ORIGINAL ARTICLE

Continuous measurements of radon and radon progeny in various public places

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Abstract

The exposure to radon in buildings open to the public and at workplaces depends on many factors, for example, forms of utilization, construction conditions, time of exposure, heating, and ventilation conditions, etc. To evaluate the radon exposure in different working environments, continuous simultaneous measurements of radon (*CRn*), equilibrium equivalent (*EEC*), and potential alpha energy (*PAEC*) concentrations for 24 hours were performed using AlphaE for CRn and DOSEman PRO from SARAD GmbH for *EEC* and *PAEC* measurements. The study considered measurements at three locations in the radon-rich spa of Narechen, Asenovgrad, and at an old mine turned museum in the town of Pernik. A comparison was made between the average values of the concentrations relating to all-day and only working hours when the measurements were completed. The CRn increases during the working hours in the museum as well as in the bath of the spa, while it decreases in the spa's treatment room. On the other hand, the EEC and PAEC are increasing at all locations. The concentrations increasing due to working hours, which are integrated into long-term measurements can cause underestimated radon exposures in radon reach working environment.

Keywords: *radon, radon progeny; continuous measurement, equilibrium factor, spa*

Radon is a significant source of indoor air pollution not only in dwellings but also in public buildings and workplaces. It is an invisible, odorless, tasteless, radioactive gas, formed as a decay product due to radium disintegration in the uranium chain. Nonstable radon emits alpha particles and produces the solid short-lived radioactive decay products known as radon progeny. Measurements of radon and its progeny concentrations, as well as safety measures, have been applied in underground mines back in the forties. Radon is classified as a Group 1, human carcinogen by the International Agency for Research on Cancer (IARC). The association between airborne concentrations of radon progenies and the risk of lung cancer was initially based on data from a study of lung cancer mortality among uranium miners and other workers exposed to very high concentrations of radon progeny. Subsequently, several epidemiological studies have demonstrated the association between radon exposure and lung cancer in households (1). Epidemiological studies have provided convincing evidence of an association between indoor radon exposure and lung cancer, even at the relatively low radon concentrations commonly found in residential buildings. Based on these circumstances, the ICRP and the World Health Organization recommended controlling and setting reference levels for exposure to radon and its progeny in dwellings (2, 3). In general, radon exposure control has focused on homes where people spend more time. Measurement of radon concentration using passive detectors is preferred for this purpose since this method allows measuring the radon concentration in a large number of buildings simultaneously for the period of the year, semi-annual, seasonal, etc. Measuring the radon concentration is suitable for estimating upper exposure limits that are adequate for assessing radon exposure in dwellings. The reliable measurements for dose assessment from radon and its progenies should take into account the possible differentiations of the concentrations due to different indoor air conditions. The various air conditions are usually found at workplaces or in places frequented by the public, where the air exchange rates can be very high or non-existent with poor ventilation. Furthermore, the results of radon measurements in public buildings and workplaces could not be evaluated as in residential buildings owing to different kinds of use, structural conditions, exposure times, heating, and ventilation conditions, etc.

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Therefore, radon exposure in buildings with public access and workplaces depends on many factors, which have to be taken into consideration in the assessment.

Measurements with passive detectors in public buildings had already started years earlier as part of the National Action Plan in Bulgaria. As a rule, the sampling period is 3 to 6 months and encompasses winter/spring or autumn/winter for the schools and kindergartens. The radon exposure assessment was based on these integrated measurements for the entire sampling period. In addition, measurements in workplaces and other specific public buildings (such as spas, museums, hospitals, etc.) have recently been carried out (4). Taking in account the specific relation of radon value to ventilation and different sources. The main objective was to evaluate radon and radon progeny concentrations in special working and public places and to identify possible differences between the 24 h concentration and only during working time. The survey was organized for checking procedures for assessment of radon exposure in special working and public places. In this article, the results of the measurements, performed at four locations, three of which are situated in a radon spa place and one in an underground museum of a former mine are presented.

Material and methods

Objects of survey

The measurements were performed in two different working environments. One of them is the premises in a rehabilitation hospital and spa hotel in Narechenski Bani, where mineral water has a high concentration of radon, and the other was an old mine turned into a museum in the town of Pernik. Since these sites are open to the public, the exposure of visitors in addition to workers to radon needs to be evaluated.

