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Selected aspects of caesium-137 contamination in wild boars (*Sus scrofa*)

Katarína Beňová[1], Alena Havelková[2], Petr Dvořák[3]

[1]University of Veterinary Medicine and Pharmacy in Košice, Department of Biology and Physiology, Košice, Slovakia
[2] Masaryk University, Faculty of Medicine, Department of Physiotherapy and Rehabilitation, Brno, Czech Republic
[3]University of Veterinary Sciences Brno, Faculty of Veterinary Hygiene and Ecology, Department of Biology and Wildlife Diseases, Brno, Czech Republic

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Abstract

Monitoring the activity of radionuclides in food is part of the monitoring system of foreign substances. A close correlation between gamma spectrometry determined by ^{137}Cs activity concentration in the meat and stomach wall (r = 0.984) was found in monitored Slovak wild boars with a low activity of ^{137}Cs . The transfer factors of the soil and the stomach content and the soil and the meat were approximately 0.07 at the median. The median transfer factor between the stomach content and the stomach wall is similar to that of the stomach wall and the meat (2.412 and 1.805). The mean value of ^{137}Cs activity concentration in the muscles of wild boars from the Czech Republic was 46.7 Bq·kg^{-1}. The mean value of ^{137}Cs activity concentration in the stomach wall was 23.7 Bq·kg^{-1}. The mutual correlation was r = 0.988. There was further correlation of ^{137}Cs activity concentration between the heart and the diaphragm (r = 0.977), the heart and the tongue (r = 0.902), and the heart and the lungs (r = 0.906). Based on the results from Slovakia and the Czech Republic, there is hope that it will be possible to use a sample from the stomach wall to determine the activity concentration of ^{137}Cs in meat, thereby replacing the commonly used and highly valued top side sample. In practice, monitoring soil contamination to predict the meat contamination of wild boars is more important than monitoring elements of the food chain. The potassium-caesium coefficient reached 5.57 in the muscles and 17.25 in the stomach wall.

Sus scrofa, radiocaesium, contamination by radionuclides, transfer factor

Two huge nuclear accidents have taken place in the history of mankind: Chernobyl (Ukraine, 1986) and Fukushima (Japan, 2011). These accidents released an extremely high activity of the ^{137}Cs isotope into the atmosphere (Lelieveld et al. 2012; Benova et al. 2016a). Monitoring the activity of radionuclides in food is part of the monitoring system of foreign substances (Steinhauser et al. 2014).

According to screening measurements conducted in European countries, high levels of radioactivity in the muscles were reported in wild boars from Šumava (Czech Republic) (Škrkal et al. 2005; Kouba et al. 2022) and Ravensburg (Germany) (Semizhon et al. 2009). The seasonal fluctuation of ^{137}Cs activity in meat samples of wild boars was observed in forests around the southern part of the Rhine. Studies conducted in Austria and Bavaria (Kocadag et al. 2017) focused on detecting ^{137}Cs and ^{40}K in the soil and muscles and the activity of ^{90}Sr in the bones of wild boars. The activity concentration of ^{137}Cs in the muscles ranged from 14.9 ± 1.5 Bq·kg^{-1} (Bavaria) to 4,711 ±3 77 Bq·kg^{-1} (Lower Austria).

With regard to the recurring high concentration of radiocaesium in the muscles of wild boars, this meat may represent the main source of radioactive exposure in humans. Radiocaesium gets into the muscles of wild boars through the consumption of underground fungus *Elaphomyces granulatus* (Hohmann and Huckschlag 2005; Dvořák et. al. 2010). To determine the radionuclide contamination, a top side (semimembranosus and adductor muscles) sample is taken. This represents a significant loss and deterioration of the hunted piece. The aim of this study was to determine whether or not it is possible to replace the highly valued top side muscles with another tissue. Furthermore, we observed

Address for correspondence:
Katarína Beňová
University of Veterinary Medicine and Pharmacy in Košice
Komenského 73, 041 81 Košice, Slovakia
Phone +421 915 984 681
E-mail: katarina.benova@uvlf.sk

the transfer factors between the soil, the stomach content, and the muscles. The degree of contamination is also related to the relationship between caesium and potassium determined by the potassium-caesium coefficient in the muscles and stomach wall.

