ORIGINAL ARTICLE

Prediction of the radon priority areas in the Slovak Republic and its experimental verification

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Abstract

***Background*:** The identification of the areas with increased indoor radon levels, generally referred to as "radon priority areas", is an internationally recognized issue. Many scientific studies propose methods for locating such areas using measured soil characteristics.

***Objective*:** To utilize a modified Neznal radon potential classification for mapping radon potential across the Slovak Republic and experimentally verifying the predictions of radon priority areas.

***Methods*:** The study applied a modified version of the Neznal radon potential classification, using measurements of soil air radon concentration and soil gas permeability, to develop a radon potential map for the Slovak Republic. Municipalities with high radon potential were primarily selected for the experimental verification of radon priority area predictions. The verification process involved comparing measured indoor radon activity concentrations against predicted values, which were derived from a previous study correlating averaged indoor radon activity concentrations with averaged Neznal radon potential for selected municipalities.

***Results*:** The investigation revealed an approximately linear relationship between the measured indoor radon activity concentrations and their predicted values, with a correlation coefficient $R^2 = 0.43$. Notably, in one municipality predicted to have medium-high radon potential, indoor radon concentrations exceeded the reference level of 300 $Bq.m^{-3}$ even in buildings constructed after 2008, highlighting the significant influence of soil radon content on indoor levels despite stricter building material standards. The analysis of radon priority areas in relation to bronchial and lung cancer mortality data across various districts in Slovakia did not show statistically significant results.

***Conclusion*:** The proposed method of predicting radon risk areas is important for radiation protection of the population against high effective doses of radon and can contribute to the successful implementation of the National Radon Action Plan of the Slovak Republic.

Keywords: *Radon*; *^{222}Rn*; *radon potential map*; *radon activity concentration*; *indoor radon levels*; *reference level*; *standardized mortality*

Preferential interest in the natural radioactive isotope ^{222}Rn (radon) worldwide is primarily related to the possibility of its accumulation in enclosed spaces. In some cases, the concentration of ^{222}Rn in dwellings or workplaces may reach levels that pose a potential health risk to their occupants (1). Therefore, in order to evaluate the area in terms of radon risk, it is important to map the so-called radon potential (RP) of the soil. Subsequently, this parameter could serve as preliminary information to determine whether additional radon measurements are required in a specific area. Based on these measurements, it can be determined whether preventive measures are necessary during the construction of new buildings or, in the case of existing buildings, where remedial measures are required to optimize the elevated levels of ^{222}Rn concentration. The current annual average reference level (RL) for radon activity concentration (RAC) in dwellings in the Slovak Republic is set at 300 Bq/m^3 according to the Collection of Laws of the Slovak Republic 87/2018 (2).

In addition, the Council Directive 2013/59 Euratom (3) obliges the member states to prepare national action plans for radon. Their task is, among other things, to search for dwellings in which the indoor RAC exceeds the established RL. The requirement for the identification of locations with an elevated indoor radon concentration, generally referred to as radon-prone areas (4) or radon priority areas (RPAs) (5, 6), is also mandated by the International Atomic Energy Agency (IAEA) (7) and the International commission on Radiological Protection

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(ICRP) (8). The ICRP defines the radon-prone area as the part of the country, where in at least 1% of the buildings, the indoor RAC reaches a value that is more than 10 times higher than the national average for indoor RAC. Alternatively, RPAs can represent areas where the radon concentration (as an annual average) in the significant number of buildings is expected to exceed the relevant national RL (though the exact number is not explicitly stated) (3). Both definitions of the RPAs refer to areas where the indoor RAC is increased due to the natural (geogenic) origin of ^{222}Rn (9), that is due to high radon content in the soil environment. In general, it is usually possible to identify the RPAs according to two main methods (10): 1) by measuring the indoor RAC directly [e.g. research in Austria (11), Italy (12), Switzerland (13), Ireland (14), Spain (15), Montenegro (16), or for Europe (17)] or, 2) by using indirect methods such as assessing the dose rate from terrestrial gamma radiation of the soil, surveying the concentration of radon in the soil air, or other parameters affecting the transport of ^{222}Rn from the soil environment such as ^{226}Ra concentration in soil, soil permeability, soil porosity, soil moisture, and others (10). Currently, the preferred method for determining the RPAs in the Slovak Republic is the second approach due to the complexity and cost of collecting a large sample of indoor RAC data across the country. The second approach primarily relies on geological parameters of the location of interest (e.g. 18–24).

This study uses a modified Neznal RP classification (25) to determine the RP distribution in the Slovak Republic. To achieve this, we used data on RAC in soil air at a depth of 0.8 m and soil gas permeability values obtained from the map server of the State Geological Institute of Dionýz Štúr (26). The distribution of RP was visualized in the form of map that covers the entire territory of Slovakia. Using the detailed 28 map segments of RP for Slovakia published in our previous study (27), we conducted an experimental verification of RPA predictions. This was done by measuring indoor RAC using passive track detectors in a total of 12 municipalities. In addition to the eight municipalities covered in our previous studies (28, 27), this study includes 4 additional high-RP municipalities. Mean indoor RAC predictions were made for these 12 municipalities based on their mean RP values, using the formula from our previous study (28). We then analyzed the relationship between the predicted and measured values of indoor RAC. We also analyzed RPA predictions against standardized bronchial and lung cancer mortality data for individual districts in Slovakia.

Furthermore, in one selected RPA municipality, indoor RAC levels were measured throughout the year. In this municipality, annual average indoor RAC values above the RL were found also in newer dwellings built after 2008. In one house, additional measurements of soil gas permeability and RAC in the soil air were performed, with the aim of determining the source of increased indoor RAC.

