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Continuous diurnal radon measurements in Bulgarian caves and dose assessment

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Abstract Bulgaria is a country in the eastern part of the Balkan Peninsula, in South-eastern Europe. The presence of many mountains and karst areas is a prerequisite for a large number of caves in the country, but only some of them are managed and accessible to tourists. The purpose of the study is continuous measurement of radon concentration in six popular Bulgarian tourist caves (Bacho Kiro, Magura, Venetsa, Saeva dupka, Snejanka, and Uhlovica), and analysis of the diurnal variation. The direct, continuous radon measurements were performed with TERA (TSR4) system (Tesla, Czech Republic). 29 radon concentration time series were considered for evaluation of radon variations during the day and night. The period of the measurement was the autumn of 2019, and only one cave (Bacho Kiro Cave) was measured during the winter. The measurements were performed at different points (gallery, halls, or other cave formations) in each of the caves. The average diurnal radon concentration in the different caves varied from 531 Bq m^{-3} (Magura cave) to 5472 Bq m^{-3} (Venetsa cave). The variation of radon concentration between distinct places in most caves was approximately 1–2 k Bq m^{-3}. No significant difference in radon concentrations was observed between night and day in a 24–96 h period measurement. The large fluctuations between the values measured at the entry (10–640 Bq m^{-3}) and exit (165–927 Bq m^{-3}) compared to those inside the cave were found only in cave Magura. The radon exposure of workers and visitors was assessed, using long-term measurements in the caves, based on the ICRP recommendation.

1 Introduction

Bulgaria is a country in the eastern part of the Balkan Peninsula, in South-Eastern Europe. The presence of many mountains and kart areas is a prerequisite for the many caves in the country, but only some of them are managed and accessible to tourists. Caves in karst areas are mostly made of limestone. The high macro-permeability of the limestone and the average content of 1.3–2.5 ppm 238U may be the cause of high concentrations of radon in some caves. Tourist caves are one of the types of public sites that can be affected by high concentrations of radon and at the same time have special environmental conditions. In caves, common measures for the reduction of radon exposure such as forced ventilation, sealing, or pressure reduction in the outlet rock cannot be applied, as these actions would damage the environment in these objects. Protecting the workers and the visitors from irradiation of radon in caves is a challenge in radiation protection. The implementation of measures to protect tourists and workers requires very coordinated action and diverse expertise to assess radon exposure. Based on numerous studies in many countries [2–7], the risks to human health from radon in homes have been well studied [8, 9] and extensive measures are in place to address elevated radon levels. In recent years, there have been similar arrangements for workplace exposure [10, 11] but there is uncertainty about some working places where the radon concentration could not be reduced. Show caves have been given particular attention for some years in this respect [12–17] among many other.

Radon (222Rn) gas is generated as a decay product of radium (226Ra), both members of the 238U chain. Radon is an alpha emitter and its decay products: 218Po, 214Pb, 214Bi, and 214Po, also decay by emitting alpha and beta particles [18]. Indoor radon poses a substantial threat to human health when build-up occurs in confined spaces such as homes, mines, and caves. The risk increases with the duration of radon exposure, and it is proportional to the radon concentration. There is currently a great deal of awareness about the health risks of exposure to high concentrations of radon and the measures taken to reduce them [19, 20].

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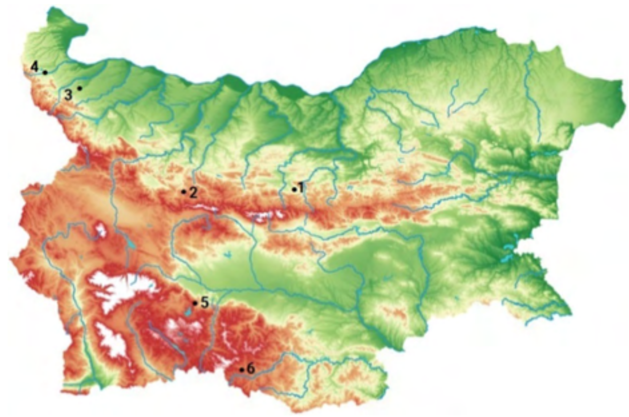

Fig. 1 Locations of the surveyed tourist caves in Bulgaria (1—Bacho Kiro, 2—Saeva dupka, 3—Venetsa, 4—Magura, 5—Snejanka, 6—Uhlovica)

The carcinogenic effect of radon has been studied and the link between radon exposure and lung cancer has been confirmed, being the second risk factor for causing the disease after smoking [21].

