RADON CONCENTRATIONS IN MULTI-STORY BUILDINGS IN MONTENEGRO

by

Perko VUKOTIĆ [1*], ***Ranko ZEKIĆ*** [2], ***Nevenka M. ANTOVIĆ*** [3], ***and Tomislav ANDJELIĆ*** [2]

[1] Montenegrin Academy of Sciences and Arts, Podgorica, Montenegro
[2] Centre for Ecotoxicological Research, Podgorica, Montenegro
[3] Faculty of Natural Sciences and Mathematics, University of Montenegro, Podgorica, Montenegro

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Change of radon concentrations in dwellings with floor level was studied in six multi-story buildings, in four towns of Montenegro with different climate conditions. The annual average radon activity concentrations in 35 dwellings are found to be very low, mostly at a level of 20-30 Bqm^{-3}. Absorbed gamma dose rates in these dwellings are in the range of 14-58 nGyh^{-1}. The low radon concentrations are a consequence of a good tightness of the structures in contact with the ground and a small contribution of building materials to radon indoors. A clear general trend of changes in radon concentrations with floor level is not observed. In most of the dwellings on different floors in the multi-story building radon concentration varies very little, mostly within measurement error. A small decrease in radon concentration is noted between the two or three floors closest to the ground, but only in some of the buildings. Therefore, a decrease of indoor radon concentration with floor level cannot be considered as a general characteristic of multi-story buildings.
Although the seasonal radon variations have not been in the focus of this study, it was found that the average radon activity concentrations in dwellings of the multi-story buildings are higher in warmer than in cooler half-year period, what is contrary to the general rule for homes in the world and in Montenegro as well.

Key words: multi-story building, year-long radon measurement, change of radon concentration with floor level

INTRODUCTION

Radon gas, natural and radioactive, is the second cause of lung cancer in the general population, after smoking. Radon comes into indoor air from different sources – the ground under and around the building, building materials, water and gas supplies, and outdoor air. The soil and rocks under the building are usually the main source of radon indoors [1]. A pressure difference between the air inside and outside the building, which occurs because the indoor air is warmer than the outdoor air, particularly in the cold winter months, causes a convection flow of soil gas, and of radon in it, from the ground into the building. Building materials are generally the second main source of radon indoors. However, in multi-story buildings, especially on the upper floors, radon which emanates from building materials generally becomes the prevailing source of radon indoors [2, 3].

Because the main mechanism of radon entry into the building is its convection flow from the ground through cracks and holes in the foundation slab, radon concentration inside the building, in general, decreases from basement and ground floor to the upper floors, in particular between the basement, ground floor and first floor [4]. This is confirmed in many cases, usually by comparing mean values of indoor radon concentrations for the same floors of different houses ([5, 6], for example), while studies on the vertical profile of indoor radon levels in the building are very limited worldwide [7].

However, exceptions to the generally accepted rule that indoor radon concentration decreases with increasing floor level are observed, particularly in some multi-story buildings.

In continental Europe, the most common are dwellings in multi-story residential buildings, with parking garages and cellars in the basement. Transfer of soil gas from the ground into the housing in buildings of this type is reduced, which results that the factors usually affecting radon concentrations in dwell-

* Corresponding author; e-mail: pvukotic@canu.ac.me

ings are less defined and their relevance varies considerably in different areas [8].

In some cases, a decrease in radon concentration was noted only between basement and ground floor. In Birmingham, England, for example, measurements of radon daughters were carried out in similar rooms on different floors in the two residential 11- and 17-story buildings [9]. Apart from the basement, a systematic reduction of radon activity with a height of floor level was not registered. A similar conclusion was obtained in Aligarh, India [10], where radon concentrations were measured in 19 almost identical rooms on every floor from the basement to the 7th floor in a multi-story building. The highest radon activity concentrations were found in the basement, and then on the ground floor, while on the upper floors they were lower and without significant mutual differences.

There are even cases that radon concentrations in buildings do not decrease with increasing floor levels, but they grow and can be higher than on the ground floor. This is caused by a so-called chimney effect, which occurs when there are vertical ducts in the building (elevator shaft, air ducts, chimneys and the like), which cause the air flow directly from the basement or ground floor upwards due to pressure difference. An example of such a situation is a part of the results obtained in research conducted in Bialystok, Poland [11].