Materials and Methods

This work included 25 wild boars (*Sus scrofa*) weighing 20–80 kg from various locations in Slovakia from 2017 to 2019. A sample was taken from the top side, the stomach wall, and the stomach content to determine the ^{137}Cs activity. The meat was rid of tendons and fat, and a 250–500 g sample was cut up into small pieces and placed into a 450 ml Marinelli container or a 200 ml polyethylene bottle. The stomach wall was cleaned, cut up, and placed into polyethylene bottles. The stomach content was placed into the above-mentioned measuring containers, without homogenization and according to the volume. The soil sample at the shooting location were analyzed to determine the transfer factors. The soil was first stripped of branches, stones, and leaves and then dried. A 450 ml sample was measured in a Marinelli container to determine the ^{137}Cs activity.

The calculation of transfer factors was determined for every piece and was given by the proportion of activity concentrations (Bq·kg^{-1}) between two elements of the food chain. Ten pieces were assessed separately. The meat samples of these ten pieces did not exceed the ^{137}Cs activity concentration of 10 Bq·kg^{-1} in relation to the soil activity. The transfer factors in 15 pieces where the meat samples exceeded the activity concentration of 10 Bq·kg^{-1}, were determined in relation to the stomach wall.

Thirty wild boars of 20–80 kg were hunted in the Czech Republic from 2019–2021 within the scope of two experiments. The first one (18 animals from the foothills of Šumava) was primarily used to determine the potassium-caesium coefficient in the muscles and in the stomach wall. The samples were modified in the same manner as the wild boar samples from Slovakia. The second experiment (12 wild boars) was used to observe the relationships between the contamination of individual organs, such as the tongue, lungs, heart, diaphragm, stomach wall, and the stomach content. Only those pieces in which the ^{137}Cs activity concentration was above the minimum detectable activity were selected for the correlation analysis. Seven pieces met this criterion.

The determination of ^{137}Cs and ^{40}K activity was conducted by means of gamma-spectrometric system, using HPG e GC 4018 semi-conductor detectors (40% efficiency, 1.8 to keV resolution) and HPG e GC 2020 (20% efficiency, 1.8 to keV resolution), with DSA-LX and DeskTop InSpektor evaluation units from Canberra Packard (Meriden, USA). The gamma-spectrometric system was certified by the Czech Metrology Institute Prague for Geometry, a 450 ml Marinelli beakers, and 200 ml polyethylene bottles.

The arithmetic mean, SEM, median, and maximum and minimum values were used for the statistical evaluation of the results. The numbers were rounded off to three significant figures, as is common for gamma spectrometric determination. Paired *t*-test was used to compare the results and to define the correlation coefficient (r). A P value ≤ 0.05 was considered significant.

Results

Table 1 shows the results of 25 hunted wild boars from different regions of Slovakia. The ^{137}Cs activity concentration value in the meat ranged from 0.4 to 37.2 Bq·kg^{-1} and from 0.1 to 21.0 Bq·kg^{-1} in the stomach wall.

The difference between the mean values of the ^{137}Cs activity in the meat and the stomach wall (2.95 and 1.74 Bq·kg^{-1}) was not significant. A close correlation was detected in the monitored wild boars in terms of the ^{137}Cs activity in the meat and the stomach wall

Table 1. Activity concentrations of ^{137}Cs and ^{40}K in the meat, stomach wall, and stomach content in wild boars hunted in Slovakia.

n = 25	Activity concentration ± combined standard uncertainty (Bq·kg^{-1})					
	Meat		Stomach wall		Stomach content	
	^{137}Cs	^{40}K	^{137}Cs	^{40}K	^{137}Cs	^{40}K
Mean	2.95 ± 0.59	335.00 ± 7.11	1.74 ± 0.18	245.00 ± 5.76	2.61 ± 0.82	258.00 ± 6.98
S.E.M.	1.44 ± 0.23	53.00 ± 0.70	0.82 ± 0.04	42.70 ± 0.41	1.03 ± 0.49	45.90 ± 0.72
Median	1.49 ± 0.16	421.00 ± 7.90	0.87 ± 0.14	210.00 ± 4.80	0.87 ± 0.14	214.00 ± 6.41
Minimum	0.40 ± 0.04	6.60 ± 1.77	0.10 ± 0.02	16.60 ± 1.53	0.17 ± 0.03	15.20 ± 2.32
Maximum	37.20 ± 5.50	739.00 ± 13.60	21.00 ± 1.01	635.00 ± 9.64	25.20 ± 12.10	923.00 ± 22.30

