Bioaccumulation of polonium ^{210}Po in cats' hair, taking into account potential factors influencing changes in its concentration

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Abstract

The main aim of this study was to determine the bioaccumulation of ^{210}Po in the hair of various cat breeds and an attempt to interpret whether the following factors, such as: breed, length of hair, gender, age, place of living or residence, weight, type of food consumed, taking medications, origin taking into account the structural division of Poland into voivodeships and physiological processes such as pregnancy and lactation have a significant influence on the concentration of this radionuclide. The obtained results show that the factors such as breed, length of hair, living of the cat in a given voivodeship and the type of food served influence the degree of ^{210}Po bioaccumulation.

Keywords ^{210}Po · Cat's hair · Radioisotopes · Kruskal–Wallis ANOVA

Introduction

Ionizing radiation is widely present on Earth. The average annual effective dose from natural sources in Poland equals 2.43 mSv. 49.4% of the background dose is derived from the radioactive gas radon, 19.1% from gamma rays and 31.5% from other sources such as cosmic rays and in-body radionuclides [7]. ^{210}Po is an interesting radioactive element due to its high radiotoxic properties. Polonium and radon are two natural radioactive materials delivering the highest natural dose to organisms [14]. There are many sources of ^{210}Po in the atmosphere, but releasing from the surface ^{222}Rn formed from ^{226}Ra , is the main one. ^{226}Ra is a decay product of uranium which is present in almost all rocks and soils formed from rocks. Another source of polonium is precipitation such as rain, snow, and atmospheric dust [22]. ^{210}Po has a 138-day half-life ($T_{1/2} = 138.376$ days) and high specific activity ($1.66 \cdot 10^{14} \text{ Bq g}^{-1}$). ^{210}Po decays into a ^{206}Pb and emits an alpha particle. Natural radiation brings many advantages in different life areas. It is used in biology, astronomy, food preservation and medicine for diagnosis, treatment, and research [15]. Despite many advantages, radiation and radioisotopes may cause damages to different organisms,

so it is important to constantly monitor radiation doses in the environment. Domestic cats are in human – animal relationships all around the world. Nowadays with a quickly growing human population which occupies more and more distant areas on the planet, cats are present on all continents and many oceanic islands. Only a few environmental factors limit their presence [16]. Anywhere they appear, cats have a huge impact on nature by preying on small mammals, birds, reptiles and amphibians. Cats were first domesticated in Egypt around 2000 BC. They were brought to Great Britain by 300 AD by the Romans, and spread worldwide by European colonists [8]. Cats were mainly domesticated in order to control pests such as mice, rats and snakes. Only recently they have started to be bred due to their beauty [6]. Hair is a good material to analyze, it is easy to collect and store. Moreover, sampling is non-invasive and non-lethal for cats. Depending on cat breed, hair may be different in many aspects (long, short, curly, silky or rough). Despite of all external differences the main structure of mammal's hair is the same. There are three layers: an outermost cuticle, an inner cortex, and a central core or medulla layers [1]. The hair consists of 45% carbon, 7% hydrogen, 28% oxygen, 15% nitrogen and 5% sulphur. Under normal conditions it contains 20–220 ppm Fe, 10–20 ppm Cu, 190 ppm Zn and 0.6 ppm I, the water content is about 12% at room temperature and it is predominantly composed of keratin, which is a protein rich in cysteine sulfhydryl (thiol) groups with binding affinity for various metals [14, 25]. Examination of

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dog's fur showed that ^{210}Po activity concentrations in hair reflected their content in the surroundings [23]. Studying animals' hair instead of blood, urine or feces from analytical and hygienic points of view is a huge advantage. Domestic animals have long been an important research model and are considered to be human-related. They share many physiological and biochemical characteristics with man and develop many of the same diseases, especially immunological syndromes [10, 11]. Metals trace in cat's organism could impact the same mechanisms that influence human health [11].

Many factors such as size and weight may potentially affect the bioaccumulation of metals within mammal's taxa [19]. A number of factors which effect on metal accumulation in mammals are reported in the literature. They can be divided into two basic categories: biotic (i.e. species, sex, age, nutrition, tissue sampled, metabolism) and abiotic (temperature, season, location including: regional variation due to local metal contamination and natural geological differences) [17].

The idea behind this study was to estimate ^{210}Po concentration in cat's hair and reach conclusions based on the average polonium concentration and statistical methods. Hair samples of 18 cat's breeds were taken from cats living in different areas of Poland. The objective of this study was to investigate if the breed, location, age, hair length, body weight, nutrition, and drugs are correlated with ^{210}Po concentration in hair using this non-lethal sampling technique. In general, hair can reflect an internal contamination and may help to assess the environmental levels of certain radionuclides. They are also a non-invasive indicator of metal exposure for highly radiotoxic, naturally occurring ^{210}Po [23, 24].

