INFLUENCE OF CLIMATE, BUILDING, AND RESIDENTIAL FACTORS ON RADON LEVELS IN GROUND-FLOOR DWELLINGS IN MONTENEGRO

by

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After year-long measurements with CR-39 detectors, nationwide radon survey was performed in 953 homes – 0.5 % of all permanently inhabited dwellings in Montenegro. Influence of 11 factors (area, climate, type of house, year of construction, basement, foundation slab, number of stories, building materials, window frames, heating, and smoking) and 35 their 35 categories on the radon concentrations in 732 ground-floor dwellings was analyzed using descriptive, univariate and multivariate methods.
Univariate analysis dropped influence of the two factors: heating and smoking. It reveals that, on average, radon concentrations in ground-floor dwellings differ at 95 % confidence level in urban and rural areas, in family houses and apartment buildings, in houses with and without basement, and in dwellings with window frames made of wood and PVC/Al. In Cf climate zone they differ from those in Cs and Df zones. Only two pairs of construction periods differ in mean radon concentrations in dwellings: 1980-1999 with 1900-1944, and with 1964-1979. Houses with one, two or three stories have almost equal average radon levels, which are higher than in buildings with more than three stories. Mean value of radon concentrations in houses made of stone are higher than in houses made of concrete, or bricks, or wood.
Multivariate analysis revealed that six of the analyzed factors: area, climate, type of house, presence of basement, number of stories, and building materials simultaneously have significant relationships ($p < 0.05$) with radon concentrations in dwellings on ground floor in Montenegro.

Key words: ground-floor dwelling, factor affecting radon concentration, univariate and multivariate analysis

INTRODUCTION

Montenegro is a Western Balkan country that emerges on the coast of Adriatic Sea, with total land area of 13812 km^2. The capital and largest town is Podgorica. The country has three regions: Coastal, Central, and Northern Region. Geologically, the Coastal Region is characterized by carbonate sediments (mainly limestone and dolostone), flysch sediments and volcanic rocks. The Central Region is a limestone and high karst area, with scarce volcanic rocks and flysch sediments. Clastites, carbonates, vulcanites, vulcanoclastites and lake sediments characterize the Northern Region. According to Köppen classification, there are three types of climate in Montenegro [1]: Cs – Mediterranean climate with hot and dry summer and mild winter, Cf – mild and wet climate with worm summer, and Df – snow-boreal climate without dry season, with fresh summer and cold winter. The Cs type of climate is present in the Coastal Region and in the valleys in municipalities of Podgorica and Danilovgrad, which belong to the Central Region. The Df type of climate exists in the region of high mountains in the Northern Region. The rest of the country is characterized by the Cf type of climate.

Many factors have influence on indoor radon concentrations [2, 3]. These factors may be classified in the following groups:
– *radon sources* (soil under building, building material, water and gas supply),
– *building construction* (presence of basement, quality of foundation and floor slabs, number of stories, presence of elevator and ventilation shafts),

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– *meteorological parameters* (temperature difference between indoor and outdoor air, wind, pressure differential between the soil and the foundations of building), and

– *living habits of occupants* (smoking, ventilation, heating and air-conditioning).

Effect of some of these factors on radon concentrations are subject of studies of many researchers worldwide, because it is usually a great deal country specific.

In Italy, using univariate analysis, Gallelli *et al*. [4] studied effect of the four factors: story level, age of building, type of heating and type of windows, on radon concentrations in dwellings of the towns Genoa and Savona, and could not confirm only the influence of the type of window frames. In the North Macedonia, Stojanovska *et al*. [5] investigated influence of the six factors, related to building characteristics, on the indoor radon concentrations in 437 dwellings all over the country. The univariate analysis has shown that the three of them: floor level, basement, and building materials, affect radon level in dwellings. In Bulgaria, Ivanova *et al*. [6] measured radon concentrations in 174 kindergartens and studied, using univariate and multivariate analysis, influence of 11 building-specific factors: elevator, basement, mechanical ventilation, type of windows, building foundation, number of floors, building renovation, building materials, type of room, type of heating, and construction period. They found that only the factor *availability of foundatio*n has no significant influence because of the small number of surveyed buildings without foundation. Yarmoshenko *et al*. [7] performed univariate analyses of a large number of national and regional radon surveys in order to analyze variance of radon concentrations with regard to geogenic and anthropogenic influencing factors. The analysis of the geometric standard deviation revealed main factors influencing the dispersion of indoor radon concentration over the territory: area of territory, sample size, measurement technique, radon geogenic potential, building construction, and living habits.

Radon measurements for the first nationwide radon survey in Montenegrin homes were completed at the end of 2015, and some of the obtained results were already published [8-10]. Data collected during the survey are now used for studing which regional and house characteristics have influence on radon concentrations in the ground-floor dwellings in Montenegro. With this aim, the descriptive statistics and univariate and multivariate analyses on the data were applied, and this paper presents the obtained results.

