



Analysis of the spatial variation of indoor radon concentrations (national survey in Bulgaria)

Kremena Ivanova¹ · Zdenka Stojanovska² · Bistra Kunovska¹ · Nina Chobanova¹ · Viktor Badulin³ · Aleksey Benderev⁴

Received: 24 September 2018 / Accepted: 3 January 2019 / Published online: 15 January 2019
© Springer-Verlag GmbH Germany, part of Springer Nature 2019

Abstract

This paper presents the methodology and results of the national radon survey in Bulgaria and its spatial variability. The measurements were carried out in 2778 dwellings using CR-39 track detectors over two successive 9 and 3-month periods from April 2015 to March 2016. The arithmetic (AM) and geometric (GM) means of annual indoor radon concentration were 111 ± 105 Bq/m³ and 81 Bq/m³ (GSD = 2.15), respectively. The distribution of data has been accepted to be log-normal. Two hypotheses have been investigated in the paper. The first one was a spatial variation of indoor radon concentration and the second was spatiality of the factor that influences radon variation. The indoor radon concentrations in the 28 districts have been significantly different, which prove the first hypothesis. The influence of the factors, geology (geotectonic unit, type of rock, and faults distance of the measuring site), type of the region, and the presence of the basement in the building on radon spatial variation, was examined. The analyses have been shown that they significantly affect radon variations but with a relatively small contribution in comparison to the radon variation between district. Furthermore, the significance and contribution of the investigated factors were different in each district, which confirmed the second hypothesis for their spatiality.

Keywords National survey · Indoor radon · Geology · Spatial variability · Bulgaria

Introduction

Radon is a naturally occurring radioactive heavy noble gas, decay product of ²²⁶Ra, which is a member of ²³⁸U chain. The main source of radon in a building is soil and rocks on which the building was built on, to a lesser extent, building materials or water supply from which ²²²Rn can be released during the water use. Radon exposure is responsible for approximately half of the total annual background radiation

exposure (UNCEAR 2000). For many people, ²²²Rn is an important source of exposure which, in principle, can be controlled to some extent. This is one of the reasons that considerable attention has been paid to radon in recent years. The leading international public health and radiation protection agencies, as the International Commission on Radiation Protection (ICRP), World Health Organization (WHO), and International Atomic Energy Agency (IAEA), updated their recommendations on radon in response to the new evidence of health risks from low and moderate exposure to radiation (ICRP 2007; WHO 2009; IAEA 2011). The main recommendation is that an appropriate system for reducing any exposure to indoor radon concentrations (CRn) should be established on the national level. The evaluation of the frequency distribution of radon concentration levels in dwellings is a base for an important component of any national radon program. Such evaluation should be obtained with national radon surveys designed and conducted in such a way as to be a representative of population exposure in dwellings. A population representative nationwide survey, recommended by WHO (2009), is one of the first stages of a national action plan aimed to reduce risks from radon exposure. The survey to directly measure radon concentration in a representative sample of dwellings is

Responsible editor: Georg Steinhauser

✉ Kremena Ivanova
kivanova1968@gmail.com; k.ivanova@ncrrp.org

- ¹ National Centre of Radiobiology and Radiation Protection, 3 Sv. Georgi Sofijski st., 1606 Sofia, Bulgaria
- ² Faculty of Medical Sciences, Goce Delcev University of Stip, 10-A Krste Misirkov st., Stip 2000, Republic of Macedonia
- ³ Bulgarian Nuclear Regulatory Agency, 69 Shipchenski prohod st., 1574 Sofia, Bulgaria
- ⁴ Geological Institute, Bulgarian Academy of Sciences, Bl.24 Acad.G.Bonchev str., 1113 Sofia, Bulgaria

generally used to estimate the distribution of indoor radon concentration.

Bulgaria adopted the national program for health protection of population by reducing the indoor radon concentration since 2014. The extensive population-weighted national radon survey was performed in Bulgaria for 1 year under the national program in order to assess the situation in the country as a whole for implementation of national radon policy.

Radon is a naturally occurring radioactive heavy noble gas, formed in the result of the decay of ^{226}Ra , which is a member of the decaying chain of ^{238}U isotope. The main source of radon in a building is soil and rocks on which the building was built on, to a lesser extent, building materials or water supply from which Rn can be released during the water use (UNSCEAR 2000, Annex B, C.1, p. 97). As a gas, the radon indoor concentrations have large temporal and spatial variability which depend on different factors. Relevant factors, which influence the indoor radon levels, could be principally divided into three groups: geology; ground characteristics, such as permeability, water content, organic matter or proximity to faults, and atmospheric condition; building characteristic factors such as type of building construction, date of building, and floor level and lifestyle including heating and ventilation routines. According to Appleton and Miles (2010), approximately 25% of the total variation of indoor radon in England and Wales can be explained by the geology. In previous study, we have proven that the effect of the characteristics of the building on radon variability has a spatial character and they are more dominant in inland cities than in the city located on the sea coast (Ivanova et al. 2017).

The objectives of this paper are to present the results from the national indoor radon survey in Bulgaria in general and to investigate the spatial radon variation over the territory of the country as well as the spatial character of the factors that influences radon variation.

Material and methods

Design of the survey

Bulgaria is situated in South-East Europe and occupies the North-East part of the Balkan Peninsula covering an area of 110,994 km². The relief of Bulgaria is varied. In the relatively small territory of the country, there are extensive lowlands, plains, hills, low and high mountains, many valleys, and deep gorges.