Materials and methods

Hair samples from cats were obtained in the process of brushing the animals. The term fur is generally confined to mammals with very thick body hair. Humans have sparse body hair, so it's usually not called fur. With cats, you will often see body hair called fur. With some "hairless" breeds, such as the sphynx, the short, downy stuff that is almost invisible is usually called "hair." In total, 339 samples of cat hair were collected for testing, which came from the various provinces of Poland. The average weight of the analyzed sample ranged from 0.3 to 5 g. General information on race, sex, age, food type, weight, place of residence, stay and any medication administered was collected from the animal owners. The following cat breeds were tested: the Domestic cat, the Ragdoll cat, the Scottish Fold cat, the Cornish Rex cat, the Neva Masquarade cat, the Devon Rex cat, the Selkirk Rex cat, the British Shorthair cat, the Norwegian Forest cat, the Maine Coon cat, the Persian cat, the Russian Blue cat,

the Siberian cat, the Somali cat, the Nebulug cat, the Angora cat, The Bengal cat and the Birman cat.

All samples were spiked with 30 μl (11.712 mBq/ml) ^{209}Po . The analyzed samples of cat hair were mineralized with the use of concentrated hot nitric acid in a closed system, and then the sample was prepared in the chloride form with concentrated hydrochloric acid. After evaporation, the dry residue was dissolved with 0.5 M HCl and filtered under reduced pressure. A little ascorbic acid was then added to the sample to reduce Fe^{3+} ions to Fe^{2+} ions. In order to determine the polonium in the studied biological material, its spontaneous electrolytic deposition ability on silver plaque was used. The prepared solution was analyzed in the teflon vessel, at the bottom of which there was a silver plaque with an active diameter of 20 mm. The electroplating of polonium was carried out at 90°C for 4 h, the sample being stirred all the time with the use of glass agitators. The measurement of polonium activity in the tested samples of cat fur was made using the Canaberra-Packard alpha spectrometer (USA). This spectrometer is made of semiconductor silicon detectors with a surface barrier with an active surface of 300 mm². The detectors used in the designation of the tested samples are silicon diodes with a thin contact layer of sputtered gold—on the "n" layer in an amount of about 40 $\mu\text{g}/\text{cm}^2$. The measurement of polonium activity in the analyzed samples of cat fur lasted about 5 days (in the case of samples with very low weights up to 2 weeks). The average recovery of ^{210}Po polonium in the analyzed biological material ranged from 79 to 98%. Statistical significance was calculated by the Kruskal–Wallis one-way analysis of variance test, which is a non-parametric test to compare samples from two or more groups of independent observation [18]. We selected this test because it doesn't require the groups to be normally distributed and is more stable to outliers. p values < 0.05 were considered as significant. To pinpoint which specific means are significant from the others we decided to use post-hoc non-parametric Dunn's Multiple Comparison test [12]. To visualize, the data results are plotted (Figs. 1, 2, 3, 4).

The results

The main aim of this study was to determine the bioaccumulation of ^{210}Po in the hair of various cat breeds and an attempt to interpret whether the following factors, such as: breed, the length of the hair (short-haired, semi-long, long-haired), gender, age, place of living (home, outside the home), place of residence (village, city), weight, type of food consumed (dry, wet, mixed, BARF), taking medications, origin (taking into account the structural division of Poland into voivodeships) and pregnancy or lactation (only for Devon Rex cats) have a significant influence on the concentration of this radionuclide. The research was carried out

Fig.1 ^{210}Po concentration in analyzed breed groups **Fig.2** ^{210}Po concentration in analyzed hair length groups

on samples from 18 acquired cat breeds. A total of 339 cat hair samples were analyzed, and the concentration of ^{210}Po

presented in the experimental part is the mean value of two sub-samples. The subject of the research were samples of

Fig.3 ^{210}Po concentration in analyzed food groups

Fig.4 ^{210}Po concentration in analyzed province groups

purebred cat hair obtained by brushing animals from their owners. A large part of the hair samples of purebred cats, especially rare ones (e.g. Birman, Nebelung and Turkish Angora), were obtained by participating in thoroughbred cat shows, e.g. in the international cat show in Gdańsk. The mean concentration of ^{210}Po in the cat hair samples ranged from 0.208 ± 0.021 mBq/g to 35.232 ± 1.056 mBq/g (Table 1). The highest concentration of the determined radionuclide was recorded in a 7-year-old Somali cat living in a city in the Lesser Poland voivodeship with a limited possibility of leaving the house and eating only BARF food. The lowest concentration of the analyzed radionuclide was measured in a 4.5-year-old female Siberian cat, living in a town in the Pomeranian Voivodeship, who did not leave the house and was fed both wet and dry food.

