

Estimation of external gamma radiation dose in the area of Bory Stobrowskie forests (PL)

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Abstract The study assessed the radiological risks associated with the presence of natural and artificial radionuclides in the Bory Stobrowskie forests (PL). Using the conversion factors given by UNSCEAR and the measurements results of ^{232}Th series, ^{238}U series, ^{40}K , and ^{137}Cs specific activities in the 10-cm soil layer the values of absorbed dose (D) and the annual effective dose equivalent derived from terrestrial gamma radiation (E) were calculated. The calculated dose was compared with doses directly measured on the area studied.

Keywords Radiological hazard · Radionuclides · Radiation dose

Introduction

Human beings are exposed to background radiation that stems both from natural and man-made sources. In general, approximately 85% of the annual total radiation dose of any person comes from natural radionuclides of both terrestrial and cosmogenic origin (Belivermis et al. 2010; NCRP 1994; UNSCEAR 2000).

Soil radionuclide activity concentration is one of the main determinants of the natural background radiation. A number of decay products of Th and U series and ^{40}K are the main components of external gamma radiation originating from soil. About two thirds of natural radioactivity which exposes public is attributed to progeny of U series and ^{222}Rn . The worldwide annual effective dose from natural sources is estimated to be 2.4 mSv (UNSCEAR 2000).

Natural radionuclides of the uranium–radium and the thorium series as well as ^{40}K are distributed in soil almost homogeneously, regardless of the depth. Their concentration depends on local geological conditions. Each year there are seasonal changes in the gamma radiation dose rate value. Additionally, daily changes and changes caused by precipitation are observed. These changes are due to differences in exhalation of radon from soil and in the case of precipitation—washing out radon isotopes from the air and deposition on the soil surface (Biernacka et al. 2004).

As a result of nuclear explosions carried out in the earth's atmosphere and the Chernobyl nuclear power station accident, the world has become polluted with radionuclides of artificial origin. Some of these long-lived isotopes (e.g., ^{137}Cs) are still eminent in the environment predominantly in surface soil, as a result of radioactive fallout from the atmosphere (Celik et al. 2008).

Radioisotopes that are present in soil significantly affect terrestrial gamma radiation levels. In the last

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decade, several studies were carried out to assess the average outdoor terrestrial gamma dose rate in air (e.g., Taskin et al. 2009; Radenković et al. 2009; Belivermis et al. 2010; Baykara and Dođru 2009; Lee et al. 2009; Faheem et al. 2008; Ngachin et al. 2008; Janković et al. 2008; Degerlier et al. 2008; Psichoudaki and Papaefthymiou 2008; El-Taher et al. 2010; Al-Hamarneh and Awadallah 2009; Nada et al. 2009).

In this paper the radiological risks associated with the presence of natural and artificial radionuclides in the Bory Stobrowskie was assessed. For this purpose radiation doses of gamma radiation were measured in situ using portable gamma spectrometer InSpector1000 (Canberra). Additionally the surface soil samples of the width 10 cm were collected and gamma radioactivity concentrations of isotopes were determined in the laboratory. From the data obtained, the doses of gamma radiation were calculated using appropriate formulas. Results of this work are important both in assessment of the risk for human health as well as in development of radiobiomonitoring methods.

Materials and methods

Soil samples were collected according to established procedures. About 2 kg of soils samples were collected from the top 10 cm of the soil. Soil samples were collected in October 2009. They were taken from Bory Stobrowskie forest, located in the northeast direction from Opole (PL) at 21 locations as shown in Fig. 1. To diminish an influence of rainfall and soil moisture on measurements results (UNSCEAR 2000), the investigations were performed during dry weather, at least 2 days after rainfall. The position of the locations was determined by using global positioning system. The samples were dried at 110°C for night and day. Each of the samples were then weighed and sealed in Marinelli beakers, 450 cm³. They were stored for 4 weeks to achieve equilibrium for ²³⁸U and ²³²Th with their respective progeny.