MATERIALS AND METHODS

Montenegro has population of about 620 000 – two thirds in urban and one third in rural areas. At the time of the last national census, in 2011, there were 188 376 permanently inhabited dwellings in the country [11]. Prevailing types of residential buildings are apartment buildings and family houses, both mostly made of concrete and bricks and without HVAC systems.

A combination of geographically based and population-weighted survey was chosen for residential radon survey in Montenegro. The first type of survey is based on a national grid of 5 km   5 km mesh, with 552 squares in it. The second type of survey is based on the both national grid and local grids. The local grids are established in towns and have a finer mesh of 0.5 km   0.5 km. In each of the squares, from both grids, one dwelling, mainly on the ground floor, was selected for radon survey. Only in the city of Podgorica, the number of sampled homes in a local square with the highest density of dwellings was increased in order to obtain a nearly uniform sampling ratio of the whole dwelling stock in the city.

Following advice of the construction expert, a house which could be regarded as representative for a grid square was identified directly in the field, and one permanently inhabited dwelling in the house was selected for radon measurement. Because the dwellings for radon survey were not selected in a completely random way, it has been proven that this method of sampling does not produce a statistically significant bias in the obtained results for radon concentrations [8].

Radon survey was successfully performed in 953 dwellings, 0.5 % of all the permanently inhabited dwellings in the country, registered during the last national census. Radon was measured in a living room or a bedroom and occupants were given flexibility to choose location. The measurement protocol involved two consecutive six-month measurements in each of the selected homes, covering the *summer* (April-September) and *winter* (October-March) half-year periods. Track-etch detectors CR-39 were used for the radon survey. *Basic* detectors were purchased from Landauer Nordic (Radtrack2 type) and *control* detectors from AGES, Austria (RSKS type). After exposure, the detectors were returned to their respective laboratories for etching and reading. Consistency and precision of radon measurements were controlled in a way that at each tenth location duplicate measurements were performed, while at each tenth (but not the same) location a *basic* and a *control* detector were placed side-by-side. Results of the paired detectors showed good agreement, generally within 10 %.

Statistical analysis of the experimental data was performed with *R* software.

RESULTS AND DISCUSSION

Descriptive statistics

Characteristics of the average annual radon activity concentrations in Montenegrin homes are given

Table 1. Characteristics of radon activity concentrations in dwellings

Dwelling floor	Number of dwellings	AM (SE) [Bqm^{-3}]	MED [Bqm^{-3}]	MAX [Bqm^{-3}]	GM [Bqm^{-3}]	GSD
Basement	5	86 (24)	105	146	67.8	2.13
Ground floor	732	131 (7)	65	2321	71.5	2.88
First floor	167	41 (4)	29	394	29.4	2.20
Second and third	32	24 (4)	18	127	19.5	1.90
Unknown	17	71 (12)	50	169	57.1	1.89
Total	953	110 (6)	52	2321	58.3	2.91

AM – arithmetic mean, SE – standard error, MED – median, GM – geometric mean, GSD – geometric standard deviation, MAX – highest radon concentration

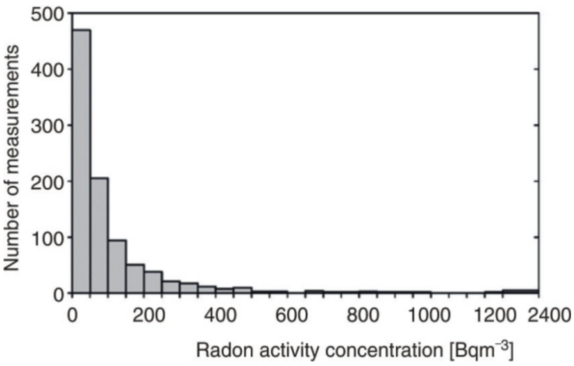

Figure 1. Frequency distribution of radon activity concentrations in 953 homes

in tab. 1, while histogram of their frequency distribution is presented at fig. 1. Geometric mean and geometric standard deviation are calculated assuming that the experimental radon data conform closely to a log-normal distribution. Comparing to the unweighted worldwide arithmetic and geometric mean values of 46 Bqm^{-3} and 37 Bqm^{-3} [12], the corresponding values of indoor radon concentrations in Montenegro (110 Bqm^{-3} and 58.3 Bqm^{-3}) are quite high – AM is 2.4 times and GM 1.6 times higher. Radon activity concentrations above the level of 300 Bqm^{-3} , which is recommended by the Council Directive 2013/59/ EURATOM [13] as the highest national reference level, are found in 7.9 % of homes.

The average radon activity concentrations, given in tab. 1, are in accordance with a general rule that indoor radon concentration decreases with increasing floor level, especially between the ground floor and the first floor [14]. Number of the surveyed dwellings in basement is too small to make any reliable conclusion on comparison of average radon levels between basements and ground floors.