The population in Bulgaria is about 7.2 million people, with an average density of 65 people per square kilometer. Bulgaria has been divided into 28 administrative-territorial units, called “districts.” The districts are further subdivided into 265 municipalities. The biggest town in the district is the center of the province and most populated. Sofia is the

capital city of Bulgaria and the largest settlement in the country. Sofia is the administrative center of both Sofia district and Sofia City district (Sofia-grad).

The aim of the study was to receive an adequate knowledge of the radon distribution in Bulgarian dwellings. To this objective, 100 detectors have been assigned to each district, which makes a total of 2800 detectors for the whole country (Fig. 1). The survey has been designed, promoted, and coordinated by NCRRP-MH (National Centre of radiobiology and radiation protection—Ministry of Health) and carried out in collaboration with the Regional Health Inspectorates. Additional instructions have been prepared for the distribution of the detectors for each district, in order to avoid unrepresentative placing of the detectors, e.g., too many detectors in one settlement. The number of detectors for the municipalities in the district has been determined according to the population. The next level of dividing the number of detectors has been between the towns and villages in the municipality again depending on their population. This kind of distribution of the dwellings sample in all towns and villages in the municipality has been used in order to cover all territory and increase representativeness. The dwellings in town and village have been randomly selected by Regional Health Inspectorates using a door-to-door approach for contacting families and distributing detectors. Figure 1 shows a map of Bulgaria with its districts, district’s name, and measuring point location. As a result, within districts, sample density is about proportional to population density, but the proportionality is different between districts.

The locations of measured dwellings have been definite with a GPS or according to the exact address through Google Map. The coordinates have been entered into GIS, which enables the relevant analyses and visualization of the obtained results.

The information about the type of building construction and other information have been filled in questionnaires for collecting by the participants with help of the Inspectorates. The percentage of investigated buildings in towns has been assessed to be 66% using the address of the dwelling completed in the questionnaire. In order to assess the representativeness of national survey, this percentage has been compared to responding percentage of the buildings in towns according to Bulgarian National Statistical Institute (BNSI 2016) for the general dataset, which is 66.3%. The percentages are approximately the same, which corroborates the representativeness of the national survey.

The radon concentration has been measured on the ground floors of the inhabited buildings. The detector has been deployed in the room where the residents spent most of their time (living room, bedroom, or children room of the dwelling). The position of radon detectors was chosen at the height of 1–1.5 m above the floors, e.g., over a wardrobe or a bookshelf, provided that it is exposed to indoor air. The point of measurement has been chosen not to be close to heat sources and not too close to the wall,

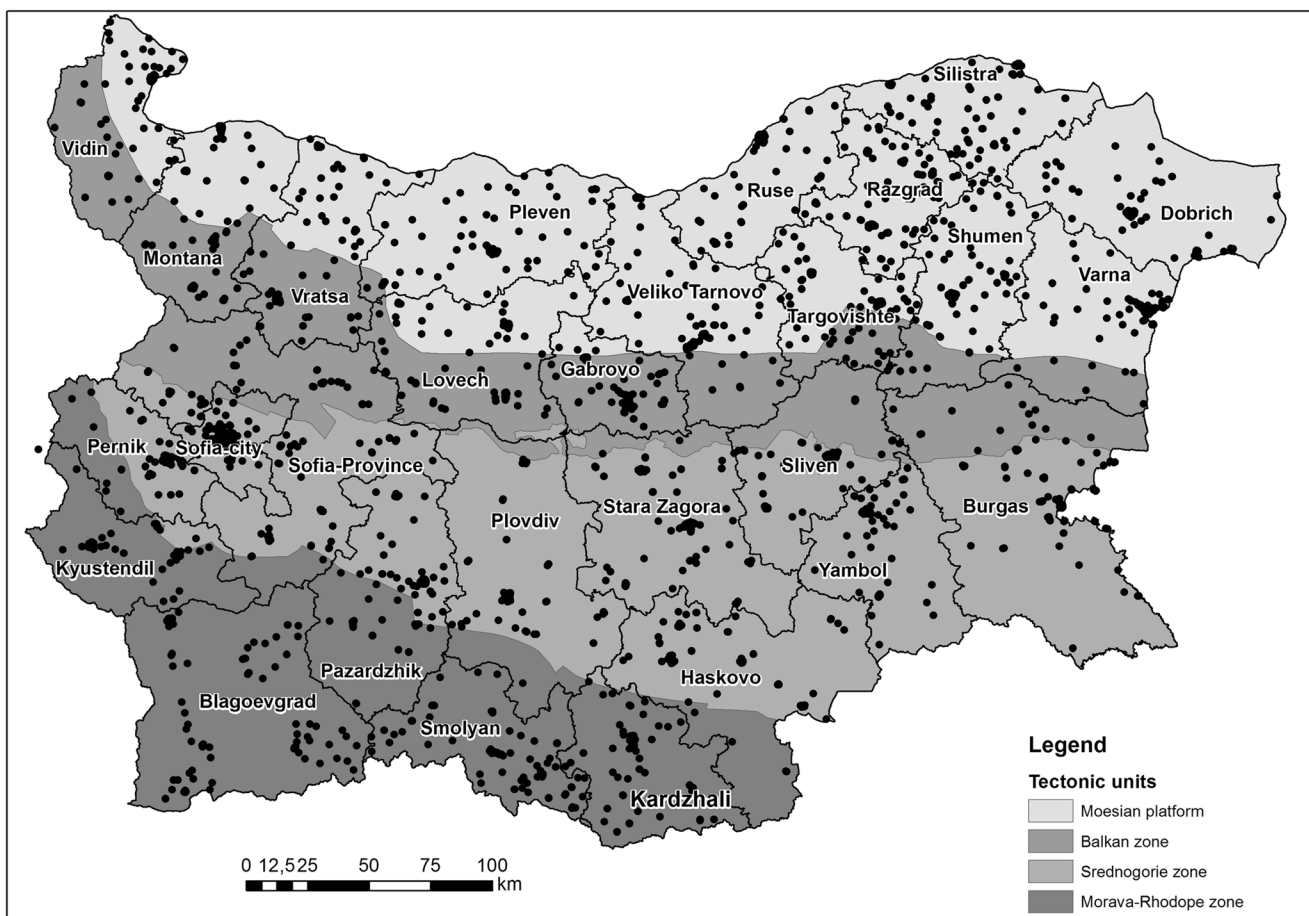


Fig. 1 Sampling points for indoor radon measurement location and tectonic units on the Bulgarian territory