The Bulgarian village of Narechenski Bani is located in the Rhodopes Mountains in southern Bulgaria in the municipality of Asenovgrad, Plovdiv district. The resort is at an altitude of 620 m. The climate in this region is transitional between the continen of southern Bulgaria and the Mediterranean in our southern border areas. The average of the highest annual maximum temperatures reaches 33°C and the lowest annual minimum temperature – minus 17°C. The place has been known since ancient times, as one of the famous spa resorts in Bulgaria. The mineral water is radon-rich. The measured radon concentration in the spring water was 630 Bq/L, during the previous survey (4). The measurements of radon and progeny concentration were carried out in three locations of Narechenski Mineralni Bani: in the bath of a spa hotel; in the treatment room of the rehabilitation hospital as well as in the 'pavilion'. The pavilion is a room where taps are situated and people fill a bottle with radon-rich water and stay there to inhale radon for 'health purposes'. The measurements in the 'pavilion' were not made for 24 h like in the others places, because it was not safe to leave the devices on the place. Radon concentration values with passive measurements during our previous study were very high (6,080 Bq/m^3), thus only control measurements were made.

Pernik is the second most populated city in western Bulgaria after Sofia. It is the main town of the Pernik district and is located on both banks of the Struma River in the Pernik Valley between the Golo Bardo, Vitosha, Lyulin, and Viskyar mountains. The town of Pernik is also known as the town of black gold. The development of Pernik is closely related to mining. In 1891 the Mining Law was adopted and the first mine of the Pernik State Mine was established. It operated until 1966, and after about 20 years it was turned into a museum in 1986. The Mining Museum is not housed in a building but it is part of an underground gallery and is the only one of its kind on the Balkan Peninsula. The galleries of the old mine are 630 m long and house about 30 expositions that follow the development of mining in Bulgaria. In the beginning, the visitors passed through a tunnel reinforced with wooden supports as in the past. Various types of equipment for reinforcement and lightning can be seen along the entire length of the galleries. An exhibition of transportation equipment is also presented, various types of locomotives and passenger trolleys, most of which are authentic and show the progress of the mining industry after 1896. The lecture and the tour in the Museum of Mining continue for about 40–60 min. The temperature in the gallery is almost the same all year round and is slightly above zero.

Measurement of radon and radon progeny

The radon concentration was measured with AlphaE, which is based on a silicon diode diffusion chamber (Saphymo GmbH, Germany). Based on the diffusion principle with a silicon detector the radon gas diffuses through the entry holes of the housing into the interior of the diffusion chamber. The detector provides a wide measurement range of up to 10 MBq/m^3 and is sufficiently sensitive for reliable measurements below 100 Bq/m^3. The equipment has built-in sensors for measuring air temperature, humidity, and pressure. The detector has the certificate of calibration and calibration uncertainty is 10%.

The real-time (continuous) measurements of the radon progeny were carried out using a DOSEman PRO (SARAD GmbH, Dresden, Germany), which was co-located with Alpha-E. The ambient air is sucked through a membrane filter by the internal pump. The radon progenies within the sampled air are deposited on the surface of the filter. The semiconductor detector, placed directly above the filter and connected to an alpha spectroscope, allows the independent determination of the filter activities of Po-218, Po-214, and Po-212. Their

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Table 1. Results of measurements in four locations and calculated equilibrium factor during the whole measurement period and working hours

Period of measurements	Mean value of quantity ± relative standard deviation	Locations			
		Baths in Narechen spa hotel	Treatment rooms in Narechen rehabilitation hospital	'Pavilion' in Narechen	Pernik underground mining museum
24 h	*CRn*, Bq/m³	256 ± 36%	332 ± 54%		172 ± 50%
	EEC, Bq/m³	111 ± 44%	121 ± 35%		35 ± 74%
	F (min-max)	0.28 – 0.57	0.17 – 0.78		0.07 – 0.69
	F	0.44 ± 20%	0.45 ± 46%		0.20 ± 65%
	PAEC, nJ/m³	619 ± 44%	679 ± 35%		195 ± 75%
Working hours	*CRn*, Bq/m³	439 ± 40%	262 ± 20%	3,096 ± 20%	302 ± 53%
	EEC %, Bq/m³	209 ± 63%	151 ± 12%	1,284 ± 18%	101 ± 24%
	F	0.46 ± 25%	0.58 ± 18%	0.41 ± 24%	0.33 ± 47%
	PAEC, nJ/m³	1,163 ± 63%	840 ± 12%	7,148 ± 10%	561 ± 24%
02/2019–10/2019			165 ± 13	6,080 ± 1,235	

concentrations are expressed with potential alpha energy concentration (*PAEC*) and equilibrium equivalent concentration (*EEC*).