Materials and methods

The first determination of the RP of the Slovak Republic was performed in the pilot study (28) covering the Mochovce region, Slovakia (~530 km^2), which is mapped with a high density (~2 measurement points per km^2 for ^{238}U, ^{40}K, and ^{232}Th in the soil and ~0.6 measurement point per km^2 for ^{222}Rn in the soil air). In this pilot study, five indirect methods of determining the soil RP were tested. For this purpose, the RACs' data in the soil air at a depth of 80 cm and soil gas permeability data were taken from the map server of the State Geological Institute of Dionýz Štúr (26). To visualize the RP maps, the *kriging* interpolation method in the geostatistical software Surfer 11 was used (29). For determining the RP, the approach proposed by Neznal et al. (25) was chosen, and the RP values were calculated with a spatial resolution of 0.005° × 0.005°. The RP scale was adjusted in such a way that the original boundary value of RP for medium-high soil radon risk was changed from the value of RP = 35 (25) to RP = 21 (27, 28). This rescaling was motivated by earlier experimental measurements of indoor RAC in a municipality from the Mochovce region, where in 54% of cases, the average RAC during the winter season exceeded the RL (28). These results suggested that the RP map should be rescaled to classify this municipality as a high-RP area instead of a medium RP area, as the original Neznal scale indicated.

This method of RPAs determination was extended to the entire territory of the Slovak Republic (shown in this study) and 28 smaller areas within the Slovak Republic (27). The borders of these areas were delineated with the intention of enhancing the reliability of RPA predictions. To that end, some areas characterized by the absence of measurement points and low population density (e.g. mountain areas) were excluded from RP mapping. The density of measurement points (^{222}Rn in the soil air and soil gas permeability) for the selected areas ranged from 0.1 to 0.6 points per km^2. Based on the Neznal RP, the predicted indoor RAC was determined according to the formula published in our previous study (27):

$$\text{indoor RAC} = (11.3 \pm 3.6)\cdot \text{RP} + (84.3 \pm 63.6). \quad (1)$$

This formula was obtained as the line of best fit between averaged RP and averaged measured indoor RAC values for six Slovak municipalities, where indoor RAC measurements were carried out previously (28).

In this way, localities with predicted elevated levels of indoor RAC were identified. Subsequently, the RPAs

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predictions were experimentally verified in selected houses and preschool facilities using RamaRn integral trace detectors (30), in a total of 12 municipalities with predicted high or low radon concentration. Measurements were predominantly performed in single-family houses with voluntary participants during the winter season (when the highest values of indoor RAC are expected), with an emphasis on placing detectors in older houses that are in direct contact with the subsoil. The homeowners were provided with information about the importance of indoor RAC measurement and correct placement of detectors and were asked to fill in the questionnaires related to the construction of the building and usage habits. Measurements were performed under the normal conditions of the household use. In 12 selected municipalities, the number of measured rooms varied from 3 to 40, with a total of 225 rooms investigated. In each dwelling, two track detectors were placed predominantly in the most occupied rooms (e.g. bedroom, living room, or children's room) in direct contact with the subsoil. After the exposure period, which typically lasted about 3 months during the winter, the detectors were evaluated in collaboration with the Czech National Institute of Nuclear, Chemical and Biological Protection (30). Based on the results of measured indoor RACs and corresponding RP values in six Slovak municipalities, a relationship for the prediction of indoor RAC as a function of RP was established (28). This relationship was then used to predict indoor RAC in 12 Slovak municipalities, including three municipalities used to determine the prediction function (Fig. 4B).

In the Rudná village (*Lat: 48.65°; Long: 20.50°*) in the district of Rožňava, the year-round measurements of indoor RAC using RamaRn passive integral track detectors (30) were performed during four seasons: spring, summer, autumn, and winter in a total of 40 rooms. According to the rescaled RP map, this municipality belongs to an area with a predicted medium-high RP (27). Older family homes that are in direct contact with the subsoil (without a basement) were preferentially chosen due to their increased potential for radon entry through the ground and potentially inadequate insulation between the subsoil and the living areas.

At the property of a house built in 2008, where the average indoor RAC was observed to be close to the RL, we conducted an additional 1-day measurement of RAC in the soil air using the RM-2 radon monitor (31), as well as soil gas permeability measurement using the portable device RADON-JOK (32). Soil air sampling was conducted to evaluate soil gas permeability and RAC at depths of 20, 40, 60, 80, and 100 cm. The representative value of RAC in the soil air was determined by averaging at least 15 measured values from the RM-2 monitor.

In order to compare individual districts of the Slovak Republic (SR) in terms of population mortality due to bronchial and lung cancer, the standardized mortality (SM) values were considered. This parameter is typically used to compare the incidence rate among different populations with varying age distributions, or to analyze incidence trends over a longer period, especially when the age distribution of the population changes. This is especially relevant for comparing regions within a country (33). For this study, the SM data covering a period of 22 years (1996–2018) for all 79 districts of the SR were acquired from the National Centre for Health Information database (34).

Results and discussion

Radon potential and indoor radon in the Slovak Republic

According to the rescaled RP map of the Slovak Republic (Fig. 1) and detailed rescaled RP maps for 28 smaller areas of the SR [published in a previous study (27)], it can be concluded that the majority of the territory of the Slovak Republic belongs to the categories of low or medium soil radon risk. However, out of 2,890 Slovak municipalities in total, 99 municipalities belong to the areas with high soil radon risk. These areas were labeled as RPAs (27), and their positions are shown in Fig. 2. An example of the RP map according to the Neznal classification (25) and that with the modified RP scale are shown in Fig. 3.