in order to reduce the impact of possible high thoron concentration on the radon measurements. Duplicate detectors have been exposed close together with the main detector in 10% of dwellings for the quality control of the measurement. In the selected dwellings, the CRn were measured for 1 year in two consecutive periods. Due to administrative reason, detectors could not be replaced on sixth month, as was planned. The first period of the detector exposure was from April to December 2015 and the second was from January to March 2016. The total losses from 2800 measured dwellings were 22 houses, which not returned the detectors from the two phases. The annual CRn for 2433 dwellings has been estimated as a weighted mean of the results from two measuring periods (weighted with exposure time). The weighting procedure, which has been applied to the current survey data, ensured that the estimate of the current national average radon level is as accurate as possible. Due to loss of detectors or refusal from dwelling inhabitants for 345 dwellings, the results of one period have been only available. In such cases, the missing CRn has been estimated using the correction factor derived from the results where the measurements in both periods were available. This procedure has been implemented in another study and has been explained from Stojanovska et al. (2013).

Indoor radon measurement and data analysis

The CRn measurements were performed using solid-state nuclear track detectors (SSNTD)-type RSFV of the Radosys Ltd. The detectors used in the survey have been stored in an aluminum gas-tight bag. Each detector contains two chips (CR-39) situated in two chambers. The main chip has been set in major diffusion chamber. The second chip with the secondary diffusion chamber has been put inside the main chamber. The secondary chip is used for radon concentration assessment, when the track number on the main chip exceeds the upper limit of the linear calibration model or if an artifact on the main chip has been detected. The radon concentration in this case is calculated through track density of the secondary detector chip by correcting with the multiplicative factor F_o given by the manufacturer ($F_o = 6.67 \text{ track/mm}^2$, $\delta(F_o) = 5.55\%$).

The analyses of detectors have been made in the laboratory of the National Centre of Radiobiology and Radiation Protection. Upon return of detectors in the laboratory, the chips have been mechanically removed from chambers and chemically etched for 3 h and 40 min in a 6.25 M NaOH solution at 90–93 °C (Hulber 2009). The chemical etching enlarges the tracks created by the alpha particles. The tracks are counted

using an optical microscope and an automated image analysis system microscope. Tracks are accepted as genuine if their size and shape fall within acceptable limits and the track density for each chip has been given from the microscope. The radon concentration has been evaluated using the calibration factor and background detectors for each batch. In order to estimate the calibration factor, the detectors from two used batches for implementation of the national survey have been exposed to radon reference atmosphere in four points—200, 500, 1000, and 2000 Bq/m³ in Radon Calibration Service Laboratory of Federal Office for Radiation Protection (BfS), Germany. For evaluation of the detectors aging from the first batch, recalibration has been performed at the end of the period, and the background tracks have been analyzed through the transit detectors sent to each district. Radon concentration (CRn) and measurement uncertainties (u_{Rn}) for two periods have been estimated following the ISO 11665-4 (2012).

The statistical analysis has been applied for evaluation of the influence of categorical factors on the CRn using the commercially available statistical software: (XLSTAT 2014) Pro 7.5 (Version 2014.5.03). The following tests were applied: data distribution has been tested by Kolmogorov-Smirnov (KS) test; for analysis of variance, Kruskal-Wallis and Mann-Whitney tests have been used. As a measure of a level of association between lnRn and coded categorical factors, the Spearman coefficient of determination (ρ^2) has been used for the assessment of correlation between the variables.

Factors affecting indoor radon concentration

Geological setting The area of Bulgaria is small; however, its geological setting is complex (Yovchev 1971, Dabovski et al. 2002, Zagorchev 2009). Rocks of various ages, origin, mineral, and chemical composition are present. Their special distribution and position are complicated as a result of the complex tectonic structure of the Balkan Peninsula (Zagorchev 1992, 1994).

The Geological Map of Bulgaria (1:100,000) and the tectonic system by Dabovski et al. (2002) have been used to study the influence of the geological setting on the radon concentrations reported at the monitoring points of the National Survey on Indoor Radon (Fig. 2). According to these information sources, the country is within the range of two great structures—the Moesian Platform and the Alpine Thrust Belt. On the territory of Bulgaria, these structures have been divided into zones (superunits), units, and subunits.

The Moesian Platform is generally composed of terrigenous-carbonate rocks of different age. The main part of the platform is built by relatively undeformed Mesozoic successions of up to 4–5 km thick sedimentary deposits. These cover unconformably a gently folded Paleozoic basement and are buried underneath Palaeogene and Neogene sediments. Quaternary deposits and loess cover considerable areas on the surface. Several larger structures can be distinguished as positive and negative elevations relative to the mean. The largest structures are the Lom Depression, the North Bulgarian Arch, and the South Moesian Platform margin.

