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FACTORS AFFECTING BACKGROUND GAMMA RADIATION IN AN URBAN SPACE*

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Abstract

Terrestrial background gamma radiation in urban surroundings depends not only on the content of radionuclides in the soil and bedrock, but also on levels of radionuclides in building materials used for the construction of roads, pavements and buildings. The aim of this study was to characterize an outdoor absorbed dose rate in air in the city of Wroclaw and to indicate factors that affect the background gamma radiation in an urban space. Gamma spectrometric measurements of the radionuclide content and absorbed dose rate in air were performed by means of portable RS-230 gamma spectrometers and at sites with various density of buildings, in the city center and in more distant districts, over pavements and roads as well as in a park, a cemetery and on four bridges. Measurements were performed at a 1-meter height. The absorbed dose rate in air ranged from 19 to 145 nGy h^{-1}, with the mean of 73 nGy h^{-1}. This paper implicates that terrestrial background gamma radiation depends on the type of building material used for the construction of roads and pavements and on the density of buildings shaping the geometry of the radiation source. The highest background gamma radiation was observed in the center of the city, where buildings are situated close to each other (nearly enclosed geometry) and pavements are made of granite. The lowest background gamma radiation was noticed on bridges with nearly open field geometry. Additionally, three profiles at the heights of 0.0, 0.5 and 1.0 m were arranged between two opposite walls of the hall of the Main Railway Station in Wroclaw, where the floor is made of various stone slabs. The results indicated that the absorbed dose rate in air varied, depending on the type of building material, but became averaged along with the height.

Keywords: uranium, thorium, potassium, gamma dose rate, natural radioactivity, building materials, urban space, portable gamma spectrometer.

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INTRODUCTION

The main contributors to natural gamma radiation are radionuclides of the ^{238}U and ^{232}Th decay series as well as ^{40}K, which are present in the environment in various amounts, depending on the type of soil and geological formation. The global, population-weighted mean of aerial outdoor absorbed dose rate in due to these radionuclides is 59 nGy h^{-1}. In Europe, the lowest mean absorbed dose rate in air is observed in Cyprus (18 nGy h^{-1}), while the highest one is found in Norway (73 nGy h^{-1}). In Poland, it equals 45 nGy h^{-1} (UNSCEAR 2000).

Spatial variability of environmental radioactivity is an important issue, as implicated TYLER et al. (1996), who developed a hexagonal sampling scheme to provide estimates of spatial variability of the soil content of radionuclides. The spatial variability of soil activity is related to many factors, such as the vertical distribution of a source within the soil, land relief or the plant cover (TYLER et al. 1996, LAEDERMANN et al. 1998).

Urban spaces are more complex environments, in which terrestrial background gamma radiation depends not only on the soil and bedrock level of radionuclides, but also on the content of radionuclides in building materials used for the construction of roads, pavements and buildings. The type of raw material or industrial waste used for building material production determines the radioactivity of building materials (MUSTONEN et al. 1997, European ... 1999*a*). Specific activity of ^{40}K in raw materials ranges from trace to several thousand Bq kg^{-1} and specific activities of radionuclides of the ^{238}U and ^{232}Th decay series vary between trace and several hundred Bq kg^{-1}. Specific activities of radionuclides in industrial waste may be greater due to the effect of enrichment in production processes (SOMLAI et al. 1996, MUSTONEN et al. 1997). Some waste and raw material contain natural radionuclides in amounts high enough to pose a radiological hazard to living beings (NEA-OECD 1979, ULBAK 1979, PAVLIDOU et al. 2006, GU et al. 2012, SOLECKI et al. 2013). SOLECKI et al. (2010) indicated that the absorbed dose rate in air in an urban environment depends on the type of building material and the thickness of a layer of the given building material. The absorbed dose rate in air for a 12.0-centimeter-thick layer of granite slabs may be more than double than that of 1.2-cm-thick layer. However, starting from the thickness of 8.4 cm, any further increment of the absorbed dose rate in air is small (SOLECKI et al. 2010). The thickness of a layer of building material is taken into account in some countries when developing regulation standards for building materials (CHEN, LIN 1996, European ... 1999*a*). MEDEIROS and YOSHIMURA (2005) showed that buildings (or more precisely, building materials) in the urban space can raise the aerial outdoor gamma dose rate by about 35% versus the one expected only from soil.