It is well known that radon and its short-lived progeny have the largest contribution to the annual effective dose received by the general population from natural radiation sources [18]. Radon measurements in caves are important to assess the radiological hazards to occupational workers and visitors. In accordance with Bulgarian radiation protection regulation [22] based on the European Directive [19], the annual effective dose for workers should not exceed 20 mSv, and the one for the population should not exceed 1 mSv.

The purpose of the study is continuous measurement of radon concentration in six popular Bulgarian tourist caves (Bacho Kiro, Magura, Venetsa, Saeva dupka, Snejanka, and Uhlovica) and analysis of the diurnal variation. In the present study, a dose estimate was performed based on passive annual radon measurements in the caves and the latest ICRP recommendations [20].

2 Materials and methods

2.1 Area of study

The surveyed tourist caves are located in different regions of Bulgaria. The geographical location of the studied objects is present on the map of the country with their codes according to Table 1 (Fig. 1). Four of the studied caves (Bacho Kiro, Saeva dupka, Venetsa, and Magura) are located in the Balkan Mountain, and the other two (Snejanka and Uhlovica) in the Rhodopes Mountain. A detailed questionnaire is filled in for each surveyed object containing relevant parameters for the characterization of the measurement site. The questionnaire included questions about the following topics: [1]location; [2]characteristics and data of the cave, including the type and type of site, the presence of a river in it; [3]information for visitors, namely working hours, number of visitors, etc., as well as [4]information about the staff: number of workers, time spent in the cave and time for a break. From the information in the questionnaires, it can be seen that the most visited cave is Magura with upper 30,000 visitors per year, and the smallest number of 16,000 is for the cave Uhlovica.

2.2 Radon measurements

The direct, continuous radon measurements were performed with TERA system (Tesla, Czech Republic), containing portable probes TSR4 and portable terminal TCR4A, which collects data from individual measuring elements and also operates the probes. A portable probe TSR4 basis is a measuring chamber with a semiconductor photodetector. Radon enters the chamber by diffusion through the input filter on the bottom of the probe. The probe measures in an autonomous and time continuous way. It processes results every 4-min intervals and from these counts a short-term moving average of radon concentration (1-h moving average—an average of 15 times 4-min process intervals). It also counts the long-term moving average of radon concentration (24 h moving average). The probe saves time and records these radon concentration values including values of humidity and temperature within its internal memory (typically at an interval of 1 h). With the TERA system, it is possible to continuously monitor the radon concentration in the range of 20 Bq m^{-3} to 1 M Bq m^{-3}, with possibilities for measuring the instantaneous radon concentration: short-term (average hourly) and long-term (daily average). The measurement uncertainty is as follows: $< 13\%$ at 300 Bq m^{-3} for 1 h; $<$ 3% at 300 Bq m^{-3} in 24 h. Data from the radon probe can be downloaded to a PC directly via a USB interface [23].

Direct and passive radon measurements were carried out in the studied caves. The data for the measurement period and the number of measured points of the tourist route for each cave are presented in Table 1. Passive measurements are presented at International Multidisciplinary Scientific Geo Conference Surveying, Geology and Mining, Ecology and Management—SGEM 2021 [24]. In this article, the 29 time series were considered for evaluation of radon variations during day and night. No significant difference in radon concentrations was observed in a 24–96 h period measurement.

The results of the passive measurements carried out with detectors RSFW for a period of one year were used to estimate the dose of personnel and tourists. Measurements were made at different points (galleries, halls, or other cave formations) in each of the caves. The number of points depends on the size of the caves and the length of the route for tourists. The studied caves are managed by different owners (municipalities, national tourist union, and private companies) and, therefore, have different working hours. All caves are open year-round. The Magura and Venetsa have the same working

Table 1 Measurements data for 6 caves

Name cave	Location, Bulgarian district	Period of direct measurements (date from/until)	Number of measured points of the tourist route	Period of passive measurements (date from/until)	Number of measured points of the tourist route
Bacho Kiro	Gabrovo	11.12–13.12.2019	7	11.12.2019–10.12.2020	10
Saeva dupka	Lovech	14.10–15.10.2019	6	14.10.2019–20.11.2020	2
Venetsa	Vidin	11.09–13.09.2019	3	11.09.2019–01.12.2020	3
Magura	Vidin	11.09–13.09.2019	7	11.09.2019–29.09.2020	9
Snejanka	Pazardzik	21.10–25.10.2019	3	21.10.2019–28.10.2020	5
Uhlovica	Smolyan	16.09–19.09.2019	3	16.09.2019–11.09.2020	6

hours throughout the year, while the others have different working hours for tourists in summer and winter. The personnel in the caves are of different numbers and annual working hours vary from 330 to 1063 h. The exact duration of the tourist route and working hours are included in the dose estimate for each cave (Table 3).

