

## Results of indoor radon activity concentration measurements using CR-39 detectors exposed in different periods

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### ABSTRACT

Indoor air quality may be compromised by elevated radon levels, a naturally occurring radioactive gas. Prolonged exposure to increased radon levels can adversely affect human health. This paper presents the results of indoor radon activity concentration measurements conducted at 20 locations using a passive method. CR-39-based radon detectors were deployed over three different exposure periods, from January to April. The aim of the study was to compare and analyse average indoor radon activity concentrations obtained over different detector exposure periods, and to determine whether reliable information on indoor air quality can be obtained using shorter exposure durations. The measured indoor radon activity concentrations ranged from 6.0 to 727 Bq/m<sup>3</sup>, 10.1 to 561 Bq/m<sup>3</sup>, and 15.1 to 480 Bq/m<sup>3</sup> for the three-month, two-month, and one-month exposure periods, respectively. Comparative analysis of the results showed that the mean ratio of radon activity concentrations for one-month to two-month, two-month to three-month, and one-month to two-month exposure periods were 1.24, 1.57, and 1.85, respectively. To establish the relationship between radon activity concentrations obtained for different exposure periods, linear regression analysis was performed. The analysis of the estimated relative percentage differences showed that the results for different exposure periods agreed within  $\pm 20\%$  at approximately 53% of the locations.

**Keywords:** radon, activity concentration, indoor air, CR-39 track detector.

### INTRODUCTION

Most human exposure to radiation originates from natural sources. Depending on the location of the radioactive source, exposure can be classified as either internal or external. Indoor environments often exhibit elevated levels of natural radiation, primarily due to radon, a naturally occurring radioactive gas. Globally, the annual effective dose attributable to radon and its short-lived progeny is estimated at 1.15 mSv, while in Europe this value amounts to 1.96 mSv. In a similar vein, the worldwide average indoor radon activity concentration is 46 Bq/m<sup>3</sup>, whereas the European average is significantly higher at 103 Bq/m<sup>3</sup> (UNSCEAR Report, 2000; Cinelli et al., 2019). Both the World Health Organisation (WHO, 2009) and UNSCEAR (UNSCEAR, 2020) emphasize that elevated indoor radon levels pose significant health risks. Specifically, the inhalation of short-lived radon decay

products and their subsequent deposition on lung tissue increase the risk of malignancy. Case-control studies have confirmed these hazards, thus establishing a clear correlation between high domestic radon concentrations and lung cancer (Darby et al., 2005; Vuković et al., 2005). To mitigate these risks, the EU Council Directive 2013/59/EURATOM recommends a reference level for annual average indoor radon activity concentration of 300 Bq/m<sup>3</sup> (EU Council Directive, 2014). To minimize health hazards from indoor radon exposure WHO proposes a reference level of 100 Bq/m<sup>3</sup>. If this level cannot be achieved, the chosen reference level should not exceed 300 Bq/m<sup>3</sup> (WHO, 2009).

Various measurement methods are employed to detect and quantify radon concentration, either directly by measuring radon itself or indirectly through its progeny. In general, radon activity concentration in air is measured using two basic techniques: active and passive samplings, which provide

short- and long-term measurements, respectively (Al-Jarallah et al., 2008; Stojanovska et al., 2016). Active measurements are mostly performed by using different ionization chambers, semiconductor detectors, proportional, and scintillation counters. These methods are suitable for short-term monitoring and require a power supply. On the other hand, passive methods, such as nuclear track detectors, thermoluminescent detectors, or charcoal adsorption, are used for long-term measurements and do not require electricity (Tanaka et al., 2017; Mphaga et al., 2024; Maringer and Blum, 2025).

