Radon monitoring in the Harmanecká Cave, Slovakia

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Abstract: Radon survey in the Harmanecká Cave was conducted from December 2023 to November 2024 using Ramarn track detectors placed in 8 stations inside the cave and one station in the cavity developed in the same karst system outside the cave. Detectors were changed every three months. Annual average of radon activity concentration inside the cave varied between 930 and 2240 Bq/m^3, in the cavity it was equal to 222.5 Bq/m^3. Seasonal variation was observed at all sites, and its different character among sites was proven. A possible relation between radon and microclimate and meteorological parameters was investigated, but no clear relationship was observed. Assessing their possible effect on radon using three-month data is therefore not appropriate and continuous measurements are needed. Estimated annual effective dose for the cave guides was below the limit of 20 mSv.

Key words: radon, cave, track detector, monitoring, effective dose

1. Introduction

Radon (^{222}Rn) is naturally occurring noble gas with half-life of 3.82 days. It is produced by an alpha decay of radium (^{226}Ra) in uranium (^{238}U) decay series. Radon is the second leading cause of lung cancer after tobacco smoking, and the most common cause of lung cancer in non-smokers (*WHO, 2009*). Therefore, radon activity concentration (RAC) in caves is monitored mainly to assess health hazard for the cave guides (*Lu et al., 2009; Lario et al., 2005; Somlai et al., 2015; Kunovska et al., 2023*). On the other hand, due to its unique characteristics, radon is widely used as a natural tracer in air exchange research between cave atmosphere and external environments (*Sainz et al., 2018; Perrier et al., 2024; Tang et al., 2025*).

The first detailed radon research in Slovak show caves was realised from

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October 1992 to September 1993, using bare CR-39 track detectors. Two monitoring stations were established in each of 12 caves then open to the public, detectors were changed after 2 weeks exposure. The results showed that the Harmanecká Cave was among three caves with the highest measured equivalent radon activity concentration level, annual average at Riverbed station was equal to 4800 Bq/m^3 and at Stray home 5040 Bq/m^3 (*Vičanová, 2003; Vičanová et al., 1997*). Spatial variations of radon were not studied.

This paper summarises the results covering a one-year period of RAC monitoring in the Harmanecká Cave. The spatial and temporal variations of RAC are evaluated and potential influencing factors are investigated. The annual effective dose for the cave guides and visitors was evaluated.

2. Materials and methods

2.1. The Harmanecká Cave

The Harmanecká Cave (N 48.8139000°, E 19.0401001°), operated by the State Nature Conservancy of Slovak Republic, Slovak Cave Administration (SCA), was discovered in 1932 and is open to tourists from 1950. The cave is located in the southern part of the Veľká Fatra Mts., in the vicinity of Harmanec town (Fig. 1A). It is a vertical-horizontal multiple branched cave of a fissure-breakdown character, which was formed in Middle Triassic dark-grey Guttenstein limestones along tectonic faults in hydraulic conditions of slow pressure water flow or almost stagnant aquifer (*Bella, 2000*). It is known for an abundant occurrence of white soft sinter – moonmilk and as an important bat hibernation locality (*Ogórek et al., 2016*).

The cave entrance is situated at 821 m above sea level, its length is 3216 m and vertical span of 75 m (`https://www.smopaj.sk`, *Slovak Museum of Nature Protection and Speleology, 2017*). It is open to tourists from May to October and closed on Mondays. The tourist route length is 1020 m and duration of the visit is one hour.

2.2. Radon monitoring

Radon survey to assess the spatiotemporal variation of RAC was carried out from December 2023 to November 2024 in eight monitoring points inside the cave: Discoverer's Dome, Dome of Pagodas, Riverbed, Depositional

Passage, Stray Dome, End of Stray Dome, Northern Labyrinth and Šavolt's Areas (Fig. 1A, B). Moreover, one detector was placed in a monitoring site Upper Vent located outside the cave (Fig. 1D, E).