2.3 Dose assessment

Passive radon measurements with RSFW-type detectors for a whole year (the results were published before) [24] were used for dose assessment. The weighted average value of the radon concentration (Bq m^{-3}), determined by the duration of stay at the point on the route, was applied for the dose assessment. The weighted average value is calculated according to the formula (1), as follows:

$$\overline{CRn} = \frac{\sum_{i=1}^{n} CRn_i.t_i}{\sum_{i=1}^{n} t_i} \quad (1)$$

where $\mathrm{CRn_i}$ is the i concentration of radon in Bq m^{-3}, and $\mathrm{t_i}$ is time spent in the cave. Parameter (i) is the location at tourist route point i for each cave. Table 2 shows the number of examined points.

To estimate the effective dose from inhalation of radon by visitors (population) and workers, the ICRP dosimetry model was applied (Publication 137). A dose assessment for the staff working in the caves was performed by summarizing the data for working hours and a dose coefficient of 1.5.10^{-5} mSv per Bq h.m^{-3} for reference workers with a breathing rate of 1.2 m^3/h [20]. The dose coefficient of 3 mSv per mJ.h.m^{-3}, which corresponds to 6.7.10^{-6} mSv per Bq h.m^{-3} assuming an equilibrium factor F of 0.4, was applied for the evaluation of population doses, according to Publication 137.

Sources of uncertainty in the estimated annual effective dose were assessed. The relative uncertainty is determined according to the following equation:

$$u = \sqrt{u_m^2 + u_t^2 + u_F^2} \quad (2)$$

where u_m is the uncertainty from radon measurement; u_t is the uncertainty of the average exposure time in the caves, assuming that values have the triangle distribution; and u_F is the uncertainty due to variations in the equilibrium factor.

3 Results and discussion

3.1 Summary of continuous diurnal radon measurements

The results of continuous diurnal radon measurements in caves are presented in Table 2. For each cave, a different number of direct measurements were performed at the same time (period, date), noted in "location within cave". For each measured point of the tourist route, the minimum, maximum and average arithmetic means of radon concentration were determined. The coefficient of variation (CV) was calculated, based on the arithmetic mean of the radon concentration at the point and the standard deviation.

The radon concentration varied at different measurement points in the cave itself. The diurnal variation of radon measurements in most caves was from 1 to 2 k Bq m^{-3} between inside places. This is probably due to the size of the various cave formations, such as halls and galleries, and the air exchange between them, as well as their depth. For the illustration, the time series from the inside places of the Bacho Kiro cave are presented in Fig. 2. Similar results have been found in research studies performed in Altamira Cave, Spain [12] as in Đurovića cave in Croatia [13] and Velebita pit in Croatia [14]. The highest arithmetic means value of the radon concentration (AM = 6632 Bq m^{-3}) was found in Hall No. 5 of the Venetsa cave, which is located deep inside the site and is the last of the tourist route. The coefficient of variation ranges from 4% (Bacho Kiro cave) to 57% (Snejanka and Magura). The highest value of CV is at the measured point "entrance" of Magura cave, which is related to the exchange of atmospheric air. The high CV value for Snezhanka Cave at the "end of route" point is most likely due to the fact that there are openings to the surface that are outside the tourist