Breed

The mean concentration of ^{210}Po in the coat of individual cat breeds was respectively: 3.395 ± 0.313 mBq/g for ragdoll cats; 3.526 ± 0.364 mBq/g for the domestic cat (*Felis catus*); 4.466 ± 0.183 mBq/g for Scottish Fold cats; 1.001 ± 0.081 mBq/g for Russian Blue cats; 6.350 ± 0.207 mBq/g for Cornish Rex cats; 5.549 ± 0.709 mBq/g for British Shorthair cats; 2.590 ± 0.184 mBq/g for the breed of Siberian cats; 6.731 ± 0.297 mBq/g for Neva Masquerade cats; 8.702 ± 0.923 mBq/g for Norwegian Forest cats; 7.787 ± 0.861 mBq/g for a Persian cat; 9.010 ± 1.096 mBq/g for maine coon cats; 22.488 ± 0.757 mBq/g for the Somali cat breed; 3.940 ± 0.378 mBq/g for a Devon Rex cat; 3.515 ± 0.247 mBq/g for Selkirk Rex cats; 21.680 ± 0.087 mBq/g for Turkish Angora cats; 19.005 ± 0.087 mBq/g for a long haired Bengal cat; 3.056 ± 0.033 mBq/g for the Birman cats and 0.895 ± 0.042 mBq/g for the Nebelung cat breed (Table 1). For the 0.05 significance level, the p value is 0.002, which indicates statistically significant differences in polonium concentration, depending on a breed. The post-hoc test shows that there are significant differences in case of such breeds as Turkish Angora, Somali and Bengal long-haired cat ($p=0.000$). These breeds are characterized by a significantly higher concentration of polonium isotope compared to others (Fig. 1). The highest concentration of ^{210}Po was observed in the hair of Somali cats, a relatively high and comparable concentration was also measured in samples of the hair of the Turkish Angora and Bengal cats. All these cats are of hair long-hair hair type and have an active lifestyle. Half-long and fluffy hair of all these cats, sometimes waterproof, characteristic tufts of hair appearing both in the ears and between the fingertips, and a protruding ruff,—this all favors a greater bioaccumulation of ^{210}Po compared to short-haired cats, which do not have the other elements

mentioned above. The concentration of the measured radionuclide decreases gradually with the length of the hair coat. The average concentration of ^{210}Po in the hair of long-haired cats was nearly 9 times higher than in shorthair cats.

Type of hair

The hair cover in most mammals protects against negative environmental factors and has a thermoregulatory function. The hair of each breed is distinguished by its characteristic length, texture, density, etc. In long-haired and semi-long hair cats, local hair thickening can be observed around the withers, abdomen, limbs or tail. The p value (0.007), which is lower than the significance level (0.05), also indicates differences in isotope concentration depending on hair length. Dunn's test indicated relevant differences in two groups: short and long coat ($p=0.001$). For long-haired group ^{210}Po concentration is significantly higher (Fig. 2). The highest mean concentration of ^{210}Po was measured in the hair of long-haired cats (18.689 ± 0.440 mBq/g), while slightly lower in the hair of semi-longhair cats (5.760 ± 0.499 mBq/g). The lowest concentration of the analyzed nuclide was observed in the hair of short-haired cats (3.940 ± 0.381 mBq/g) (Table 1). In long-haired and semi-long-haired animals, local hair thickeners, such as ruff or hair between the fingertips, often appear, which are not found in short-haired cats. It can therefore be concluded that the "long fur" gene shared by both longhair and semi-longhair cats is important for the bioaccumulation of radionuclides.

Gender

Nearly 3 times higher concentration of the analyzed nuclide was measured in the hair of males (8.911 ± 0.467 mBq/g) than in the hair of female cats (3.221 ± 0.207 mBq/g). This suggests that the degree of bioaccumulation of ^{210}Po in the hair coat may be related to the sex factor. However, Kruskal–Wallis test showed slight statistically significant differences among analyzed groups ($p=0.073$). Male cats are generally heavier. Male cats, compared to female cats, have a lower tendency to accumulate body fat in relation to muscle tissue. However, it should be remembered that the degree of bioaccumulation of polonium ^{210}Po in cat hair may be closely related to animal feed, possibility of going out into the fresh air, etc., and these factors are not included in this statement.

Age

The concentration of ^{210}Po in cat hair samples, depending on the age of the animals, ranged from 0.208 ± 0.021 mBq/g to 35.232 ± 1.056 mBq/g. The highest average concentration