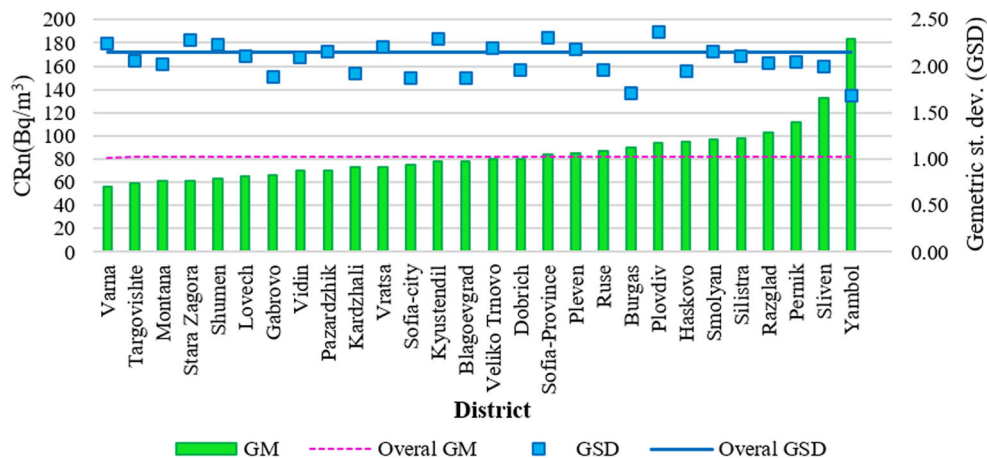
The Alpine thrust belt is divided into two orogenic systems—the South Carpathian and the Balkan system. The South Carpathian orogenic system is present only in a small area in northwestern Bulgaria and there are not many sampling points within it. Therefore, for the purpose of this study, it has been united with the Balkan orogenic system.

The Balkan orogenic system is subdivided into three tectonic zones: Balkan, Srednogorie, and Morava-Rhodope.

The Balkan Zone comprises subunits. It is composed of various terrigenous, terrigenous-carbonate, and terrigenous coal-bearing sediments, with widespread flysch, flysch-like, and molasse successions and small occurrences subvolcanic and volcano-sedimentary rocks, as well as rocks that are metamorphosed to various degrees. These make up a relatively thick continental crust (38–34 km) gradually thinning toward the Moesian platform.

The Srednogorie zone is distinguished by thick volcano-sedimentary successions and numerous intrusive bodies in a

Fig. 2 Geometric means (GM) and geometric standard deviation (GSD) of indoor radon distribution according to Bulgarian districts



relatively thin (35–28 km) continental crust. Terrigenous, terrigenous-carbonate, and terrigenous coal-bearing sediments, various magmatic, and metamorphosed rocks are also present.

The Morava-Rhodope zone includes widely exposed high-grade metamorphic basement complexes; frequent intrusive bodies of different sizes; isolated Palaeogene basins with continental and shallow marine sediments associated with mostly acid and intermediate volcanic rocks, thick continental crust (50–52 km) in the central parts of the zone, thinning to 34–37 km in SE and NW direction.

Sediments of Tertiary intraorogenic continental and shallow marine basins cover and mask large areas within the Srednogorie and Morava-Rhodope zone. Alluvium is deposited along the river valleys in the area of the Alpine Thrust Belt.

The influence of the faults on the CRn according to their distance to the dwelling has been investigated also in the study. A fault is a planar fracture or discontinuity in a volume of rock, across which there has been significant displacement as a result of rock-mass movement. Faults are differed according to their angle of dip and their relative displacement, but their species have been not considered in the survey because of insufficient number sampling points in their impact area. The distance between the dwelling location and tectonic faults was extracted from the geological maps by GIS methods.

Type of region The settlements could be classified as rural or urban depending on the density of human-created structures and resident people in a particular area. Urban areas include town and cities while rural areas include villages and hamlets. The settlements in Bulgaria are united in municipalities and then in larger regions—districts. There are one town and several villages in the municipalities. Urban and rural areas differ in economic, social, and environmental terms, which have been reflected by the type of buildings in them. The difference between the regions has been investigated in the study.

Presence of the basement Building surfaces in contact with the ground provide an ingress route into room air through construction joints and settlement cracks by pressure-driven flow (Hintenlane and Al-Ahmady 1992). The influence of building construction with or without a basement on indoor radon concentration has been assessed.

Results and discussion

Descriptive statistic and data distribution

The descriptive statistic of the annual radon concentrations (CRn) in 2778 dwelling is presented in Table 1. The distribution

Table 1 Descriptive statistic of annual radon concentrations measured in 2778 dwellings

Statistic	CRn
No. of observations	2778
Minimum, Bq/m ³	11
Maximum, Bq/m ³	1314
Median, Bq/m ³	78
Arithmetic mean (AM), Bq/m ³	111
Standard deviation (SD), Bq/m ³	105
Geometric mean (GM), Bq/m ³	81
Geometric standard deviation (GSD)	2.15
Percentage of buildings with < 100 Bq/m ³	61%
Percentage of buildings with 100–300 Bq/m ³	33%
Percentage of buildings with > 300 Bq/m ³	6%