Since a change of radon concentration in dwellings with floor level depends on the characteristics of geological substrate and structure of the building, climatic conditions and living habits of residents, all of which can be very specific to individual countries and regions, it was desirable and useful to study the change of radon concentrations in the multi-story buildings in Montenegro. This especially because of some controversy about a general validity of the rule that radon concentration decreases with floor level in multi-story buildings and because of the fact that approximately two-thirds of the Montenegrin population live in urban areas and the majority of them in multi-story buildings.

Montenegro is a Western Balkan country on the Adriatic Sea, fig. 1. It has a total land area of 13 812 km^2 and a population of about 620 000. The capital and largest town is Podgorica. The country is administratively divided into 23 municipalities. Unofficially, it is also divided in three regions: Coastal Region, Central Region, and Northern Region.

From a geologic aspect, the Coastal Region is characterized by carbonate sediments (mainly limestone and dolostone), and flysch sediments and volcanic rocks. The Central Region is limestone and karstic area, with scarce volcanic rocks and flysch sediments. Clastites, carbonates, volcanites, volcaniclastites, and lake sediments characterize the Northern Region.

According to Koppen classification, there are three types of climate in Montenegro [12]: Cs – Mediterranean climate with hot and dry summer and mild winter, Cf – mild and wet climate with warm summer, 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 valleys in the municipalities of Podgorica and Danilovgrad, which are parts of the Central Region. The Df type of climate exists in a region of high mountains in the Northern Region. The rest of the country belongs to the Cf type of climate.

In order to avoid biases and wrong conclusions which might occur by comparing mean values of indoor radon concentrations for the same floors of different houses, the vertical profile of indoor radon levels was studied in the six multi-story residential buildings in different regions of Montenegro by comparing radon concentrations in dwellings on different floors in the same building. The results of the study are presented in this paper.

MATERIALS AND METHODS

Radon activity concentrations were measured in dwellings on different floors in the six multi-story residential buildings, in order to study their change with the floor level. The buildings are located in four towns in Montenegro. Two of those towns, Podgorica and Bar, belong to the Central and the Coastal region, respectively, with warm climate (Cs type of climate), and the other two, Nikšić and Bijelo Polje, are in the Central and the Northern region, respectively, with cooler climate (Cf type of climate), which causes different needs of their inhabitants in heating and ventilation of dwellings over the year.

The two of the studied buildings are in the city of Podgorica (designated as PG-1 and PG-2), two in the town of Nikšić (NK-1 and NK-2), one in the town of Bar (BR) and one in the town of Bijelo Polje (designated as BP).

The CR-39 track-etch detectors of the two reputable manufacturers were used for long-term radon measurements: Radtrak2 of the Landauer Nordic (in the buildings NK-1, NK-2, PG-2, and BP) and RSKS of the Radosys (in PG-1 and BR). In all six buildings, radon was measured during the two consecutive six-month periods, from the beginning of November 2014 to the end of October 2015, in one dwelling on most of the floors in the buildings. After exposure detectors were sent to the manufacturers' laboratories for etching and track counting. Minimum detectable radon activity for 6-month exposure of RSKS detectors is about 1 Bqm^{-3} and up to 10 Bqm^{-3} of Radtrak2 detectors.

Absorbed gamma radiation dose was also measured in the dwellings surveyed on radon, one meter above the floor and one meter away from the wall. Canberra InSpector 1000 Digital Hand-Held Multi-

Figure 1. Map of Montnegro

channel Analyzer, with 2" 2" NaI detector (energy range: 50 keV to 3 MeV) was used for dose-rate measurements.

During the radon and gamma-dose measurements, the questionnaires on physical and other features of buildings and dwellings, as well as on the living habits of their occupants were completed.

The studied multi-story buildings have in common the following features: they are residential, they are built on a flat terrain, their structure is made of concrete, foundation slab over the ground is made of reinforced concrete with more than 5 cm in thickness, ceilings are also made of reinforced concrete, buildings have no HVAC systems (heating of dwellings is with wood or electricity), and all dwellings in each of the buildings are connected to ventilation chimneys leading from the basement to the roof of the building. Five of these buildings are built in the period 1971-1989 while building NK-2 was built in the period 2001-2009. The only difference between multi-story buildings in Montenegro built in those two periods is that the older ones have doors and window frames originally made of wood, while in those built after the year 2000 a modern joinery, made of PVC or aluminum, is often present.