The measurement of activity in samples of woodland soil was carried out by means of a gamma spectrometer with a germanium detector HPGe (Canberra) of high resolution: 1.29 keV (FWHM) at 662 keV and 1.70 keV (FWHM) at 1,332 keV. Relative efficiency was 21.7%. Energy and efficiency

calibration of the gamma spectrometer was performed with the standard solutions type MBSS 2 (Czech Metrological Institute, Praha), which covers an energy range from 59.54 to 1,836.06 keV. Geometry of calibration source was Marinelli (447.7±4.48 cm³), with density 0.985±0.01 g/cm³, containing ²⁴¹Am, ¹⁰⁹Cd, ¹³⁹Ce, ⁵⁷Co, ⁶⁰Co, ¹³⁷Cs, ¹¹³Sn, ⁸⁵Sr, ⁸⁸Y, and ²⁰³Hg. Geometry of samples container was Marinelli, 450 cm³. Measuring process and analysis of spectra were computer controlled with use of the software GENIE 2000. The radiation spectrum was recorded day and night.

The activity concentrations of ²³²Th and ²³⁸U were calculated assuming secular equilibrium was established with their decay products. For concentrations of ²³²Th and ²³⁸U, the following gamma transition lines were used: ²³²Th series, ²²⁸Ac (911 keV); ²³⁸U series, ²¹⁴Pb (351.9 keV) and ²¹⁴Bi (609.2 keV). The activity concentration of ⁴⁰K was determined from the peak area of 1,460 keV line. The 661.66 keV gamma transition was used to determine the ¹³⁷Cs concentration.

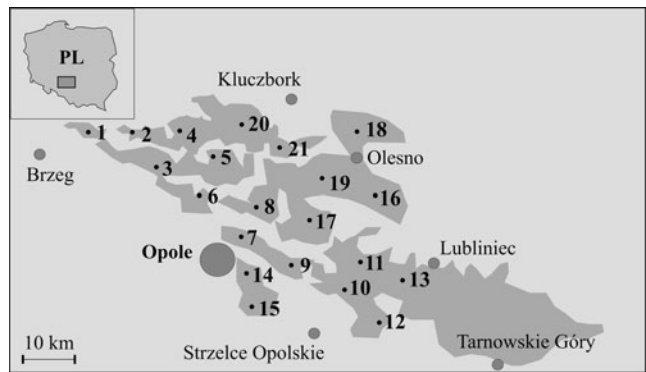
Gamma radiation dose rate (*H*) was determined with Canberra portable scintillation spectrometer InSpector1000. This spectrometer is an easy to use, hand-held, digital and multichannel analyzer ideal for the environment monitoring purposes. The dose measured corresponds to the equivalent dose on the depth 10 mm of human tissue (*H**10). This quantity estimates the effective dose of radiation for all types of penetrating radiation, including cosmic radiation (User's Manual 2004). The spectrum analysis was carried out using Genie-2000 (Gamma Analysis Option model S501C) software package.

Results and discussions

The results of activity concentrations in the soil samples in the Bory Stobrowskie area are given in Table 1 for the radionuclides, and δ is measurement uncertainty. In this table min is the lowest value in data, Q1 is the lower quartile, median is the median, mean is the arithmetic mean, Q3 is the upper quartile, and max is the highest value.

The concentrations found in the present study ranged from 3.35 to 10.68 Bq/kg dry mass (d.m.; the mean is 6.94 Bq/kg d.m.) for ²³⁸U series, from 0.00 to 12.90 Bq/kg d.m. (the mean is 7.86 Bq/kg d.m.) for

Fig. 1 Locations of soil samples



²³²Th series, from 73.6 to 214.7 Bq/kg d.m. (the mean is 147.6 Bq/kg d.m.) for ⁴⁰K, and from 9.2 to 696.3 Bq/kg d.m. (the mean is 178.9 Bq/kg d.m.) for ¹³⁷Cs.

