Heliyon 10 (2024) e37144

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Evaluating radon concentration and temporal correction factors in residential and workplace buildings: A comparison of passive and active methods

Tiberius Dicu [a,*], Marius Botoş [b], Alexandra Cucoş [a], Şerban Grecu [a], Ştefan Florică [a,c], Arthur Tunyagi [d]

[a] "Constantin Cosma" Radon Laboratory (LiRaCC), Faculty of Environmental Science and Engineering, "Babeş-Bolyai" University, Fântânele Street, No. 30, Cluj-Napoca, Romania
[b] Faculty of Civil Engineering, Technical University of Cluj-Napoca, C. Daicoviciu Street, No. 15, Cluj-Napoca, Romania
[c] SC RadonControl SA, Fântânele Street, No. 30, Cluj-Napoca, Romania
[d] Faculty of Physics, "Babeş-Bolyai" University, M. Kogălniceanu Street, No. 4, Cluj-Napoca, Romania

A R T I C L E I N F O

Keywords:
actual radon exposure
Residential
Temporal correction factors
Workplaces

A B S T R A C T

Effective mitigation of the health impacts of radon exposure begins with accurate measurement of this environmental contaminant. Typically, radon surveys require measurements over a period of several months. This process involves the application of temporal correction factors (TCF). Disparities in indoor radon concentration (IRC) are evident across building types. While the integrated technique has traditionally been considered the most reliable for measuring IRC, the active method is becoming more prevalent due to the availability of commercial radon measurement instruments. The aim of this study is to compare IRC using passive (CR-39) and active (ICA device) methods across 69 indoor spaces, including 35 workplaces and 34 residential buildings. The investigation was conducted over a span of one year and included 966 CR-39 detectors that were replaced every 3 and 6 months, respectively, to assess seasonal fluctuations and facilitate the computation of TCF. Statistically significant differences in IRC were observed between residential and workplace buildings ($p < 0.001$). Among workplaces, educational and research institutions showed the highest average IRC (166 Bq/m^3), while hospitals exhibited the lowest (25 Bq/m^3). Significant differences in TCF were found between the two measurement methods ($p < 0.05$), making TCF specific to the passive method inapplicable to active method. Moreover, distinctions between workplace and residential buildings, including the presence of air conditioning units and differing occupancy patterns, lead to substantial differences in both IRC ($p < 0.001$) and TCF. The assessment of radon exposure based on room occupancy duration revealed substantial variations: workplaces showed lower actual exposure (62 Bq/m^3 vs. 75 Bq/m^3, $p < 0.001$), while residential settings, particularly at night, displayed higher exposure (278 Bq/m^3 vs. 245 Bq/m^3, $p = 0.02$) than integrated measurements suggest. Continuous monitoring systems offer critical insights into true radon exposure levels.

* Corresponding author.
E-mail address: tiberius.dicu@ubbcluj.ro (T. Dicu).

https://doi.org/10.1016/j.heliyon.2024.e37144
Received 8 May 2024; Received in revised form 26 August 2024; Accepted 28 August 2024
Available online 31 August 2024

1. Introduction

Contrary to popular belief, the risk of exposure to ionizing radiation from indoor radon concentration (IRC) is greater than from nuclear energy and even from the largest man-made source of ionizing radiation, namely radiological medicine [1]. Of the 20,000 breaths we take a day, around 16,000 are from indoor sources. As a result, IRC accounts worldwide for about 50 % of the overall amount of ionizing radiation to which human beings are exposed [2]. Estimates show that IRC contributes 60 % of the total exposure in Europe and approximately 75 % in Romania [3]. About 8–15 % of lung cancer cases are caused by residential radon, which is the leading environmental driver of this disease [4]. However, radon is a risk factor that can be controlled and reduced at reasonable cost, thereby saving many lives. In this sense, knowing IRC for each individual building represents a first step in this approach regarding the public health protection against radiation. This characteristic is particularly crucial since radon exhibits significant temporal and spatial fluctuation, making it impossible to generalize the results of a particular area or building's neighbours. Numerous variables, including geology, soil characteristics, the presence of fissures and cracks at the soil-building interface, indoor - outdoor temperature differences, wind direction and speed, building materials, type of ventilation, occupancy patterns, can affect the amount of radon indoors [5–8]. The primary source of radon is represented by bedrock, respectively the soil on which the building is located. Being a gas, resulting from the decay of Ra-226, radon can escape by gaseous diffusion and convection from the matrix in which it was formed [9,10]. The geological and soil characteristics could lead to the configuration of regions with high radon concentrations, namely radon priority area (RPA). This "label" will affect all types of buildings, including public or workplaces, as a result of the transposition of Directive 2013/59/Euratom in the national legislation, within the European Union member states. In certain countries, like Spain, it is necessary to conduct radon measurements for all buildings with workplaces situated in RPA [11]. In contrast, in Romania, radon measurements are mandatory for all public and workplace buildings, regardless of whether the region is classified as RPA or not [12].

In addition to the spatial fluctuation, IRC highlighted a high temporal dispersion, depending on the period of the day or the year in which the measurement takes place. The increase in the temperature difference between indoor and outdoor environments results in the emergence of two distinct patterns: a daily variation, characterized by high concentrations at night, and a seasonal variation, with elevated levels during the colder months [13–15]. However, extreme reverse seasonal variations of IRC have been identified in certain situations [16]. Most of radon surveys conducted worldwide indicate the integrated (passive) method as the most proper measuring method for indoor radon exposure [17]. Using the integrated method of measuring IRC by track detectors gives an accurate result, but only as an average value for the period during which the detector was exposed. Owing to temporal variations registered for radon concentrations, 12-month measurements are considered the ideal solution to measure annual IRC (AIRC). The undertaking of extensive measurements for the length of one full year is impractical for several reasons. These include the necessity to consider real estate transactions, rehabilitation and reconstruction works, and the possibility of losing the detector. In this regard, most of the radon surveys made a concession by providing semiannual or quarterly intervals for which temporal correction factors (TCF) were used to estimate AIRC [17]. To cover this issue, several countries developed a database of TCF [18–22]. Burke & Murphy, (2011) highlight the danger in using a single set of TCF for the entire country [8]. Several parameters, such as the type of soil, building [19,21,22], climate, region [8,21], or the outside temperature [23] can induce important variations of TCF from one building to another. The absence of seasonal variations of indoor radon was also identified and attributed to the presence of the mechanical ventilation [24]. This aspect suggests that the approach to apply TCF to buildings with distinctive characteristics, for instance the existence of mechanical ventilation or different occupancy pattern (e.g. workplace buildings), is limited, regardless of the period or location of the measurement. A comparative investigation conducted in Canada between federal buildings and homes revealed a notable disparity in radon concentrations, with workplaces exhibiting significantly lower levels, primarily to a higher ventilation rate and a better construction, as concluded by Whyte et al. [25]. A similar analysis which targeted Austria, Finland, Germany, and Italy indicated that indoor radon levels in homes and workplaces are significantly different [26]. In this analysis, Trevisi et al. pointed out that although dwellings can be used to outline the distribution of radon in each area, they do not represent all buildings as a result of the influence of different anthropogenic factors. The air conditioning was identified as an additional factor influencing IRC in workplace buildings [27].