The following additional data are also available from the completed questionnaires:

- Building BR in Bar has neither a basement nor a ground floor. Walls are made of concrete. All sampled dwellings have good insolation, electrical heating and air-conditioning provided, and they are ventilated every day.
- Building PG-1 in Podgorica also has no basement nor ground floor. Concrete and bricks are materials of the walls. All sampled dwellings have good insolation, they are ventilated every day, and only the ones located on the 3rd and 6th floor, are air-conditioned. Dwelling on the 1st floor is heated with wood, and the others electrically.
- Building PG-2 in Podgorica has 6 stories – ground floor and 5 upper floors. There is no basement. Walls are made of bricks. All sampled dwellings have poor insolation. They are ventilated every day. Dwelling on the 1st floor is heated with wood, and the others electrically.
- Walls of building NK-1 in Nikšić are made of concrete and concrete blocks. Sampled dwellings are not air-conditioned, they are ventilated every day, they are heated by wood, and they have good insolation.

– Building NK-2 in Nikšić has walls which are made of concrete blocks. All sampled dwellings have good insolation, they are ventilated daily, while air-conditioning is only provided in sampled dwellings on the 2nd and 5th floor. Heating of dwellings on the 2nd floor is electrical, of that on the 4th floor is central and of the other dwellings is with wood.
– Walls of building BP in Bijelo Polje are made of bricks. All sampled dwellings have poor insolation. They are ventilated every day and have no air-conditioning. They are heated with wood, except for dwellings on the 2nd and 3rd floor which are heated electrically. Radon activity concentration in a dwelling on the 3rd floor was not obtained because radon detectors were damaged.

RESULTS AND DISCUSSION

Indoor gamma dose rates

Although the existence of correlations between experimentally determined gamma dose rate and radon concentration in indoor air of residences is very uncertain [13], it was interesting to know and analyze dose rates of gamma radiation in the studied multi-story buildings.

Generally, due to building materials, the gamma dose rate is higher indoors than outdoors, worldwide on average 1.4 times higher, so that the worldwide average absorbed gamma dose-rate in the indoor air is 84 nGyh^{-1}, while the average levels for countries are mostly in the range of 52-105 nGyh^{-1} [14].

The gamma dose rates in dwellings of the six multi-story buildings in Montenegro, presented in tab. 1, are relatively low, 2-3 times lower than the worldwide average. Since building materials, which are generally the main factor of elevated gamma doses indoors in comparison with outdoors, are in the same time the second main source of radon indoors, these results indicate that construction materials of these buildings do not create high indoor radon concentrations.

The relative contribution of construction materials is more significant where the total radon concentration in a dwelling is low [15], as it is the case in this study. In the EU, the typical contribution from construction materials to ^{222}Rn concentration indoors is estimated to be in the range of 10-20 Bqm^{-3} [1] which is at the level of radon concentrations that were measured in more than a half of all dwellings in the six multi-story buildings in Montenegro.

Table 1 shows that indoor gamma dose rates are practically equal, within measurement errors, in dwellings on all floors in the buildings BR, PG-1, PG-2 and NK-1, that in the building NK-2 the dose rate is slightly higher on the 5th floor in comparison

Table 1. Absorbed dose rates of gamma radiation in the sampled dwellings

Building/ Floor	D SD [nGyh^{-1}]					
	BR	PG-1	PG-2	NK-1	NK-2	BP
0			27 1.6		36 2.2	
1	16 1.0	32 1.9	25 1.5	28 1.7	34 2.0	55 3.3
2	16 1.0	29 1.7	25 1.5	28 1.7	33 2.0	45 2.7
3	15 0.9	30 1.8	24 1.4	29 1.7	35 2.1	58 3.5
4	15 0.9	31 1.9	25 1.4	27 1.6	37 2.2	58 3.5
5	16 1.0	32 1.9	24 1.4	26 1.6	40 2.4	53 3.2
6	–	30 1.8		–		–
7	14 0.8			–		–
8				–		45 2.7
9				29 1.7		

D – absorbed dose rate; SD – standard deviation

with lower floors, while in the building BP there are significant differences in gamma doses between floor levels, but with irregular occurrence. Gamma doses are the lowest in the building BR, and the highest in the building BP, while in the other four multi-story buildings they are on similar levels. From the available data recorded in questionnaires it was not possible to conclude what causes those differences in indoor gamma doses.