In order to obtain reliable conclusions about the effects of different factors (region and house characteristics and living habits of occupants, collected in questionnaires) on the radon activity concentrations in Montenegrin homes, only the radon activity concentrations in the ground-floor dwellings are analyzed. Reasons for this decision are the following:

– the number of 732 surveyed ground-floor dwellings is high enough to guarantee meaningful statistical results, what is not the case with the number of dwellings on the other floors, and

– these dwellings are more exposed to radon influx from the ground under the houses.

Descriptive statistics of radon activity concentrations in the ground-floor dwellings, sorted by 11 factors and their 35 categories, for which there were enough answers in the questionnaires for a good statistic, is given in tab. 2. The GM and GSD are calculated assuming that the experimental radon data are log-normal. Box-whiskers diagrams of radon concentrations in the ground-floor dwellings, for the analyzed factors and their categories, are presented at fig. 2.

Table 2 shows that, on average, radon activity concentrations are about 50 % higher in rural than in urban homes, and that they are twice higher in family houses than in apartment buildings. It should be noticed that factors area and type of house are mutually dependent. All rural houses in Montenegro are single family homes, usually with thin slab-on-ground foundation permeable to soil gas, and the older ones have only ground level while the newer are mostly two-level houses. Finding that, on average, radon concentrations are much higher in rural than in urban homes in Montenegro, is in accordance with observations in other countries [15, 16]. Also, in many countries it was observed that radon activity concentrations are significantly higher in single-family houses than in apartment buildings [15-20].

Radon concentrations are, on average, much higher in the climate zone Cf than in the other two climate zones (tab. 2, fig. 2). This is somehow unexpected, because although the Cf zone has mild and wet climate with worm summer, the indoor radon concentrations in that zone are on average twice higher than in the Df zone with fresh summer and cold winter, which therefore, requires closed windows in dwellings much longer during a year. This indicates that radon concentration levels cannot be explained by the weather conditions alone, without also considering geological characteristics of the area belonging to a climate zone and construction characteristics of houses. Therefore, it has to be noticed that a great part of the area with the Cf climate is characterized by the presence of limestones and even high karst, where there are many cracks in rocks which facilitate radon transport from depth to the surface under buildings.

Table 2. Factors and corresponding radon concentrations for 732 ground-floor dwellings

Factor and their categories	Number of dwellings	AM (SE) [Bqm^{-3}]	MED [Bqm^{-3}]	$C_{Rn,max}$ [Bqm^{-3}]	GM [Bqm^{-3}]	GSD
Area						
Urban	384	106 (7)	57	1267	62.2	2.72
Rural	348	158 (13)	79	2321	83.1	3.00
Climate zone						
Cf	436	154 (11)	83	2321	88.2	2.77
Cs	255	101 (10)	48	1267	53.0	2.89
Df	41	75 (12)	46	322	49.9	2.46
House type						
Family house	615	142 (9)	73	2321	79.0	2.83
Apartment building	115	72 (10)	40	713	41.3	2.64
Year of construction						
Before 1900	36	158 (33)	64	803	83.9	3.16
1900-1944	69	205 (40)	82	2208	98.5	3.22
1945-1963	108	137 (16)	77	966	79.0	2.89
1964-1979	198	144 (16)	70	2321	79.0	2.94
1980-1999	277	105 (10)	55	1267	59.1	2.74
2000 and later	41	90 (13)	64	398	62.8	2.39
Basement						
Yes	203	86 (8)	50	1222	53.0	2.61
No	525	147 (10)	72	2321	79.8	2.92
Foundation slab						
None	126	116 (12)	66	766	67.4	2.86
5 cm thick	70	225 (43)	93	2321	113.3	3.03
> 5 cm thick	524	124 (8)	64	2208	69.4	2.83
Stories						
One	165	149 (19)	76	2321	81.4	2.89
Two	365	137 (10)	71	2208	78.2	2.77
Three	136	118 (15)	57	1267	62.8	2.92
More than three	59	64 (15)	34	766	35.9	2.64
Building materials						
Concrete	102	118 (15)	56	964	62.8	3.00
Bricks	265	100 (7)	59	836	62.8	2.58
Concrete/bricks	62	85 (11)	62	463	60.9	2.20
Stone	75	185 (24)	103	829	105.6	2.97
Stone/concrete/bricks	104	218 (33)	104	2321	111.0	3.00
Wood	40	54 (10)	32	354	35.5	2.44
Wood/concr./bricks/stone	79	169 (32)	78	2208	86.5	3.13
Window frames						
Wood	269	123 (10)	69	1222	74.1	2.68
PVC or Al	91	164 (29)	95	2321	98.8	2.50
Heating						
None	84	175 (40)	62	2321	75.9	3.22
Wood or coal	517	120 (7)	66	1222	70.8	2.77
Electricity or central	129	146 (19)	59	1267	70.8	3.19
Smoking						
Yes	407	126 (8)	65	1185	70.8	2.89
No	325	138 (13)	66	2321	72.2	2.89