Table 1 The ^{210}Po concentration in cat's hair samples

	Average [Bq kg^{-1}]	Median [Bq kg^{-1}]	Min [Bq kg^{-1}]	Max [Bq kg^{-1}]
<i>Race</i>				
Somali	22.488 ± 0.757	19.897 ± 0.238	13.021 ± 0.041	35.232 ± 1.056
Turkish Angora	21.680 ± 0.087	21.109 ± 0.102	18.276 ± 0.105	24.817 ± 0.054
Bengal long-haired	19.005 ± 0.087	18.788 ± 0.091	16.521 ± 0.112	19.100 ± 0.029
Maine Coon	9.010 ± 1.096	7.068 ± 0.800	1.896 ± 0.263	15.812 ± 0.426
Norwegian Forest	8.702 ± 0.923	6.878 ± 0.443	0.877 ± 0.105	25.907 ± 2.993
Persian	7.787 ± 0.861	4.554 ± 0.495	0.718 ± 0.056	20.335 ± 2.625
Siberian Neva	6.731 ± 0.297	4.608 ± 0.225	0.851 ± 0.082	27.357 ± 0.616
Cornish Rex	6.350 ± 0.207	6.121 ± 0.056	5.632 ± 0.805	7.211 ± 0.078
British shorthair	5.549 ± 0.709	3.115 ± 0.322	0.479 ± 0.042	19.572 ± 3.699
Scottish Fold	4.466 ± 0.183	3.671 ± 0.162	3.151 ± 0.162	7.281 ± 0.414
Devon Rex	3.940 ± 0.378	2.504 ± 0.375	1.103 ± 0.110	11.241 ± 0.89
Felis catus	3.526 ± 0.364	1.951 ± 0.204	0.208 ± 0.021	13.905 ± 1.858
Selkirk rex	3.515 ± 0.247	3.415 ± 0.278	1.603 ± 0.101	5.199 ± 0.105
Ragdoll	3.395 ± 0.313	3.799 ± 0.288	1.063 ± 0.054	5.998 ± 0.202
Sacred Birman	3.056 ± 0.033	3.003 ± 0.027	2.008 ± 0.009	4.128 ± 0.033
Siberian	2.590 ± 0.184	2.147 ± 0.145	0.687 ± 0.059	7.071 ± 0.272
Russian Blue	1.001 ± 0.081	0.971 ± 0.068	0.612 ± 0.033	1.507 ± 0.117
Nebelung	0.895 ± 0.042	0.999 ± 0.040	0.540 ± 0.056	1.041 ± 0.024
<i>Type of hair</i>				
Short-hair	3.940 ± 0.381	2.674 ± 0.208	0.208 ± 0.021	19.572 ± 3.699
Semi longhair	5.76 ± 0.499	3.998 ± 0.237	0.540 ± 0.056	27.357 ± 0.616
Longhair	18.689 ± 0.440	19.041 ± 0.106	0.718 ± 0.056	35.232 ± 1.056
<i>Sex</i>				
Male	8.911 ± 0.467	5.199 ± 0.204	0.551 ± 0.077	35.232 ± 1.056
Female	3.221 ± 0.207	5.897 ± 0.396	0.208 ± 0.021	28.943 ± 0.139
<i>Diet</i>				
Dry	3.366 ± 0.302	2.431 ± 0.171	0.624 ± 0.076	13.19 ± 1.18
Wet	7.041 ± 0.984	3.525 ± 0.374	0.749 ± 0.120	25.907 ± 2.993
Mix	6.086 ± 0.414	3.44 ± 0.219	0.208 ± 0.021	27.357 ± 0.616
BARF	16.594 ± 0.387	18.788 ± 0.105	3.601 ± 0.053	35.232 ± 1.056
<i>Place of residence</i>				
House	6.613 ± 0.415	3.535 ± 0.179	0.208 ± 0.021	35.232 ± 1.056
House + Out	10.314 ± 0.518	7.071 ± 0.279	0.971 ± 0.068	33.349 ± 1.068
Shelter	1.043 ± 0.099	0.766 ± 0.076	0.624 ± 0.076	1.917 ± 0.171
<i>Voivodeship</i>				
Greater Poland	4.928 ± 0.315	5.623 ± 0.247	1.393 ± 0.16	7.071 ± 0.272
Kuyavian-Pomeranian	6.785 ± 0.356	4.684 ± 0.190	0.208 ± 0.021	22.874 ± 0.109
Lesser Poland	12.985 ± 0.355	6.121 ± 0.208	0.612 ± 0.033	35.232 ± 1.056
Łódź	19.154 ± 0.337	18.982 ± 0.102	8.309 ± 0.237	27.357 ± 0.616
Lublin	3.056 ± 0.033	3.003 ± 0.027	2.008 ± 0.009	4.128 ± 0.033
Lubusz	10.890 ± 0.314	7.281 ± 0.414	4.863 ± 0.433	20.527 ± 0.095
Masovian	16.296 ± 0.651	18.652 ± 0.141	3.525 ± 0.374	25.907 ± 2.993
Pomeranian	4.512 ± 0.439	3.039 ± 0.213	0.416 ± 0.055	23.753 ± 3.394
Podkarpackie	3.940 ± 0.378	2.504 ± 0.375	1.103 ± 0.110	11.241 ± 0.890
Warmian-Masurian	12.371 ± 0.993	13.021 ± 0.105	0.877 ± 0.105	19.812 ± 0.103
West-Pomeranian	6.218 ± 0.671	1.027 ± 0.067	0.540 ± 0.056	20.335 ± 2.625
<i>Weight</i>				
Less than 2.5 kg	4.753 ± 0.220	2.218 ± 0.171	0.416 ± 0.055	22.874 ± 0.109
2.5 to 5 kg	6.971 ± 0.354	3.764 ± 0.170	0.208 ± 0.021	28.943 ± 0.139
5 to 7.5 kg	8.241 ± 0.555	4.837 ± 0.256	0.479 ± 0.042	35.232 ± 1.056

Table 1 (continued)