Change of radon concentration with floor level

The results of radon measurement in the six multi-story buildings in Montenegro are given in tab. 2. Already at the first sight it is obvious that the annual average radon activity concentrations in the buildings, no matter to which town and climate zone they belong, are very low, mainly at a level of 20-30 Bqm^{-3} and nowhere exceeding 53 Bqm^{-3}. They are about ten times lower than the current reference level in Montenegro (400 Bqm^{-3} – annual average radon gas concentration; adopted in 1998 and based on the 90/143/Euratom [16]) and they do not pose any significant health risk for the residents.

Since the main sources of radon indoors are generally the ground underlying the building and building materials, it can be concluded that such low radon concentrations are mainly conditioned by:
– The tightness of the structures in contact with the ground, *e. i.*, by the thick and intact reinforced concrete foundation slabs over the ground, present in all six buildings. They significantly prevent the influx of radon gas from the ground into buildings, which is in accordance with situation characteristic for the continental part of Europe [8].
– The low exhalation rate of radon from materials used for the construction of buildings.

This means that construction characteristics of the studied buildings have a more significant effect on indoor radon concentrations than climatic conditions,

Table 2. Radon activity concentrations in the studied buildings

Building	Town	Number of stories (+ basement)	Floor	C_{Rn} (SU) *winter* [Bqm^{-3}]	C_{Rn} (SU) *summer* [Bqm^{-3}]	C_{Rn} (SU) annual [Bqm^{-3}]	Ratio $C_{Rn,w}$ and $C_{Rn,s}$
BR	Bar	7 (no)	1	12 (6)	20 (6)	16 (4)	0.60
			2	8 (6)	26 (6)	17 (4)	0.31
			3	20 (6)	25 (7)	22 (5)	0.80
			4	9 (6)	22 (6)	16 (4)	0.41
			5	16 (6)	22 (6)	19 (4)	0.73
			7	12 (6)	17 (6)	14 (4)	0.70
PG-1	Podgorica	6 (no)	1	49 (9)	57 (10)	53 (7)	0.86
			2	41 (9)	53 (10)	47 (7)	0.77
			3	33 (8)	26 (6)	30 (5)	1.27
			4	24 (7)	35 (7)	30 (5)	0.68
			5	20 (7)	30 (7)	25 (5)	0.67
			6	55 (10)	30 (7)	42 (6)	1.83
PG-2	Podgorica	6 (no)	0	16 (4)	36 (6)	26 (4)	0.44
			1	22 (6)	19 (4)	20 (4)	1.16
			2	12 (4)	15 (4)	14 (3)	0.80
			3	17 (6)	17 (4)	17 (4)	1.00
			4	23 (4)	26 (6)	24 (4)	0.88
			5	28 (6)	17 (4)	22 (4)	1.65
NK-1	Nikšić	9 (yes)	1	21 (4)	32 (6)	26 (4)	0.66
			2	27 (4)	31 (4)	29 (3)	0.87
			3	25 (4)	30 (4)	28 (3)	0.83
			4	32 (6)	28 (4)	30 (4)	1.14
			5	32 (6)	36 (6)	34 (4)	0.89
			9	40 (6)	29 (4)	34 (4)	1.38
NK-2	Nikšić	6 (yes)	0	26 (4)	51 (8)	38 (4)	0.51
			1	16 (4)	32 (6)	24 (4)	0.50
			2	22 (6)	35 (6)	28 (4)	0.63
			3	14 (6)	28 (4)	21 (4)	0.50
			4	43 (6)	37 (6)	40 (4)	1.16
			5	23 (6)	34 (6)	28 (4)	0.68
BP	Bijelo Polje	8 (yes)	1	14 (4)	28 (6)	21 (4)	0.50
			2	15 (4)	24 (4)	20 (4)	0.62
			3*	–	–	–	–
			4	20 (4)	18 (4)	19 (4)	1.11
			5	16 (4)	22 (4)	19 (4)	0.73
			8	18 (4)	24 (4)	21 (4)	0.75

Floor 0 – ground floor; * – radon detectors were damaged, C_{Rn} – radon activity concentration, SU – standard measurement uncertainty, $C_{Rn,w}$ and $C_{Rn,s}$ – winter and summer radon concentrations, respectively *winter* – period November-April, *summer* – period May-October

i. e., habits of residents in terms of heating and ventilation of their housing.