Radon monitoring was carried out during the microclimatic research conducted by SCA, therefore all nine stations were equipped with Barologgers 5 sensors (Solinst, Canada) for monitoring of air temperature and pressure with one-hour measuring interval. Moreover, one sensor was placed outside the cave for atmospheric temperature and pressure monitoring. Passive alpha track detector Ramarn (SÚJCHBO, Milín, Czech Republic), with Kodak LR 115 film located at the bottom of the diffusion chamber was used in this survey (*Thinová and Burian, 2008*). Detectors were stored in plastic boxes to protect them against dripping water. Air entered the boxes by diffusion through a perforation in the walls (Fig. 1C).

Stations 1–5 were situated directly on the tourist route mainly at stop locations for the visitors and stations 6–8 were in inaccessible areas. Monitoring station 9 was located in an approximately 7 m long inclined narrow karst cavity, situated on the slope of the hill, close to the tourist pathway leading to the cave. This cavity is not connected to the Harmanecká Cave, but is probably a part of the same karst system (Fig. 1D, E).

Radon detectors were changed after three months exposure. After the collection the set of detectors was sent to the SÚJCHBO laboratory for an evaluation.

2.3. Effective dose assessment

Effective dose assessment for the cave guides and visitors was performed according to ICRP 137 (*ICRP, 2017*) recommendation using following formula:

$$\mathrm{E} = \mathrm{RAC} \times \mathrm{T} \times \mathrm{DCF}\,, \qquad (1)$$

where RAC is radon activity concentration (Bq/m^3), T is duration of the exposure (hours) and DCF is dose conversion factor (mSv per Bq.h/m^3).

For cave guides ICRP 137 suggested using DCF $= 1.5 \times 10^{-6}$ mSv per Bq.h/m^3. According to Act of law 87/2018 on Radiation Protection (*National Council of the Slovak Republic, 2018*), effective dose limit in Slovakia for occupational worker is equal to 20 mSv per year and for general public the limit is 1 mSv per year.