On the other hand, workplace radon exposure is much more subtle and the 2013/59/Euratom Directive does not clearly specified whether or not the AIRC must be representative for the radon exposure during working hours. An overestimation of the actual exposure to radon in the case of daytime work and an underestimation for the nighttime work activities is expected following the use of integrated measurement methods for radon concentration assessment, as pointed out by Bochicchio [28]. In a study covering 33 workplaces, Venoso et al. identified a disparity of around 20 % in the average radon concentration between working hours and the entire day [29]. Based on a study conducted in a school and a day-care centre, Rydock et al. concluded that the only way to make an effective assessment of radon exposure is by measuring it during the time when the building is being used [30]. In addition, the 2013/59/Euratom Directive does not stipulate if TCF specific to workplaces or those specific to residential buildings should be applied. In fact, according to our knowledge, there is no study to target TCF in the workplaces.

As such, real time monitoring of indoor radon for long-time periods (months to years) using continuous radon monitors (active method) can give a better understanding of the risk associated with the exposure to this pollutant. The active method enables the assessment of the IRC for any given period, considering the occupancy program. They also assist in identifying the impact of user activity on the indoor radon dynamics, which facilitates the planning of practical strategies for improving the quality of indoor air. As such, for a rigorous assessment of radon exposure it is especially important to have access to continuous data and exposure timeframe in different type of buildings (residential and public/workplaces) and to combine these data to generate a time-weighted estimates of radon exposure.

Hence, the primary objective of the present study was to conduct a comprehensive year-long monitoring of IRC in both residential and public/workplace buildings, employing both the passive and active method. The secondary objective was to compute the TCF based on the measurement method and building destination. The evaluation of the IRC in accordance with the work schedule allowed the assessment of the actual radon exposure.

2. Material and method

2.1. Design of the study and indoor radon measurements

For the selection of the buildings involved in the study, two different strategies were chosen depending on the destination of the monitored building: residential or public/workplace. For the residential environment, the existing databases within LiRaCC laboratory were used, targeting dwellings with high IRC. The selection of the buildings, including work and public spaces, was based on media campaigns and the employers' declared interest following the transposition of the 2013/59/Euratom Directive into national legislation. In the context of the international significance of radon monitoring and its impact on public health, Romanian legislation has been aligned with the European regulations by introducing the reference level (RL) of 300 Bq/m^3 for all types of buildings [12]. According to this normative act, screening measurements using the passive method are mandatory in Romania, throughout the country, regardless of the region or RPA, for all buildings with a high degree of occupancy (schools, kindergartens, hospitals, dormitories, nurseries, universities, etc.), and for the buildings in which workplaces are organized, or any other buildings with public access or similar use. In accordance with the legislation, remedial measures for protection against radon must be implemented in all buildings where RL levels are exceeded.

The study's eligibility criteria encompass the requirement to allow radon monitoring in the bedroom or living in a residential setting or the room where the activity takes place in a workplace building. Additionally, participants must have Internet connectivity to send recorded data from the radon monitor (ICA device). Priority was given to buildings where the monitored room was situated on the ground or mezzanine level. Subsequently, to achieve the desired number of buildings, consideration was also given to those placed on the upper floors.

As part of the monitoring campaign, both passive, represented by solid-state nuclear track (CR-39) detectors (Radosys Ltd, Hungary), and active methods, through the ICA device, were used. To highlight the time variability of IRC, the passive detectors were organized within a kit (Lemon kit) that presented 6 detectors organized in 3 categories depending on the measurement period: yellow (3 months), lime (6 months), green (12 months), each being in duplicate for the assessment of the variability induced by the detector (Fig. 1).

The detectors in the yellow position were replaced every 3 months, those in the lime position were replaced every 6 months, while those in the green position were placed at the beginning of the campaign, being collected at the end of one year exposure. As such, the first campaign was conducted between November 2022 and February 2023, the second campaign between February and May 2023, the third campaign between May and August 2023, and the fourth campaign from August to the end of November 2023, the measurement period being 3 months. For the six months measurements, the first campaign coincided with the first two three-month campaigns, starting in December 2022, and ending in May 2023, while the second campaign ended in November 2023, the month in which the detectors from the 12-months campaign were also collected. Thus, 14 detectors were used for each monitored room, a total of 966 CR-

Fig. 1. Monitoring the IRC through passive method (CR-39 detectors, organized within the Lemon kit - left), respectively active method (ICA device - right).

39 detectors being used in the current survey.

The ICA device, a continuous radon monitor developed by the LiRaCC research team using TSRS2 radon sensor (Tesla, Czech Rep.) was installed in the same room, where the Lemon kit was placed. A detailed description of the ICA device is made by Tunyagi et al. [31].

The CR-39 detectors were mounted and collected by a member of the research team. After each measurement campaign, the detectors were collected and then processed and analysed at the LiRaCC laboratory, following the manufacturer's approach, as described by Cucoş et al. [32]. The accuracy of radon measurements conducted using passive detectors was assessed through the participation of the LiRaCC laboratory in the calibration exercise held by BfS (Germany) in 2022. The calibration factor was determined to be 0.98, with a 95 % confidence interval of ±0.06.

In the case of ICA devices, the calibration was conducted inside a radon chamber equipped within LiRaCC laboratory using Rad7 (Durridge Company Inc., USA) and AlphaGUARD PQ 2000PRO (Bertin SA, France) devices as a reference. In the situation where the relative percentage difference between measured and reference concentration was higher than ±25 %, the calibration factor within the radon sensor was adjusted. The radon source used was a pitchblende stone with an activity of 4.1 kBq.

The study concerned 34 residential buildings, of which 25 from the cities of Cluj-Napoca, 7 from Timişoara and two from Bucharest. All public/workplace buildings (n = 35) were selected from Cluj-Napoca. In the case of residential buildings, 32 are single-family houses, and two are apartment blocks, one of the apartments being located on the ground floor and the other on the 4th floor. Among the public/workplace buildings, there were 12 educational and research institutions, 14 business offices, 6 medical offices, 2 hospitals and a residence hall.

2.2. Statistical analysis

The statistical analysis of the data was performed using IBM SPSS 24 (IBM Corp., Armonk, NY, USA) and OriginPro 2024 (OriginLab Corporation, Northampton, MA, USA) software. The Wilcoxon signed-rank test was used to compare two paired samples, while Mann–Whitney test was applied for two independent samples. The decision to use non-parametric tests was influenced by the small sample size and the distribution of the data. The results are reported in these situations as medians (Mdn.). Additionally, the data are presented as arithmetic or geometric means with specific standard deviations (SD or GSD), to facilitate comparison of the results with those from the literature. To assess the degree of agreement provided by two distinct approaches, Lin's concordance correlation coefficient (CCC) was applied. The relative percentage difference (RPD) was used to assess the difference between the two results. The RPD was set at ±25 % based on the guidelines provided by the American Association of Radon Scientists and Technologists [33]. This threshold aligns with the expected range of precision for the individual percent difference for radon measurements. The significance level α was chosen at 0.05.