Based on the results presented in tab. 2 and at fig. 2, the change of radon concentration with floor level will be considered separately for each of the multi-story buildings.

Dwellings on all floors in the multi-story building BR have practically the same annual average radon concentration (within the measurement errors).

In the building PG-1, which has neither basement nor ground floor, there is a decrease of indoor radon concentration from the 1st to the 3rd floor. Radon concentration in dwellings on the 3rd, 4th, and 5th floor is almost the same and rises again in a dwelling on the 6th floor because of a relatively increased value during the *winter* half-year period.

It seems that there is also a decrease in radon concentrations from the ground floor to the 2nd floor, and then an increase towards the 4th and 5th floor in the building PG-2. However, taking into account measurement errors, annual average radon concentrations are practically the same in dwellings on the ground, 1st, 4th, and 5th floor, and slightly higher than those on the 2nd and 3rd floor.

Indoor radon activity concentrations are lower in the building PG-2 than in the building PG-1. Since the construction characteristics of the two buildings are similar, possible cause for that might be a poor insolation of dwellings in the building PG-2, which makes temperature difference between indoor and outdoor air smaller than in the building PG-1 with good insolation, and as a consequence a smaller influx of radon from ground into building PG-2.

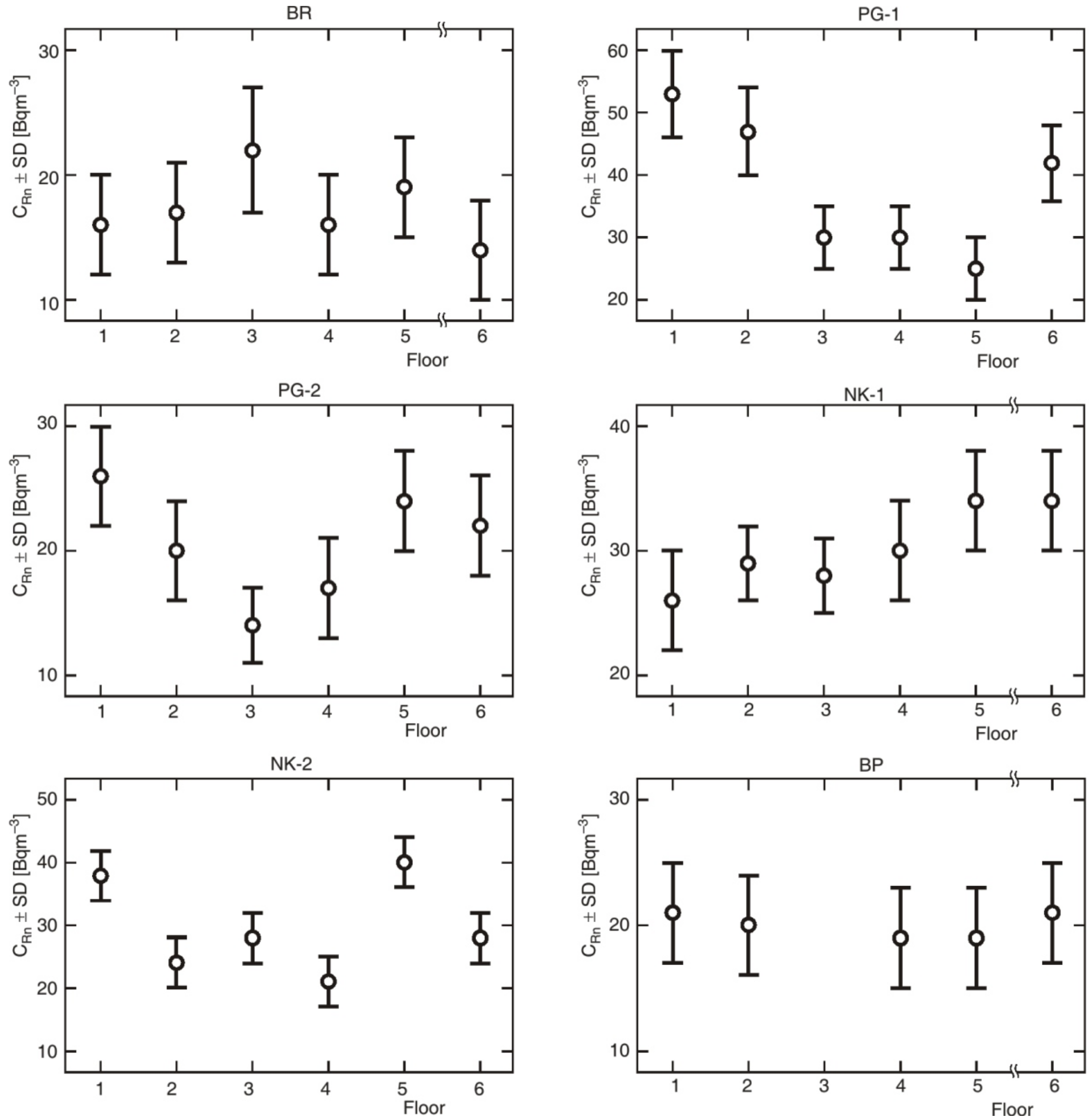

Figure 2. Radon concentrations in the six multi-story buildings

It looks as if there is a general trend of a very slight increase in annual average radon concentration with increasing floor level in the building NK-1. However, differences in radon concentrations in dwellings on all floor levels are within the limits of standard measurement uncertainties and therefore it should be concluded that there is no significant change of radon concentration with floor level in this building.

In the building NK-2, the radon concentration in dwelling on the ground floor is significantly higher than in dwellings on the upper floors, except in the dwelling on the 4th floor where it is the highest because of the unknown reason (only known specificity of that dwelling is that it has central heating). With exception of this anomaly, radon concentrations in dwellings from the 1st to the 5th floor are practically equal (within the measurement errors), which means that a decrease in radon concentration exists only between the ground floor and the 1st floor.

Finally, annual average radon activity concentrations in dwellings on all floors in the eight-story building BP are truly equal.