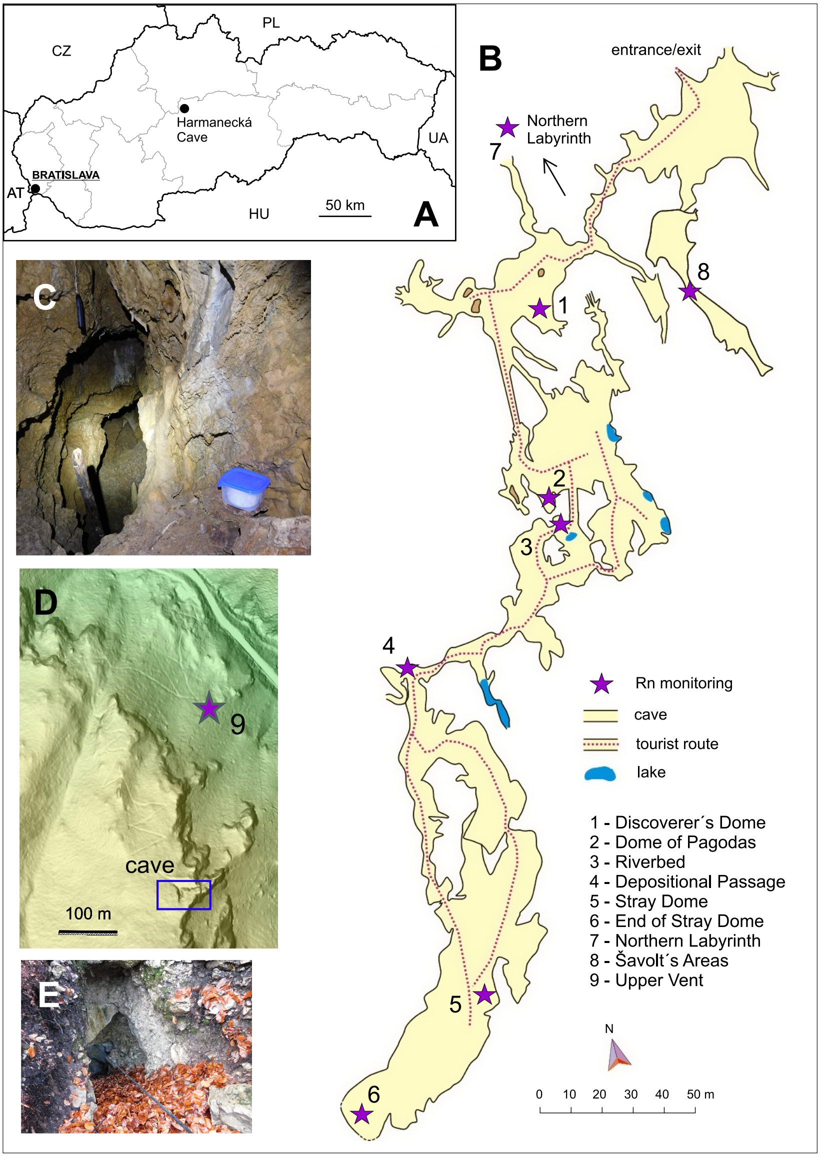

Fig. 1. Location of the Harmanecká Cave (A), cave map with monitoring sites (B), example of a monitoring site with barologger hanging from the ceiling and radon detector placed in a box (C), position of monitoring site 9 outside the cave (D) and entrance to the monitoring site 9 (E).

3. Results and discussion

3.1. Temporal and spatial variation of radon

With one exception, RAC values measured over the considered period in the Harmanecká Cave were generally less than 3500 Bq/m^3. Temporal and spatial variations of RAC were proven and are depicted on Fig. 2. RAC values measured in the Harmanecká Cave ranged in these intervals: Discoverer's Dome (85 – 1950 Bq/m^3), Dome of Pagodas (385 – 2100 Bq/m^3), Riverbed (130 – 2100 Bq/m^3), Depositional Passage (150 – 2500 Bq/m^3), Stray Dome (430 – 2150 Bq/m^3), End of Stray Dome (960 – 4300 Bq/m^3), Northern Labyrinth (370 – 2900 Bq/m^3), Šavolt's Areas (780 – 2500 Bq/m^3) and Upper Vent (50 – 390 Bq/m^3). The highest annual average of RAC inside the cave was found at the End of Stray Dome, the lowest at the Šavolt's Areas (Table 1).

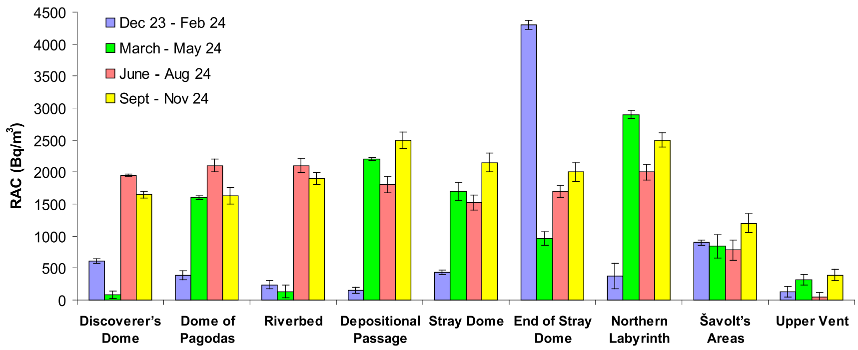

Fig. 2. Temporal and spatial variation of RAC in the Harmanecká Cave.

The most common seasonal cycle of RAC in caves is characterised by a maximum during summer months and minimum in winter (*Lu et al, 2009; Gregorič et al., 2011; Smetanová et al., 2020; Briestenský et al., 2022*). However, inverse seasonal cycles were documented too (*Lario et al, 2005; Sainz et al., 2018*) or both types of cycles occurred in different places in the cave (*Perrier et al., 2024*), or two maxima per year were observed (*Mihailović et al., 2015*).