S.E.M. - standard error of the mean

(r = 0.984). In contrast, ^{40}K showed a significant (P = 0.05) difference between the mean activity in the meat (335 Bq·kg^{-1}) and stomach wall (245 Bq·kg^{-1}), however, with no significant correlation (r = −0.175). Despite the large variability, there was a similar distribution in both radionuclides, also indicating a relatively low difference between the arithmetic mean and the median for both ^{137}Cs and ^{40}K (Table 1). The ^{137}Cs activity concentration was significantly below the limits.

The transfer factors between the soil, stomach content, and meat in wild boars hunted in Slovakia are stated in Tables 2 and 3. The transfer factors between the soil and the stomach content and the soil and the meat are stated in Table 2. They are especially similar at the median, at approximately 0.07.

Table 2. Transfer factors of ^{137}Cs in wild boars in relation to the soil activity (activity concentration in meat up to 10 Bq·kg^{-1}).

n = 10	Soil / Stomach content	Stomach content / Meat	Soil / Meat
Mean	0.102	1.886	0.174
S.E.M.	0.022	0.454	0.094
Median	0.078	1.326	0.071
Maximum	0.302	3.922	0.990
Minimum	0.007	0.324	0.023

S.E.M. - standard error of the mean

Table 3 shows the transfer factors in relation to the stomach wall. The median transfer factor between the stomach content and the stomach wall is similar to that of the stomach wall and the meat (2.412 and 1.805). However, the variation range of both values is very large in terms of individual pieces.

Table 3. Transfer factors of ^{137}Cs in wild boars in relation to the stomach wall (activity concentration in meat up to 10 Bq·kg^{-1}).

n = 15	Content / Stomach wall	Stomach content / Meat	Stomach wall / Meat
Mean	3.926	8.263	2.055
S.E.M.	0.788	1.799	0.200
Median	2.412	4.811	1.805
Maximum	11.058	24.550	4.475
Minimum	1.792	2.273	1.186

S.E.M. - standard error of the mean

Table 4 shows the values of ^{40}K and ^{137}Cs activity in the muscles and stomach wall of 18 wild boars hunted in the Czech Republic. These values were used to calculate the potassium-caesium coefficient. The highest coefficient values in the muscles reached 31.8 and the lowest values were 0.15. In the stomach wall, the values were 20.8 and 0.13. Although the difference between the mean and the median potassium-caesium coefficient is not high, the variation range is enormous.

In fifteen of the eighteen above-stated samples, the ^{137}Cs activity in the muscles was higher than the ^{137}Cs activity in the stomach wall. The mean value of the ^{137}Cs activity for these fifteen muscle samples was 46.68 Bq·kg^{-1}. In the stomach muscle, it is 23.69 Bq·kg^{-1}. The mutual correlation is r = 0.988.

Table 4. Calculation of the potassium-caesium coefficient in the muscle and stomach wall of wild boars.

n = 18	Muscle			Stomach wall		
	Activity concentration ($Bq \cdot kg^{-1}$)		Potassium: Caesium	Activity concentration ($Bq \cdot kg^{-1}$)		Potassium: Caesium
	^{40}K	^{137}Cs	Coefficient	^{40}K	^{137}Cs	Coefficient
Mean	59.70	52.40	5.60	47.20	41.20	5.70
S.E.M.	6.17	16.32	1.75	4.47	19.12	1.33
Median	59.90	19.20	3.03	49.20	12.70	4.10
Maximum	139.00	207.00	31.80	77.00	341.00	20.80
Minimum	10.30	2.39	0.15	15.20	1.01	0.13

S.E.M. - standard error of the mean

Only 7 out of 12 wild boars hunted in the Czech Republic were used in the second experiment. For use in inter-tissue correlation analysis, the activity concentration of no tissue should have been below the minimum detected activity. The results are shown in Table 5. Due to significant variability, the dependence of activity concentration on the type of tissue monitored ($P = 0.365$) was not proven using the ANOVA variance analysis.