The activity concentrations of ²³⁸U and ²³²Th series and ⁴⁰K measured in becquerels per kilogram were used to calculate the dose rate, *D*, in nanograys per hour at a height of 1 m above the ground using the following relationship (UNSCEAR 2000):

$$D_I(\text{nGy/h}) = 0.604C_{Th} + 0.462C_U + 0.042C_K \quad (1)$$

Because the area where research was conducted is contaminated by ¹³⁷Cs in calculations activity of this isotope was considered and the dose was calculated from Eq. 2 (Celik et al. 2008; Jibiri and Bankole 2006; Jibiri et al. 2007):

$$D_{II}(\text{nGy/h}) = 0.427C_U + 0.662C_{Th} + 0.043C_K + 0.03C_{Cs} \quad (2)$$

Table 2 shows outdoor absorbed dose rates in air inferred from concentrations of radionuclides in

soil. Table 3 shows the average radionuclides activities in soil and absorbed doses in air from different part of the world, compared with those of the present study. Table 3 shows that the measurement average activities natural radionuclides are lower than the world average value.

In the case of isotope ¹³⁷Cs, activity is much higher. This is due to the fact that the area of performance measurement Bory Stobrawskie coincides with the Opole Anomaly, the area where ¹³⁷Cs activity after the nuclear power plant breakdown in Chernobyl has been elevated.

In Figs. 2 and 3 the distributions of doses calculated from Eqs. 1 and 2 are shown. A gray bar located on the *x*-axis shows the range that contains 95% of the values. In Table 3 the calculated and measured values of radiation suppose that dose rates are lower than those given in the world average value of 51 nGy/h (UNSCEAR 2000).

To estimate the annual effective doses, one has to take into account the conversion coefficient from absorbed dose rate in air to effective dose and

Table 1 Characteristics of the radioactivity of soils in the Bory Stobrawskie area

	Radioactivity concentration (Bq/kg d.m.)							
	²³⁸ U series	δ ²³⁸ U series	²³² Th series	δ ²³² Th series	⁴⁰ K	δ ⁴⁰ K	¹³⁷ Cs	δ ¹³⁷ Cs
Min	3.35	0.34	0.00	0.00	73.6	5.9	9.2	0.3
Q1	5.46	0.48	6.47	0.55	131.5	7.4	28.8	1.1
Median	6.73	0.65	7.85	0.68	152.9	8.5	46.8	2.5
Mean	6.94	1.47	7.86	1.33	147.6	10.4	178.9	5.8
Q3	8.21	1.20	8.74	1.29	174.6	12.0	277.4	6.3
Max	10.68	7.76	12.90	7.67	214.7	26.7	696.3	43.9

Table 2 Outdoor absorbed dose rates in air inferred from concentrations of radionuclides in soil

	Calculated dose rate	
	D_I (nGy/h)	D_{II} (nGy/h)
Min	4.642	5.90
Q1	12.54	13.18
Median	13.81	19.44
Mean	14.15	19.88
Q3	16.58	25.65
Max	19.67	35.01

the outdoor occupancy factor. In the UNSCEAR recent report (UNSCEAR 2000), the committee used 0.7 Sv/Gy for the conversion coefficient from absorbed dose in air to effective dose received by adults, and 0.8 for the indoor occupancy factor, implying that 20% of the time is spent outdoors, on average, around world. The effective dose equivalent

rate, in units of millisievert/year, is calculated from the following formula:

$$E(\text{mSv/year}) = D(\text{nGy/h}) \times 24(\text{h}) \times 365(\text{day}) \\ \times 0.2(\text{spent outdoors}) \\ \times 0.7 \text{ conversion coefficient} \times 10^{-6} \quad (3)$$

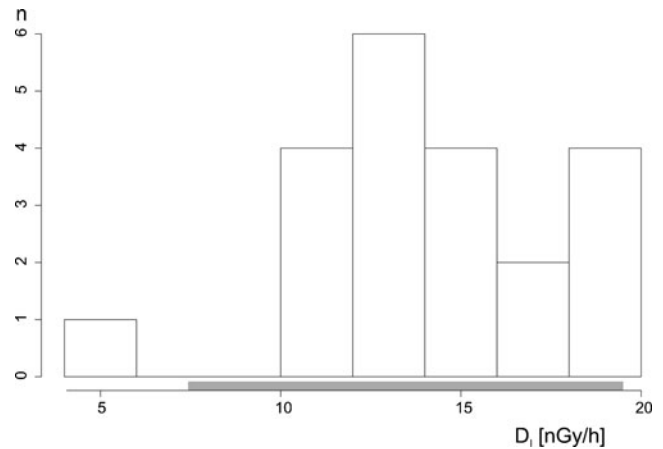
In Table 4 the outdoor absorbed dose rates in air inferred from concentrations of radionuclides in soil compared with the direct measurements are shown. The data in Table 4 show that the results of measurements in situ are almost one order of magnitude higher than the calculated dose values. This is a result of differences between measured and calculated dose rates. The spectrometer Inspector 1000 calculates the $H \times 10$ dose in which more than in E_I and E_{II} radiation sources are taken into account.