Short-term measurements last from several minutes to a week and typically utilize active techniques. Conversely, long-term measurements last from one month to a year and rely on passive, integrated methods to provide a representative average exposure (Ocwelwang et al., 2021). Generally, long-term measurements are considered to last from two months and longer; however, standards for radon in air of the International Organization for Standardization (ISO) define them as period longer than one month (International Organization for Standardization, 2019; IAEA, 2019). Short-term measurements serve as a primary indicator for identifying high radon levels and quickly verifying the effectiveness of performed mitigation strategies. Active measurements provide high precision and rapid data, but they are not practical for long-term monitoring. On the other hand, passive detectors are ideal for long-term monitoring because they provide a reliable estimate of the average radon activity concentration over an extended period.

The primary advantage of CR-39 detectors is their ability to integrate results over extended exposure periods, making them far more reliable for measuring low levels of radioactivity where active methods often face high uncertainty. Several studies have shown that passive radon detectors, such as CR-39 detectors, often yield higher average results for radon concentrations compared to active radon techniques (Abo-Elmagd et al., 2005; Sethabela et al., 2022; Al-Jarallah et al., 2008). Prolonged exposure of CR-39 detectors in environments with high radon concentration can lead to a high track density, track saturation, and overlapping. In such cases, it is difficult to read the tracks on the detector, and the linearity between tracks density and radon exposure is disrupted (Gaillard et al., 2007). For CR-39 detectors, used in this study, a saturation limit is greater than 6000 kBq/m<sup>3</sup> (RadoSys, User Manual).

The average radon activity concentration in air is used to estimate annual effective dose and assess associated health risks. For precise estimation of annual effective dose from radon it is important to properly describe the exposure profile. The concentration of radon in air is subject to fluctuations daily and seasonally, where the maximum values of the radon activity concentration are present in the early morning hours, and during the year in autumn or winter months (Udovičić et al., 2011; Sferle et al., 2020; Belete and Shiferaw, 2022). Also, radon concentration depends on meteorological conditions including temperature, relative humidity, pressure, as well as ventilation conditions, building occupancy, and human activities (Aquilina and Fenech, 2019; Podstawczyńska, 2015). One of the advantages of the active devices are built-in sensors which enable that the additional parameters, such as temperature, pressure and relative humidity can be measured simultaneously with radon concentration (Sethabela et al., 2022). Active devices also enable the analysis of radon fluctuations during the day or in a longer period. On the other hand, CR-39 detectors, as integrating passive technique, do not allow the analysis of daily or seasonal radon variation. To estimate the average annual effective dose from radon, it is necessary to use the annual average radon concentration. This result is obtained by measurement carried out over a period of one year, or as the mean value of three-month measurements for each season during the year. The results of the CR-39 detectors during each season enable the comparison of results across all seasons and establishment of the seasonal correction factors (Ibrahimi and Miles, 2009).

The focus of this study is the passive measurement method utilizing CR-39 solid-state nuclear track detectors (SSNTDs). This method is based on the registration of alpha particle traces, originating from radon decay, within a dielectric detector. Standard protocols for this system typically suggest an exposure period of three to six months (Radosys, User's manual). Therefore, most studies employing this technique adhere to a minimum three-month exposure (Ulug et al., 2004; Stojanovska et al. 2017; Mbida et al., 2023; Kasumović et al., 2014). National radon programmes in many countries are performed using the nuclear track detectors and involves simultaneously measuring of the indoor radon during a year (Stojanovska et al., 2017). Detectors are usually exposed in four successive periods of three months and results are examined with respect to seasonal variation, the

building material, and presence or absence of a cellar (Smetanová et al., 2015). In study conducted in dwellings of the Penisola Sorrentina, South Italy, detectors were exposed in two successive six months periods (Quarto et al., 2013). Additionally to radon measurement, the annual effective dose due to indoor radon inhalation was assessed and the statistical relationship between radon measurements and building characteristics was tested. Stojanovska et al. (2016) in their research analysed the influence of different exposure time of detectors on the average radon activity concentration. Research was performed in primary schools where two CR-39 detectors were simultaneously deployed in different periods of exposure, one during the whole year and the other one for nine months, excluding the summer vacations. As concluded in this study dissimilarities in the measured values were not significant, and influence of different exposure time is not identified. Comparative study of the short- and long-term indoor radon measurements carried out using passive integrating electret detectors is presented by Vuchkov et al. (2013). The study was conducted in two phases at same locations: short-term measurement with 10 days duration and long-term measurement along a period of six months. The results of this study showed a significant correlation between the two set measurements. In the scientific literature, there are also studies comparing active and passive methods (Sethabela et al., 2022; Al-Jarallah et al., 2008; Abo-Elmagd et al., 2005).