To assess the TCF, two strategies were chosen. For the comparison based on the measurement method, the TCF computation was chosen by performing the ratio between the AIRC and the specific value of each measurement campaign. Therefore, TCF are limited to three- or six-months measurement campaigns. On the other hand, for the generation of TCF, reported according to the start month and the duration of the measurement (from one month to 11 months), the data measured with the ICA device were strictly used. In this sense, the initial hourly average radon time series was transformed using a geometric moving average over a 1-month period into a second time series of the same length by appending the first available data points at the end of the time series. To each value of this additional time series, an index ranging from 1 to 12 was assigned. The index 'j' was assigned if the middle day of the period fell between the midpoint of the (j-1)th and jth months. Based on these indexes, a vector of twelve geometric mean radon concentrations, denoted as m_j, for each month j, was calculated. Since IRC show seasonal periodicity, it can be assumed that seasonal patterns could be represented by Fourier series as linear combinations of sine and cosine functions [23,34]:

$$\widetilde{m}_j = \widetilde{\beta}_0 + \widetilde{\alpha}_1 \sin\left(\frac{\pi j}{6}\right) + \widetilde{\beta}_1 \cos\left(\frac{\pi j}{6}\right) \quad (1)$$

The coefficients were computed using the least squares method and utilized to determine the adjusted $\widetilde{m}_j$ values necessary for deriving the seasonal correction factors using the model proposed by Pinel et al. [34].

For each location, a matrix twelve by eleven of seasonal correction factors was derived using the adjusted $\widetilde{m}_j$ values. The seasonal

Table 1
Descriptive statistics regarding AIRC depending on the type of monitored building.

Building type	Building destination	No.	AIRC (Bq/m^3)				
			Min.[a]	AM (SD)	GM (GSD)	Mdn.	Max.
Residential	Dwellings	33	21	267 (168)	209 (2.2)	110	655
	Flat	2	64	83 (26)	80 (1.4)	83	101
Public/Workplace	Business office	14	19	114 (83)	84 (2.3)	105	297
	Educational & research institutions	12	38	166 (204)	106 (2.5)	92	761
	Medical office	6	21	68 (42)	56 (2.1)	66	123
	Hospital	2	19	25 (8)	24 (1.4)	25	30

[a] Min. – Minimum, AM – Arithmetic Mean, SD – Standard Deviation, GM – Geometric Mean, GSD – Geometric Standard Deviation, Mdn. – Median, Max. – Maximum.

correction factor matrix can be calculated as follows:

$$\tilde{f}_{j,t} = \frac{t}{12} \frac{\sum_{k=1}^{12} \tilde{m}_k}{\sum_{k=j}^{j-t-1} \tilde{m}_k} \tag{2}$$

The means of seasonal correction factors, along with their corresponding standard errors, lower and upper confidence intervals, were then calculated by aggregating all seasonal factor matrices.

3. Results and discussion

3.1. Descriptive statistics using passive method

Residential buildings showed an AIRC arithmetic mean of 252 Bq/m^3, with a range from 21 to 655 Bq/m^3 (Table 1). The average value (121 Bq/m^3) computed for the public/workplace buildings is identical to the one reported by Cosma et al. for residential buildings in Cluj County, where the buildings in question are located [35]. When examining the institution's profile, it is seen that educational and research institutions have the highest average (166 Bq/m^3), the maximum AIRC (761 Bq/m^3) belonging to a classroom among all public/workplace buildings. In a survey conducted by Martin-Gisbert et al. among 3140 workplaces, the Education & Culture sector, which includes schools, universities, kindergartens, etc., was shown to be most affected to radon exposure [11]. The arithmetic and geometric means computed for educational and research institutions in the present study are close to those reported in neighbouring countries, such as Bulgaria (AM = 132 Bq/m^3, GM = 101 Bq/m^3) [36], Serbia (AM = 119 Bq/m^3, GM = 100 Bq/m^3) [37] or Bosnia and Herzegovina (AM = 128 Bq/m^3, GM = 99 Bq/m^3) [38]. Similar values were reported by Burghele & Cosma for the Romanian schools monitored in two neighbouring counties, namely Sălaj (AM = 180 Bq/m^3) and Satu Mare (AM = 169 Bq/m^3) [39].

The lowest average levels of the AIRC are found in hospitals (25 Bq/m^3) and medical offices (68 Bq/m^3) due to stringent indoor air regulations. Comparable results have been reported in studies that targeted hospitals in Poland [40], Japan [41] or Taiwan. In the case of the latter, high values were recorded especially when air conditioning systems were turned off during off-hours [42]. The AIRC measured in the residence hall was 200 Bq/m^3, while the business office showed an arithmetic mean of 144 Bq/m^3, with the maximum value falling below the reference threshold.

The AIRC values for 12 residential buildings exceed the RL of 300 Bq/m^3, while for the public/workplace buildings only in two cases. As anticipated, by applying the non-parametric Mann-Whitney test, a statistically significant difference was obtained between the medians of radon concentrations when considering the building type ($p < 0.001$). The difference can be attributed to both to the criteria applied when selecting residential buildings (drawing from existing databases of dwellings with increased radon levels) and the characteristics of workplace buildings, particularly the use of mechanical ventilation units during working hours.

As stated earlier, the CR-39 detectors were placed in pairs to assess the variability of the detectors. The differences recorded for radon concentrations at the pair level were not statistically significant ($p = 0.58$), regardless of the measurement campaign duration (from 3 months to one year). A linear relationship between the radon values was obtained from pairs of CR-39 detectors, with a coefficient of determination of 0.995. The calculated value for CCC is 0.99, suggesting an excellent level of concordance between the outcomes generated by the detector pairs.

By evaluating the coefficient of variation (CV) at the pair level, an average value of 6 % was obtained with limits between 0 and 72 %. It should be noted that this coefficient of variation has an average value of 3 % (limits: 0–13 %) for measurements above the reference level of 300 Bq/m^3, 5 % (limits: 0–31 %) for those in the range of 100–300 Bq/m^3, respectively 10 % (limits: 0–72 %) for those below the value of 100 Bq/m^3. When comparing the CV values of the measurement pairs with those specified in the US EPA protocol for radon measurements [43], it was found that 1.2 % of the detectors exceeded the warning level, while 0.4 % exceeded the control limit if the IRC was lower than 148 Bq/m^3. For concentrations above this threshold, only one detector exceeded the control limit. Comparable results were reported by Carpentieri et al. in a study that involved the exposure of paired CR-39 detectors for 6-months period [44]. These results indicate the accuracy of the results provided by this type of detectors even for radon concentrations slightly higher than the background value.