Experimental verification of the established predictions of the RPAs has so far been performed in 10 municipalities with predicted high soil RP (Table 1) in a total of 145 rooms in direct contact with the subsoil (non-basement rooms). In these municipalities, the RL of the indoor RAC was exceeded in 43% of the measurements. Indoor radon measurements have also been performed in two municipalities with low predicted soil RP (19 rooms in contact with the subsoil). In these municipalities, the RL was exceeded only in 11% of cases (27). Based on the measurements in these 12 municipalities, an approximately linear relationship (R^2 = 0.43) was found between indoor RAC values predicted according to formula (1) and experimentally measured indoor RAC values (Fig. 4B).

Figure 4B shows an approximately linear relationship between the measured values of indoor RAC and their predicted values according to formula (1). From the figure, it follows that within the standard uncertainties, there is a good agreement between these parameters. The outlier value in the data represents a municipality that is located in the area with an anomalous radon concentration in the soil air (Lat.: 48.69°, Long.: 20.54°). If this outlier is excluded from the correlation analysis, the Pearson correlation coefficient improves significantly (from R^2 = 0.43 to R^2 = 0.91).

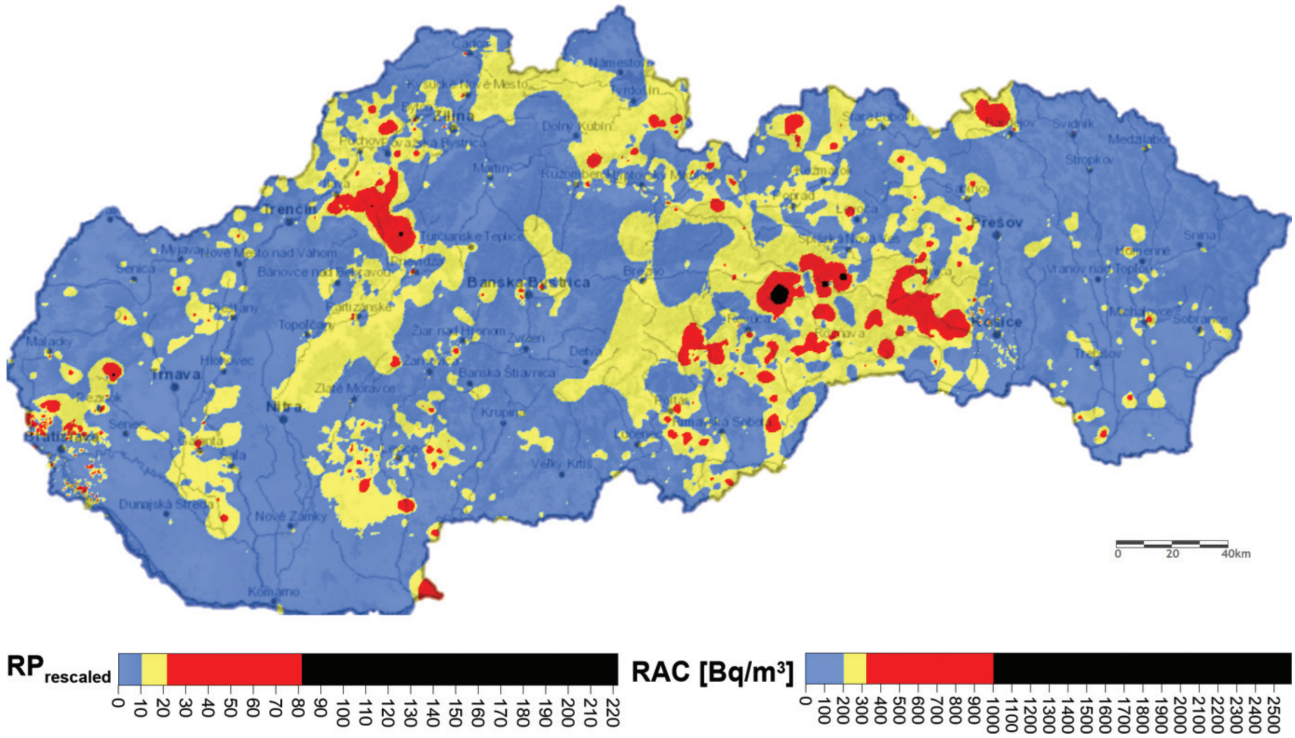

Fig. 1. Distribution of radon potential in the Slovak Republic calculated according to Neznal et al. (25). Compared to the original Neznal classification, the RP has been rescaled. Here, RAC stands for the indoor radon activity concentration predicted by formula (1).