The maximum recorded gamma radiation dose rate was 0.050 $\mu\text{Sv/h}$ (0.438 mSv/year). This dose is lower than the dose limit referred to in the Regulation

Table 3 Average radionuclides activities in soil and absorbed doses in air from different part of the world, compared with those of the present study

Country	Averaged radionuclide activity in soil (Bq/kg; UNSCEAR 2000)			Average activity ^{137}Cs in soil (Bq/kg), Anonymous 1998	Absorbed dose rate in air (nGy/h), UNSCEAR 2000
	^{238}U series	^{232}Th series	^{40}K	^{137}Cs	
Belgium	26	27	380	11.6	43
Bulgaria	45	30	400	–	70
China	32	41	440	–	62
Denmark	17	19	460	34.6	52
Greece	25	21	360	48.0	56
Hong Kong	59	95	530	–	87
India	29	64	400	–	56
Iran	28	22	640	–	71
Japan	33	28	310	–	53
Luxemburg	35	50	620	20.5	49
Poland	26	21	410	25.5	45
Portugal	44	51	840	–	84
Romania	32	38	490	58.8	59
Spain	32	33	470	5.0	76
Switzerland	40	25	370	58.13	45
United States of America	40	35	370	–	47
World average	8–160 (32)	4–130 (40)	100–700 (420)	–	–
Present study	6.94	7.86	147.6	178.9	14

Fig. 2 Histogram of D_I distribution calculated from Eq. 1



of the Council of Ministers of 18 January 2005, on dose limits (Regulation of the Council of Ministers (Poland), Anonymous 2005). According to the above-mentioned document, the dose limit for the general public (caused mainly by artificial ionizing radiation sources), expressed as an effective dose, is 1 mSv per calendar year. This dose limit may be exceeded in a calendar year provided that within the next five calendar years its total value does not exceed 5 mSv (above the level of natural background). Though the doses E_I and E_{II} are not fully compatible with H , comparison of their values was performed.

To compare the measured and the calculated dose rates, functions available in the MS Excel spreadsheet were utilized. For variances and means comparison, the F and the t test were used, respectively.

Comparison of variances ratios E_I to H and E_{II} to H showed that they can be regarded as different at p

level <0.001 . For means comparison the t test for samples with different variances was used. It was found that both mean E_I and E_{II} were significantly different than mean H , at p level <0.001 . Additionally to compare results obtained from two different methods of doses calculation and the measured dose, the t test for pairs was used. Here again significant influence of dose determination method on the result was confirmed, at p level 0.001.

Rather poor relationship between E_I and H was found. The correlation coefficient value was 0.46, supposing existence of other important sources of gamma radiation in environment that were not included in the formula used in calculations. Further statistical analysis revealed a relationship between E_{II} and H . In the range of the measured H doses, a good linear relationship with calculated E_{II} can be concluded (Fig. 4). The slope of the relationship was 8.3 (with standard error 1.2), the intercept was 0.00 (with