The main aim of this study was to indicate how the type of building material and density of buildings the shape the geometry of the source affect the background gamma radiation in a town. Although there are several studies about the airborne outdoor absorbed dose rate in towns (Levin, Stoms 1969, Yoshimura et al. 2004, Ghorabie 2005, Cresswell et al. 2013, Licinio et al. 2013), the background gamma radiation in Polish cities has not been the subject of detailed studies. This research describes the background gamma radiation in the city of Wroclaw. The results are relevant in view of the recently approved Basic Safety Standards for protection against dangers arising from exposure to ionising radiation (*Council Directive* 2013). The research emphasizes the need to control building materials in terms of radiological safety. Determinations of the aerial absorbed dose rate in various locations across Wrocław enabled us to distinguish sites with low and high background gamma radiation within the urban space and to identify building materials responsible for greater exposure to ionising radiation. The results of our preliminary study were presented during a local conference.

MATERIAL AND METHODS

In situ gamma spectrometric measurements of potassium K, uranium U and thorium Th content in the bedrock as well as in building materials used for the construction of roads, pavements and buildings were performed in the urban space of Wroclaw. The methodology of measurements was developed in the survey financed by the European Union as a part of Innovative Economy Operational Programme. Measurements were conducted in places of various density of buildings, in the city center and in the outskirts, over pavements and roads as well as in Grabiszynski Park, Grabiszynski Cemetery and on four bridges: Uniwersytecki, Pomorski, Tumski and Piaskowy Bridge. Measurements were performed at the height of 1 meter above the ground by means of portable RS-230 gamma spectrometers coupled with a Bismuth Germanate (BGO) detector. The sampling time was 3 minutes. The IAEA (2003) recommends a sampling time in a range of 2-6 minutes. Nowak (2013) performed laboratory studies on the sampling time impact on the standard error of a mean (SEM). Measurements were conducted on granite slabs characterized by mean specific activities of ^{40}K, ^{238}U, ^{232}Th equal 836 Bq kg^{-1}, 62 Bq kg^{-1}, 41 Bq kg^{-1}, respectively. Six variants of the sampling time were tested: 30 s, 60 s, 90 s, 120 s, 180 s and 240 s. In each case, a series of 30 measurement was performed. Taking into account the accuracy of results and the economy of field measurements, the sampling time of 180 s (3 min) was selected. Standard errors of the means for ^{40}K, ^{238}U, ^{232}Th achieved at the three-minute sampling time were 5 Bq kg^{-1}, 1 Bq kg^{-1}, 1 Bq kg^{-1}, respectively. Standard errors refer to a series of 30 measurements performed in a laboratory.

Additionally, three profiles at the heights of 0.0, 0.5 and 1.0 m were arranged between two opposite walls of the hall of the Main Railway Station in

Wrocław. The floor of the hall is made of various stone slabs arranged in parallel belts. The widest one, made of grey granite, lies in the center of the hall, with narrower belts of diorite and, further away, porphyric ones running on either side. The most exterior belts, situated close to the walls, are again made of grey granite.

According to the producer, a RS-230 gamma spectrometer ensures high sensitivity and its performance is similar to a 21 in^3 (390 cm^3) Sodium Iodide (NaI) detector commonly used with larger portable devices. The RS-230 gamma spectrometer, 259 mm x 81 mm x 96 mm in size and weighing just 2.04 kg is lighter, is more convenient than comparable systems. Portable spectrometers are useful for taking measurements of airborne dose rate in places with many sources of radiation, such as urban spaces. Urban areas are complex in terms of the geometry of a source. There are areas of nearly open field geometry, such as parks, cemeteries or bridges, as well as areas of nearly enclosed geometry, such as tunnels, underpasses and areas among buildings.