Regarding the year of construction, houses in Montenegro are grouped in six categories based on the building properties characterizing certain periods of the country's development. Table 2 and fig. 2 show that houses built between 1900 and 1944 have the highest average radon concentrations and those built after year 1980 the lowest, while the houses built in the other three periods have similar average (AM and GM) radon levels. The highest average radon concentrations in the old Montenegrin houses can be explained by the fact that they are made of stone and have stone-slabs flooring permeable to radon from soil. The similar was concluded in some other researches [20-22]. The lowest radon concentrations in the newer Montenegrin houses, which are

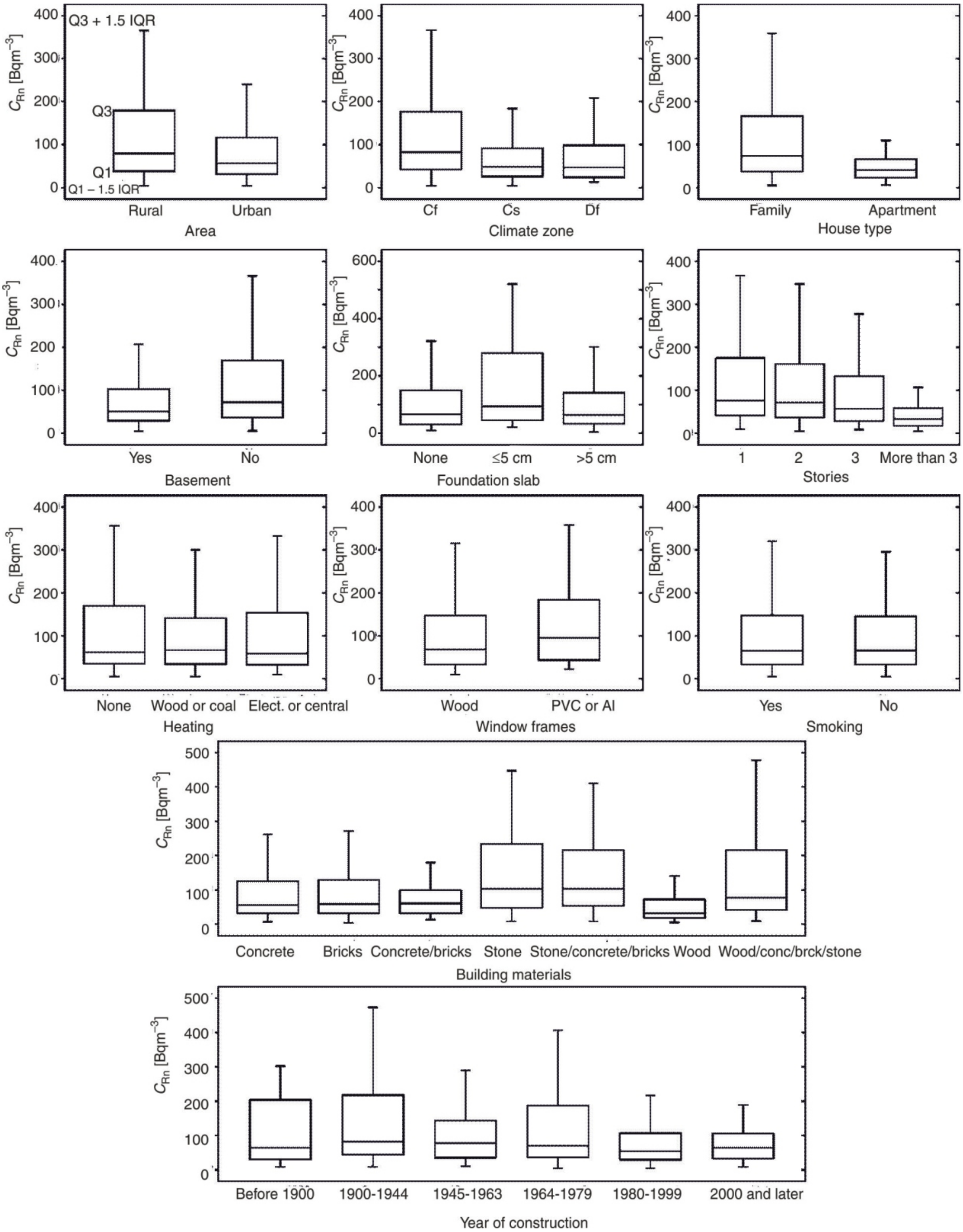

Figure 2. Box plots of radon concentrations for the analyzed factors

mainly multi-story buildings with floor above the ground made of slabs of reinforced concrete, are in accordance with finding of Nikolopoulos *et al*. [19].

As expected, basement has an important impact on indoor radon levels. The average radon concentration in ground-floor dwellings in houses with basement is 41 % smaller than in houses without basement. The similar situation was observed in other countries [5, 6, 17, 23].