As a summary, the following can be said relating to the change of the annual average radon activity concentrations with floor level in the studied multi-story buildings:

– Radon concentrations in dwellings on all floor levels are equal within the limits of measurement error in the buildings in Bar and Bijelo Polje and in the building NK-1 in Nikšić.
– Radon concentrations in the building PG-2, in Podgorica, are practically the same in dwellings

on the ground, 1st, 4th, and 5th floor, and slightly higher than those on the 2nd and 3rd floor.

– There is a decrease of indoor radon concentration with floor height from the 1st to the 3rd floor in the building PG-1, in Podgorica, while in the building NK-2, in Nikšić, radon concentration on the ground floor is somewhat higher than on the upper floors, except on the 4th floor where it is same as on the ground floor.

This summary shows that there is no clear general trend of change of radon activity concentration with floor level in the studied six multi-story buildings in Montenegro. The same was noted in multi-story buildings in Liguria, Italy [8]. Also, finding for the two high-rise buildings in England [9] that, except for the ground floor, there is no systematic decrease of radon concentration with increasing floor level is in accordance with the case of the building NK-2 and partly of the building PG-1 in Montenegro. All this leads to the conclusion that a decrease of radon concentration with increasing floor level cannot be regarded as a general characteristic of all multi-story buildings.

Related to this conclusion, it is interesting to see which results could be obtained by comparing the mean values of annual average radon activity concentrations in sampled dwellings on the same floors of the six multi-story buildings but having in mind that they may not be valid for all buildings individually. Those mean values are given in tab. 3.

Based on tab. 3, it can be said that the radon concentrations in the studied multi-story buildings are the highest in dwellings on the ground floor and that a decrease of radon concentration exists from the ground floor to the 1st floor, with a ratio of the arithmetic means 1.20. A gradient of changes in radon concentrations from the 1st floor upward cannot be noticed because the mean and median values of radon concentrations oscillate. Analysis of variance (ANOVA) shows that the difference of mean radon concentrations between the 1st and the 2nd, 3rd, and 4th floor is not statistically significant at a significance level of 0.05 ($p = 0.91$, $p = 0.64$, and $p = 0.98$, respectively). All this means that radon from the ground has an effect, albeit weak, only on the radon concentrations on the ground floor.