Radon progeny concentration is expressed as *PAEC*, which is defined as the sum of the alpha energy of all short-lived radon progenies in a volume of air (J/m³). The *PAEC* of any mixture of radon progeny in the air can also be expressed as the so-called *EEC*, of their parent nuclide, radon. The *EEC* corresponding to a non-equilibrium mixture of radon progeny in the air is the activity concentration of radon in radioactive equilibrium with its short-lived progeny having the same *PAEC*, as the actual non-equilibrium mixture (5).

Measurements of the *CRn* and *EEC* were used to estimate the equilibrium factor *F*:

$$F = \frac{EEC}{CRn}$$

This factor characterizes the disequilibrium between the mixture of the short-lived progeny and their parent nuclide in the air in terms of potential alpha energy. Typical values of *F* are approximately 0.4 in buildings and 0.2 for ventilated environments such as in underground mining (5, 6).

Results and discussion

The results from the four locations are presented in Table 1, they relate separately to the measurements for the whole day and the working hours. Since these short measurements only integrated the daily radon variation, the results of the concentrations are not comparable with the annual reference levels. The long-term measurements were carried out with passive detectors in rehabilitation hospitals (4) and such measurements are currently being carried out in the museum. The radon long-term results averaged the variations on a seasonal or annual level, but cannot be used for a more precise assessment of the radon concentration during working hours.

From Table 1 it can be seen, that during working hours, the *CRn* increases, to about double the value in the bath of the spa and to about three times the value in the museum, due to the non-operation of ventilation. On the other hand, *CRn* decreased in the spa's treatment room, consistent with the conclusion drawn during the radon measurements at a manganese mine in Hungary – *CRn* decreased twice during working hours (7). The best way to reduce *CRn* is through ventilation systems. Another way of reducing the *CRn* but not so efficient is opening the doors and windows frequently, as in schools. The *CRn* decrease during school hours, while increasing at weekends (8).

The measured *CRn* and EEC together with calculated *F*, for the hospital and spa hotel, and the museum are shown in Figs. 1–3. As can be seen from Fig. 1, in treatment rooms where mineral water is used, the *CRn* and *EEC* vary widely. In addition, the equilibrium factor (*F*) varies from 0.20 to 0.80, which can be explained by an increase of *CRn* when the baths are filled with water at the beginning of the day and the window is closed, that is, ventilation is reduced when people use the baths. Throughout the time survey in the rooms of the rehabilitation hospital, revealed that the premises have a ventilation system, but it was not used. This trend can also be seen in Fig. 3 for the spa hotel in Narechen. Although the measurement period is not complete it is visible that *CRn* is lower during the night. The reason is that people leave the windows open. Unlike the hospital, in the underground museum, there is no such variation of *CRn* and EEC, because of the ventilation system.