Table 2 and fig. 2 do not show the expected continual decrease in average radon activity concentration with the increase of foundation slab thickness. Surprisingly, it was found that ground-floor dwellings in houses without any compact foundation slab have the same average radon concentration as those in houses with foundation slabs of high quality (concrete slabs with more than 5 cm in thickness), while average indoor radon concentrations are twice higher in houses with foundation slabs of solid materials with thickness less than 5 cm. Although this observation is somewhat in accordance with finding in Switzerland [18], it should be taken with reservation because, certainly, thickness and quality of foundation slab are not well known to all dwellers.

All characteristic values of average radon activity concentrations (AM, MED, GM) decrease continually with increasing number of stories in houses from one to more than three, which means that multistory apartment buildings, due to construction reasons, are built tighter for ingress of radon from the ground into building than small family houses.

Result that, on average, the smallest radon activity concentrations are in Montenegrin houses made of wood and the highest in those made of stone or any combination of stone with other building materials (tab. 2, fig. 2) is in accordance with the findings in some other countries [5, 19, 21, 22]. Average radon concentrations are not much different in Montenegrin houses made of concrete, or of bricks, or of their combination.

The AM of radon activity concentrations is a little higher in dwellings heated with electricity or centrally, than in those heated with wood or coal, while their GM are equal. Surprisingly, both the AM and GM are the highest in dwellings without heating, what is contrary to a general rule that heating increases pressure difference between air under house and indoor air and boosts entry of radon gas from soil into house [3].

While smoking has no any evident impact on radon levels in Montenegrin dwellings, the modern tight, energy saving frames of windows (made of PVC or aluminum) make that indoor radon levels are higher than in case of old-fashioned wooden frames.

Univariate analysis

In order to examine in a closer and more reliable way the individual impacts of the region, house, and living characteristics and their categories on the residential radon activity concentrations in Montenegro, univariate analysis was carried out on the data for 732 ground-floor dwellings.

Applying Shapiro-Wilk and Kolmogorov-Smirnov tests on the experimental radon data, it has been concluded that experimental data set, for average annual radon activity concentrations in Montenegrin homes, does not conform to a log-normal distribution [8], just like in a number of other countries [21, 24-28]. In the Montenegrin case, it has been shown [8] that subtracting 7 Bqm^{-3} from experimental indoor radon concentrations, as assumed radon concentration in outdoor air, and giving a small positive value of 5 Bqm^{-3} to all negative and zero values, resulted because of this subtraction, in order to avoid losing experimental data points, transform the experimental data to a set of data which pass both mentioned statistical tests of log-normality.

Univariate analysis (UVA) was used to test significance of influence of the 11 factors and to compare the mean radon values associated with different categories of the factors. The UVA was applied on the logarithmically transformed data for radon concentrations $\ln (C_{Rn} - 7)$ as a dependent variable and the factors as independent variables. In this analysis each factor was estimated independently.

The null hypothesis is that there is no difference in mean values for a pair of categories. If there are only two categories of a studied factor, *t*-test was applied, while in a case that factor has more than two categories ANOVA was used. Result of *t*-test is a *p*-value, based on which the null hypothesis should be rejected if it is below a threshold of significance ($p < 0.05$). Result of ANOVA is a *p*-value of *F*-test for a factor on the whole, as well as values of p.adjust for individual testing of differences of mean values of all pairs of factor's categories. Here, *p*-value less than 0.05 means that there is at least one pair of categories for which the difference of their mean values is statistically significant, while *p.adjust* values less than 0.05 show which pairs of categories have significantly different mean values.

The results obtained by UVA, presented in tab. 3, show that all the studied factors, except smoking and heating, have influence on radon activity concentrations in the Montenegrin ground-floor dwellings, because in each of these nine factors there is at least one pair of its categories for which the difference in mean values of radon concentrations is statistically significant at a level of 95 %.

Mean values of ln-transformed radon concentrations in ground-floor dwellings differ significantly in urban and rural areas, in family houses and apartment buildings, in houses with and without basement and in dwellings with window frames made of wood and PVC or aluminum.

The UVA reveals that there is no a significant difference in mean ln-values of radon concentrations in Cs and Df climate zone (*p.adjust* = 97.4 %), which is an unexpected result, because this pair of climate zones has the strongest mutual contrast: Cs is characterized by hot and dry summer and mild winter and Df by fresh summer and cold and snowy winter. Both of these climate zones show significantly different mean ln-values of residential radon concentrations in comparison with Cf climate zone. All this confirms that climate, which determines ventilation and heating habits of occupants, has no dominant impact on indoor radon concentrations over the other factors, especially geological substrate and construction characteristics of houses.