	Average [Bq kg ⁻¹]	Median [Bq kg ⁻¹]	Min [Bq kg ⁻¹]	Max [Bq kg ⁻¹]
7.5 and more	4.661 ± 0.428	2.315 ± 0.242	0.551 ± 0.077	15.812 ± 0.426
<i>Place of living</i>				
Village	7.711 ± 0.405	7.139 ± 0.218	0.971 ± 0.068	33.349 ± 1.068
City	4.904 ± 0.468	3.545 ± 0.443	0.208 ± 0.021	35.232 ± 1.056
<i>Additional remarks</i>				
Without drugs	5.089 ± 0.223	4.128 ± 0.033	0.208 ± 0.021	35.232 ± 1.056
Drugs	8.830 ± 0.338	8.571 ± 0.894	0.830 ± 0.092	15.812 ± 0.426
Pregnant cats	2.271 ± 0.224	2.271 ± 0.365	1.906 ± 0.462	2.636 ± 0.242
Nursing cats	2.894 ± 0.301	3.790 ± 0.397	1.103 ± 0.110	3.790 ± 0.397
<i>Age</i>				
To 3 years	7.482 ± 0.806	4.458 ± 0.095	0.208 ± 0.021	28.943 ± 0.044
From 3 to 6 years	9.465 ± 0.728	4.837 ± 0.256	0.491 ± 0.333	33.349 ± 1.068
From 6 to 9 years	2.760 ± 0.758	3.941 ± 0.242	0.208 ± 0.021	35.232 ± 1.056
Over 9 years	2.761 ± 0.430	1.659 ± 0.018	0.401 ± 0.036	7.945 ± 0.586

of the determined radionuclide was measured in the hair of cats between 3 and 6 years of age (9.465 ± 0.728 mBq/g), while the lowest in the hair of cats between 6 and 9 years (2.760 ± 0.758 mBq/g) and over 9 years of age (2.761 ± 0.430 mBq/g) (Table 1). But used Kruskal–Wallis test do not showed statistically significance differences in polonium isotope concentration among analyzed age groups ($p=0.085$). Older cats are usually less active than younger animals, thus they go out to the fresh air less, where, as indicated in the theoretical part of the work, there are many factors that can significantly contribute to the accumulation of ^{210}Po in the hair. The diet of older and younger animals is an important component, which may also affect greater bioaccumulation of polonium nuclide in the hair of younger animals.

Place of residence and living

The average concentration of the determined radionuclide in the hair of indoor cats (those staying only at home) was 6.613 ± 0.415 mBq/g, while in the hair of animals that come out and living outside (10.314 ± 0.518 mBq/g) (Table 1). The obtained results do not differ significantly, although the higher concentration measured in the hair of cats going outside may be related to a lot of meteorological factors—phenomena occurring in the atmospheric air, such as rainfall, snowfall, drizzle or wind.

Kruskal–Wallis test showed only slight statistically significant differences between these groups ($p=0.068$), but in the case of significance level 0.05 they could not be treated as statistically significant.

A higher concentration of the analyzed radionuclide was measured in the hair of animals living in the countryside (7.711 ± 0.405 mBq/g), while a lower concentration was observed in the hair of cats living in cities

(4.904 ± 0.468 mBq/g) (Table 1). Most of the cats living in the countryside had unrestricted access to move freely outside the home, while the cats that lived in the city had limited access (usually a garden, balcony, terrace or a short walk, as these animals are reluctant to walk on a leash). Cats living in rural areas mostly have unlimited possibility to move in the fresh air, therefore they are characterized by a great curiosity about the world and developed strongly hunter instinct. Cats living in urban areas often have a limited ability to freely go outside the home, most often they are animals bred for exhibition or demonstration purposes. Indoor cats are not directly exposed to atmospheric radionuclides. Moreover, it is known that the rapid development of technology and the changes taking place in the modern world have a large impact on the natural environment. One of the main sources of pollution of the biosphere are industrial plants that emit both gaseous and dust substances as well as substances containing various types of toxic substances. The spread of radioactive isotopes is one of the dangerous effects of the development of civilization and industry. Dust contained in the atmosphere, along with radionuclides, falls on the above-ground parts of plants and into the soil. They are taken by plant roots or animals and thus incorporated into the food chain. The conducted research showed that cats living in the countryside and cats that leave the house have a higher concentration of ^{210}Po in the coat. This allows for the conclusion that the cat's place of residence and existence has a large impact on the bioaccumulation of radionuclides in the hair coat of animals, if only because cats who do not leave the house are protected against exposure to environmental radionuclides or natural background radiation. The source of radionuclides in the natural environment in the emission area is both polluted soil and the atmosphere. Radionuclides can come from two types of sources: natural and anthropogenic. The natural origin of radionuclides is associated with volcanic eruption,

rock weathering, soil-forming processes, forest fires or ocean evaporation. The sources of anthropogenic environmental pollution include: fuel combustion, both in power plants and combined heat and power plants, as well as district or local heat plants, home furnaces, non-ferrous and iron metallurgy, waste incineration and transport [2–5, 13].

Weight

The highest concentration of ^{210}Po was measured in the hair of cats whose weight range between 5 to 7.5 kg (8.241 ± 0.555 mBq/g) and between 2.5 to 5 kg (6.971 ± 0.354 mBq/g), while the lowest in the hair of heavier animals, above 7.5 kg (4.661 ± 0.428 mBq/g). The weight of a cat depends largely on the way it is fed, metabolism and activity, which is closely related to the age of the cat. Young cats show a greater willingness to play and explore the surrounding space, so they are usually slimmer. With increasing age, the cat becomes more lethargic and its body weight can increase by up to 20%. As a result of these changes, the bioavailability of polonium increases, which carries the risk of its higher toxicity in relation to animals.