Seasonal cycles observed in the Harmanecká Cave differed among sites. Although the highest measured radon activity during the one-year monitoring period was found in winter season, winter maximum appeared only at one site (End of Stray Dome). In other stations the seasonal minimum was mostly observed during winter (Dome of Pagodas, Depositional Passage, Stray Dome, Northern Labyrinth), or in the spring season (Discoverer's Dome, Riverbed, End of Stray Dome). However, in Discoverer's Dome and Riverbed also winter RAC was low and winter-spring RAC was significantly lower in comparison with summer-autumn RAC levels. Outside the cave in the station Upper Vent the seasonal minimum appeared in the summer months, though winter radon level was also low.

Table 1. Summary of RAC measured at nine monitoring sites and arithmetic mean value AM (DD – Discoverer's Dome, DOP – Dome of Pagodas, R – Riverbed, DEP – Depositional Passage, SD – Stray Dome, ESD – End of Stray Dome, NL – Northern Labyrinth, SA – Šavolt's Areas and UV – Upper Vent).

RAC (Bq/m^3)	Dec 23 – Feb 24	Mar – May 24	June – Aug 24	Sept – Nov 24	AM
DD	610 ± 70	85 ± 30	1950 ± 100	1650 ± 130	1073.75
DOP	385 ± 60	1600 ± 100	2100 ± 110	1625 ± 90	1427.50
R	240 ± 50	130 ± 25	2100 ± 130	1900 ± 130	1092.50
DEP	150 ± 35	2200 ± 140	1800 ± 115	2500 ± 150	1662.50
SD	430 ± 70	1700 ± 110	1520 ± 115	2150 ± 150	1450.00
ESD	4300 ± 200	960 ± 65	1700 ± 120	2000 ± 110	2240.00
NL	370 ± 40	2900 ± 180	2000 ± 160	2500 ± 150	1942.50
SA	900 ± 80	840 ± 80	780 ± 70	1200 ± 90	930.00
UV	130 ± 30	320 ± 60	50 ± 20	390 ± 55	222.50

In several stations (Depositional Passage, Stray Dome, Northern Labyrinth) the summer RAC was lower than radon levels measured in spring and autumn seasons, suggesting the presence of two radon maxima per year. In Šavolt's Areas the highest RAC was found in autumn. In this site radon levels during the year were comparable, with no distinct seasonal variation as on other sites in the cave and moreover, also the lowest among monitoring sites inside the cave. However, the real nature of seasonal changes at individual sites can only be determined through detailed research, preferably using continuous RAC monitoring.

3.2. Effects of microclimate and meteorological parameters on RAC

The three-month RAC data were examined in relation to microclimate and meteorological parameters.

The relation of internal air temperature measured at 8 sites inside the cave and RAC data is depicted on Fig. 3. Internal air temperature was almost stable in Dome of Pagodas, Stray Dome, End of Stray Dome and Northern Labyrinth, while distinct short-term variations were registered in the rest of the stations. Annual variation of RAC was observed at each site, also on sites with stable air temperature. The type of seasonal variation of RAC did not seem to be connected with the type of seasonal change of internal air temperature. Three-month average of internal temperature was calculated and compared with RAC data, however no relation was found.

Seasonal variation of radon is often explained by changes of airflow driven by change in natural ventilation of the cave. The temperature difference between the inside air and outside atmosphere is often the main driving force for annual radon variation (*Gregorič et al., 2011; Smetanová et al., 2020; Briestenský et al., 2022; Tang et al., 2025*). Figure 4 shows daily averages of atmospheric temperature and pressure over one year. The relationship between the temperature difference between internal and atmospheric temperature and atmospheric pressure with RAC data on selected monitoring sites is illustrated on Fig. 5. Due to the narrow range of measured internal air temperatures the course of temperature difference is identical for all monitored stations, even with stable or varying internal temperature. No relation was found between RAC and temperature difference, as well as between three-month average of this temperature difference. Similarly, no influence of atmospheric pressure was observed.