Table 3. Results of the univariate analysis for 732 ground-floor dwellings

Variable	Pair of categories	Diff (95 % CI)	*p*-value	*p.adjust*
Area	Urban – Rural	0.34 (0.16 – 0.52)	<0.001	
Climate zone	Cs – Cf	–0.62 (–0.84 – –0.39)	<0.001	<0.001
	Df – Cf	–0.66 (–1.13 – –0.20)		0.002
	Df – Cs	–0.04 (–0.52 – 0.43)		0.974
House type	Family – Apartment	0.99 (0.79 – 1.18)	<0.001	
Year of construction	2 – 1	0.20 (–0.52 – 0.93)	0.002	0.967
	3 – 1	–0.04 (–0.72 – 0.64)		1.000
	4 – 1	–0.02 (–0.66 – 0.62)		1.000
	5 – 1	–0.38 (–1.01 – 0.25)		0.510
	6 – 1	–0.30 (–1.11 – 0.51)		0.894
	3 – 2	–0.25 (–0.79 – 0.30)		0.785
	4 – 2	–0.22 (–0.72 – 0.27)		0.788
	5 – 2	–0.58 (–1.06 – –0.11)		0.006
	6 – 2	–0.50 (–1.20 – 0.19)		0.303
	4 – 3	0.02 (–0.40 – 0.45)		1.000
	5 – 3	–0.34 (–0.74 – 0.06)		0.160
	6 – 3	–0.26 (–0.91 – 0.39)		0.867
	5 – 4	–0.36 (–0.69 – –0.03)		0.023
	6 – 4	–0.28 (–0.89 – 0.32)		0.770
	6 – 5	0.08 (–0.51 – 0.67)		0.999
Basement	Yes – No	–0.46 (–0.66 – –0.27)	<0.001	
Foundation slab thickness	0 cm – 5 cm	–0.62 (–1.05 – –0.19)	0.001	0.002
	>5 cm – 5 cm	–0.57 (–0.94 – –0.20)		0.001
	>5 cm – 0 cm	0.05 (–0.24 – 0.33)		0.923
Stories	2 – 1	–0.02 (–0.32 – 0.27)	<0.001	0.997
	3 – 1	–0.32 (–0.68 – 0.04)		0.102
	>3 – 1	–1.02 (–1.50 – –0.55)		<0.001
	3 – 2	–0.30 (–0.61 – 0.02)		0.069
	>3 – 2	–1.00 (–1.44 – –0.56)		<0.001
	>3 – 3	–0.70 (–1.19 – –0.21)		0.001
Building materials	2 – 1	0.06 (–0.35 – 0.47)	<0.001	0.995
	3 – 1	0.04 (–0.53 – 0.61)		1.000
	4 – 1	0.62 (0.08 – 1.16)		0.013
	5 – 1	0.69 (0.19 – 1.18)		0.001
	6 – 1	–0.66 (–1.32 – 0.00)		0.050
	7 – 1	0.38 (–0.15 – 0.92)		0.331
	3 – 2	–0.02 (–0.52 – 0.48)		1.000
	4 – 2	0.56 (0.09 – 1.02)		0.008
	5 – 2	0.62 (0.22 – 1.04)		<0.001
	6 – 2	–0.72 (–1.32 – –0.12)		0.008
	7 – 2	0.32 (–0.13 – 0.78)		0.352
	4 – 3	0.58 (–0.03 – 1.19)		0.075
	5 – 3	0.65 (0.08 – 1.22)		0.014
	6 – 3	–0.70 (–1.42 – 0.02)		0.063
	7 – 3	0.35 (–0.26 – 0.95)		0.616
	5 – 4	0.07 (–0.47 – 0.61)		1.000
	6 – 4	–1.28 (–1.97 – –0.58)		<0.001
	7 – 4	–0.23 (–0.80 – 0.34)		0.893
	6 – 5	–1.35 (–2.01 – –0.69)		<0.001
	7 – 5	–0.30 (–0.83 – 0.23)		0.625
	7 – 6	1.04 (0.36 – 1.73)		<0.001
Window frames	Wood – PVC/Al	–0.36 (–0.61 – –0.11)	0.006	
Heating	Wood/Coal – None	–0.09 (–0.44 – 0.25)	0.763	0.806
	El./Central – None	–0.13 (–0.54 – 0.28)		0.751
	El./Central – Wood/Coal	–0.03 (–0.32 – 0.25)		0.958
Smoking	Yes – No	–0.02 (–0.20 – 0.16)	0.808	

Year of construction: 1 – before year 1900, 2 – 1900-1944, 3 – 1945-1963, 4 – 1964-1979, 5 – 1980-1999, 6 – year 2000, and later
Building materials: 1 – concrete, 2 – bricks, 3 – concrete and bricks, 4 – stone, 5 – stone and concrete/bricks, 6 – wood, 7 – wood and concrete/bricks/stone

Regarding the year of construction as a factor, among many of category pairs only two pairs show significant difference in mean ln-values of radon concentrations in dwellings:
– 1980-1999 and 1900-1944 (*p.adjust* = 0.6 %), and
– 1980-1999 and 1964-1979 (*p.adjust* = 2.3 %). This can be explained by the construction characteristics of houses from these two pairs of time periods. In the houses from 1980-1999 period, foundation slabs and ceilings of reinforced concrete more or less successfully prevents flow of radon from soil under a house into basement and further into ground floor, while in houses from 1900-1944 period (stone-slabs flooring), radon from soil enters smoothly into basement and ground floor. The difference between pairs 1980-1999 and 1964-1979 is significant but less pronounced than in the previous case, because the houses built in 1964-1979 period have foundations made of thin concrete slabs and ceilings usually made of wooden beams, which enable some flow of radon gas from the soil into basement and ground floor.

