfer factor (TF)	
	$^{239+240}Pu$	^{238}Pu
Berries – kidney	0.038-0.463	0.124-0.678
Berries – liver	0.014-0.171	0.051-0.277
Berries – muscle	0.013-0.160	0.029-0.162
Trees parts – kidney	0.007-0.090	0.028-0.068
Trees parts – liver	0.003-0.033	0.012-0.028
Trees parts – muscle	0.003-0.031	0.007-0.016
Forrest litter – kidney	$0.2\cdot10^{-3}$-$23.1\cdot10^{-3}$	-
Forrest litter – liver	$0.09\cdot10^{-3}$-$8.6\cdot10^{-3}$	-
Forrest litter – muscle	$0.08\cdot10^{-3}$-$8.0\cdot10^{-3}$	-

idaea), the concentration was 21.6 mBq·kg^{-1} dw. In pine (*Pinus sylvestris*) and spruce (*Picaea excelsa*) needles the plutonium concentration was higher – sometimes over 100 mBq·kg^{-1} dw (with very small ^{238}Pu contribution); spruce bark contains 208 mBq·kg^{-1} dw of $^{239+240}Pu$ and 31 mBq·kg^{-1} dw of ^{238}Pu. In conifer needles from southern Poland the $^{239+240}Pu$ concentration was estimated to be 0-15 mBq·kg^{-1} dw, in spruce bark 11-25 mBq·kg^{-1} dw, in ferns (*Athyrium* sp) 10-138 mBq·kg^{-1} dw. in ferns (*Athyrium* sp). from north-eastern Poland the plutonium concentration was even higher than in the spruce: 244 mBq·kg^{-1} dw of $^{239+240}Pu$ and 8 mBq·kg^{-1} dw of ^{238}Pu [46, 69]. The values of plutonium bioaccumulation factors (BCF) for different plants eaten by deer were calculated to be 0.001-0.17, but for berries and mushrooms they could reach the value of 0.3 [70-72].

On the basis of the plutonium concentration in different plants and forest litter the transfer factors (TF) to deer defined as the ratio of plutonium radionuclide concentration in animal or plant to the concentration in food or soil were also calculated (Table 5). The data indicate that the biggest $^{239+240}Pu$ transfer factor was from berries to kidneys (0.038-0.463), and he lowest values for the forest litter to muscle transfer ($0.08\cdot10^{-3}$–$8.0\cdot10^{-3}$) and these values are higher than the TF for beef meat ($8.8\cdot10^{-8}$–$3.0\cdot10^{-3}$) and sheep meat ($2.0\cdot10^{-5}$–$8.5\cdot10^{-5}$) [73]. The transfer of plutonium to liver and muscle was the lowest, but forest litter and tree parts periodically are the main food [68].

The effective radioactivity doses were calculated based on the data (Table 6). The biggest values of effective dose were obtained for kidney, smaller for liver, and the smallest for muscles. As the average consumption of venison in Poland was estimated at 0.08 kg per year [64], the annual effective dose would be $0.32\cdot10^{-4}$ µSv (for $^{239+240}Pu$) and $0.16\cdot10^{-4}$ µSv (for ^{238}Pu) from kidneys, $0.11\cdot10^{-4}$ µSv (for $^{239+240}Pu$) and $0.04\cdot10^{-4}$ µSv (for ^{238}Pu) from muscle.

Table 6. Effective dose from plutonium isotopes ^{238}Pu and $^{239+240}Pu$ after consumption of 1 kg of deer meat.

Tissue	Pu isotope	Mean value µSv	Min µSv	Max µSv
Kidney	^{238}Pu	$3.99\cdot10^{-4}$	$1.50\cdot10^{-4}$	$6.92\cdot10^{-4}$
	$^{239+240}Pu$	$2.01\cdot10^{-4}$	$0.99\cdot10^{-4}$	$3.04\cdot10^{-4}$
Liver	^{238}Pu	$1.50\cdot10^{-4}$	$0.82\cdot10^{-4}$	$2.78\cdot10^{-4}$
	$^{239+240Pu}$	$0.83\cdot10^{-4}$	$0.60\cdot10^{-4}$	$1.06\cdot10^{-4}$
Muscle	^{238}Pu	$1.40\cdot10^{-4}$	$0.45\cdot10^{-4}$	$4.00\cdot10^{-4}$
	$^{239+240}Pu$	$0.48\cdot10^{-4}$	-	-

This would yield only $1.71 \cdot 10^{-6}$% (muscles) and $7.18 \cdot 10^{-6}$% (liver and kidney) of the total annual effective dose from natural sources [65]. This indicates that there is no radiological risk coming from plutonium radionuclides contained in deer meat for the population.

Conclusions

Isotopes of ^{238}U and ^{234}U are accumulated in the tissues and organs of deer from northern Poland, but do not pose any radiological threat to humans with regard to consumption of game meat at levels characteristic to Poland. At the mean consumption rate of game meat (0.08 kg annually per capita in Poland), and assuming that game meat = deer meat, it was calculated that game meat would cause an annual radiation dose of only $9.9 \cdot 10^{-6}$-$4.16 \cdot 10^{-5}$ μSv. Plutonium in tissues of deer from northern Poland also does not pose any threat to potential consumers, as it could cause radiation doses of $0.15 \cdot 10^{-4}$–$0.48 \cdot 10^{-4}$ μSv. The concentration of ^{238}Pu and $^{239+240}$Pu in deer tissues from northern Poland are generally higher than those in human tissues, but lower than in the tissues of the reindeer or caribou (*R. t. caribou*) [1, 44, 45, 74, 75].

The concentrations of uranium and plutonium in liver, muscle and kidney of deer did not depend on age, sex, or species of animals, nor the location from which they were hunted. Differences in the amounts uranium and plutonium accumulated in the tissues and organs of particular specimens could depend on individual food preferences, habitat, and medical condition. Plutonium exposure was equally distributed in the regions of northern Poland and tissues of wild animals reflect its background level and accumulate independently in all analyzed tissues at different levels.

The contents of uranium and plutonium in tissues and organs of deer from northern Poland are rather low, but the examined tissues can be used to monitor the environment and deliver information about background radiation levels.

Acknowledgements

The authors would like to thank the Ministry of Sciences and Higher Education for financial support of this work under grant Nos. DS/8460-4-0176-0 and BW/8000-5-0249-9.

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