A comparative study of short- and long-term indoor radon measurements in Dhahran, Saudi Arabia, was carried out using active and passive techniques, respectively (Al-Jarallah et al., 2008). In the short-term measurement, radon concentration was measured every 1 h for a total period of 24 h using a gas analyser type Alpha Guard 2000 PRQ, while passive radon CR-39 dosimeters were used for long-term measurement for a 6-month period. The results of study revealed a poor correlation between the two measurements and the long-term measurements showed higher concentrations by a factor of 1.3. Sethabela et al. (2022) compare the results from three-month measurements conducted with active and passive radon measurement techniques, where AlphaGUARD model PQ 2000, Airthings wave monitor and Solid-State Nuclear Track Detector (SSNTD) were used. Relatively higher radon concentrations were obtained from the passive radon detector in comparison to the results from active detectors.

The previously mentioned studies, as well as many others available in the literature, mostly compare long-term measurements lasting one year or six months, with periods of one season or shorter. The use of the seasonal correction factor in estimating the mean annual concentration is also emphasized. Measurements that last less than a month for example a week or less, are considered as a screening measurement and serve for a faster indication of the radon level. Shorter measurements are carried out using active devices.

In this research, CR-39 detectors were deployed at 20 locations. At each site, measurements were conducted using three detectors installed for different durations: one, two, and three months. The aim of the research was to determine and compare average indoor radon activity concentrations across these varying exposure periods. Measurements were performed under the same seasonal and spatial conditions. Validating shorter exposure durations would allow for faster assessment of indoor air quality, enabling more timely implementation of protection measures based on estimated annual effective doses and associated health risks. The research results can contribute to the optimization of measurement protocols from the aspect of exposure time.

## MATERIALS AND METHODS

Radon activity concentration measurements were conducted at 20 locations. The measuring locations ranged from the rooms in single-family houses and apartment buildings to faculty offices and laboratories. The measurements utilized CR-39 solid-state nuclear track detectors (SSNTDs), each enclosed within a cylindrical diffusion chamber (RSKS type, RadoSys Co., Budapest, Hungary) with a height of 55 mm and a radius of 26 mm. The detector chips measured  $10 \times 10 \text{ mm}^2$  with a thickness of 1 mm. The CR-39 material is sensitive to alpha particles but not to beta and gamma radiation, as well as environmental factors such as temperature and relative humidity (RadoSys, User's manual; Mamont-Cieřla et al., 2010). The density of tracks accumulated on the detector surface is directly proportional to the radon gas concentration both within the diffusion chamber and the surrounding indoor air (Al-Jarallah et al., 2008).

The cylindrical diffusion chambers with detectors were placed on surfaces such as shelves or cabinets at a height of 1 to 2 m above the floor.

Positions of detectors were away from direct airflow, heating sources and sunlight, and at a distance of at least 20 cm from walls, other objects, and furniture. The measurements were performed across all locations during the same season (January to April), with three detectors for different exposure intervals installed simultaneously at each site. These three detectors were placed close to each other, and to ensure consistency, they remained stationary throughout the monitoring period. The first detector was exposed for three months starting in the third week of January. The second was deployed approximately 30 days later for a two-month period, and the third was installed for one month. At the end of the exposure intervals, all three detectors were collected simultaneously and taken to the laboratory for analysis.