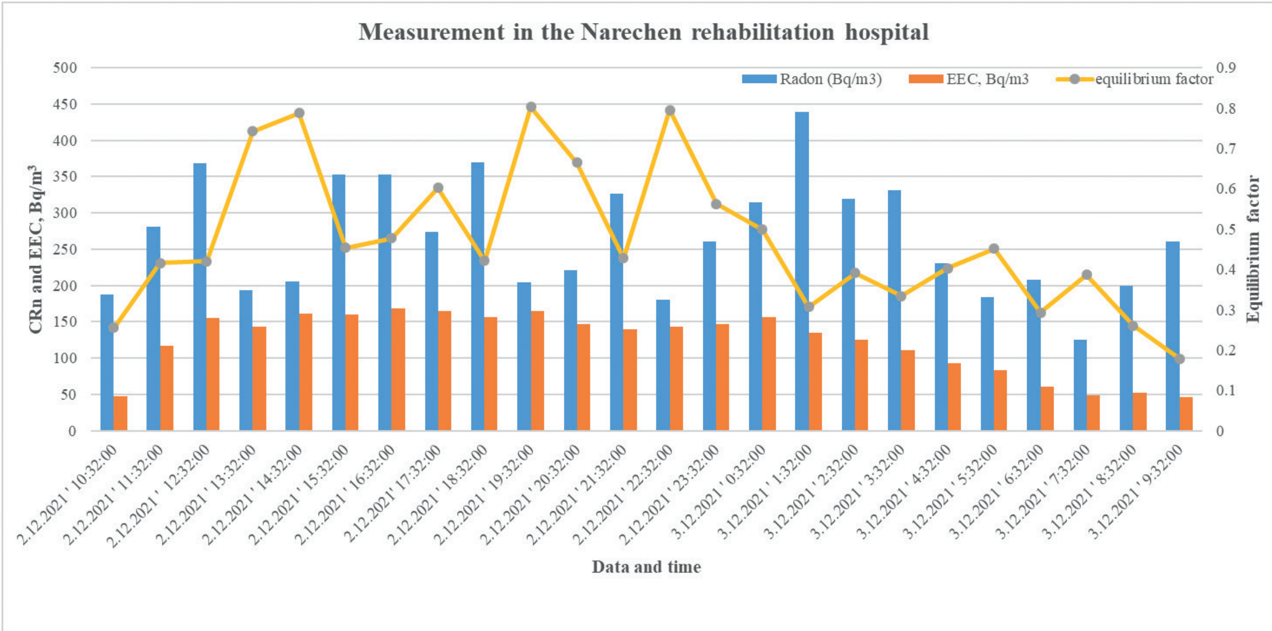

Fig. 1. Radon and equilibrium equivalent concentration and calculated equilibrium factor at treatment rooms in Narechen rehabilitation hospitals.

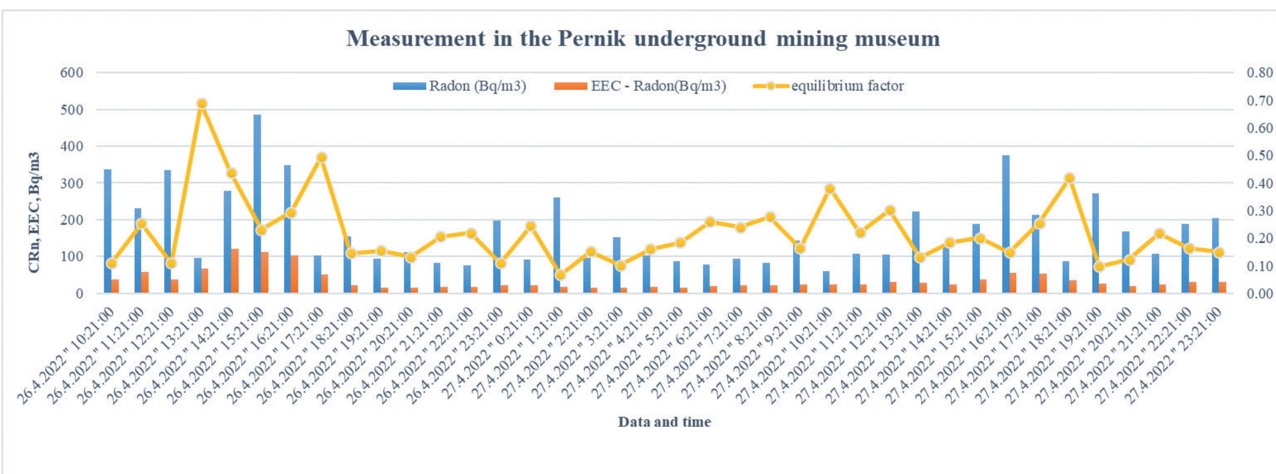

Fig. 2. Radon and equilibrium equivalent concentration and calculated equilibrium factor at the underground mining museum in Pernik town.

The *CRn* values increase during working hours only. The underground galleries are permanently ventilated (Fig. 2), but due to high noise, the ventilation system is switched off during working hours or when entering for a tourist tour. From Figs. 1 and 2 it can be seen that during working hours the *CRn* increases and the equilibrium factor changes.