Table 2 Summary data of continuous diurnal radon measurements

Cave name	Location within cave	Measured period (date from–to)	Time measured interval (h)	Min, Bq m^{-3}	Max, Bq m^{-3}	AM, Bq m^3	CV, %
Bacho Kiro	Entrance	11.12–13.12.2019	48	10	57	29	36
	End of route	11.12–13.12.2019	48	1611	2861	2477	6
	Small stalactites	11.12–13.12.2019	48	3699	5169	4384	11
	Small purgatory	11.12–13.12.2019	48	2407	3955	3472	7
	Ritual hall	11.12–13.12.2019	48	3445	4069	3693	4
	Lone stalacton	11.12–13.12.2019	48	867	2285	1414	31
	Sword meadow	11.12–13.12.2019	48	3508	4211	3899	4
Saeva dupka	Entrance	14.10–15.10.2019	24	2150	3341	2935	29
	"Kupena"	14.10–15.10.2019	24	2468	2871	3308	25
	Collapse	14.10–15.10.2019	24	2348	3054	2869	17
	Concert hall	14.10–15.10.2019	24	746	1932	1026	30
	Space hall	14.10–15.10.2019	24	2483	3382	3029	21
	Office	14.10–15.10.2019	24	15	32	48	25
Venetsa	Entrance	11.09–13.09.2019	48	4140	4750	4736	9
	Hall №3	11.09–13.09.2019	48	4713	5138	5049	6
	Hall №5	11.09–13.09.2019	48	5607	7176	6632	17
Magura	Entrance	11.09–13.09.2019	48	10	640	346	57
	Collapse	11.09–13.09.2019	48	440	886	681	18
	Stalacton	11.09–13.09.2019	48	177	787	619	15
	Concert hall	11.09–13.09.2019	48	201	716	549	16
	Fallen pine	11.09–13.09.2019	48	402	771	585	19
	"Jabba"	11.09–13.09.2019	48	210	629	452	21
	Exit	11.09–13.09.2019	48	165	927	484	39
Snejanka	Alley in front of a great hall	21.10–25.10.2019	96	1092	1976	1584	11
	Great hall	21.10–25.10.2019	96	1190	2023	1635	10
	End of route	21.10–25.10.2019	96	199	1315	533	57
Uhlovica	Draperies	16.09–19.09.2019	60	449	1994	1003	28
	Octopus	16.09–19.09.2019	60	1713	2626	2140	9
	Sintrovi lakes	16.09–19.09.2019	60	2567	3923	3322	8

route. Snejanka cave has only one large hall and has a total length of the tourist route of 220 m. The cave has the smallest volume of the studied caves.

It was found that temperature and humidity in the caves are constant for the measurement period. For the temperature, the reason is that rock is slow to transmit heat. Humidity is nearly 100% in investigated caves. Similar to temperature, humidity is more stable farther into a cave as well as in caves with one entrance and/or small entrances. The values of temperature, pressure, and radon concentration in Uhlovica cave are presented in Fig. 3. It could be seen that the parameters are constant for the measurement period.

A difference was found in the cave with two entrances. In cave Magura is large fluctuations between the values measured at the entry and exit compared to those inside the cave. Most likely, these differences are due to the natural ventilation of the entrance, where the radon value is from 10 to 640 Bq m^{-3} and the exit with variations from 165 to 927 Bq m^{-3} (Table 3). Caves with high air flow are usually large and have more than one entrance. Air pressure inside a cave always tries to equalize with the outside air pressure. If air pressure outside the cave is greater, air moves into the cave and vice versa and defines the nature ventilation.

3.2 Dose assessment of visitors and workers

The weighted average values of the radon concentration were used to calculate the doses. Only for one cave—Saeva dupka, the value of the radon concentration measured in the middle of the site was used, due to

Table 3 Dose assessment in six caves

Code cave	Name cave	Duration tourist route (h)	Weighted average CRn (Bq m^{-3})	Working time (h per year)	Dose employee (mSv a^{-1})	Dose population (μSv a^{-1})
1	Bacho Kiro	1.17	1811	750	**8.2**	6.1
2	Saeva dupka	0.50	591[a]	330	1.2	2.0
3	Venetsa	0.75	1991	1063	**12.7**	6.7
4	Magura	1.17	226	1034	1.4	0.8
5	Snejanka	0.58	672	495	2.0	2.3
6	Uhlovica	0.75	541	610	2.0	1.8