The RS-230 gamma spectrometer operating in the Assay Mode displays results as the (%), U (ppm), Th (ppm) content and absorbed dose rates in air DR (nGy h^{-1}) generated by these radionuclides. The uranium ^{238}U and thorium ^{232}Th content is calculated on the basis of gamma rays emitted by ^{214}Bi (1765 keV) and ^{208}Tl (2615 keV), respectively, under the assumption that secular equilibrium exists between all of the radioisotopes within the decay series. The uranium ^{238}U and thorium ^{232}Th content measured as above is denoted as the equivalent uranium (eU) and equivalent thorium (eTh) content. All the results of ^{238}U and ^{232}Th herein should be understood as eU and eTh, respectively. With regards to the ^{238}U decay series, results may be referred as the radium ^{226}Ra content because radionuclides from ^{226}Ra on are the most important from the perspective of radiological protection. Analogously, regarding the ^{232}Th decay series, results may be referred to as the thorium ^{228}Th content. The potassium K content is calculated from gamma rays emitted by ^{40}K (1461 keV), which presents a constant admixture (0.012%) of natural potassium (IAEA 2003).

Concentrations of radionuclides (K in %, U in ppm, Th in ppm) were converted to specific activities (^{40}K, ^{238}U, ^{232}Th in Bq kg^{-1}), using the conversion factors proposed by the IAEA (2003), which are as follows: 1% K = 313 Bq kg^{-1} ^{40}K, 1 ppm U = 12.35 Bq kg^{-1} ^{238}U (^{226}Ra), 1 ppm Th = 4.06 Bq kg^{-1} ^{232}Th. Subsequently, to assess the contribution of particular radionuclides into the total terrestrial absorbed dose rate in air ($DR_{K,U,Th}$), absorbed dose rates in air (in nGy h^{-1}) generated by particular radionuclides (DR_K, DR_U, DR_{Th}) were calculated using appropriate conversion factors. Conversion factors proposed by various authors differ slightly (Beck 1972, Markkanen 1995). In this study, dose rates in air at the one-meter height generated by ^{40}K, ^{238}U series and ^{232}Th series were calculated using the following conversion factors (nGy h^{-1} Bq kg^{-1}): 0.043, 0.427, 0.662, respectively (UNSCEAR 1988, EC 1999*b*). The calculated absorbed dose rates in air generated by particular radionuclides were summed up to obtain the total terrestrial absorbed dose rate in air, which in fact was the same value as the dose rate displayed on the gamma spectrometer. The total terrestrial absorbed dose rate in air was calculated from:

$$\text{dose rate in air (nGy h}^{-1}\text{)} = 0.043\ S_K + 0.427\ S_U + 0.662\ S_{Th}\,,$$

where: S_K, S_U, S_{Th} are specific activities of ^{40}K, ^{238}U series and ^{232}Th series in Bq kg^{-1}, respectively.

RESULTS AND DISCUSSION

The outdoor absorbed dose rate in air at the height of 1 meter varied from 19 to 145 nGy h^{-1}, with the mean of 73 nGy h^{-1}. This value is 24% above the world's mean (59 nGy h^{-1}) and 62% above the mean for Poland (45 nGy h^{-1}) published in the UNSCEAR report (2000). Specific activities of ^{40}K, ^{238}U and ^{232}Th in the measurement points ranged between 157 and 1158 Bq kg^{-1}, 14 and 116 Bq kg^{-1}, 7 and 91 Bq kg^{-1}, respectively, with the respective means of 634 Bq kg^{-1}, 43 Bq kg^{-1} and 41 Bq kg^{-1}. The participation of ^{238}U in forming the absorbed dose rate in air varied from 19 to 35%, ^{232}Th from 24 to 41%, and ^{40}K from 24 to 45%.

The results varied depending on the type of building materials used for the construction of roads and pavements as well as the land use, connected with the density of buildings. The analysis of our results in terms of the type of building material showed that the highest radionuclide content as well as the highest absorbed dose rate in air were obtained from measurements performed above pavements made of granite cubes or slabs. The mean absorbed dose rate in air was 108 nGy h^{-1} and mean specific activities of ^{238}U, ^{232}Th and ^{40}K were 62 Bq kg^{-1}, 62 Bq kg^{-1} and 937 Bq kg^{-1}, respectively (Table 1).