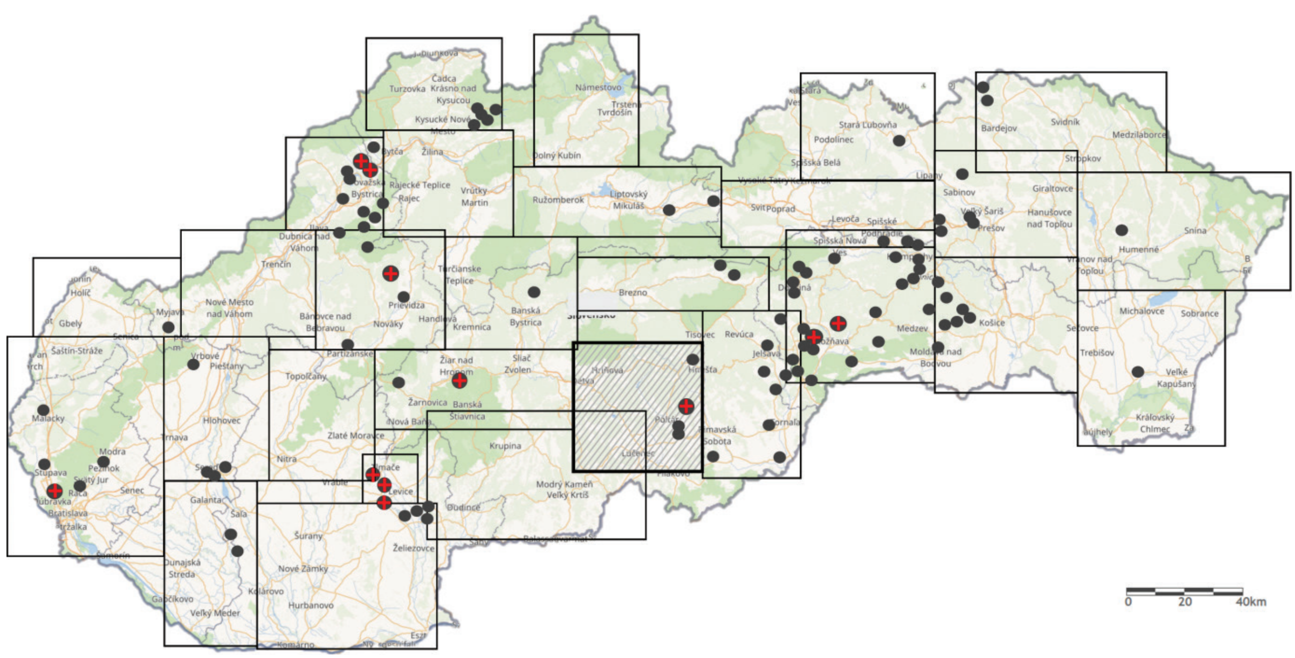

Fig. 2. In this map of the SR, the rectangles represent 28 map segments, for which the Neznal RP with a modified scale was determined (27). Black circles represent the positions of the 99 Slovak municipalities located in RPAs. In addition, the red cross symbols inside black circles represent the municipalities where indoor RAC was measured by track detectors as part of the experimental verification of RPA predictions. The results of the performed measurements are listed in Table 1. The highlighted square delineates the area shown in detail in Figure 3.

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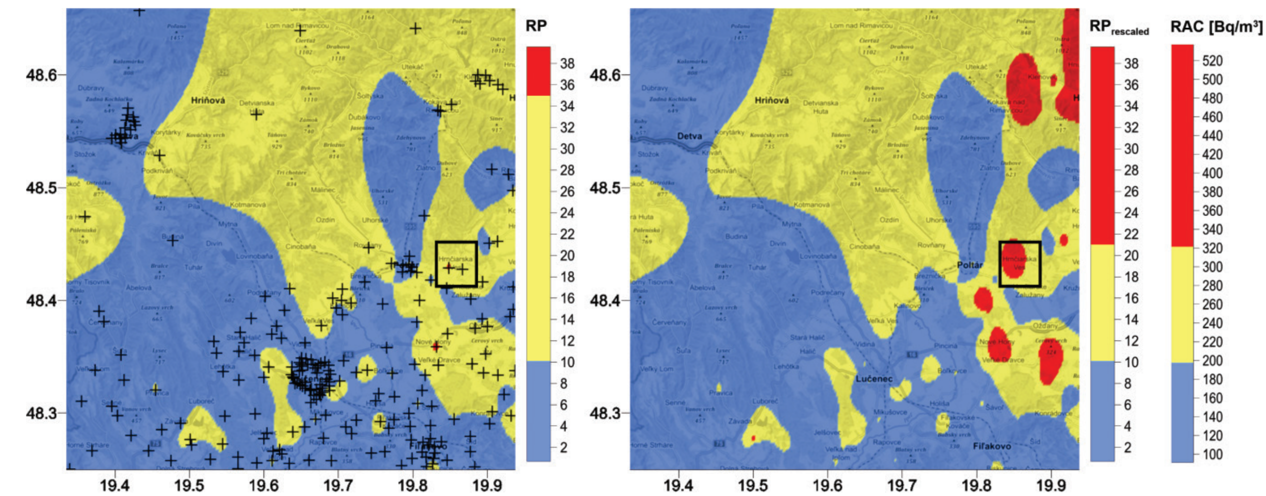

Fig. 3. Left: An illustrative example of an RP map with the original Neznal RP scale (25). The cross symbols represent the soil radon and soil gas permeability measuring points. Right: The same locality with a modified RP scale. Here, RAC stands for the indoor RAC predicted according to formula (1). The empty square highlights the municipality where indoor RAC measurements were performed. The measurement results for this municipality are shown in the last row in Table 1.

Table 1. Experimental verification of indoor RAC in 10 localities with high predicted RP levels (these municipalities are marked with the red cross in Fig. 2). Indoor radon levels were determined based on the measurements performed in rooms that are in direct contact with the subsoil. The references in parentheses refer to measurements published in previous studies

Lat. [°]	Long. [°]	Number of inhabitants	Number of rooms	Range of measured indoor RAC [Bq/m³]	Indoor RAC above RL (%)
48.69	20.54	596	8	620–2,440	100 (27)
48.19	17.03	~30,000	17	060–570	35 (27)
48.53	18.98	371	3	1,021–1,128	100 (27)
48.23	18.39	596	14	130–787	50 (35)
48.21	18.45	1,259	16	150–720	68 (28)
48.13	18.46	895	32	80–1,040	34 (28)
48.65	20.50	708	22	45–800	27
49.19	18.44	689	15	70–1,130	40
49.18	18.45	1,171	11	50–1,100	45
48.43	19.86	943	7	95–1,000	43