Due to its position outside the cave, the course of internal air temperature in the Upper Vent station was different and its daily averages ranged from 8.65 and 20.31 °C. Similarly, no influence of all above mentioned parameters on RAC data measured in the Upper Vent station was confirmed (Figs. 5, 6).

Three-month average values provide just an approximate course of seasonal change of RAC and therefore are not suitable for evaluating the effects of microclimate and meteorological parameters on radon levels. The continuous radon monitoring is necessary for the better understanding of RAC annual behaviour.

3.3. Effective dose assessment

Effective doses received by the cave guides and visitors were estimated according to ICRP 137 recommendations using equation (1).

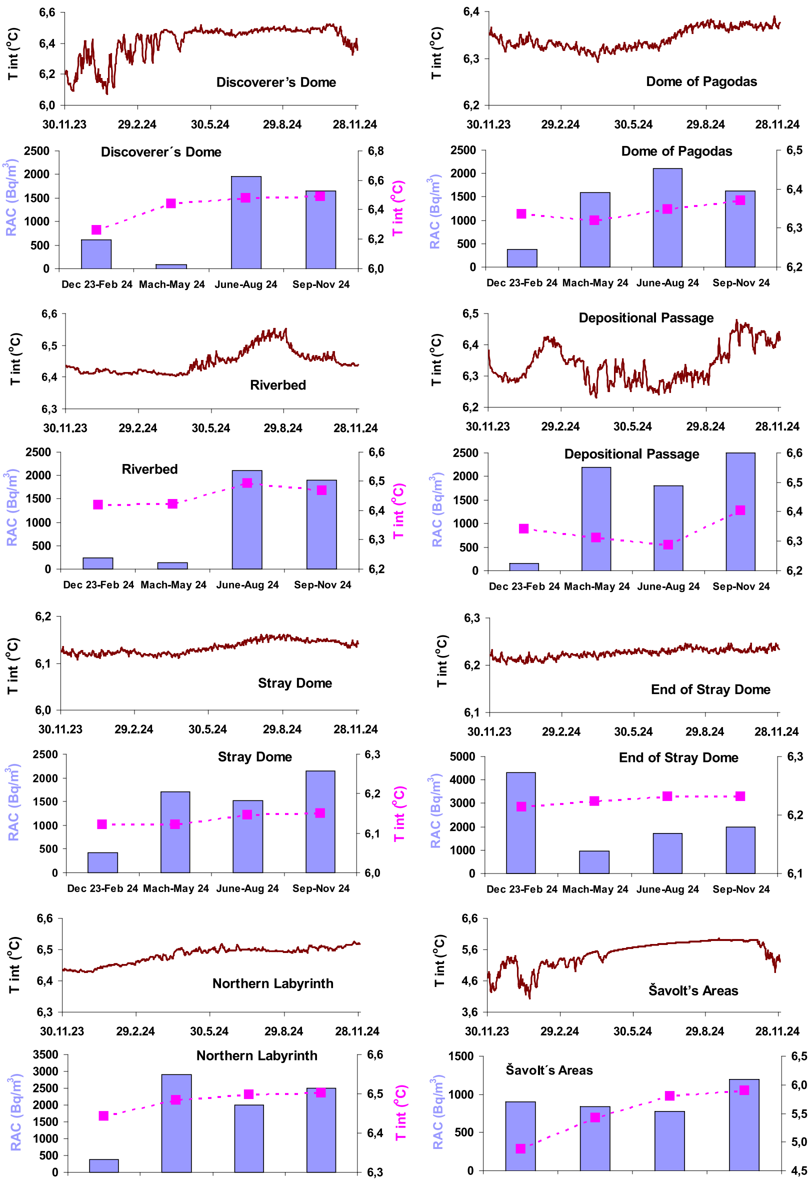

Fig. 3. Daily average values of internal air temperature measured at 8 stations in the Harmanecká cave compared to RAC measured at each station during four seasons over a year and the average value of internal air temperature during these seasons.