[a]For the Saeva dupka cave, weighted average CRn is not taken

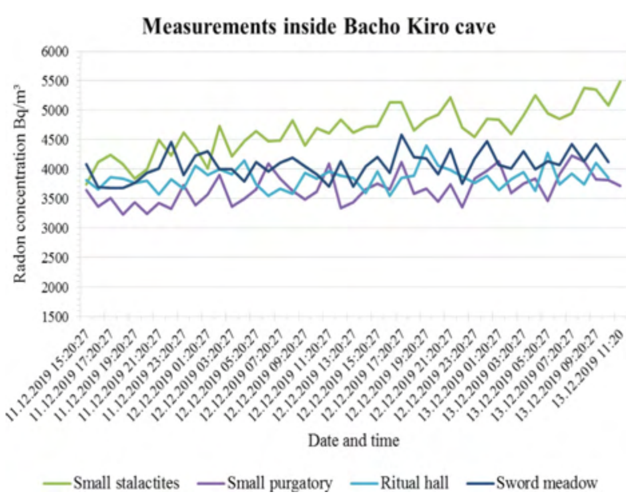

Fig. 2 Radon time series from the inside of the Bacho Kiro cave

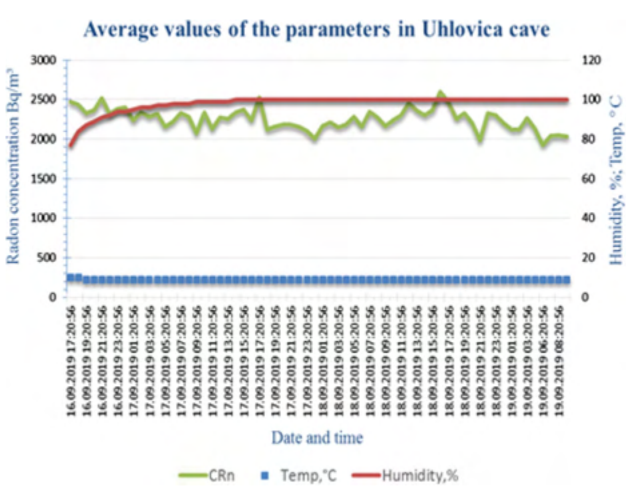

Fig. 3 Results of temperature, pressure, and CRn in Uhlovica cave

losses of detectors. The values of effective dose obtained for the visitors to the caves vary from 6.7 to 0.8 μSv for one annual visit (Table 3). The effective doses of the public during the tour route in all caves are much less than the dose limit of 1 mSv, according to the regulation [19, 22]. Assuming that a tourist visits all the caves in 1 year, his effective dose of radon inhalation will be 19.7 μSv per year. More authors come to similar conclusions about the annual doses of radon received by the population when visiting caves [15–17].

Effective doses for workers range from 1.2 mSv per year (Saeva dupka) to 12.7 mSv per year (Venetsa cave). Uncertainties in the assessment of exposure of radon concentration, include uncertainties from the measurement, which was assessed to be 0.2 Bq m^{-3}, according to our standard working procedure; uncertainties from the exposure time in the cave, assuming that the value has a triangular distribution and was evaluated to 0.4 and the uncertainties of equilibrium factor, according to Onishchenko and Zhukovsky is 0.24 [25]. The combined standard uncertainty calculated according to Eq. (2) is 0.5.

Higher annual doses of up to 120 mSv have been assessed in caves located in the United Kingdom [26, 27] and Viento cave (41 mSv) in Tenerife [28]. The estimated doses for tour guides in Snejanka cave (2 mSv per year) and Uhlovica cave (2 mSv per year) are approximately similar to those in the Gadime Cave (3.7 mSv per year) in Kosovo [29].

According to the Bulgarian legislation for workplaces where the average annual activity of radon in the air exceeds 300 Bq m^{-3} and where the individual effective dose of workers is likely to exceed 6 mSv for 1 year, planned exposure situation should be considered and appropriate case-specific measures for radiation protection must be approached. If we compare these values with the Bulgarian legislation [22], the estimated effective dose for workers is lower than 6 mSv per year in the caves: Magura, Saeva dupka, Uhlovica, and Snejanka. The results for Venetsa (12.7 mSv per year) and Bacho Kiro (8.2 mSv per year) are higher (bold values in Table 3). Introducing engineering measures such as ventilation to mitigate employee exposure could damage the natural environment of the caves, so administrative controls such as tracking working time spent in the caves should be instituted, or an increase in the number of tour guides.

4 Conclusions

Radon concentration was measured in six tourist caves of Bulgaria, which accept visitors throughout the year. The average radon concentration greatly differs between studied caves (531–5472 Bq m^{-3}). The variation in most tourist caves was approximately 1–2 k Bq m^{-3} between measurements inside places the cave. This is probably due to the size of the various cave formations and the air exchange between them, as well as their depth. It was found that temperature and humidity in the caves are constant for the measurement period. There is no difference in diurnal radon concentrations in investigated caves observed in the measurement period.

The estimated effective dose for cave workers varies from 1.2 mSv per year to 12.7 mSv per year and for visitors from 0.8 μSv per year to 6.7 μSv per year. It is necessary to introduce radiation protection measures in the caves where high doses have been estimated, to limit the radon exposure of workers.

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Data availability The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request. Data from passive measurements of radon concentration in caves are available at link https://www.sgem.org/index.php/elibrary-research-areas?view=publication&task=show&id=8340.

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