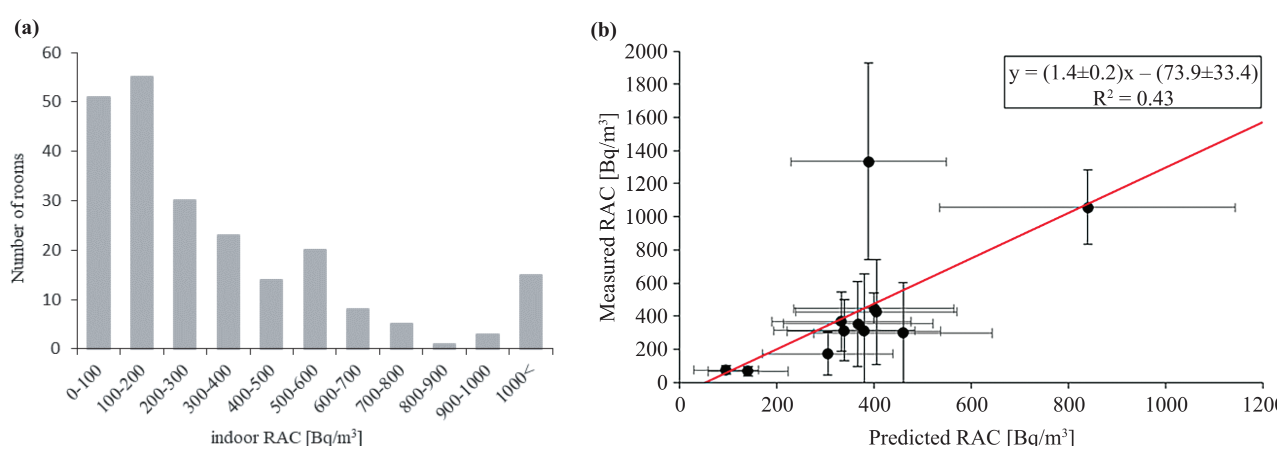

Fig. 4. (A) Frequency distribution of indoor radon concentration values measured in 225 rooms in direct contact with the subsoil in 12 localities of the Slovak Republic. (b) Relationship between the measured indoor RAC and RAC predicted according to formula (1) for these 12 localities. Horizontal and vertical lines represent the standard deviations of the data.

Table 2. The results from the year-round integral measurements of indoor RAC [Bq/m^3] in Rudná village (Lat: 48.65°; Long: 20.50°). The rows denoted as 'Contact' contain results for rooms in direct contact with the subsoil. The rows denoted as 'Basement' contain results for rooms without direct contact with the subsoil (houses with basements)

Period		Number	Min. RAC	Max. RAC	Mean RAC	Med. RAC	III. quartile
I. (Dec–Feb)	All rooms	40	45	**800**	187 ± 141	150	220
	Contact	22	45	**800**	213 ± 165	170	270
	Basement	18	55	415	156 ± 103	140	160
II. (March–May)	All rooms	34	70	570	188 ± 110	145	210
	Contact	20	70	570	208 ± 119	175	270
	Basement	14	70	380	160 ± 92	125	183
III. (June–Aug)	All rooms	26	20	300	80 ± 57	65	100
	Contact	17	20	300	82 ± 62	70	100
	Basement	9	30	140	76 ± 48	40	120
IV. (Sep–Nov)	All rooms	26	50	400	192 ± 99	170	248
	Contact	16	50	350	195 ± 94	173	263
	Basement	10	70	400	187 ± 111	155	193

The bolded values highlight the highest RAC measurements in winter, which are nearly 3 times higher than the RL.

Year-round measurement of indoor radon in Rudná village

Increased values of indoor RAC were also found during the year-round measurement in Rudná (*Lat: 48.65°; Long: 20.50°*). The results from all four measurement periods, which roughly correspond to winter, spring, summer, and autumn are summarized in Table 2. Elevated indoor RAC levels were found during this measurement campaign, with the maximum RAC of 800 Bq/m^3 obtained in the first period (winter season). Increased percentages of RAC exceeding RL were mainly found in rooms in direct contact with the subsoil. Indoor RAC measured in rooms of the dwellings in Rudná village during all seasons of the year is shown in Fig. 5. For some houses, indoor RAC results are not available for some measurement periods. This is due to lack of interest in further measurements by the homeowners. As expected, the highest averaged indoor RAC value (213 ± 165 Bq/m^3 for dwellings in direct contact with the subsoil) was observed in the winter season (Table 2), while the lowest indoor RAC levels were obtained in the summer season (RAC = 76 ± 48 Bq/m^3 for rooms with a basement). Furthermore, in each season of the year, averaged indoor RAC values for rooms in direct contact with the subsoil are higher than those measured in houses with basements.

Figure 5 also includes two newer family houses built in 2008 (FH-14) and 2020 (FH-11), in which the average RAC levels were close to the RL. Overall, the obtained results confirm that rescaled RP maps allow for a targeted search for houses with high levels of indoor radon.

The following figure shows the results of the year-long indoor RACs measurements in selected rooms of the two houses built relatively recently (in 2008 and 2020), in which the average RAC levels were close to the RL (Fig. 6).

In the vicinity of house FH-14, additional experimental measurements of soil gas permeability and RAC in soil air were performed at depths of 20 cm, 40 cm, 60 cm, 80 cm, and 100 cm. During soil air sampling, an impermeable clay layer was breached (see Fig. 7 below documenting a sudden increase in soil gas permeability at a depth of 100 cm), resulting in unusually high RACs of 118.1 ± 3.3 kBq/m^3 at a depth of 80 cm and 138.3 ± 3.3 kBq/m^3 at 100 cm. It is likely that this impermeable clay layer was also punctured when the foundations of the building had been laid, which may currently result in radon accumulation under and around the foundations of the house. Due to the pressure gradients between the indoor and the soil environment, this accumulated radon may subsequently diffuse into the interior through various leaks in the walls of the house.