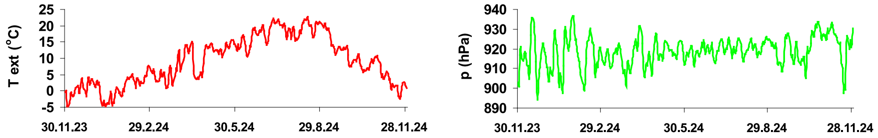

Fig. 4. Daily average of atmospheric temperature and pressure measured outside the Harmanecká Cave.

Three-month effective doses for the cave guides were estimated, based on the total number of hours spent in the cave (Table 2) and RAC calculated as the average of RAC measured on five monitoring stations situated along the tourist route (stations 1 – 5) in a given three-months period.

The results of effective dose calculation for the cave guides are summarised in Table 3. In tourist season June – August 2024, seven temporary guides were employed in the Harmanecká Cave and they received effective

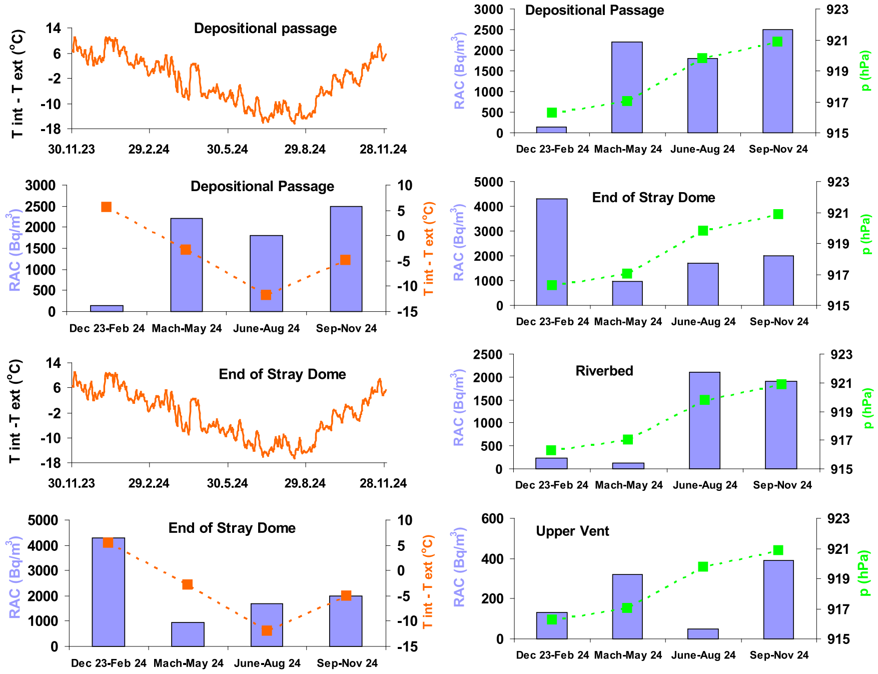

Fig. 5. Left: Daily average values of temperature difference at selected stations compared to RAC measured during four seasons over a year and the average value of temperature difference during these seasons. Right: RAC measured during four seasons over a year and the average value of atmospheric pressure during these seasons in selected stations.

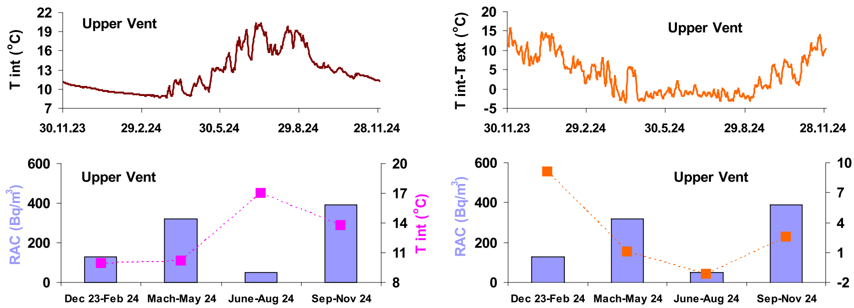

Fig. 6. Daily average values of internal air temperature, resp. temperature difference at Upper Vent stations compared to RAC measured during four seasons over a year and the average value of internal air temperature, resp. temperature difference during these seasons.