Table 1

Mean specific activities (Bq kg^{-1}) and mean absorbed dose rate in air (nGy h^{-1}) at 1.0 m depending on the type of building material used for the construction of roads and pavements

Building material	Absorbed dose rate in air (nGy h^{-1})	Specific activity (Bq kg^{-1})		
		^{238}U	^{232}Th	^{40}K
Granite cubes and slabs	108 ± 5	62 ± 5	62 ± 4	937 ± 44
Stone slabs other than granite	35 ± 9	25 ± 6	17 ± 5	313 ± 72
Concrete cubes	52 ± 3	31 ± 2	28 ± 2	478 ± 29
Asphalt	44 ± 7	31 ± 5	23 ± 4	360 ± 70
None (Grass)	26 ± 9	19 ± 4	16 ± 6	275 ± 76

Uncertainty values represent the standard errors of the mean.

The lowest results were observed in parks and squares (open green areas smaller than parks), which are places where no building materials were used, even though the influence of nearby buildings and elements of landscape architecture cannot be neglected. The mean absorbed dose rate in air was 26 nGy h^{-1} and mean specific activities of ^{238}U, ^{232}Th and ^{40}K were 25 Bq kg^{-1}, 17 Bq kg^{-1} and 313 Bq kg^{-1}, respectively (Table 1). The median of the absorbed dose rate in air in places covered with grass equalled 28 nGy h^{-1}, which was half the median reported by Medeiros and Yoshimura (2005), such as 66 nGy h^{-1} .

The analysis of our results in terms of the location of measurement points and the land use indicated that the lowest background gamma radiation was on the bridges (Table 2). The part of Uniwersytecki Bridge made of red granite cubes of the rapakivi type was an exception. There, the highest background gamma radiation was noted out all of the measurement points. The absorbed dose rate in air reached 145 nGy h^{-1} and specific activities of ^{238}U, ^{232}Th and ^{40}K were 116 Bq kg^{-1}, 91 Bq kg^{-1} and 814 Bq kg^{-1}, respectively. At the other measurement points on bridges (excluding the result for red granite) absorbed dose rates in air were low and ranged from 19 to 39 nGy h^{-1} with the mean of 26 nGy h^{-1} (Table 2). The low background gamma radiation on bridges results from a low radionuclide content in the Odra River waters. Solecki et al. (2010) performed gamma spectrometric measurements on a wooden pier, thus measuring background gamma radiation above the water surface caused by the presence of radionuclides in the Odra River and in the air. Measurements from a boat on a river or lake at a distance at least 200 m from the shore are commonly performed to estimate the background due to cosmic radiation and atmospheric radon (IAEA 2003). The absorbed dose rate in air was 8 nGy h^{-1} and specific activities of ^{238}U, ^{232}Th and ^{40}K were 9 Bq kg^{-1}, 4 Bq kg^{-1} and 30 Bq kg^{-1}, respectively (Solecki et al. 2010).

Table 2

Mean specific activities (Bq kg^{-1}) and mean absorbed dose rate in air (nGy h^{-1}) at 1.0 m depending on the land use

Location	Absorbed dose rate in air (nGy h^{-1})	Specific activity (Bq kg^{-1})		
		^{238}U	^{232}Th	^{40}K
Pavements and roads among buildings	94 ± 6	51 ± 3	53 ± 4	847 ± 58
Bridges	32 ± 20	35 ± 16	26 ± 13	318 ± 101
Bridges excluding the fragment covered by the red granite	26 ± 4	19 ± 3	13 ± 2	219 ± 22
Embankments	82 ± 8	48 ± 9	46 ± 3	720 ± 63
Cemetery	49 ± 8	32 ± 1	26 ± 6	423 ± 78
Park	37 ± 9	24 ± 8	19 ± 5	323 ± 58

Uncertainty values represent the standard errors of the mean.

The highest mean absorbed dose rate in air (94 nGy h^{-1}) was observed in the case of pavements and roads surrounded by buildings (Table 2). The greatest results were noted in the center of the city, which is characterized by high density of buildings and pavements made of granite. In this case, the geometry is far from open field and every wall of surrounding buildings is a source of gamma radiation.

The values of absorbed dose rate in air in various points of Wroclaw are presented in Figs 1-3.