Table 5. ^{137}Cs activity concentration in individual wild boar tissue used for correlation analysis (pigs with all tissue activity higher than the minimum detected activity).

n = 7	^{137}Cs activity ($Bq \cdot kg^{-1}$)					
	Tongue	Lungs	Heart	Diaphragm	Stomach wall	Stomach content
Mean	11.00	5.61	8.97	10.40	9.62	3.03
S.E.M.	3.76	0.89	2.31	3.69	3.55	0.71
Median	8.70	5.37	7.11	9.57	6.01	2.79
Maximum	32.50	8.59	19.30	23.60	28.00	6.16
Minimum	2.29	1.44	1.80	0.10	1.43	0.77

S.E.M. - standard error of the mean

Table 6 shows the closest correlation between the ^{137}Cs activity concentrations in the heart and diaphragm, correlation coefficient r = 0.977. Another strong correlation was found between the heart and the tongue (r = 0.902) as well as between the heart and the lungs (r = 0.906). Lower correlation coefficient values were recorded between the ^{137}Cs activity of the lungs and the diaphragm (r = 0.888) and the diaphragm and the tongue (r = 0.848). The lowest correlation was recorded between the heart and the stomach content (r = 0.098), which indicates virtually zero dependence between these samples. The stomach content also had a very weak correlation with all other tested tissues. The negative correlation (r = −0.395) between the stomach content and the stomach wall was also low.

Table 6. Correlation coefficients (r) of the dependence of ^{137}Cs activity concentration between tissues.

r	Tongue	Lungs	Heart	Diaphragm	Stomach wall	Stomach content
Tongue	1					
Lungs	0.772	1				
Heart	0.902	0.906	1			
Diaphragm	0.848	0.888	0.977	1		
Stomach wall	0.410	0.635	0.537	0.648	1	
Stomach content	0.219	0.135	0.098	0.189	-0.395	1

Discussion

The samples collected in Slovakia came from several locations. We wanted to confirm the stability of low values of environmental contamination, as we have also stated in our other publications (Benova et. al. 2016b; Kanta and Benova 2021; Benova et. al. 2021). The situation is similar when comparing results from other European countries (Poland, the Czech Republic, Germany, Austria) (Krolak et. al. 2010; Kocadag et. al. 2017).

In contrast, this work monitored eight 12-month-old wild boars out of the 18 pieces hunted in the foothills of Šumava (Czech Republic), with a mean ^{137}Cs activity in the muscles of 78 Bq·kg^{-1}. This result is more than double that of the other 10 older pieces hunted (36 Bq·kg^{-1}). There is a hierarchy when hunting for food which favours older and stronger individuals. These individuals consume the majority of the prey. Thus, younger and weaker animals search for food by digging in the ground, which results in the consumption of the common underground fungus *Elaphomyces granulatus*, the main source of ^{137}Cs (Dvořák et. al. 2010). Since individuals younger than 12 months weigh less, there is a higher concentration of radiocaesium in their bodies compared to older boars that weigh more. The ^{137}Cs contamination is lower in older, heavier wild boars.

The results in Table 1 (from Slovakia) show that there is hope that it will be possible to use a sample from the stomach wall to determine the ^{137}Cs activity concentration in meat, thereby replacing the commonly used and highly valued meat sample. The difference between the mean values of ^{137}Cs activity concentration in meat and the stomach wall (2.95 and 1.74 Bq·kg^{-1}) was not significant given the very close correlation ($r = 0.984$). The results were similar in the Czech Republic, and were used for the calculations in Table 4. The ^{137}Cs activity was higher in the muscles than the ^{137}Cs activity in the stomach wall in 15 out of the 18 samples. The mean value of ^{137}Cs activity in the muscles of these fifteen samples was 46.7 Bq·kg^{-1}. The mean value in the wall of the stomach was 23.7 Bq·kg^{-1}. The correlation coefficient was again high, $r = 0.988$. These results show that it suffices to take a sample from the stomach wall of wild boars to examine the ^{137}Cs activity. If the ^{137}Cs activity in the stomach wall is below 300 Bq·kg^{-1}, then the ^{137}Cs activity in the muscles will be lower than that stated maximum permissible value of 600 Bq·kg^{-1} (Regulation [EC] No. 178/2002 of the European Parliament and of the Council).