The centralized results according to the measurement campaign and type of building are shown in Table 2.

Table 2
Descriptive analysis of the radon concentration measured with CR-39 detectors, depending on the measurement campaign and the type of building.

Campaign duration	Campaign No.	IRC (Bq/m^3)[a]	
		Residential	Public/Workplace
3 months	I	365 ± 262	153 ± 188
	II	298 ± 220	117 ± 150
	III	74 ± 57	88 ± 137
	IV	303 ± 236	127 ± 153
6 months	I	318 ± 205	128 ± 157
	II	193 ± 142	112 ± 145
12 months	–	252 ± 168	121 ± 135

[a] Data are presented as AM ± SD.

Consistent with expectations, throughout the 3-month campaign, the average of IRC is highest during the cold season (campaign I) and lowest in the warm season (campaign III). Even in the case of the six-month campaigns, a notable disparity can be noted in the average values computed for residential buildings, specifically 318 and 193 Bq/m^3, respectively. Thus, by applying the non-parametric Wilcoxon test, a statistically significant difference was obtained between the ranks in radon concentration for the two 6-months campaigns, at the level of residential buildings ($p < 0.001$). The correlation coefficient between the two campaigns was determined to be 0.89 ($p < 0.001$). The significant difference in IRC can be attributed to the discrepancy in outdoor temperatures during the two campaigns, with an average temperature of 4.6 °C for the first campaign and 18.2 °C for the second. In fact, a similar pattern was observed in the three-month campaign, where an increase in the average temperature led to a decrease in the average IRC. As such, the arithmetic mean rose from 3.6 °C to 5.5 °C, and then to 18.8 °C during the first three campaigns, each lasting three months. This was followed by a slight decrease to 17.6 °C in the final campaign. These values are specific to the city of Cluj-Napoca. In Timișoara, the average temperatures were approximately 2 °C higher for each campaign.

In the case of public/workplace buildings, the difference between the average values is less obvious (128 vs. 112 Bq/m^3), being at the threshold of statistical significance ($p = 0.052$), in this case the degree of correlation being 0.95 ($p < 0.001$). A statistically significant difference was obtained between the IRC medians depending on the type of building, regardless of the measurement campaign ($p < 0.001$). The difference between the two types of buildings was significant ($p < 0.001$), even when considering only the buildings from Cluj-Napoca. This approach was taken to eliminate the regional impact of geological and climatic factors.

3.2. Active vs. passive method

The degree of concordance between the two methods, passive (CR-39 detectors) and active (ICA device) is indicated in Table 3, as well as the average IRC values for the measurement campaigns according to the measurement method.

The median of RPD between active and passive devices is 10 %, being lower (7 %) for IRC higher than 300 Bq/m^3. Statistically significant differences were obtained between IRC according to the measurement methods ($p < 0.05$). Venoso et al. reported better results in a study that sought to monitor radon levels using both passive (CR-39) and active (TSR 4M, Tesla, Czech Rep.) methods [29]. A potential reason for the improved outcomes could be attributed to the 6-months duration over which the study was conducted. According to Table 3, the CCC coefficient indicates poor concordance for the 3-month campaigns, except for the May–August campaign (III), respectively a moderate concordance for the 6-month campaigns, the annual campaign having a substantial concordance (0.95). Higher values for CCC are specific for the 6-month campaigns compared to the 3-month campaigns, notably 0.92 and 0.93. An in-depth examination of the data collected by the TSRS2 radon sensor revealed a negative correlation between humidity variability during a specific measurement campaign and the agreement between passive and active measures, as quantified by the CCC, as a potential explanation for the differences obtained between the two methods. For the annual campaign, the CCC value (0.95) is higher than the value (0.92) reported by Dicu et al. as a result of an investigation conducted in 71 residential buildings in Romania using the same type of passive and active detectors [45].

3.3. TCF

Table 4 displays the TCF values based on the building type, respectively the measurement method. In this instance, the TCF are computed as the ratio between AIRC and radon concentration specific to a certain measurement campaign. As such, the values presented in Table 4 represent the geometric means of the TCF computed for each individual building, together with the 95 % confidence interval. The use of the geometric mean was preferred to minimize the impact of excessive values. The computed TCF are significantly lower for the active method in the first and the third campaigns for residential buildings ($p = 0.01$), respectively third campaign for public/workplace buildings, as a result of the measurements conducted for a period of three months ($p = 0.01$). Significantly lower values were obtained using the active method even during the first 6-month campaign, for both residential and public/workplace buildings ($p < 0.05$). For workplace buildings, the TCF are significantly higher for the first and second three-month campaigns, and for the first 6-months campaign, compared to residential buildings, regardless of the measurement method ($p < 0.05$). However, for the third three-month campaign, as well as for the 6-month second campaign the TCF for public/workplace buildings are significantly lower compared to residential buildings ($p < 0.05$). These results indicate both the existence of significant differences in TCF

Table 3
Descriptive analysis of the radon concentration measured by the two methods, alongside the coefficient of concordance (CCC).

Campaign duration	Campaign No.	IRC (Bq/m^3)[a]		CCC
		Passive method	Active method	
3 months	I	253 ± 252	303 ± 315	0.83
	II	204 ± 212	194 ± 172	0.78
	III	86 ± 123	93 ± 118	0.96
	IV	181 ± 176	172 ± 153	0.87
6 months	I	218 ± 208	220 ± 200	0.93
	II	149 ± 155	127 ± 133	0.92
12 months	–	180 ± 170	161 ± 155	0.95

[a] Data are presented as AM ± SD.

Table 4
Temporal correction factors (TCF) depending on the measurement method, respectively the destination of the building.

Campaign duration	Campaign	Residential buildings		Public/workplace building	
		Passive method	Active method	Passive method	Active method
3 months	I	0.73* (0.67–0.79)	0.65[a] (0.58–0.73)	0.86[b] (0.79–0.94)	0.84[b] (0.75–0.94)
	II	0.91 (0.79–1.06)	0.89 (0.81–0.97)	1.17[b] (1.09–1.25)	0.97[a] (0.92–1.03)
	III	2.65 (1.79–3.93)	2.11[a] (1.58–2.82)	1.45[b] (1.25–1.69)	1.27[a,b] (1.12–1.44)
	IV	0.90 (0.76–1.07)	0.91 (0.82–1.00)	0.94 (0.86–1.02)	0.99 (0.91–1.06)
6 months	I	0.83 (0.76–0.91)	0.74[a] (0.68–0.81)	1.08[b] (1.00–1.17)	0.92[a,b] (0.86–0.99)
	II	1.33 (1.18–1.49)	1.39 (1.25–1.54)	1.07[b] (0.97–1.19)	1.12[b] (1.03–1.23)

*The values are shown as geometric mean, respectively 95 % confidence interval.
[a] statistically significant difference depending on the measurement method for the same type of building ($p < 0.05$).
[b] statistically significant difference depending on the destination of the building ($p < 0.05$).

depending on the measurement method and the building type, as well as the lack of consistency in the trend of these differences at the annual level.