of the measured radon concentrations is accepted to be log-normal (Daraktchieva et al. 2014). The obtained geometric mean and geometric standard deviation (in brackets) have been found to be 81 Bq/m³ (2.15). The similar GM have been reported for some other European countries such as those of Republic of Macedonia GM = 84 Bq/m³ (Stojanovska et al. 2012), Hungary GM = 82 Bq/m³, Slovenia GM = 87 Bq/m³, Estonia (GM = 92 Bq/m³), Finland (GM = 84 Bq/m³), and Czech Republic (GM = 94 Bq/m³) (UNSCEAR 2000). The CRn in 61% of the observed buildings has been found to be < 100 Bq/m³, in 33% of buildings between 100 and 300 Bq/m³ and in 6% above 300 Bq/m³. Considering many factors affecting CRn variability, a wide range of GSD appeared in the literature. For example, our GSD = 2.15 is higher than the GSD = 1.86 reported for 437 dwellings in much territory smaller neighboring county Macedonia (Stojanovska et al. 2012). Furthermore our GSD is lower than GSD reported for Hungary GM = 82 Bq/m³ (GSD = 2.7) (UNSCEAR 2000); Montenegro GM = 58.3 Bq/m³ (GSD = 2.91), (Vukotic et al. 2018); and Ireland Gm = 77 Bq/m³ (GSD = 2.4) (Dowdall et al. 2017) and higher than values reported in surveys in Sokobanja (Serbia) GM = 102 Bq/m³ (GSD = 1.79) (Bossew et al. 2014) and Kosovo GM = 143 Bq/m³ (GSD = 1.7) (Gulan et al. 2013).

Spatial variability of CRn has been confirmed. CRn are significantly different between districts (KW, *p* < 0.0001). The GM in the district varies from 57 Bq/m³ (2.24) for Varna district to 184 Bq/m³ (1.69) for Yambol district (Fig. 2). The GM of CRn in 12 districts is higher in comparison to the overall GM of CRn which could be seen on the same figure. In general, the variability in districts is lower than the variability pertaining to the whole territory. Only in nine districts, GSD is higher than the overall GSD. This result is logical, bearing in mind that the factors influencing radon variation have larger spatial variability on a larger territory,

Table 2 Descriptive statistic of CRn grouped by geological parameters

Geological parameters		N	Rn (Bq/m ³)			Percentage of dwellings with CRn			
			Range	AM (SD)	GM (GSD)	< 100 Bq/m ³	100–300	> 300	
Tectonic unit	Balkan zone	374	13–686	90 (79)	69 (2.04)	70%	28%	2%	
	Moesian platform	1078	11–631	103 (91)	76 (2.14)	64%	31%	6%	
	Morava-Rhodope zone	432	16–1310	111 (117)	81 (2.10)	65%	30%	5%	
	Srednogorie zone	893	12–1314	129 (121)	95 (2.17)	53%	39%	8%	
Rock type	High metamorphic	191	13–524	99 (90)	75 (2.07)	70%	25%	5%	
	Igneous rocks (effusive)	13	17–1310	214 (344)	110 (3.07)	54%	31%	15%	
	Igneous rocks (intrusive)	96	15–517	105 (97)	78 (2.12)	60%	34%	5%	
	Low metamorphic	18	19–198	74 (52)	58 (2.13)	67%	33%	0%	
	Sedimentary rocks (lithified)	1261	11–1060	105 (95)	78 (2.11)	64%	30%	6%	
	Sedimentary rocks (partially lithified)	125	17–425	85 (78)	60 (2.24)	70%	27%	2%	
	Sedimentary rocks (unlithified)	889	13–1314	120 (110)	89 (2.14)	56%	37%	7%	
	Volcanogenic-sedimentary rock	184	12–846	136 (134)	97 (2.23)	52%	39%	9%	
	Faults distance	0–100 m	32	11–329	101 (93)	67 (2.58)	63%	34%	3%
		100–300 m	72	26–376	95 (72)	76 (1.90)	68%	29%	3%
		300–500 m	86	19–452	90 (85)	67 (2.06)	74%	21%	5%
> 500 m		2587	12–1314	112 (106)	82 (2.15)	61%	33%	6%	

instead of on a smaller one, where the effects are more uniform, in general. This hypothesis has been examined and proved in another survey (Appleton and Miles 2010). The lowest GSD (1.69 and 1.70) have been obtained for the districts, which are neighbor to Yambol and Burgas district, while the higher relate to the following districts: Stara Zagora (GSD = 2.28), Kyustendil (2.30), Sofia-Province (2.30), Plovdiv (2.36). The similarities between the values of the GSD for neighboring districts are noticeable. Furthermore, the analysis has been shown that the value of the GSD is not related to the GM of CRn and to the number of measurements in each district since they were practically the same.

Factors affecting indoor radon concentration spatial variability

The effect of geological setting on CRn variability was analyzed. The statistic of CRn grouping by the available geological parameters is shown in Table 2.

The analysis of variance has shown that the CRn are significantly different between tectonic units ($p < 0.0001$) (Table 2, Fig. 3). Further, multiple pairwise comparisons have shown that CRn measured in the Srednogorie zone are higher in comparison to all other tectonic units, while as the lowest values are related to the Balkan zone. The values of CRn to

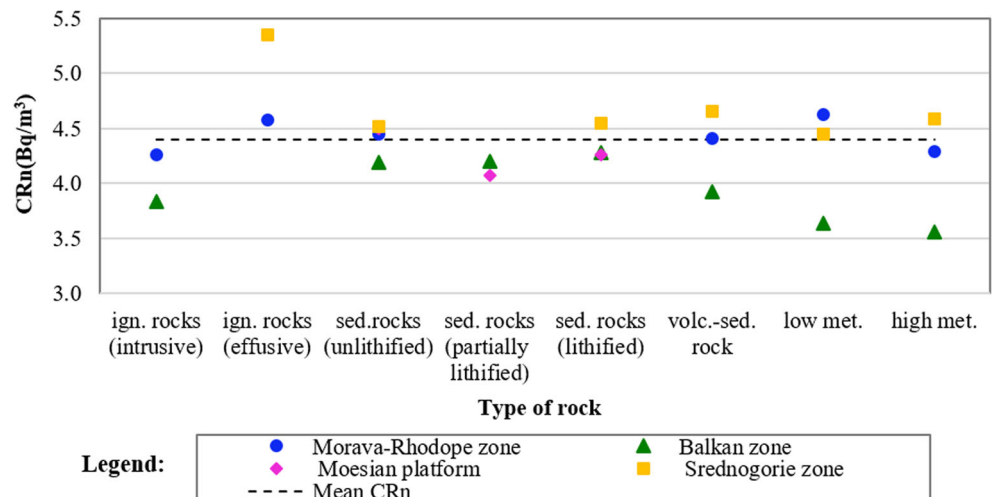
Fig. 3 Geometric mean of CRn grouped by the type of rock and tectonic zone