According to the available geological maps, the village of Rudná is located in an area with ore and mineralogical uranium deposits (26). Given the current emphasis on stricter standards for building materials (as one of the sources of radon), this could indicate that these newer houses (Fig. 6) are located on radon-rich subsoils, as was experimentally verified for house FH-14. Radon-rich subsoil can have a significant influence on indoor RAC. Another possible source of elevated indoor radon levels in newly built houses is reduced ventilation rates as a result of improved building insulation against the outside environment.

Lung cancer mortality versus radon potential

In order to compare individual districts of the Slovak Republic in terms of population mortality due to bronchial and lung cancer, the SM data covering a period of 22 years (1996–2018) were considered. The results are visualized graphically in Fig. 8 and as a map in Fig. 9. In Fig. 9,

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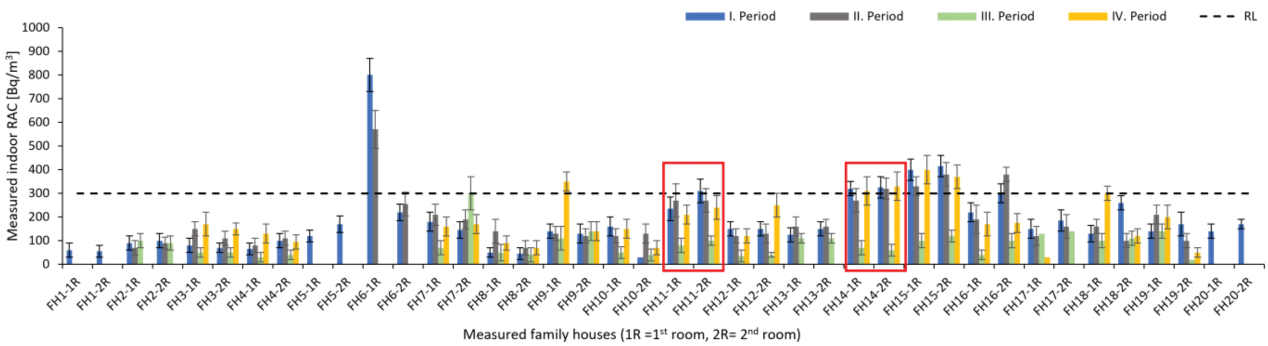

Fig. 5. Indoor radon activity concentration for all rooms in the dwellings of Rudná village measured in the four periods roughly corresponding to winter, spring, summer, and autumn. The columns highlighted in red squares correspond to two recently built houses – one in 2008 (FH-14) and the other in 2020 (FH-11).

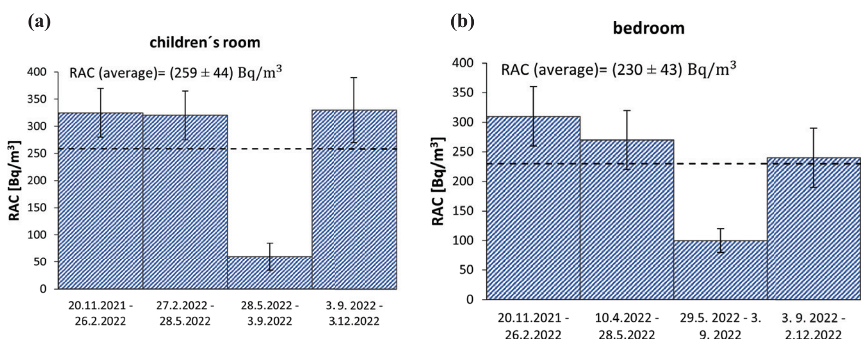

Fig. 6. Left: Indoor radon levels in a 2nd room of a house built in 2008 (FH-14 2R). Right: Indoor radon levels in a 2nd room of a house built in 2020 (FH-11 2R).

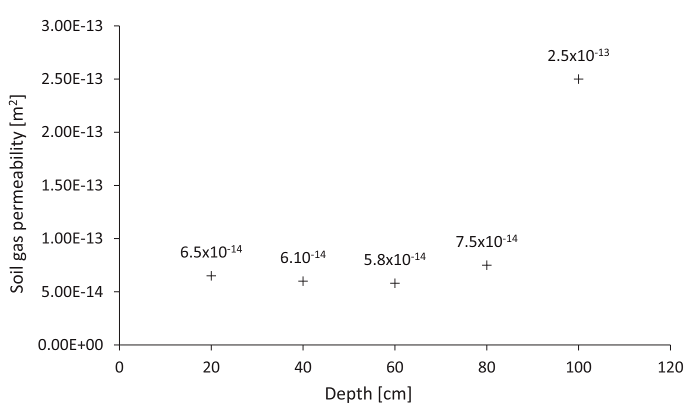

Fig. 7. Increase of soil gas permeability after breaching an impermeable clay layer during soil air sampling at a depth of 100 cm at the site of the single-family house FH-14 (built in 2008). In this house, the average indoor RAC was close to the RL of 300 Bq/m^3.

individual districts are highlighted in colors corresponding to a specific range of percentile values (green = 0–25th percentile, yellow = 25th–50th percentile, orange = 50th–75th percentile, red = 75th–95th percentile, black = 95th–100th percentile). The list of the districts with SM values exceeding or equal to the 3rd quartile value (58 ≤ SM) is shown in Table 3. In total, 20 districts of the SR belong to this category.