Diet

The obtained results of the content of the analyzed nuclide, depending on the type of the food served, are varied and may indicate that this factor significantly influences the level of bioaccumulation. The highest concentration of ^{210}Po was recorded in the hair of animals fed on BARF food (Biologically Appropriate Raw Food) (food based on raw meat) (16.594 ± 0.387 mBq/g), while the lowest in the hair of cats fed on dry food (3.366 ± 0.302 mBq/g). Applied Kruskal–Wallis ANOVA showed statistically relevant differences between these groups ($p=0.014$) (Fig. 3). The BARF food, as previously indicated, is based on raw meat, which is to some extent composed of, inter alia, water. As shown by previous scientific research, ^{210}Po easily accumulates in both water and raw meat. A similar dependence also applies to the feeding of animals with wet food, in the form of cans, meat in jelly, pates, etc., or mixed, which also to some extent consist of water and pieces of raw material.

Medications

The mean concentration of ^{210}Po in the hair of cats that did not take medications is almost half higher (8.830 ± 0.388 mBq/g) than in cats that did use them (5.089 ± 0.223 mBq/g) (Table 1). The highest concentration of the analyzed radionuclide was measured in the hair of a cat that was taking medication (15.812 ± 0.426 mBq/g). Due to such a diverse and unequal number of samples, as well as the lack of data on the length of time in which cats

took a given pharmaceutical, it is difficult to conclusively determine whether the administration of drugs to animals has any effect on the bioavailability of ^{210}Po .

Administrative division into voivodeships

The dependence of the average concentration of ^{210}Po in cat hair given administrative division into voivodeships was checked in samples obtained from 11 voivodeships. Applied statistical test showed statistically significant differences between another voivodeships ($p=0.005$). Dunn's test pinpointed relevant differences in two voivodeships: Łódź and Masovian (Fig. 4). The highest average concentration of ^{210}Po was recorded in the hair of cats living in the Łódź Voivodeship (19.154 ± 0.337 mBq/g), Masovian Voivodeship (16.296 ± 0.651 mBq/g) and Lesser Poland (12.985 ± 0.355 mBq/g), while the lowest was measured in the hair of animals in the Lublin Voivodeship (3.056 ± 0.033 mBq/g) and Podkarpackie Voivodeship (3.940 ± 0.378 mBq/g) (Table 1). The highest maximum concentration of ^{210}Po was measured in the hair sample of a cat from the Lesser Poland voivodeship (35.232 ± 1.098 mBq/g), which may probably be associated with much higher air pollution in this voivodeship due to much greater industrialization compared to other voivodeships. The source of radionuclides in the vicinity of metallurgical plants is the atmosphere, namely the precipitation of dust emitted into the atmosphere. The amount of radionuclides retained on the hair of cats depends primarily on the type of surface on which the dust from the emissions settles. The level of pollution is also determined by factors such as the distance of the studied crops from the emission of pollutants, as well as weather conditions, primarily the amount of precipitation, and the direction, strength and frequency of winds blowing in the emission area [9, 20]. Relatively high concentrations of ^{210}Po were also recorded in the Warmian-Masurian voivodeship (12.371 ± 0.993 mBq/g), but most of the samples of Maine Coon hair were obtained from this part of our country, which, due to the length of the coat, were characterized by a high concentration of the analyzed radionuclide. The Lesser Poland Voivodeship is located in a basin where air exchange is weaker than, for example, in Pomeranian region located by the sea, where the exchange is more fluid. Besides, due to the existing mines, it is one of the most industrialized regions of Poland. The basis of the industry of Łódź Industrial District is, in turn, the chemical, textile, electrical machinery and leather and footwear industries—the main source of air pollution in the province. Masovian voivodeship is the anthropogenic emission from the household sector (surface emission), from communication (line emission) and from industrial activity (point emission). This region is the largest in terms of area, population and employment. The second largest industrial district in

Poland also functions in this region. Apart from the Warsaw district, the industry of this district is co-created by smaller industrial centers, in former voivodeship cities, with Plock and Radom playing a slightly greater role among them. The largest industrial enterprises in Masovian voivodeship most often represent the food industry (approx. 34%) and the electromechanical industry (approx. 21%), followed by the power and wood industry.