Table 3 Descriptive statistic of CRn grouped by the presence or absence of the basement in the building and type of the region

		N	Rn (Bq/m ³)			Percentage of dwellings with CRn		
			Range	AM (SD)	GM (GSD)	< 100 Bq/m ³	100–300 Bq/m ³	> 300 Bq/m ³
Presence of basement	No	1017	11–1314	132 (126)	97 (2.17)	52%	40%	8%
	Yes	1760	12–720	99 (88)	74 (2.10)	67%	29%	5%
Type of region	Rural	933	12–1310	125 (110)	94 (2.11)	54%	38%	8%
	Urban	1844	11–1314	104 (102)	76 (2.15)	65%	30%	5%

Moesian platform are lower than average for the country. A significant effect of rock type under a building on radon variation has been also confirmed ($p < 0.0001$). The higher CRn originated from the igneous effusive and volcanogenic-sedimentary rocks in comparison to other types of rocks. The radon emanation depends on the uranium concentration (and therefore of radium) in the rock substrate on a geochemical point of view, for that the rocks genesis has an important impact on indoor CRn. The granite contained and the specific activities of uranium (respectively radium) in igneous rocks (effusive) and volcanogenic-sedimentary rocks are higher than another type of rocks (UNSCEAR 2000 Annex B, C.1, p. 98). These types of rocks and all magmatic groups are connected to the Srednogorie zone and this could determine the high radon concentrations in the zone (Fig. 3). Moreover, the most of former uranium mining sites have been situated in the Srednogorie and Morava-Rhodope zone so increased radon risk from bedrock has been expected (Dikov and Bozhkov 2004). The lowest CRn were observed on the low metamorphic rocks in Balkan zone and sedimentary rock (partially lithified) in the Moesian platform. On the other hand, the GSD of the igneous rocks (effusive) is the highest, which shows the highest variation and means that not only the concentration of uranium in rocks influences the CRn. The permeability and thickness of superficial rock deposits also

influence radon exhalation from the soil, but the relatively small number of radon measurements did not allow evaluating these features.

The impact of faults on the territory of Bulgaria to the CRn has been difficult to determine because the bulk of the sampling points has been located outside the zones of potential influence. Only 7% of all samples are placed at a distance of fewer than 500 m from the geologically mapped faults. Karstification and fault line could explain the higher CRn, as the research in the Jura Mountains in Switzerland from Savoy et al. (2011) has shown, but it should be applied on a regional level. Drawing consistent conclusions for Bulgaria requires more detail investigation of fault line types and radon measurement on the regional scale.

The type of region (urban and rural) and the presence of a basement in the building on CRn variation have been also examined and the effect has been statistically significant (KW, $p < 0.0001$). The descriptive statistic for both factors is given in Table 3. The higher CRn are measured in a rural area in comparison to urban one. In general, these differences arise from the type of building, or of the characteristics that control the radon entrance in it and radon dynamics. Furthermore, the buildings in the rural area are smaller and older (wall cracks existence are ways of radon entrance into a building). The same difference has been investigated on the pilot indoor radon survey in regions in Bulgaria (Ivanova et al. 2013). The existence of a basement in the building is a factor that significantly reduces the CRn in it. This well-known fact published in many publications (Ivanova et al. 2017; Stojanovska et al. 2016; Stojanovska et al. 2017; Müllerová et al. 2016) has been confirmed in our study too.

An analysis of the impact of the basement presence in building on the concentration of radon in different regions (rural and urban) has been carried out. The results are presented in Fig. 4 and are shown that the main difference in the CRn in buildings with and without a basement is in urban regions as well as the type of region affected only the buildings with basement. This could be explained by the old buildings and by the lack of basements in most of the buildings in rural regions.

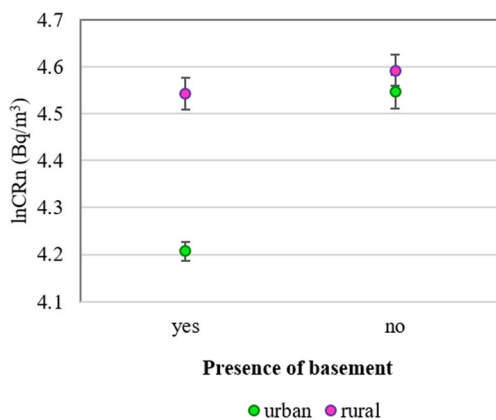
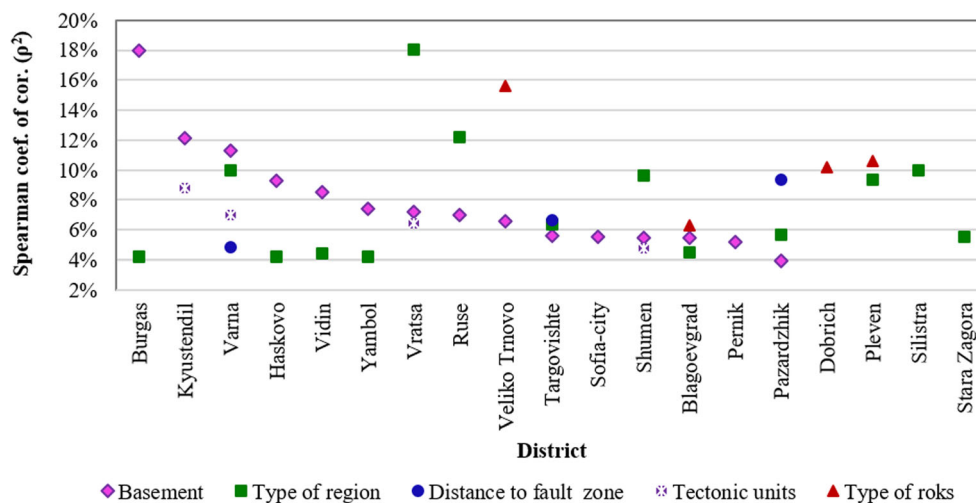