A moderate level of agreement was seen between the true (ITC calculated for the 12-month exposure) and estimated AIRC, using TCF during the 6-month monitoring campaigns. This was determined by the CCC, regardless of whether the data were evaluated based on the type of building (0.92 for residential and 0.94 for workplaces) or as a whole (0.94). For three-month measurement campaigns, the level of agreement for residential buildings is poor, with the lowest values seen during the summer campaign (0.56), followed by autumn (0.68), winter (0.78), and spring (0.92). However, when it comes to workplace buildings, the level of agreement is moderate for the summer (0.84), spring (0.92), and winter (0.94) campaigns, but it is substantial for the autumn campaign (0.95). Consequently, the spring campaign yields optimal outcomes for residential buildings, whereas autumn and winter are more suitable for workplaces. In a study conducted by Müllerová et al. (2022) involving 56 rooms in Slovakia, the best agreement was found for the autumn and winter seasons in the residential buildings.

Fig. 2 illustrates TCF in relation to the month when radon measurement begins, as well as the duration of the measurement, based on the type of building being monitored with active device. The variations of TCF are displayed for both residential buildings (top) and workplace buildings (bottom). The upper graph depicts measurements conducted over a period of either 3- or 6-months, which is the most frequently used duration for passive measurements.

The graph on the right illustrates the starting month for the measurements, which are February, May, August, and November, mirroring the four campaigns conducted in the present study. As expected, the maximum TCF values are specific to the months of May and June for the 3-month measurement period, regardless of the building type. However, during the 6-month measurements, the peak values are specific to the months of March and April for residential buildings, and April and May for workplace buildings. This shift in peak values for residential buildings indicates that the summer months have a more significant effect on the TCF compared to workplace buildings. This can also be observed by examining the TCF values listed in Table S1 (residential buildings) and S2 (workplace buildings), which vary according to the initial month and duration of measurement, as well as the specific type of building.

The computation of the RPD between TCF for the two types of buildings, based on a 3-month measuring period, results in values within the ±25 % range for January through March and August through October. For a span of 6 months, only the months of March to May yield RPD levels that exceed the 25 % threshold. In the scenario where the radon measurement begins in February, only for the measurement period of one month, the RPD indicates a value exceeding the 25 % threshold between the TCF associated with the two types of buildings (Fig. 3). This scenario also applies when measurements start at the end of the warm season (August). Conversely, if measurements begin in months marking the start of the warm season (May or June), there is significant fluctuation in TCF during short-term measurements (up to 6 months). It is only after the 7-month period that the TCF values tailor for residential buildings align with those of workplace buildings, as indicated by a RPD in the predetermined interval ±25 %. If the initial month is November, the DRP for TCF will fall between the ±25 % range only after at least 6 months measurement duration. These findings suggest that using TCF, which are tailored for residential buildings, to estimate AIRC in workplace buildings can lead to inaccurate estimations. This holds true even if the measurements are conducted for a duration of 6 months or if the initial month is at the beginning of the hot or cold season.

3.4. AIRC: overall vs. actual exposure

For workplace buildings, 80 % of the participants reported that their work hours are between 8 a.m. and 6 p.m. Additionally, 12 % stated that the occupancy time is non-stop in the monitored space (working from home), while 8 % indicated that their work hours are either in the afternoon or only a few hours per week in the investigated room. Therefore, using the data obtained with the active method, it was possible to calculate the actual level of exposure to IRC, while considering the specified duration of occupancy. The RPD between the annual exposure to radon, calculated as an average for the period of actual occupation and the entire period, range from −53 % to 14 %, with an average value of −11 %. Thus, the radon concentration during the period of actual occupation (Mdn. = 71 Bq/m^3) is significantly lower than the calculated concentration for the whole interval (Mdn. = 78 Bq/m^3), with a p-value of 0.003. If the analysis is carried out strictly for those situations in which the occupation interval is between 8 a.m. and 6 p.m. then the RPD between the medians reaches −17 % (62 Bq/m^3 vs. 75 Bq/m^3), $p < 0.001$ (Fig. 4). The ratio between the radon level during working hours and the overall exposure was determined, resulting in an average value of 0.86, with limits ranging from 0.47 to 1.00. These findings align