Pregnancy and lactation

With regard to the biological factor, only the hair of Devon Rex cats was tested, as no information was obtained about such physiological processes of other cats. The Devon Rex cats included both nursing and pregnant cats. The concentration of ^{210}Po in the hair of nursing cats was slightly higher (2.894 ± 0.301 mBq/g) than in the hair of pregnant cats (2.271 ± 0.224 mBq/g). The slight difference obtained is small and is probably related to the production of food by nursing cats. During pregnancy, the cat's behavior changes as she becomes more lethargic, sluggish, gets tired quickly and sleeps more. This condition can of course vary depending on the general condition of the female cat and the number of fetuses developing in her. A female cat in an advanced stage of pregnancy sometimes eats up to twice as much food as it does on a daily basis. The most important thing in a nursing cat's diet is to provide her with high-energy food and fresh meat. It is estimated that during lactation the demand for food increases fourfold in cats. Both of these physiological processes depend mainly on the appropriate food, and studies taking into account the cat's food showed that significant differences were found only between the type of food (wet, dry, BARF). In general, pregnant or lactating cats are given more food, and although the analysis carried out for the purposes of this study showed that some dependence can be concluded in relation to the weight of the cat, the changed physiology of cats is relatively short-lived, so it does not significantly affect the bioaccumulation of the analyzed radionuclide. During pregnancy and lactation, cats have a much higher energy requirement than other adult cats, therefore they can be fed with free access to food. Kittens accumulate adipose tissue from the beginning of pregnancy, as it is the energy reserve for the lactation period. A cat's pregnancy usually lasts from 63 to 65 days, and lactation from 8 to 12 weeks. In females, unlike in bitches, body weight increases linearly from the beginning of pregnancy due to the accumulation of extra fat. Before the birth itself, your body weight may be 40% higher than before pregnancy. However, this is a relatively short time in relation to the average cat's life span and perhaps because of this these physiological factors do not determine the degree of bioaccumulation of the analyzed radionuclide.

Conclusions

The main aim of this study was to determine the bioaccumulation of ^{210}Po in the hair of various cat breeds and an attempt to interpret whether the following factors, such as: breed, the length of the hair, gender, age, place of living or residence, weight, type of food consumed, taking medications, origin and pregnancy or lactation have a significant influence on the concentration of this radionuclide. The conducted research did not allow to unequivocally determine whether the sex of the animals, weight and age have a significant influence on the concentration of ^{210}Po . The degree of bioaccumulation of ^{210}Po in the hair of cats is independent of physiological processes such as pregnancy or feeding. The conducted studies have shown that the degree of bioavailability of ^{210}Po is not affected by medications administered to animals, although any differences were difficult to observe due to the range of cats that were given drugs and cats that were not sick. It seems, however, that the type of drug taken, the duration of its intake or the size of doses in the body of sick cats could cause the concentration of the analyzed radionuclide to be varied and it would be difficult to prove that this factor may have a potential impact on the concentration of ^{210}Po .

The type of food consumed also had a significant impact on the concentration of ^{210}Po in the cat's hair coat. The analysis of the tested biological material showed that the concentration of the analyzed radionuclide in the hair of the tested animals consuming raw meat (16.594 ± 0.387 mBq/g) and wet food (7.041 ± 0.984 mBq/g) was much higher than the average content of ^{210}Po in the hair of cats fed dry food (3.366 ± 0.302 mBq/g). The BARF diet is becoming more and more popular among animal lovers. Proponents of this method of nutrition believe that it is the most appropriate food for their four-legged pets. The main advantages of this diet are, above all, the complete absence of preservatives, high digestibility of the food and the content of vitamins, fatty acids, micro- and macroelements. The basic assumption of this diet is the administration of meals composed of natural, raw ingredients (meat, bones and offal), which means that the digestive tract and the entire physiology of animals do not undergo any changes in the process of domestication. The nutritional needs of animals are therefore similar to those of their close relatives, that is, wild animals. Animal products can be supplemented with a small addition of vegetables and fruits. Previous studies have shown that meat products are characterized by a high degree of bioaccumulation of ^{210}Po [21].

All cats, except for individual features such as the shape of the head or the length of the hair, have a similar size and appearance. Nevertheless, it seems that cat breed may have an influence on the degree of bioaccumulation of ^{210}Po in the coat. It is difficult to confirm it unequivocally due to the fact

that next to the cat breed, the long, semi-long or short hair gene is very often present. Certain features, such as cat's ruff, i.e. hair located around the cat's neck, or a kind of collar, the so-called cat's "pants", ie thick and long fur growing under the tail and on the hind legs, and additional hair between the paws of animals, are characteristic of only some cat breeds.

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Declarations

Conflicts of interest There are no conflicts to declare.

Human and animal rights The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to and the appropriate ethical review committee approval has been received. The authors confirm that they have followed EU standards for the protection of animals used for scientific purposes.