Fig. 4 lnCRn in buildings with and without basement belonging in a different type of regions

Fig. 5 Spearman coefficient of determination as a measure of the relationship between factors and CRn in a different district. (Presented values have significance on a 95% confidence level)



The spatiality of investigated factors

In order to study spatiality of the factors, the correlation between CRn and factors has been analyzed in each district. As a measure, the Spearman coefficient of determination (ρ^2) has been used (Ivanova et al. 2017). The ρ^2 values for each district where correlations were significant are presented in Fig. 5. It is obvious that a factor effect on the CRn variations in each district is different. For example, the significant radon variability effect from the rock type factor has been observed in the four districts (Blagoevgrad, Veliko Tarnovo, Pleven, Dobrich) with ρ^2 in a range from 6.3 to 15.6% (Fig. 5). Unlike geology factors, the region and basement factors significantly affect radon variation in most of the districts. The influence of the type of region on the CRn is significant in 14 districts with ρ^2 in a range from 4.2 to 18%. The analysis of basement availability in the building has been indicated the significant influence on CRn in 15 districts with ρ^2 in a range from 5.2 to 18% (Fig. 5).

The two investigated factors—basement availability and type of region—appear to influence radon variations in parallel at most of the districts. The CRn variation has been affected by the presence of basement but has not been by the type of region in three districts. This could be because in those districts there is only one type of region, as “Sofia city” district does not have a rural area, “Pernik” district is a region almost of a rural type. The regions without an influence of the presence of basement on radon variation are “Pleven,” “Silistra,” and “Stara Zagora” districts. This could be explained by different construction styles of building in these regions.

The variations in geological formations and an evaluation of the factors affecting CRn in the districts mean that conclusions drawn for one area cannot necessarily be extrapolated to in adjoining areas even with the same geological formations (Miles and Ball 1996). The analysis of indoor radon variation by districts indicates the different types of influence on the

local level, which demonstrated the need for the regional evaluation of the factors for predicting model of radon variability.

Conclusions

The national indoor radon survey in Bulgaria has been conducted. The arithmetic (111 Bq/m^3) and geometric means (81 Bq/m^3) for the country have been obtained. The percentage of dwellings with annual average radon activity concentrations above 300 Bq/m^3 is 6%. The analysis could be the basis for the adopted national radon reference level of 300 Bq/m^3 , above which exposure is considered inappropriate and should be optimized with priority.

The classification of geological units on the Bulgarian territory has been investigated and the analysis of variance has shown that the CRn are significantly different between tectonic units and type of rocks. The multiple pairwise comparisons have been shown that CRn measured in the Srednogorie zone, which mostly contains the igneous rocks (effusive) and volcanogenic-sedimentary rocks, are higher in comparison to all other tectonic units. The survey has been designed as a population representative nationwide survey, but nevertheless, the analysis has proved the dependency of indoor radon level on geology. On the other hand, the study provides the bases of the classification of rock types, widespread on the tectonic units according to the radon concentration, which could be used for modeling of geogenic radon in Bulgaria and detail survey. The analysis and classification of the tectonic and rocks could be used for applying the graded approach for further evaluation of radon potential of the municipalities and their prioritization. The impact of investigated factors, type of regions and the presence of the basement on the annual radon concentration, have been observed and should be considered in the evaluation of radon potential too.

The analysis of the radon variation has shown statistically significant difference between the CRn in the different districts. The effects of the examined factors on the radon variations in each district were with different contributions, thus confirming the hypothesis for the factor spatiality. The results provide useful data for the future work under National radon action plan and the limitation of radon exposure, including expanding the number of measurement to better take into account geological factors.

Acknowledgements The national survey has been conducted under the National Radon Program, funded by the Bulgarian Ministry of Health. The authors express their gratitude to the 28 Regional Health Inspectorates in the country, for the well-organized distribution of detectors and to all households who participated in the survey. A special acknowledgement to Peter Bossew from the German Federal Office for Radiation Protection, Berlin, Germany, for his careful manuscript reading and helpful comments.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