If the ^{137}Cs activity in the stomach wall exceeds 300 Bq·kg^{-1}, it is necessary to examine the top side muscles. In specific cases, the stomach wall may have a higher ^{137}Cs activity concentration than the muscles. This may be caused by the wild boar consuming contaminated food shortly before being hunted. This was observed in pieces when the stomach wall had a ^{137}Cs activity concentration of 134 Bq·kg^{-1} higher than in the muscles.

The wild boar is a migrating omnivore, so we replaced the determination of the ^{137}Cs activity in the plants at the shooting location with stomach content activity for the purposes of studying the transfer. The transfer factors between the soil, stomach content, and meat are stated in Table 2. The transfer factors between the soil and the stomach content, and between the soil and meat are similar at the median, approx. 0.07. The large difference between the maximum and minimum values may be attributed to the significant variability of the wild boar's food chain. Completely different results were found in the transfer factors between the stomach content and meat, where no rarefaction was determined. On the contrary, the transfer factor was > 1 in both the arithmetic mean and the median. However, the variability of the transfer factor's arithmetic mean (0.3–3.9) is important. The transfer factor in three of the ten observed pieces was > 3. This means that the food chain element representing the source of contamination had left the stomach when the wild boar was shot. This is in line with the assumption that wild boars are contaminated by a lower amount of food with a high ^{137}Cs activity concentration.

Radiocaesium gets into the meat of wild boars primarily through the consumption of underground fungus *Elaphomyces granulatus*s with an extreme ability to accumulate (transfer factor up to 150) as some wild boars, especially piglets, consume this fungus (Hohmann and Huckschlag 2005; Dvořák et al. 2010). Other elements of the food chain are not so important.

In order to predict the contamination of wild boar meat in practice, it is more important to monitor the contamination of the soil rather than elements of the food chain. However, we must keep in mind that the mean migration route of wild boars ranges within tens of kilometres. While the values of surface soil activity ($Bq \cdot m^{-2}$) correspond with the individual soil layers, this does not have to be so in the case of the activity concentration of the soil ($Bq \cdot m^{-3}$). When monitoring plant soil transfer, an aggregated transfer coefficient would be more appropriate (Mihalik et al. 2017).

Another aim of this work was to define the dependence of the ^{137}Cs activity between individual tissue samples based on a correlation analysis. A very strong correlation was found between the ^{137}Cs activity in the heart and the diaphragm (0.977). On the contrary, a very weak correlation was found between the heart and the stomach content (0.098). The only negative correlation (−0.395) was found between the stomach content and stomach wall. However, this correlation is still too weak to confirm it as a fact. A very weak dependence was recorded in the stomach content alone. The reason for this is that the stomach contains food that the wild boar had eaten in the past several hours. In contrast, ^{137}Cs activity in tissues reflects the environment the wild boar has been moving around over the last month and the level of food contamination. Therefore, the stomach wall is not in a direct correlation with the stomach content.

The most significant correlation was found between the ^{137}Cs activity in the diaphragm and the heart. The results of the correlation coefficient ($r = 0.977$) show a direct dependence between these samples. This result shows that either a heart sample or a diaphragm sample can be taken to examine the ^{137}Cs activity in wild boars. If the activity in the diaphragm does not exceed 600 $Bq \cdot kg^{-1}$, i.e. the highest permissible level of contamination, it is highly likely that ^{137}Cs activity will not be higher in any other sample. Nevertheless, apart from the stomach content, the heart shows the best correlation with all samples. The correlation relationships between the heart and other samples ranged from 0.537 to 0.977. If the heart is removed instead of the diaphragm to determine the ^{137}Cs activity, it is necessary to use the whole heart. However, the heart is an organ that can be used for human consumption. Therefore, the diaphragm seems to be more suitable for sampling, however, which is not considered a hunting law (inner organs, especially the heart, lungs, and liver belong to the hunter who killed the animal).