Fig. 3 Histogram of D_{II} distribution calculated from Eq. 2

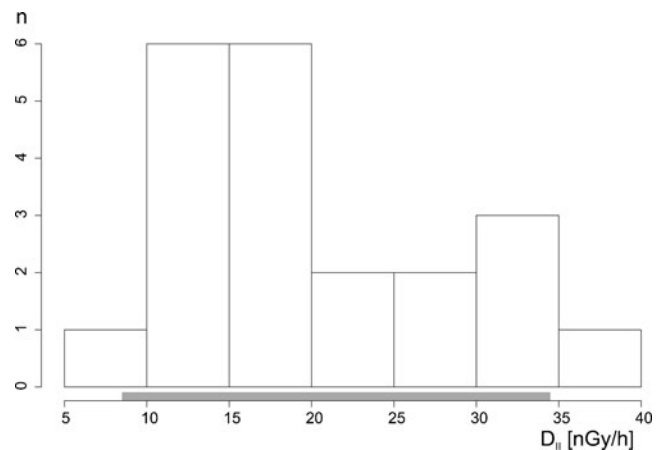
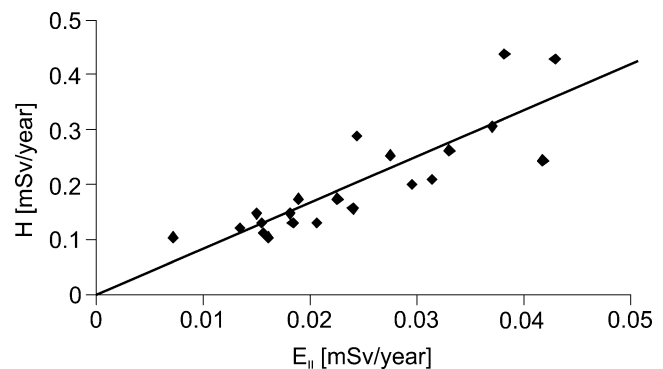


Table 4 Outdoor absorbed dose rates in air inferred from concentrations of radionuclides in soil compared with direct measurements

	Calculated dose rate		Measured dose rate <i>H</i> (mSv/year)
	<i>E</i> _I (mSv/year)	<i>E</i> _{II} (mSv/year)	
Min	0.0057	0.0072	0.105
Q1	0.0154	0.0162	0.131
Median	0.0169	0.0226	0.175
Mean	0.0174	0.0244	0.204
Q3	0.0203	0.0315	0.254
Max	0.0241	0.0429	0.438

standard error 0.03), and the value of correlation coefficient was 0.86. The intercept value did not differ significantly from 0, and the relationship can be simplified to proportion. It can be concluded that the values of the measured dose rate *H* is about eight times bigger than the calculated *E*_{II} and contribution of ¹³⁷Cs has to be taken into consideration while estimation of gamma radiation dose rate.

Direct measurement on the level of 1 m above the ground detects radiation from a large area. Additionally, in situ measurement detects activity of isotopes occurring in other than soil parts of the environment and cosmic rays. Therefore, direct measurement of gamma dose rate seem to be more representative for area studied than the dose rate calculated from the known activity of isotopes in the soil. Comparing the ranges of activity changes of ²³²Th series, ²³⁸U series, ⁴⁰K, and ¹³⁷Cs, one can notice that changes in radiocesium activities in soil were the highest. Relatively uniformly distributed activities of natural soil isotopes composed mainly the average dose, whereas ¹³⁷Cs activities caused variability in radiation doses.

Fig. 4 Relationship between measured and the calculated gamma dose rates

It can be supposed that on the area investigated, other than soil radiation sources determinate radiation dose rate. Specific influence of ¹³⁷Cs on radiation dose can be supposed. Because of similarity of its chemical properties to K, it can be efficiently transported from soil to forest plants, raising the total dose of radiation from the sources other than soil.

Though a considerable difference between gamma dose rate was determined in situ and measured, it is possible to recalculate the doses obtained using different methods. It is particularly important in situations when only soil samples are available for measurements.

Conclusions

- The radioactivities of natural isotopes determined in the 10-cm layer of soil on the area studied did not exceed the average world value;
- In calculations of gamma dose rate, the local radioactive contamination has to be taken into account;
- Sources of radiation other than soil determine dose rate on the examined area;
- Calculated and directly measured values of gamma radiation doses are lower than the dose limit set out by the Council of Ministers Ordinance of 18 January 2005 (Regulation of the Council of Ministers (Poland); Anonymous 2005);
- The data obtained are important both for assessing the risk for human health as well as environmental radiobiomonitoring;
- The results can be used as a reference point for radiological mapping the area of Bory Stobrawskie forests.

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