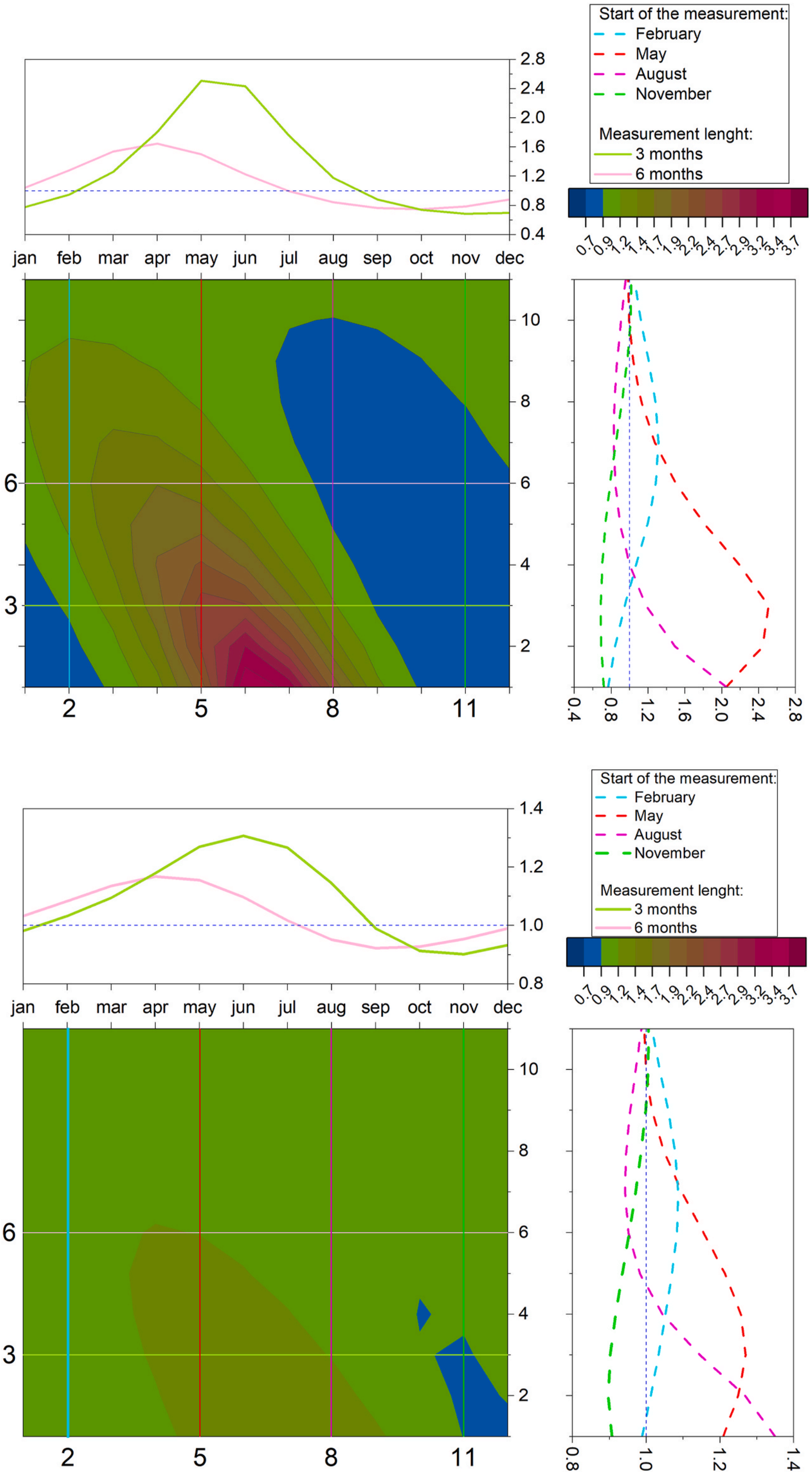

Fig. 2. TCF depending on the starting month and duration of the measurement according to the type of building: residential (top), public/workplace (bottom).

with the results (0.8, with limits between 0.5 and 1.0) reported by Venoso et al. from a comparable study conducted in 33 workplaces, specifically focusing on buildings with radon levels exceeding 150 Bq/m^3 [29].

In 50 % of residential buildings, the declared period of occupancy includes exposure during the night (from 8 p.m. to 7 a.m.).

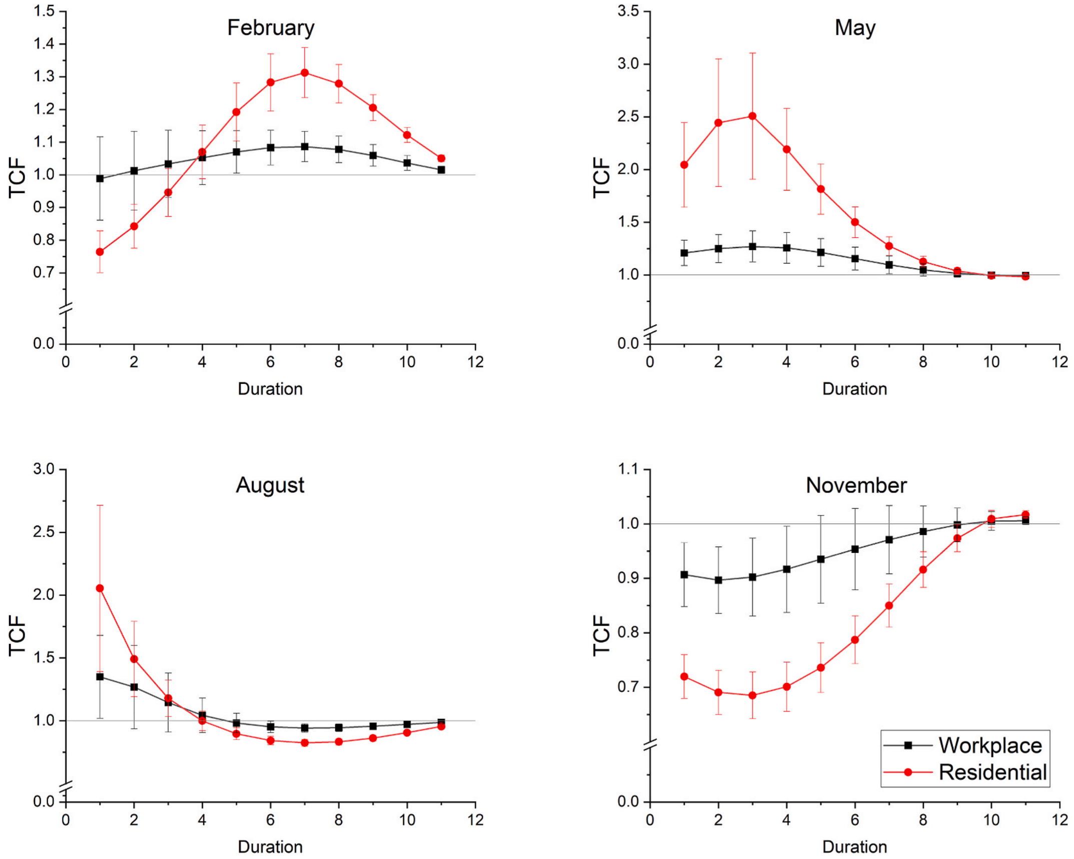

Fig. 3. Comparison of TCF variation depending on the starting month and the duration of the measurement for residential and workplace buildings (the values are reported as GM ± 95 % CI).

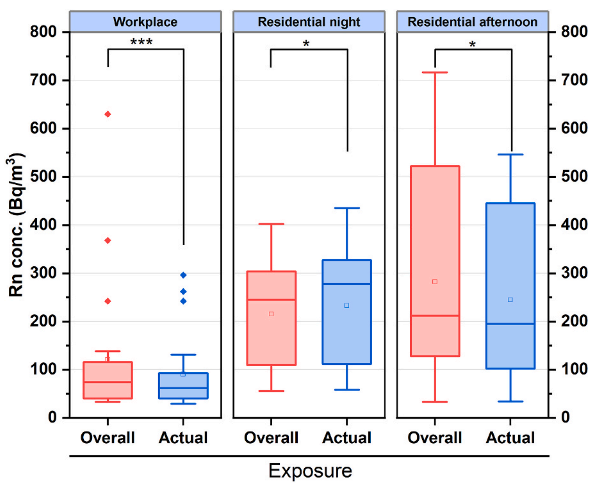

Fig. 4. Actual vs. overall radon exposure depending on the occupancy period (*p < 0.05; ***p < 0.001).

Additionally, 40 % of buildings stated that the period of occupancy covers the interval from 5 p.m. to 9 p.m. In cases where the exposure occurred at night, the radon concentration (Mdn. = 278 Bq/m^3) is significantly higher than the overall computed concentration (Mdn. = 245 Bq/m^3), with a p-value of 0.02. The RPD between medians is 13 %. When analysing the situations when the exposure occurred between 5 p.m. and 9 p.m., the radon concentration (Mdn. = 195 Bq/m^3) is significantly lower compared to the overall exposure (Mdn. = 212 Bq/m^3), with a RPD between medians of −8%.

4. Conclusion

The increasing number of instruments that are capable of continuous radon measurements has led to a shift in consumer behaviour, with an increasing inclination towards self-conducted measurements over reliance on licensed laboratories. The trend towards using commercial active devices is evident even in research groups, as the number of scientific papers using long-term active monitoring is consistently growing. While the integrated method presents distinct advantages, the momentum behind continuous measurements, driven by both consumer demand and scientific utility, necessitates a reassessment of strategies for IRC assessment.