The relationship among the number of municipalities predicted as RPAs for individual districts of the SR ('RPA municipalities'), the RP values corresponding to these municipalities, and averaged standardized bronchial and lung cancer mortality data for individual districts of the SR was analyzed (Fig. 10). The results show low correlation between the SM values for individual districts and the number of RPA municipalities (R = 0.008), as well as between

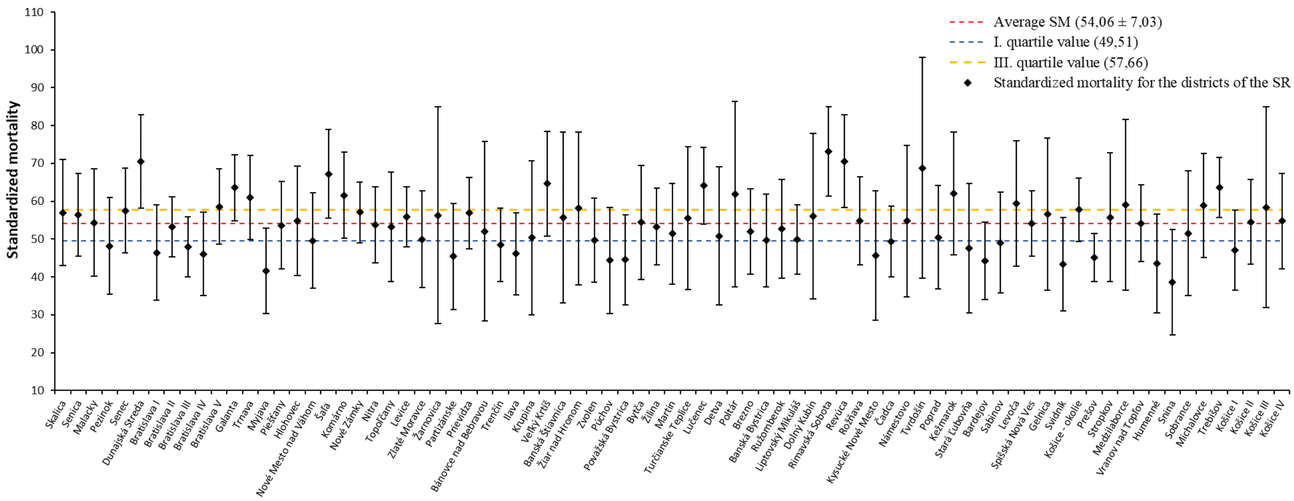

Fig. 8. Standardized bronchial and lung cancer mortality data for individual districts of the Slovak Republic. Black circles are averaged values of SM for the period of 22 years (1996–2018), and vertical lines represent standard deviation of the data.

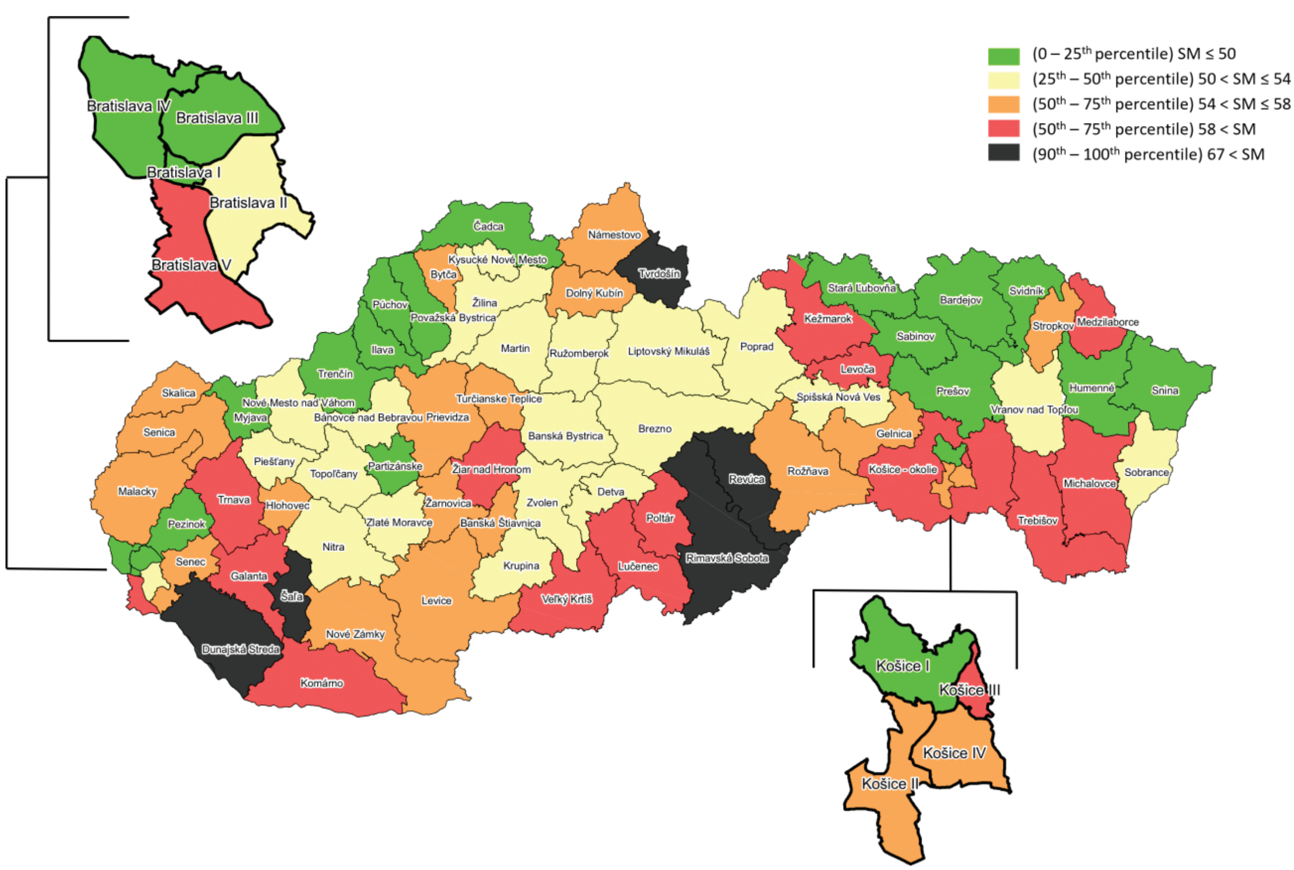

Fig. 9. Standardized mortality in the districts of the SR divided into 5 percentile ranges.