Table 3. Mean value of radon concentrations by floors in all buildings together

Floor	Sampled dwellings	AM (SE) [Bqm^{-3}]	MED [Bqm^{-3}]
0	2	32.0 (6.0)	32
1	6	26.7 (5.4)	22.5
2	6	25.8 (4.9)	24
3	5	23.6 (2.4)	22
4	6	26.5 (3.6)	27
5	6	24.5 (2.4)	23.5
6-9	4	27.8 (6.3)	27.5

AM – mean value of radon concentrations in sampled dwellings on the same floor in all six buildings, SE – standard error of the mean, MED – median

Table 4. Mean value of radon concentrations for all dwellings in the multi-story building

Building	AM (SE) *winter* [Bqm^{-3}]	AM (SE) *summer* [Bqm^{-3}]	AM (SE) annual [Bqm^{-3}]	MED annual [Bqm^{-3}]
NK-1	29.5 (2.7)	31.0 (2.8)	30.2 (1.3)	30
NK-2	24.0 (4.2)	36.2 (3.2)	30.1 (3.1)	28
BR	12.8 (1.8)	22.0 (1.3)	17.4 (1.1)	16
PG-1	37.0 (5.6)	38.5 (5.4)	37.8 (4.5)	36
PG-2	19.7 (2.3)	21.7 (3.3)	20.7 (1.8)	21
BP	16.6 (1.1)	23.2 (1.6)	19.9 (0.4)	20

AM – mean value of radon activity concentrations in all sampled dwellings in the building, SE – standard error of the mean, MED – median

Similar results, obtained in a similar way – averaging radon concentrations by floors in different buildings, are reported for Italian towns Genoa and Savona [8]. Radon concentrations were measured in 177 dwellings in Genoa and 133 in Savona. Significant differences in the mean radon activity concentrations were found between the ground and 1st floors and higher floors, which indicate that radon from the ground has an impact particularly on the first two floors in the buildings. That impact was expressed by a ratio of the radon activity concentration on the first two floors (ground and first floor) and the concentrations on the upper floors, which is in Genoa 1.20 and in Savona 1.56.

It is also interesting to compare the mean values of the radon concentrations for all sampled dwellings in a given multi-story building, which are presented in tab. 4.

The result that the mean radon concentration in all dwellings in a multi-story building is the lowest in the building BR in Bar is somehow expected and can be understood as a result of climatic conditions, *i. e.*, habits of occupants to keep windows open most of the time because the town of Bar, which is on the Adriatic coast, has the most moderate climate in Montenegro throughout the year. However, this explanation does not hold for the town of Bijelo Polje, where the climate is pretty much cooler but the average radon concentration in all dwellings in the studied building BP is the lowest after the one in Bar, nor for the building PG-1 in Podgorica, where summers are the warmest in Montenegro and winters are very mild and, in spite of that, the average radon concentration in this building is significantly higher than in all other studied buildings.

This situation can be interpreted as a confirmation of the earlier conclusion that the radon concentration in dwellings of the studied multi-story buildings are predominantly determined by the quality of foundation and floor slabs and building materials they are built of, while the climatic conditions and habits of residents are less important affecting factors. However, it could be interesting to research further if the low indoor radon concentrations in the building BP in the town of Bijelo Polje at the mountainous north of Montenegro, which are the lowest after the building BR in the southern town of Bar on the Adriatic Coast, could be caused by a poor insolation of dwellings in the building BP, and therefore the small indoor-to-outdoor air temperature and pressure differences which result in a small ingress of radon from ground into building.

Seasonal radon variations

Although the seasonal indoor radon concentrations have not been in the focus of this study, tab. 4 points out to an unexpected and therefore very interesting result, that the average *seasonal* radon activity concentrations in dwellings of all six studied multi-story buildings, with no exception and no matter to which climate zone they belong, are higher in the warmer (*summer*) than in the cooler (*winter*) half-year period. Even tab. 2, which provides more details, shows that in 26 of 35 sampled dwellings in the multi-story buildings the radon concentrations are higher in the *summer* than in the *winter* period. The ratio between *winter* and *summer* radon concentrations ranges from 0.31 to 1.83, with an arithmetic mean of 0.83 and a median value of 0.75. Overall, this situation is contrary to the general rule in the world that radon concentrations in homes are higher in winter than in summer season [17], as well as in autumn-winter than in spring-summer half-year period [18, 19]. It is even inverse to the seasonal variations found in the national radon survey in 953 dwellings in Montenegro, after which the geometric mean of radon concentrations are in average 51 % and arithmetic mean even 73 % higher during the *winter* than the *summer* half of the year [20].