This study compares two *in-situ* measuring methods. Active devices perform comparably to the integrated technique over periods longer than six months (CCC >0.92). However, for three-month campaigns, CCC varied (0.78–0.96), highlighting limitations of active devices, especially their sensitivity to humidity fluctuations.

In response to market demands, there is a notable trend towards reducing measurement periods, necessitating the use of specific TCF for estimating AIRC. Our study reveals significant differences in TCF between the two measurement methods, even when their agreement was moderate or substantial according to IRC. Consequently, TCF developed for passive methods are not applicable to active methods. Moreover, distinctions between workplace and residential buildings, including the presence of air conditioning units and differing occupancy patterns, lead to substantial differences in both IRC and TCF.

Radon levels vary by room occupancy duration. In workplaces, actual exposure is lower than integrated measurements suggest. In homes, nighttime exposure is higher. As such, continuous monitoring can reveal true radon exposure levels.

Radon research laboratories can aid in integrating commercial active devices by addressing their limitations through regular calibrations and sensor accuracy improvements. This study provides a comprehensive dataset on TCF applicability based on measurement method and building type. Future analyses using time series from active methods can further enhance TCF adjustments, focusing not only on the stating month and the duration of the measurement, but also on distinct factors influencing radon concentration variations. This consideration gains prominence among growing evidence of interannual variations, underscoring the importance of such refinements.

Funding

The present work has received financial support by a grant from the Romanian Ministry of Research, Innovation and Digitization, CNCS - UEFISCDI, project number PNIII- P1-1.1-TE-2021- 0249, within PNCDI III. The research was also supported by the project ID P_37_229, Contract No. 22/September 01, 2016, with the title "Smart Systems for Public Safety through Control and Mitigation of Residential Radon linked with Energy Efficiency Optimization of Buildings in Romanian Major Urban Agglomerations SMART-RAD-EN" of the POC Program in study design.

Data availability statement

The datasets used and/or analysed during the current study are available from the corresponding author (T. D.), upon reasonable request.

CRediT authorship contribution statement

Tiberius Dicu: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Marius Botoş:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Formal analysis. **Alexandra Cucoş:** Resources, Investigation. **Şerban Grecu:** Visualization, Validation, Software, Investigation, Formal analysis. **Ştefan Florică:** Investigation. **Arthur Tunyagi:** Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e37144.

References

[1] A. Gonzalez, J. Anderer, Radiation versus radiation: Nuclear energy in perspective, IAEA Bullet. 2 (1989) 21–31. https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull31-2/31205642131.pdf (Accessed 27 March 2024).

[2] UNSCEAR, Sources and Effects of Ionising Radiation, Vol 1, United Nations Scientific Committee on the Effect of Atomic Radiation, Report to the General Assembly with Scientific Annexes, 2008.