The results of measurements performed in the hall of the Main Railway Station in Wroclaw indicated that the greatest variation in airborne absorbed dose rate depending on the type of building material is visible at the ground level (Figure 4). For measurements performed directly on building materials used for the floor construction, the highest absorbed dose rate in air was observed in the case of diorite, lower in the case of granite and porphyry. The results for the profiles at 0.5 meter and 1.0 meter indicated that the absorbed dose rate in air becomes averaged along with the height. The aerial absorbed dose rate ranged from 92 to 165 nGy h^{-1} for measurements performed at 0.0m, from 109 to 136 nGy h^{-1} for measurements performed at 0.5m and from 97 to 118 nGy h^{-1} for measurements performed at 1.0m. The mean absorbed dose rate in air and the standard error for the means at the levels of 0.0m, 0.5m and 1.0m were 134 ± 5 nGy h^{-1}, 123 ± 2 nGy h^{-1} and 109 ± 1 nGy h^{-1}, respectively. In the case of measurements performed at the height of 1.0 m, a shielding effect of an information board covering one of the investigated walls is visible. The absorbed dose rate in air close to that wall is slightly lower than elsewhere (Figure 4).

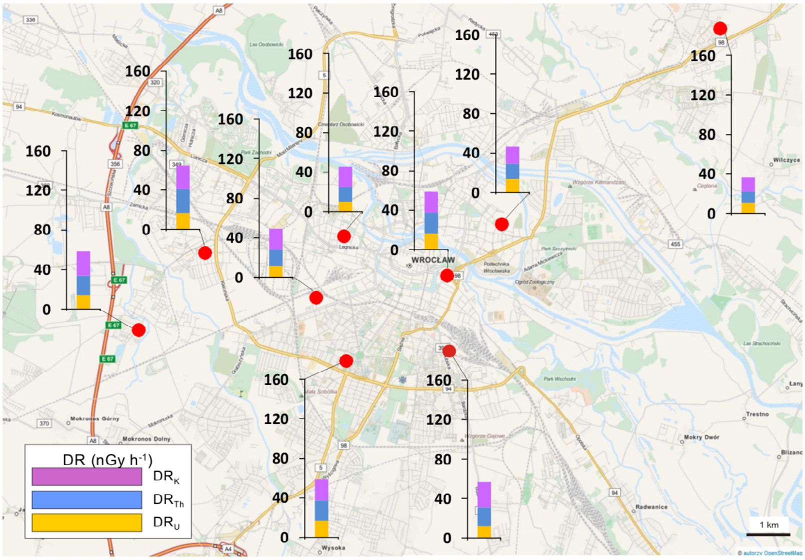

Fig. 1. Absorbed dose rate in air (nGy h^{-1}) in various districts of Wroclaw: DR_K, DR_{Th}, DR_U – contribution of K, Th series and U series, respectively

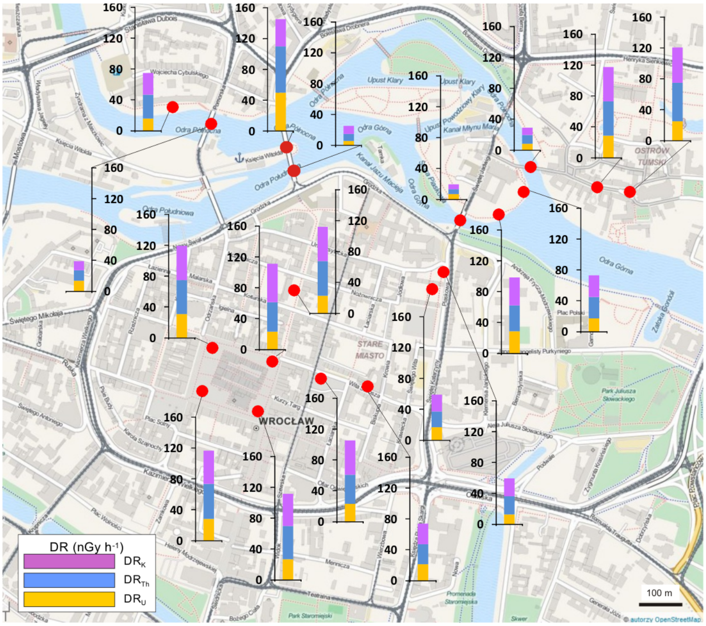

Fig. 2. Absorbed dose rate in air (nGy h^{-1}) in the centre of Wroclaw: DR$_K$, DR$_{Th}$, DR$_U$ – contribution of K, Th series and U series, respectively