Table 2. Number of hours (H) spent by permanent (1 – 2) and temporary cave guides (A – G) in each season in the Harmanecká Cave.

H	Dec 23 – Feb 24	Mar – May 24	June – Aug 24	Sept – Nov 24
1	30	25	45	45.5
2	30	95	61	162
A	–	–	74	–
B	–	–	109	–
C	–	–	34	–
D	–	–	105	–
E	–	–	148	–
F	–	–	23	–
G	–	–	96	–

Table 3. Effective doses (ED) for permanent (1 – 2) and temporary cave guides (A – G).

ED (mSv)	Dec 23 – Feb 24	Mar – May 24	June – Aug 24	Sept – Nov 24	sum
1	0.163	0.429	1.278	1.223	3.093
2	0.163	1.629	1.733	4.775	8.300
A	–	–	2.102	–	–
B	–	–	3.097	–	–
C	–	–	0.966	–	–
D	–	–	2.983	–	–
E	–	–	4.205	–	–
F	–	–	0.653	–	–
G	–	–	2.727	–	–

doses from interval (0.65 – 4.20 mSv) per three-month period, depending on a number of hours they spent in the cave. Two permanent guides visited the cave during the whole year and they received 3.09, resp. 8.30 mSv per year. Although the guide 2 spent fewer hours in the cave during summer season than in the spring, effective dose for summer season was higher, due to higher RAC in comparison with spring months. For all guides, the effective dose was significantly below the limit of 20 mSv per year.

Tourist season in the Harmanecká Cave starts in May and lasts until the end of October. Due to three-month monitoring periods which resulted in an average RAC value for each season of the year, the effective dose for the visitors was calculated only for the period of June – August 2024. Visitors who completed a circuit lasting 60 min received 28 μSv per visit.

Assuming the measured equilibrium factor in Slovak show caves (*Jílek, 2019*), the following formula can be also used for effective dose estimation:

$$E = RAC \times T \times DCF \times F \times 5.6 \times 10^{-6}\,, \tag{2}$$

where DCF is expressed in mSv per mJ.h.m^{-3}, according to ICRP 137 for cave worker DCF is 6.6 mSv per mJ.h.m^{-3}. Equilibrium factor F = 0.678 for the Harmanecká Cave, determined at the station Depositional Passage.

Using formula (2), effective doses for cave guides and visitors increased. The permanent guide 1 received 5.166 mSv per year and the guide 2 received 13.866 mSv per year. Temporary guides received effective doses from 1.092 to 7.024 mSv per summer tourist season. Visitors received 48 μSv per visit. Even using F determined specifically for this cave, the effective doses for cave guides remained below the limit 20 mSv per year.

4. Conclusion

Radon survey performed in three-month periods during one year at 8 sites in the Harmanecká Cave and one site situated in the cavity outside the cave proved both seasonal and spatial variations of RAC. The course of seasonal variation among stations differed. The highest annual average of RAC was found in station End of Stray Dome, the lowest at Šavolt's Areas.

Possible influencing factors (internal air temperature, atmospheric temperature, temperature difference and atmospheric pressure) on RAC at all monitoring sites were analysed, but their impact on three-month average values was difficult to assess. This preliminary radon survey showed that

3-month resolution radon data provided just a simple insight on radon levels and their changes in the cave during a year, but the character of seasonal variations of radon and understanding the impact of influencing factors on it can only be revealed using detailed continuous monitoring.

The estimated effective doses for both permanent and temporary employed cave guides were significantly less than 20 mSv per year.

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