There are very few known cases, related to the peculiar situations, that indoor radon levels are higher in warmer than in cooler periods of the year [21-24]. The reasons for those specific seasonal radon variations, contrary to the general rule, are found to be in karstic terrain and ventilation habits of residents [21], in house location on a hill slope [22, 24], or in presence of natural holes in the soil from which a flow of radon gas can reach the indoor environment [23]. However, none of these reasons holds for the studied six multi-story buildings in Montenegro and having no explication yet for this, further research into this matter is needed.

An also known specific case that, on average, indoor radon concentrations in 25 houses in 13 villages of Kosovo and Metohija, Serbia, during the two consecutive six-month periods are nearly equivalent [25], could be explained by the fact that the two exposure periods (December to June and June to December) have a similar overall mixture of cold and warm months.

CONCLUSIONS

Gamma dose rates in dwellings of the six studied multi-story buildings are in the range of 14 to 58 $nGyh^{-1}$, mainly 2-3 times lower than the worldwide average value. This result indicates that the construction materials of these buildings do not create high indoor radon concentrations.

The annual average radon activity concentrations in dwellings of the six multi-story buildings are very low – mainly at a level of 20-30 Bqm^{-3}, with the maximum value of 53 Bqm^{-3}.

Surprisingly, in all six buildings, regardless of a climate zone they belong to, the average indoor radon concentrations were higher in warmer (November-April) than in cooler (May-October) half-year period. This is contrary to the general rule in the world and even to the results of the national residential radon survey in Montenegro and has not yet been explained.

Tick and intact foundation slabs of reinforced concrete prevent the influx of radon from the ground into the buildings almost entirely, so that building material becomes equally important or even primary source of radon in the most of dwellings, especially those on the upper floors. Climatic conditions, *i. e.*, residents' habits in terms of heating and ventilation of their housing are influencing factors of less importance.

A clear general trend of changes in indoor radon concentrations with floor level is not observed. In most of the dwellings on different floors in the multi-story building radon concentration varies very little, mostly within measurement error. A small decrease in radon concentration is noted between the two or three floors closest to the ground, but only in some of the buildings. Therefore, a decrease of indoor radon concentration with floor level cannot be considered as a general characteristic of multi-story buildings.

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AUTHORS' CONTRIBUTIONS

The research was initiated, and a manuscript written by P. Vukotić, with the valuable contribution of N. M. Antović. R. Zekić performed radon measurements and descriptive statistics of the data, while T. Andjelić measured gamma-dose rates.

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КОНЦЕНТРАЦИЈЕ РАДОНА У ВИШЕСПРАТНИЦАМА У ЦРНОЈ ГОРИ

Перко ВУКОТИЋ, Ранко ЗЕКИЋ, Невенка М. АНТОВИЋ, Томислав АНЂЕЛИЋ

Промена концентрација радона у становима са висином спрата проучавана је у шест вишеспратница, у четири града у Црној Гори са различитим климатским условима. Нађено је да су средње годишње концентрације активности радона у 35 станова веома ниске, већином на нивоу 20-30 Bqm^{-3}, а јачина апсорбоване дозе гама-зрачења у тим становима је у опсегу 14-58 $nGyh^{-1}$. Овако ниске концентрације радона последица су добре заптивености зграда у контакту са тлом и малог доприноса грађевинског материјала радону у згради. Јасан општи тренд промене концентрације радона са висином спрата није констатован. У већини станова на различитим спратовима у вишеспратницама концентрација радона варира веома мало, углавном у границама грешке мерења. Мало смањење концентрације радона примећено је између два или три спрата најближа тлу, али само у неким од испитиваних зграда. Према томе, смањење концентрације радона са висином спрата не може се сматрати општом карактеристиком вишеспратница.
Иако сезонске варијације радона нису биле у фокусу овог истраживања, нађено је да су средње сезонске концентрације активности радона у становима вишеспратница веће у топлијој него у хладнијој половини године, што је супротно општем правилу за станове у свету, као и у Црној Гори.

Кључне речи: вишеспратница, годишње мерење радона, промена концентрације радона са висином спрата