the SM values and averaged RP for all municipalities within a district ($R = 0.03$). The correlation between these variables is not significant. Furthermore, the data analyzed carry little statistical weight, as the analysis of health effects according to Brenner et al. (36) requires data at the level of 1 million individuals for a reliable demonstration of the increase in mortality rate, since mortality at low radiation doses is statistically significant only in a very large population.

To summarize, the differences in mortality rates between districts have been recorded, but due to the small

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Table 3. Districts of the SR with SM values in the 4th quartile. The districts and their SM values emphasized in bold signify that these SM values rank in the top 5% - specifically, they are within the 95th to 100th percentile range

District of the SR	SM ± σ_{SM}	District of the SR	SM ± σ_{SM}
Bratislava V	58 ± 10	Michalovce	59 ± 14
Dunajská Streda	**71 ± 12**	Poltár	62 ± 24
Galanta	64 ± 9	**Revúca**	**71 ± 12**
Kežmarok	62 ± 16	**Rimavská Sobota**	**73 ± 12**
Komárno	62 ± 11	**Šaľa**	**67 ± 12**
Košice – okolie	58 ± 8	Trebišov	64 ± 8
Košice III	58 ± 27	Trnava	61 ± 11
Levoča	59 ± 17	**Tvrdošín**	**69 ± 29**
Lučenec	64 ± 10	Veľký Krtíš	65 ± 14
Medzilaborce	59 ± 23	Žiar nad Hronom	58 ± 20

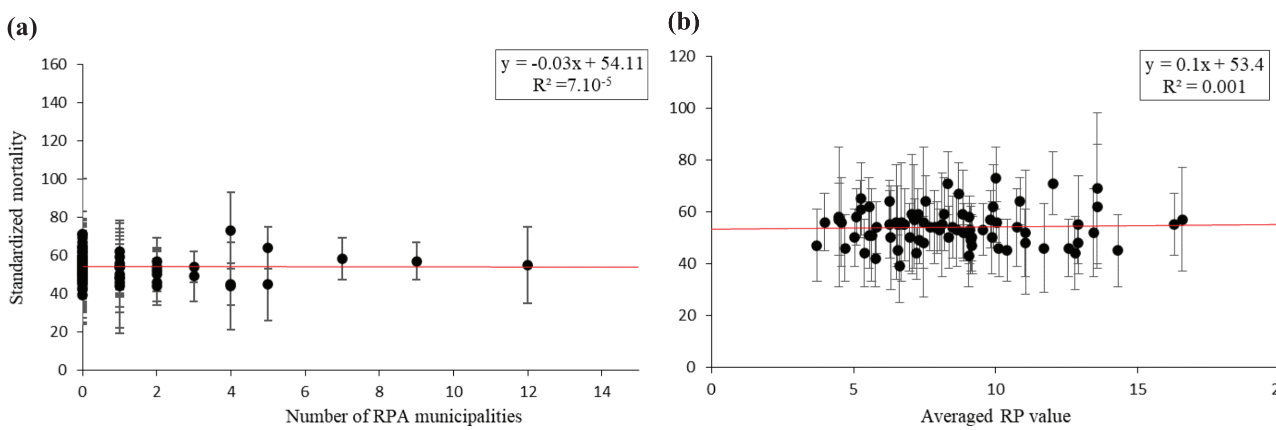

Fig.10. Left: Relationship between standardized lung cancer mortality and the number of municipalities located in RPAs within individual districts of the SR. Right: SM vs. averaged RP values corresponding to all municipalities within individual districts. Each datapoint represents the data for one district.

number of inhabitants in these districts, these results do not have the necessary statistical power to draw any firm conclusions. In addition, other factors such as smoking habits and lifestyle might play a significant role in lung cancer mortality, and it would be very difficult to separate these factors from the effect of radon exposure.

Conclusion

The presented method of identification and subsequent experimental verification of RPAs due to indoor radon exposure in the dwellings of Slovakia has proved to be reliable and effective. As a result, based on good agreement between the measured and predicted indoor RAC for 12 municipalities, priority measurements of indoor radon concentration in areas with predicted high RP should be performed. In the village of Rudná, indoor radon measurements were carried out throughout the year. The results indicate that elevated levels of radon can be found even in houses built relatively recently and according to modern standards. Analysis of the relationship between the standardized lung cancer mortality for individual districts of the Slovak Republic and RP yielded statistically insignificant results; therefore, no direct dependence between these two parameters was confirmed. Other factors such as smoking habits and lifestyle are likely to play a significant role in lung cancer mortality, and the effects of these individual factors cannot be clearly separated. Finally, the proposed method of predicting radon risk areas is important for radiation protection of the population against high effective doses of radon and can contribute to the successful implementation of the National Radon Action Plan of the Slovak Republic.

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Conflict of interest and funding

The authors declare no potential conflicts of interest.

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