- Appleton DJ, Miles HCJA (2010) A statistical evaluation of the geogenic controls on indoor radon concentrations and radon risk. *J Environ Radioact* 101(10):799–803
- Bossew P, Žunić ZS, Stojanovska Z, Tollefsen T, Carpentieri C, Veselinović N, Komatina Z, Vaupotić J, Simović RD, Antignani S, Bochicchio F (2014) Geographical distribution of the mean radon concentrations in primary schools of Southern Serbia - application of geostatistical methods. *J Environ Radioact* 127:141–148
- Bulgarian National Statistical Institute (2016) Statistical yearbook 2015
- Dabovski C, Boyanov I, Khrishev K, Nikolov T, Sapounov I, Yanev Y, Zagorchev I (2002) Structure and Alpine evolution of Bulgaria. *Geol Balc* 32(2–4):9–15
- Daraktchieva Z, Miles JCH, McColl N (2014) Radon, the lognormal distribution and deviation from it. *J Radiol Prot* 34:183–190
- Dikov D, Bozhkov I (2004) Uranium deposits in Republic of Bulgaria – state of art and potential. *Review of Bulgarian Geological Society* 75(1–3):131–137
- Dowdall A, Murphy P, Pollard D, Fenton D (2017) Update of Ireland's national average indoor radon concentration - application of a new survey protocol. *J Environ Radioact* 169–170:1–8
- Gulan LR, Bochicchio F, Carpentieri C, Milic GA, Stajic JM, Krstic DZ, Stojanovska Z, Nikezic DR, Zunic ZS (2013) High annual radon concentration in dwellings and natural radioactivity content in nearby soil in some rural areas of Kosovo and Metohija. *Nucl Technol Radiat* 28:60–67
- Hintenlane DE, Al-Ahmady KK (1992) Pressure differentials for radon entry coupled to periodic atmospheric pressure variations. *Indoor Air* 2(12):208–215
- Hulber E (2009) Overview of PADC nuclear track readers. Recent trends and solutions. *Radiat Meas* 44(9–10):821–825
- IAEA (2011) Radiation protection and safety of radiation sources: international basic safety standards general safety requirements part 3 no. GSR part 3 IAEA Vienna
- ICRP (2007) The 2007 recommendations of the International Commission on Radiological Protection. ICRP Publication 103 Annals of the ICRP 37 (2–4) (Oxford: Pergamon)
- International Organization for Standardization (2012) Measurement of radioactivity in the environment — air: radon-222. Part 4: integrated measurement methods for the determination of the average radon activity concentration in the atmospheric environment using passive sampling and delayed analysis. ISO 11665–4:2012
- Ivanova K, Stojanovska Z, Tsenova M, Badulin V, Kunovska B (2013) Pilot survey of indoor radon in the dwellings of Bulgaria. *Radiat Prot Dosim* 157(4):594–599
- Ivanova K, Stojanovska Z, Tsenova M, Kunovska B (2017) Building-specific factors affecting indoor radon concentration variations in different regions in Bulgaria. *Air Qual Atmos Health* 10(9):1151–1161
- Miles J, Ball K (1996) Mapping radon-prone areas using house radon data and geological boundaries. *Environ Int* 22(1):779–782
- Müllerová M, Kozak K, Kovács T, Smetanová I, Csordás A, Grzadziel D, Holý K, Mazur J, Moravcsík A, Neznal M, Neznal M (2016) Indoor radon survey in Visegrad countries. *Appl Radiat Isot* 110:124–128
- Savoy L, Surbeck H, Hunkeler D (2011) Radon and CO₂ as natural tracers to investigate the recharge dynamics of karst aquifers. *J Hydrol* 406:148–157
- Stojanovska Z, Januseski J, Boev B, Ristova M (2012) Indoor exposure of population to radon in the FYR of Macedonia. *Rad Prot Dosim* 148(2):162–167
- Stojanovska Z, Bossew P, Tokonami S, Zunic ZS, Bochicchio F, Boev B, Ristova M, Januseski J (2013) National survey of indoor thoron concentration in FYR of Macedonia (continental Europe - Balkan region). *Radiat Meas* 49:57–66
- Stojanovska Z, Boev B, Zunic ZS, Ivanova K, Ristova M, Tsenova M, Ajka S, Taleski V, Bossew P (2016) Variation of indoor radon concentration and gamma dose rate in different outdoor and indoor environments. *Radiat Environ Biophys* 55(2):171–183
- Stojanovska Z, Ivanova K, Bossew P, Boev B, Zunic Z, Tsenova M, Curguz Z, Kolarz P, Zdravkovska M, Ristova M (2017) Prediction of long-term indoor radon concentration based on short-term measurements. *Nucl Technol Radiat* 32(1):77–84
- UNSCEAR (2000) Sources and effects of ionising radiation. Volume 1: report to the general assembly with scientific annexes. Annex B. exposures from natural radiation sources UNSCEAR 2000 report, C.1. United Nations, New York, p 98
- Vukotic P, Antovicb N, Djurovic A, Zekic R, Svrkota N, Andjelic T, Svrkota R, Mrdak R, Bjelica N, Djurovic T et al 2018 Radon survey in Montenegro – a base to set national radon reference and “urgent action” level. *J Environ Radioact*. S0265-931X(17)30680-X
- WHO (2009) Handbook on indoor radon: a public health perspective. World Health Organization, Geneva
- XLSTAT (2014) Tutorials, statistical application for Microsoft Excel, New York, NY. Addinsoft 1995–2014. <http://www.xlstat.com>. Accessed 27 May 2017
- Yovchev Y (ed) (1971) Tectonic structure of Bulgaria, PH Technika, Sofia, p 558 (in Bulgarian)
- Zagorchev I (1992) Neotectonics of the central parts of the Balkan Peninsula: basic features and concepts. *Geogr Rundsch* 81(3):635–654
- Zagorchev I (1994) Alpine evolution of the pre-alpine amphibolite facies basement in South Bulgaria. *Mitt Österr Geol Ges* 86:9–21
- Zagorchev I (2009) Geomorphological zonation of Bulgaria. Principles and state of the art. *C R Acad Bulg Sci* 62(8):981–982