Dividing the mean ^{137}Cs activity of the diaphragm samples by the mean value of the heart samples gives a ratio of 1.16. Nevertheless, we would need many more samples and a certain number of samples above and below the limit values to confirm that the transfer of ^{137}Cs takes place in the same way for both high and low measured ^{137}Cs activity. No above-limit values of the ^{137}Cs activity concentration were detected during the analysis. The ANOVA variance analysis did not prove the dependence of activity concentration on the type of tissue ($P = 0.365$). This result further implies that sampling a specific type of tissue is not so important in this case.

Radioactivity analysis conducted as a part of food monitoring in Japan indicated a higher level of ^{137}Cs activity in the meat of wild boars, especially in Fukushima, but also in other areas monitored from 2011 to 2015. The ^{137}Cs activity in the muscles was higher in comparison to the heart, liver, or kidneys of wild boars (Fuma et al. 2016).

Gulakov (2014) focused on the distribution of ^{137}Cs in the bodies of wild boars from various distances from the Chernobyl power plant. The mean ^{137}Cs activity in the muscles ranged within 10,000–46,000 $Bq \cdot kg^{-1}$. However, in the kidneys of some animals, the activity reached values of up to 660,000 Bq·kg^{-1}. Although the measured ^{137}Cs activity in the heart and lungs was much higher than in the same samples in our work, the correlation coefficients were similar. Gulakov (2014) discovered a significant correlation (r = 0.98) in the case of a less contaminated zone of Chernobyl and a value of 0.80 in the most affected area of Chernobyl. Our results are similar. The measured correlation coefficient between the heart and the lungs was r = 0.906. Therefore, there was a significant dependence between the ^{137}Cs activity of the heart and the lungs.

Based on the assessment of individual correlations (Table 6) and other results, the suitability of representative sampling for the determination of the ^{137}Cs activity in wild boars can be recommended as follows: diaphragm → heart → lungs → tongue → stomach wall → stomach content.

Potassium and caesium have similar effects in the body. Caesium has a tendency to replace potassium. Knowing these two parameters, it is then possible to calculate the potassium-caesium coefficient. Generally, the higher the potassium-caesium coefficient, the higher potassium and the lower caesium concentrations there are in the body, which is good for the organism. When exposed to caesium, it is very important to maintain a high potassium concentration in the body. Caesium can replace potassium in the sodium-potassium pump functionality. The mean value indicating the potassium-caesium coefficient in the muscles of wild boars is 5.57 (Table 4). The high variability is proven by the sample results with a ^{137}Cs activity concentration of 181 Bq·kg^{-1} and ^{40}K at 27.5 Bq·kg^{-1}, where the potassium-caesium coefficient of 0.15 represents the minimum detected value. In contrast, in samples with a ^{137}Cs activity concentration of 2.39 Bq·kg^{-1} and ^{40}K at 76 Bq·kg^{-1}, the potassium-caesium coefficient was 31.8. These values are comparable with the values from the research in the region of Levice in Slovakia in 2018 (Kanta and Beňová 2018), which were subsequently used to calculate the coefficients. The mean potassium-caesium coefficient value was 26.9. For samples with the highest value of ^{137}Cs (14 Bq·kg$^{-1)}$ and ^{40}K (330 Bq·kg^{-1}) activities, the potassium-caesium coefficient thus showed a value of 23.6.

The potassium-caesium coefficient can also be compared in the stomach wall. The mean value of the potassium-caesium coefficient is 17.25 in samples from the Šumava hunting grounds and 17.01 in samples from Levice in Slovakia. These values are very similar. This means that the ^{40}K activity in the stomach wall of wild boars from both regions is at the same level.

In conclusion, based on the results from Slovakia and the Czech Republic, there is hope that it will be possible to use a sample from the stomach wall to determine the activity concentration of ^{137}Cs in meat, thereby replacing the commonly used and highly valued rump sample.

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