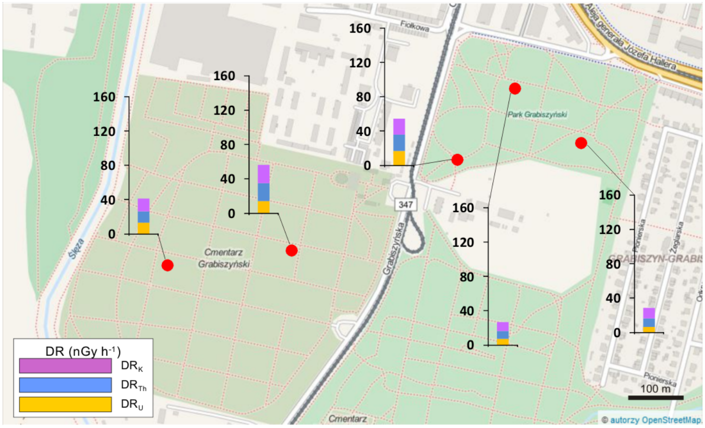

Fig. 3. Absorbed dose rate in air (nGy h^{-1}) in Grabiszynski Park and Grabiszynski Cemetery: DR$_K$, DR$_{Th}$, DR$_U$ – contribution of K, Th series and U series, respectively

Various types of building materials contain different concentrations of radionuclides. This variation is visible in the case of measurements performed on the flooring surface (Table 3). Along with the height, the results become averaged (Tables 4, 5).