The UVA confirms previous unexpected finding from descriptive statistics of experimental data, that there is no difference in mean values of indoor radon concentrations between houses without any compact foundation slab and houses with foundation slab made of concrete with more than 5 cm in thickness (*p.adjust* = 92.3 %). Regarding the corresponding average indoor radon concentrations, both these cases differ significantly from houses with foundation slab made of concrete less than 5 cm thick.

Buildings with more than three stories have mean values of radon concentration which are different (lower) than in houses with one, two or three stories, while the houses with one, two or three stories have more or less equal average radon levels. This finding indicates that multistory buildings, with more than three stories, as the large structures have such construction characteristics that considerably prevent ingress of radon gas from the ground into building through foundation slab.

Mean value of radon concentrations in houses made of stone, or combination of stone with concrete or bricks, differ significantly from mean radon levels in the houses made of concrete, made of bricks, or made of wood. Houses made of wood have significantly different mean indoor radon level from houses made of other building materials or their combination, except for those made of combination of concrete and bricks. Mean radon levels in the houses made of concrete, made of bricks, or made of combination of these two materials, do not differ statistically significant.

Multivariate analysis

In order to examine the effect of all studied factors simultaneously on the radon activity concentrations in 732 ground-floor dwellings, multivariate analysis (MVA) was employed. The statistical model was applied on the normally distributed data from the transformed set ln (C_{Rn} – 7), using logarithmically transformed data for radon concentrations as a dependent variable and those factors as independent variables. A backward stepwise regression was applied on the ln-transformed data in order to identify statistically significant factors that affect radon concentrations. Even if only one category of a studied factor has statistical significance, that is *p*-value is less than 0.05, then that factor in whole is statistically significant.

It was taken that the applied regression model does not contain intercept, and therefore the regional factor Area, as the first analyzed factor, is presented with all its categoris. In case of all other factors, one of the categories was used as a benchmark with coefficient equal zero.

Results of the MVA are given in tab. 4. They show that the six factors: area, climate, type of house, presence of basement, number of stories, and building materials, have a statistically significant relationships to the radon activity concentrations in ground-floor dwellings in Montenegro. This means that the regression dropped the two factors: year of construction and thickness of foundation slab, which the UVA has found to have influence on radon concentrations in dwellings. The factor 'window frames' was not considered in the multivariate analysis, because a relatively small number of known data in questionnaires on this characteristic, if considered, could cause loss of data and bias in a sample for multivariate analysis.

Table 4 shows that there are statistically significant differences between categories of the factors: area, climate, type of house, and presence of basement, with all of these categories driving differences between the factors.

The two categories driving differences, in the factor stories, are houses with more than three stories and houses with three stories, with stronger impact of the first mentioned category. This finding of the MVA is partly different from the corresponding ones obtained by the UVA.

In building materials, categories concrete, bricks, concrete/bricks and combination wood/concrete/bricks/stone, do not differ mutually in a statistically significant way, while categories wood, stone and stone/concrete/bricks, are having a significant effect on the radon concentrations in dwellings. These findings are very similar to the corresponding ones obtained by the UVA.

For a sake of comparison, examples of application of MVA, in some European countries, that revealed factors significant to radon indoor concentrations, some of them which are the same as in Montenegrin case, will be mentioned here. For 983 randomly selected homes in Spain, Barros-Dios *et al.* [22] analyzed seven variables and found that four of them influence domestic radon concentration, the two

Table 4. Results of the multivariate analysis of the factors that affect radon concentrations in dwellings on ground floor

Factors and their categories	Dwellings	Estimate (SE)	*t*-value	*p*-value
Area				
Urban	384	3.92 (0.18)	22.37	<0.001
Rural	348	3.90 (0.16)	23.94	<0.001
Climate zone				
Cf	436	0		
Cs	255	–0.35 (0.11)	–3.06	0.002
Df	41	–0.53 (0.19)	–2.79	0.005
House type				
Family house	615	0		
Apartment building	115	–0.45 (0.13)	–3.45	0.001
Basement				
Yes	203	0		
No	525	0.59 (0.10)	6.03	<0.001
Stories				
One	165	0		
Two	365	–0.11 (0.11)	–0.97	0.330
Three	136	–0.35 (0.15)	–2.32	0.020
More than three	59	–0.74 (0.20)	–3.77	<0.001
Building materials				
Concrete	102	0		
Bricks	265	0.09 (0.13)	0.67	0.504
Concrete/bricks	62	0.09 (0.18)	0.51	0.610
Stone	75	0.66 (0.18)	3.70	<0.001
Stone/concrete/bricks	104	0.54 (0.16)	3.38	0.001
Wood	40	–0.80 (0.22)	–3.58	<0.001
Wood/concr./bricks/stone	79	0.21 (0.18)	1.17	0.243