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References

1. Beernaert J, Schiers J, Leirs H, Blust R, Van Hagen R (2007) Non-destructive pollution exposure assessment by means of wood mice hair. *Environ Pollut* 147:443–451. <https://doi.org/10.1016/j.envpol.2006.04.025>
2. Boryło A, Skwarzec B, Olszewski G (2012) The radiochemical contamination (^{210}Po and ^{238}U) of zone around phosphogypsum waste heap in Wiślinka (northern Poland). *J Environ Sci Health Part A Toxic/Hazard Subst Environ Eng* 47(5):675–687. <https://doi.org/10.1080/10934529.2012.660052>
3. Boryło A, Nowicki W, Olszewski G, Skwarzec B (2012) Polonium (^{210}Po), uranium (^{234}U , ^{238}U) isotopes and trace metals in mosses from Sobieszewo Island, northern Poland. *J Environ Sci Health Part A Toxic/Hazard Subst Environ Eng* 47(12):1831–1842. <https://doi.org/10.1080/10934529.2012.689549>
4. Boryło A, Nowicki W, Skwarzec B (2013) The concentration of trace metals in selected cultivated and meadow plants collected from the vicinity of a phosphogypsum stack in northern Poland. *Pol J Environ Stud* 22(2):347–356
5. Boryło A, Olszewski G, Skwarzec B (2013) A study on lead (^{210}Pb) and polonium (^{210}Po) contamination from phosphogypsum in the environment of Wiślinka (northern Poland). *Environ Sci Process Impacts* 15:1622–1628. <https://doi.org/10.1039/c3em00118k>
6. Bradshaw KWS (1992) The cat: domestication and biology. In: Bradshaw KWS (ed) *The behavior of the domestic cat*. CAB International, Wallingford, Oxon, pp 1–15
7. Central Statistical Office (2019) Department of Spatial and Environmental Research, Environmental Protection
8. Coleman JS, Temple SA, Craven SR (1997) Cats and wildlife: a conservation dilemma. Misc. Publications, USDA Cooperative Extension, Univ. of Wisconsin, Wisconsin, p 6
9. Damek-Poprawa M, Sawicka-Kapusta K (2004) Histopathological changes in the liver, kidneys, and testes of bank voles environmentally exposed to heavy metal emissions from the steelworks and zinc smelter in Poland. *Environ Res* 96(1):72–78. <https://doi.org/10.1016/j.envres.2004.02.003>
10. Dunlap KL, Reynolds AJ, Bowers PM, Duffy LK (2007) Hair analysis in sled dogs (*Canis lupus familiaris*) illustrates a linkage of mercury exposure along the Yukon River with human subsistence food systems. *Sci Total Environ* 385:80–85. <https://doi.org/10.1016/j.scitotenv.2007.07.002>
11. Dunlap KL, Reynolds AJ, Duffy LK (2006) Total antioxidant power in sled dogs supplemented with blueberries and the comparison of blood parameters associated with exercise. *Comp Biochem Physiol Part A: Mol Integr Physiol* 143(4):429–434. <https://doi.org/10.1016/j.cbpa.2005.09.007>
12. Dunn OJ (1964) Multiple comparisons using rank sums. *Technometrics* 6:241–252
13. Fenech M (2000) The in vivo micronucleus technique. *Mutat Res* 455:81–95
14. Holm E, Gwynn J, Zaborska A, Gäfvert T, Roos P, Henricsson F (2010) Hair and feathers as indicators of internal contamination of ^{210}Po and ^{210}Pb . Final report from the NKS-B HAIRPOL activity, NKS-217. ISBN 978-87-7893-287-7
15. International Atomic Energy Agency Vienna (2018) Radiation protection and safety in medical uses of ionizing radiation. Specific Safety Guide No. SSG-46
16. Jones E (1977) Ecology of the feral cat, *Felis calus* (L.), population at Marion Island. *Austral Wildl Res* 4:249–262
17. Martinez-Alvarez RM, Morales AE, Sanz A (2005) Antioxidant defenses in fish: biotic and abiotic factors. *Fish Biol Fish* 15:75–88
18. McDonald JH (2014) *Handbook of Biological Statistics*, 3rd edn. Sparky House Publishing, Baltimore, MA, pp 157–164
19. McLean CM, Koller CE, Rodger JC, MacFarlane GR (2009) Mammalian hair as an accumulative bioindicator of metal bioavailability in Australian terrestrial environments. *Sci Total Environ* 407:3588–3596
20. Neri M, Fucic A, Knudsen LE, Lando C, Merlo F, Bonassi S (2003) Micronuclei frequency in children exposed to environmental mutagens: a review. *Mutat Res* 544:243–254
21. Skwarzec B, Boryło A, Prucnal M, Strumińska-Parulska D (2010) Accumulation of uranium (^{234}U and ^{238}U) and plutonium ($^{239+240}\text{Pu}$) in tissues and organs of cervid in northern Poland. *Pol J Environ Stud* 19(4):771–778
22. Skwarzec B, Strumińska-Parulska D, Boryło A, Kabat K (2012) Polonium, uranium and plutonium radionuclides in aquatic and land ecosystem of Poland. *J Environ Sci Health Part A, Toxic/Hazard Subst Environ Eng* 47(3):479–496. <https://doi.org/10.1080/10934529.2012.646153>
23. Strumińska-Parulska DI, Szymańska K, Skwarzec B (2015) Determination of ^{210}Po in hair of domestic animals from Poland and Norway. *J Radioanal Nucl Chem* 306:71–78
24. Strumińska-Parulska DI, Szymańska K, Skwarzec B (2015) Radiolabel ^{210}Pb and $^{210}\text{Po}/^{210}\text{Pb}$ activity ratios in dogs' hair. *J Environ Sci Health Part A* 50:1180–1186
25. Tridico SR, Houck MM, Kirkbride KP, Smith ME, Yates BC (2014) Morphological Identification of animals hairs. *Forensic Sci Int* 238:101–107

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