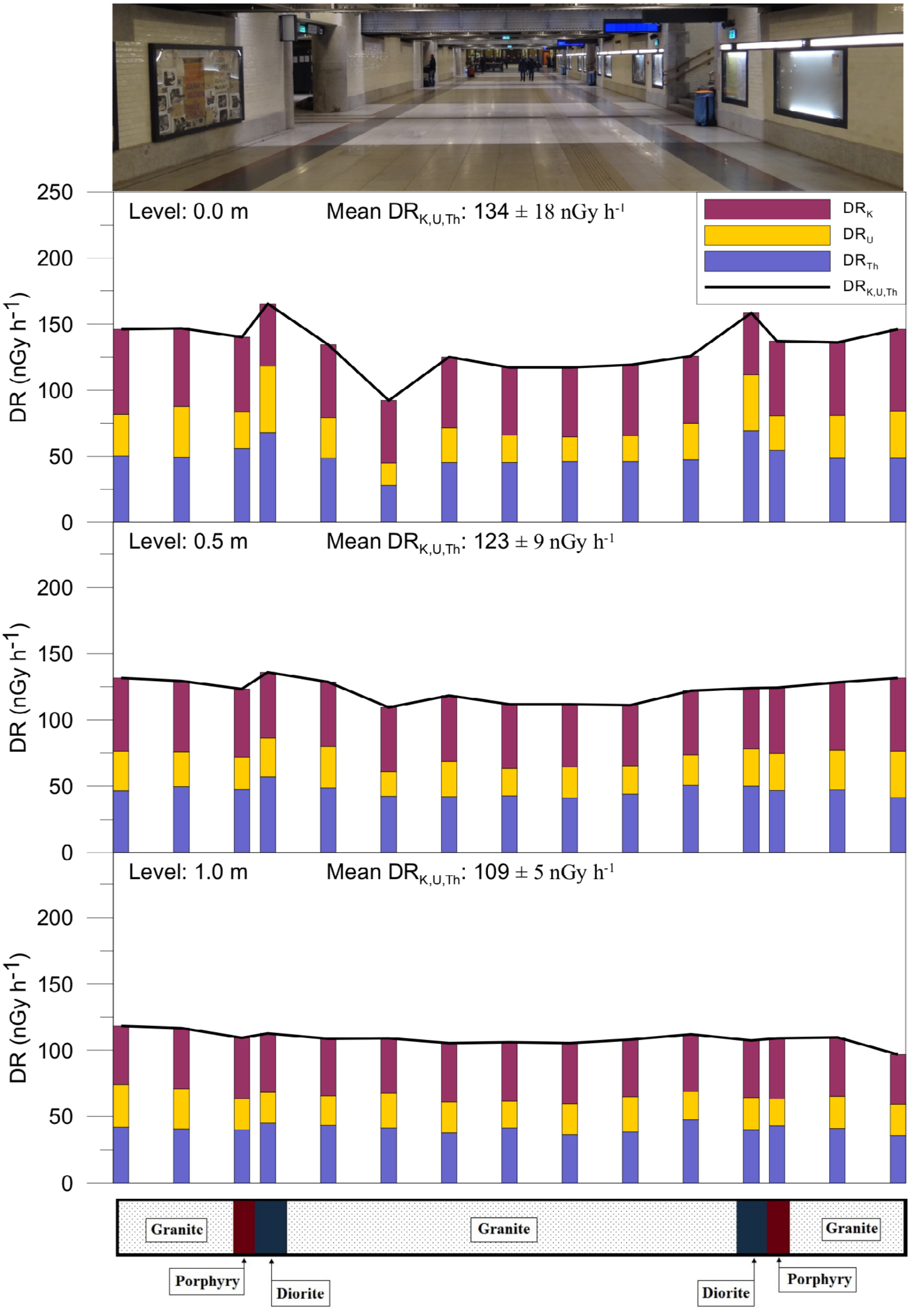

Fig. 4. Absorbed dose rate in air (DR in nGy h^{-1}) in the hall of the Main Railway Station. Uncertainty values represent the standard errors of the mean

Table 3

Results of measurements performed on the flooring surface of the hall of the Main Railway Station

Building material	Specific activity (Bq kg^{-1})		
	^{40}K	^{238}U	^{232}Th
Granite	1502	73	76
Granite	1377	89	75
Porphyry	1315	64	85
Diorite	1096	117	103
Granite	1283	72	73
Granite	1096	40	43
Granite	1252	61	69
Granite	1189	48	69
Granite	1221	43	70
Granite	1252	46	69
Granite	1189	64	71
Diorite	1096	98	105
Porphyry	1315	61	83
Granite	1283	74	74
Granite	1440	82	74
Mean	1260 ± 31	69 ± 6	76 ± 4

Uncertainty values represent the standard errors of the mean.

Table 4

Results of measurements performed at 0.5 m above the flooring surface of the hall of the Main Railway Station

Building material	Specific activity (Bq kg^{-1})		
	^{40}K	^{238}U	^{232}Th
Granite	1283	70	70
Granite	1252	61	75
Porphyry	1189	57	72
Diorite	1158	68	86
Granite	1127	73	74
Granite	1127	43	64
Granite	1158	62	64
Granite	1127	48	65
Granite	1096	54	63
Granite	1064	49	67
Granite	1127	53	77
Diorite	1064	65	76
Porphyry	1158	64	71
Granite	1189	69	72
Granite	1283	82	63
Mean	1160 ± 18	61 ± 3	71 ± 2

Uncertainty values represent the standard errors of the mean.

Table 5

Results of measurements performed at 1.0 m above the flooring surface of the hall of the Main Railway Station

Building material	Specific activity (Bq kg^{-1})		
	^{40}K	^{238}U	^{232}Th
Granite	1033	74	64
Granite	1064	70	62
Porphyry	1064	54	61
Diorite	1033	54	68
Granite	1002	52	66
Granite	970	61	63
Granite	1033	54	57
Granite	1033	47	63
Granite	1064	54	55
Granite	1002	62	58
Granite	1002	49	72
Diorite	1002	57	60
Porphyry	1064	47	65
Granite	1033	57	62
Granite	876	54	54
Mean	1018 ± 13	56 ± 2	62 ± 1

Uncertainty values represent the standard errors of the mean.

CONCLUSIONS

The investigation indicated that terrestrial background gamma radiation in an urban space depends on the type of building materials used for the construction of roads and pavements inasmuch as on the density of buildings forming the geometry of the source. The highest background gamma radiation was observed in the city center, where buildings are situated close to each other (nearly enclosed geometry) and pavements are made of granite. The lowest background gamma radiation was noticed on bridges, with nearly open field geometry. Moreover, the measurements performed in the hall of the Wroclaw Main Railway Station indicated that the absorbed dose rate in air above multi-material surfaces became averaged along with the height. The results presented in this paper may be relevant with regards to the urban planning. The research indicates that various building materials cause different gamma exposure to human beings and some building materials, such as granite, may be responsible for an enhanced absorbed dose rate in air in the urban space. Simultaneously, some of the materials may shield against gamma radiation.

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