of which were construction year and building materials. Analyzing 44 631 measurements from the national radon database, Hauri *et al*. [16] found six relevant predictors for indoor radon levels in Switzerland, among which the two were the type of house and year of construction. For radon survey in 963 Greek dwellings, Nikolopoulos *et al*. [19] analyzed nine factors and found that four of them have influence on indoor radon concentrations, the three of which are type of house, year of construction and building materials. In the UK, Hunter *et al*. [29] confirmed influence of the four factors, among them house type and double glazing, while Miles *et al*. [30] found that only glazing type and number of stories have significant relationship with radon concentrations.

CONCLUSIONS

Descriptive statistics of indoor radon concentrations in 732 ground-floor dwellings in Montenegro suggest that the factors: area, climate, house type, year of construction, basement, foundation slab, number of stories, building materials, window frames, and heating, have influence on radon concentrations, while smoking has no effect on them.

The univariate analysis of the radon indoor data indicates (at a level of significance of 95 %) that all the studied factors, except smoking and heating, have influence on radon levels in ground-floor dwellings in Montenegro. It reveals that, on average, radon concentrations in ground-floor dwellings differ significantly in urban and rural areas, in family houses and apartment buildings, in houses with and without basement, and in dwellings with window frames made of wood and PVC/Al. In Cf climate zone they differ from those in Cs and Df zones. Only two pairs of construction periods differ in mean radon concentrations in dwellings: 1980-1999 with 1900-1944, and with 1964- 1979. Houses with one, two or three stories have almost equal average radon levels, which are higher than in buildings with more than three stories. Mean value of radon concentrations in houses made of stone are higher than in houses made of concrete, or bricks, or wood. Wooden houses have the lowest mean indoor radon level.

The multivariate analysis additionally dropped the two factors: year of construction and foundation slab, showing that the six factors: area, climate, type of house, basement, number of stories, and building materials, affect simultaneously radon activity concentrations in the ground-floor dwellings in Montenegro. It reveals that there is a statistically significant difference between all categories of the factors area, climate, type of house and presence of basement. The two categories driving differences in the factor stories are the houses with three and more stories, while in the factor building materials categories wood, stone, and combination of stone, concrete and bricks, are those which have a significant effect on the radon concentrations in dwellings.

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AUTHORS' CONTRIBUTIONS

The research was initiated and manuscript written by P. Vukotić, with valuable contribution of N. Antović, who also coordinated the radon survey. R. Zekić, T. Andjelić, and N. Svrkota performed radon measurements and collected data about houses and dwellings, while R. Mrdak provided categorization of construction periods of houses. A. Djurović performed univariate and multivariate analysis of the data, and A. Dlabač descriptive statistics and drew the figures.

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УТИЦАЈ КЛИМАТА, ГРАЂЕВИНСКИХ И РЕЗИДЕНЦИЈАЛНИХ ФАКТОРА НА НИВОЕ РАДОНА У СТАНОВИМА У ПРИЗЕМЉУ У ЦРНОЈ ГОРИ

Након дванаестомесечног мерења са детекторима CR-39, средње годишње концентрације радона одређене су у 953 стана широм Црне Горе, што је 0.5 % свих стално настањених станова у њој. Утицај 11 фактора (подручје, климат, тип зграде, година изградње, постојање подрума, темељна плоча, број спратова, грађевински материјал, оквири прозора, грејање и пушење) и 35 њихових категорија на концентрације радона у 732 стана у приземљу анализиран је дескриптивном, униваријантном и мултиваријантном методом.

Униваријантна анализа одбацила је утицај два фактора: грејања и пушења. Она показује да се, у средњем, концентрације радона у становима у приземљу разликују статистички значајно (ниво поверења 95 %) у урбаним и руралним подручјима, у породичним кућама и стамбеним зградама, у кућама са и без подрума и у становима са оквирима прозора од дрвета и оних од PVC/Al. У климату Cf оне се разликују од оних у Cs и Df климату. Само два пара периода изградње, 1980-1999 са 1900-1944 и са 1964-1979, разликују се по средњим концентрацијама радона у становима. Куће са једним, два и три спрата имају готово једнаке средње нивое радона, који су већи него у зградама са више од три спрата. Средње вредности концентрација радона у каменим кућама веће су од оних у кућама изграђеним од бетона, или од опека, или од дрвета.

Мултиваријантна анализа показује да од анализираних фактора шест њих – подручје, климат, тип зграде, постојање подрума, број спратова и грађевински материјал, симултано значајно корелирају ($p < 0.05$) са концентрацијама радона у становима у приземљу у Црној Гори.

Кључне речи: станови у приземљу, фактор који утиче на концентрацију радона, униваријантна и мултиваријантна анализа