[3] P. Bossew, et al., On harmonization of radon maps, Journal of the European Radon Association (Mar. 2022), https://doi.org/10.35815/radon.v3.7554.
[4] A.C. George, The history, development and the present status of the radon measurement programme in the United States of America, Radiat. Protect. Dosim. 167 (1–3) (Nov. 2015) 8–14, https://doi.org/10.1093/rpd/ncv213.
[5] J. Silva, N. Lopes, A. Curado, L.J.R. Nunes, S.I. Lopes, A pre-diagnosis model for radon potential evaluation in buildings: a tool for balancing ventilation, indoor air quality and energy efficiency, Energy Rep. 8 (Jun. 2022) 539–546, https://doi.org/10.1016/J.EGYR.2022.02.100.
[6] T. Dicu, et al., Exploring statistical and machine learning techniques to identify factors influencing indoor radon concentration, Sci. Total Environ. 905 (Dec. 2023) 167024, https://doi.org/10.1016/J.SCITOTENV.2023.167024.
[7] C. Briones, et al., Multiparametric analysis for the determination of radon potential areas in buildings on different soils of volcanic origin, Sci. Total Environ. 885 (Aug) (2023), https://doi.org/10.1016/j.scitotenv.2023.163761.
[8] Ó. Burke, P. Murphy, Regional variation of seasonal correction factors for indoor radon levels, Radiat. Meas. 46 (10) (Oct. 2011) 1168–1172, https://doi.org/10.1016/J.RADMEAS.2011.06.075.
[9] L. Gulabyants, M. Livshits, A. Kalaydo, K. Kovler, Resistance of building foundation to radon penetration, J. Build. Phys. 43 (5) (May 2019) 456–473, https://doi.org/10.1177/1744259119844533.
[10] A. Tsapalov, K. Kovler, Annual monitoring of soil radon behavior and entry into building, Journal of the European Radon Association (Mar. 2022), https://doi.org/10.35815/radon.v3.7630.
[11] L. Martin-Gisbert, et al., Radon exposure and its influencing factors across 3,140 workplaces in Spain, Environ. Res. 239 (Dec. 2023) 117305, https://doi.org/10.1016/j.envres.2023.117305.
[12] CNCAN, Order of the President of CNCAN No. 153/27.07.2023, 2023. MO No. 729/08.08.
[13] A.R. Denman, N.P. Groves-Kirkby, C.J. Groves-Kirkby, R.G.M. Crockett, P.S. Phillips, A.C. Woolridge, Health implications of radon distribution in living rooms and bedrooms in U.K. dwellings — a case study in Northamptonshire, Environ. Int. 33 (8) (Nov. 2007) 999–1011, https://doi.org/10.1016/J.ENVINT.2007.01.011.
[14] R.G.M. Crockett, C.J. Groves-Kirkby, A.R. Denman, P.S. Phillips, Significant annual and sub-annual cycles in indoor radon concentrations: seasonal variation and correction, Geological Society, London, Special Publications 451 (1) (Jan. 2018) 35–47, https://doi.org/10.1144/SP451.2.
[15] B. Majborn, Seasonal variations of radon concentrations in single-family houses with different sub-structures, Radiat. Protect. Dosim. 45 (1–4) (Dec. 1992) 443–447, https://doi.org/10.1093/rpd/45.1-4.443.
[16] C. Di Carlo, et al., Extreme reverse seasonal variations of indoor radon concentration and possible implications on some measurement protocols and remedial strategies, Environmental Pollution 327 (Jun. 2023) 121480, https://doi.org/10.1016/j.envpol.2023.121480.
[17] G. Pantelić, et al., Qualitative overview of indoor radon surveys in Europe, J. Environ. Radioact. 204 (Aug. 2019) 163–174, https://doi.org/10.1016/J.JENVRAD.2019.04.010.
[18] J.C.H. Miles, C.B. Howarth, N. Hunter, Seasonal variation of radon concentrations in UK homes, J. Radiol. Prot. 32 (3) (Sep. 2012) 275–287, https://doi.org/10.1088/0952-4746/32/3/275.
[19] K. Kozak, et al., Correction factors for determination of annual average radon concentration in dwellings of Poland resulting from seasonal variability of indoor radon, Appl. Radiat. Isot. 69 (10) (Oct. 2011) 1459–1465, https://doi.org/10.1016/J.APRADISO.2011.05.018.
[20] H. Baysson, S. Billon, D. Laurier, A. Rogel, M. Tirmarche, Seasonal correction factors for estimating radon exposure in dwellings in France, Radiat. Protect. Dosim. 104 (3) (May 2003) 245–252, https://doi.org/10.1093/oxfordjournals.rpd.a006188.
[21] Z. Stojanovska, J. Januseski, P. Bossew, Z.S. Zunic, T. Tollefsen, M. Ristova, Seasonal indoor radon concentration in FYR of Macedonia, Radiat. Meas. 46 (6–7) (Jun. 2011) 602–610, https://doi.org/10.1016/J.RADMEAS.2011.04.022.
[22] M. Müllerová, L. Mrusková, K. Holý, I. Smetanová, A. Brandýsová, Estimation of seasonal correction factor for indoor radon concentration in Slovakia: a preliminary survey, J. Radioanal. Nucl. Chem. 331 (2) (Feb. 2022) 999–1004, https://doi.org/10.1007/s10967-021-08139-3.
[23] Z. Daraktchieva, New correction factors based on seasonal variability of outdoor temperature for estimating annual radon concentrations in UK, Radiat. Protect. Dosim. (Sep. 2016), https://doi.org/10.1093/rpd/ncw270.
[24] D. Steck, " Indoor radon exposure uncertainties caused by temporal variation,", IRPA 11 (2004).
[25] J. Whyte, R. Falcomer, J. Chen, A comparative study of radon levels in federal buildings and residential homes in Canada, Health Phys. 117 (3) (Sep. 2019) 242–247, https://doi.org/10.1097/HP.0000000000001057.
[26] R. Trevisi, et al., Radon levels in dwellings and workplaces: a comparison with data from some European countries, Journal of the European Radon Association (Mar. 2022), https://doi.org/10.35815/radon.v3.7581.
[27] F. Marley, A.R. Denman, P.S. Phillips, Studies of radon and radon progeny in air conditioned rooms in hospitals, Radiat. Protect. Dosim. 76 (4) (Apr. 1998) 273–276, https://doi.org/10.1093/oxfordjournals.rpd.a032274.
[28] F. Bochicchio, Protection from radon exposure at home and at work in the directive 2013/59/Euratom, Radiat. Protect. Dosim. 160 (1–3) (Jul. 2014) 8–13, https://doi.org/10.1093/rpd/ncu101.
[29] G. Venoso, et al., Impact of temporal variability of radon concentration in workplaces on the actual radon exposure during working hours, Sci. Rep. 11 (1) (Aug. 2021) 16984, https://doi.org/10.1038/s41598-021-96207-9.
[30] J.P. Rydock, A. Næss-Rolstad, J.T. Brunsell, Diurnal variations in radon concentrations in a school and office: implications for determining radon exposure in day-use buildings, Atmos. Environ. 35 (16) (Jun. 2001) 2921–2926, https://doi.org/10.1016/S1352-2310(00)00515-X.
[31] A. Tunyagi, T. Dicu, A. Cucos, B.-D. Burghele, G. Dobrei, An innovative system for monitoring radon and indoor air quality, Rom. J. Phys. 65 (1–2) (2020).
[32] A. Cucoş Dinu, et al., Thorough investigations on indoor radon in Băiţa radon-prone area (Romania), Sci. Total Environ. 431 (Aug. 2012) 78–83, https://doi.org/10.1016/J.SCITOTENV.2012.05.013.
[33] AARST, Performance Specifications for Instrumentation Systems Designed to Measure Radon Gas in Air (MS-PC 2015), 2015.
[34] J. Pinel, T. Fearn, S.C. Darby, J.C.H. Miles, Seasonal correction factors for indoor radon measurements in the United Kingdom, Radiat. Protect. Dosim. 58 (2) (Feb. 1995) 127–132, https://doi.org/10.1093/oxfordjournals.rpd.a082606.
[35] C. Cosma, A. Cucos (Dinu), and T. Dicu, "Preliminary results regarding the first map of residential radon in some regions in Romania," Radiat. Protect. Dosim., vol. 155, no. 3, pp. 343–350, Jul. 2013, doi: 10.1093/rpd/nct015.
[36] K. Ivanova, Z. Stojanovska, M. Tsenova, V. Badulin, B. Kunovska, Measurement of indoor radon concentration in kindergartens in Sofia, Bulgaria, Radiat. Protect. Dosim. 162 (1–2) (Nov. 2014) 163–166, https://doi.org/10.1093/rpd/ncu251.
[37] F. Bochicchio, et al., Radon in indoor air of primary schools: a systematic survey to evaluate factors affecting radon concentration levels and their variability, Indoor Air 24 (3) (Jun. 2014) 315–326, https://doi.org/10.1111/ina.12073.
[38] Z. Ćurguz, et al., Long-term measurements of radon, thoron and their airborne progeny in 25 schools in Republic of Srpska, J. Environ. Radioact. 148 (Oct. 2015) 163–169, https://doi.org/10.1016/J.JENVRAD.2015.06.026.
[39] B.D. Burghele, C. Cosma, Thoron and radon measurements in Romanian schools, Radiat. Protect. Dosim. 152 (1–3) (Nov. 2012) 38–41, https://doi.org/10.1093/rpd/ncs143.
[40] Z. Mnich, et al., Radon concentration in hospital buildings erected during the last 40 years in Białystok, Poland, J. Environ. Radioact. 75 (2) (Jan. 2004) 225–232, https://doi.org/10.1016/J.JENVRAD.2003.12.006.
[41] S. Oikawa, N. Kanno, T. Sanada, J. Abukawa, H. Higuchi, A survey of indoor workplace radon concentration in Japan, J. Environ. Radioact. 87 (3) (Jan. 2006) 239–245, https://doi.org/10.1016/J.JENVRAD.2005.12.001.
[42] C.C. Lin, S.J. Lin, P.Y. Li, M.S. Lee, C.Y. Ting, Radon levels and dose assessment at the basement workplaces of hospitals in different regions of Taiwan, Radiat. Phys. Chem. 218 (May 2024) 111530, https://doi.org/10.1016/J.RADPHYSCHEM.2024.111530.

[43] United States Environmental Protection Agency and Office of Radiation and Indoor Air, Protocols for Radon and Radon Decay Product Measurements in Homes, 1993. EPA 402-R-92-003.

[44] C. Carpentieri, et al., Assessment of long-term radon concentration measurement precision in field conditions (Serbian Schools) for a survey carried out by an international collaboration, Radiat. Protect. Dosim. 145 (2–3) (May 2011) 305–311, https://doi.org/10.1093/rpd/ncr042.

[45] T. Dicu, et al., A new approach to radon temporal correction factor based on active environmental monitoring devices, Sci. Rep. 11 (1) (May 2021) 9925, https://doi.org/10.1038/s41598-021-88904-2.