Continuous measurements covering working hours show that a coefficient derived from the ratio of *CRn* during working hours to *CRn* during 24 h can be introduced. The resulting radon concentration with passive measurements should be multiplied by this factor or the following equation should be applied:

$$\mathrm{CRn} = \mathrm{CRn}_1 \times \frac{\mathrm{CRn}_{2w}}{\mathrm{CRn}_2}$$

where CRn_1 is long-term measurement
CRn_{2w} is short-term measurement during working hours
CRn_2 is short-term measurement during the whole period

Thus, the assessment of exposure will take into account the ventilation of the premises during working hours or

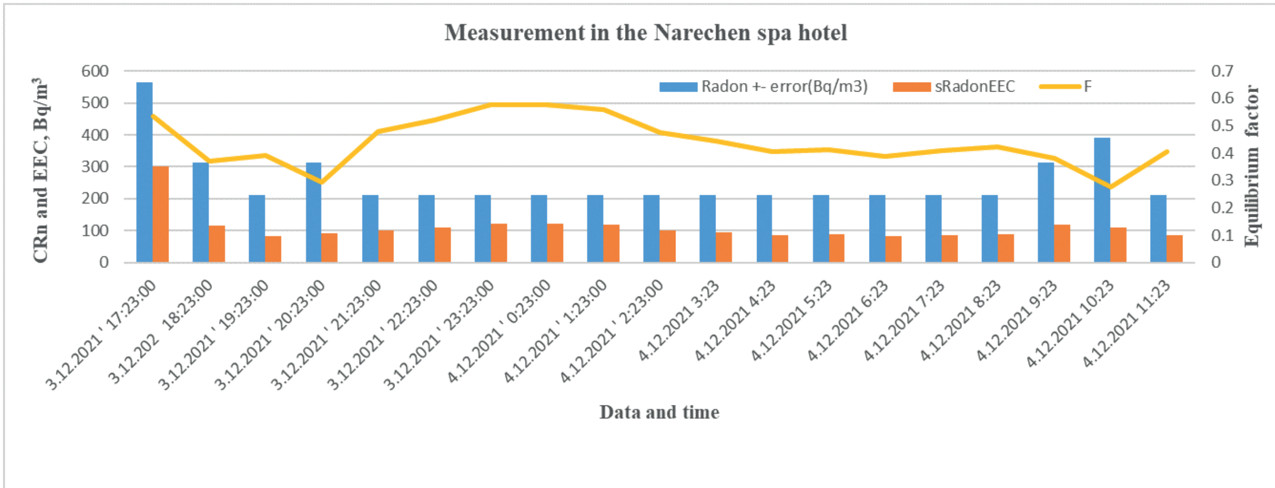

Fig. 3. Radon and equilibrium equivalent concentration and calculated equilibrium factor in the bath of a Narechen spa hotel.

the presence of people in them. Based on the survey, the modification of our measurement procedure for working places and buildings with public access for buildings with high occupancy factor/buildings with public access, such as schools and kindergartens, etc., and working places will do. The continuous measurement will be performed when the indoor radon concentration measured with passive detectors is around the reference level (300 Bq/m^3) and for all identified special places.

The highest values are measured in the spa pavilion, which was confirmed previously as the highest concentration measured (6,080 Bq/m^3) with passive detectors. After the survey, the mayor of Narechenski Bani was informed about taking action to inform the population, as well as to remove the structure that closes the fountains.

Conclusion

The survey highlights potential problems that may arise when determining workplace exposure to radon. The results indicate that the measurement protocols in some workplaces and public places are deficient. From the results the following could be concluded:

- The workplaces in the spa and underground museum could be identified as public places where the radon and its progeny concentrations increase during working hours.
- These sites should be identified and further investigated as there is a high degree of uncertainty associated with the calculations and possible discrepancies in the CRn measurements.
- The radon and its progeny concentrations vary depending on the type of workplace, so the measurement with passive detectors should be carried out in several places.
- The detailed investigation of the ventilation during working hours should be considered. Continuous direct measurements of radon should be carried out when the value is around and above the reference level.
- The ratio of the radon concentration during working hours and the whole period of short-term measurement could give a factor to multiply the result of the long-term measurements with passive detectors to obtain the average value during the hours which the premises are occupied (during the working hours). In this way, the assessment of radon exposure during working hours will be more realistic.

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