The experimental analyses commenced with the etching process, where detectors were immersed in a 6.25 M sodium-hydroxide solution at a constant temperature of 90 °C for 4.5 hours. This was followed by a neutralisation phase using a solution of 200 ml of 20% vinegar in 4000 ml of distilled water. Subsequently, the detectors were rinsed with 4000 ml of distilled water and left to dry. Alpha track counting was performed using the RadoMeter System, consisting of the RadoMeter–RM software for track analysis and data processing and an automated microscope equipped with a B&W CCD camera at 100x magnification (Figure 1). The recorded track densities (tracks/mm<sup>2</sup>) were converted into radon activity concentrations (Bq/m<sup>3</sup>) based on the specific calibration factor and exposure duration for each detector. All experimental procedures were conducted in strict accordance with the RadoSys System User Manual. Standard uncertainty was calculated according to Equation 1.

$$\sigma = \sqrt{\sigma_{\rho}^2 + \sigma_K^2 + \sigma_{\tau}^2} \quad (1)$$

where:  $\sigma_{\rho} = \frac{1}{\sqrt{N}} + 0.004$  – relative uncertainty in track counting,  $N$  – the number of tracks in a detector,  $\sigma_K$  – calibration coefficient uncertainty (for CR-39  $\sigma_K = 0.18$ ), and  $\sigma_{\tau}$  – uncertainty due to transport of detector (Tresnjo et al., 2017).

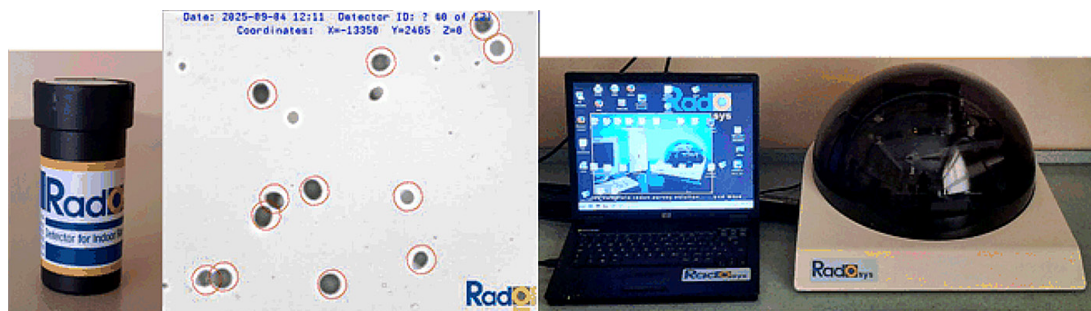
All experimental procedures were conducted in strict accordance with the RadoSys System User Manual. Statistical analysis was performed on the radon activity concentrations obtained

across the different exposure periods. To evaluate relationships among the measurements, the paired-sample t-test, Pearson's correlation coefficient, and linear regression were employed. Additionally, relative percentage differences were calculated to assess variability. All statistical computations were conducted using the Microsoft Office Excel Data Analysis ToolPack.

## RESULTS AND DISCUSSION

The radon activity concentrations ( $C_{Rn}$ ) for the three different exposure periods are presented in Table 1, including the range and mean values for each location. For the Phase 3M (three-month exposure), the mean, minimum, and maximum concentrations were 62.1, 6.0, and 727 Bq/m<sup>3</sup>, respectively. The mean, minimum, and maximum concentrations were 56.8, 10.1 and 561 Bq/m<sup>3</sup> for the Phase 2M (two-month exposure), while Phase 1M (one-month exposure) yielded 57.8, 15.1 and 480 Bq/m<sup>3</sup>. Across 19 of the 20 locations, the mean values remained below the European indoor average of 103 Bq/m<sup>3</sup>, and were comparable to reported averages for other countries in the region (Cinelli et al, 2019; Pantelić et al., 2018).

According to the results, it can be concluded that significantly elevated radon activity concentrations were detected at location L7 (Table 1), with recorded values of  $727 \pm 133$  Bq/m<sup>3</sup>,  $561 \pm 103$  Bq/m<sup>3</sup> and  $480 \pm 92$  Bq/m<sup>3</sup> for the three-, two-, and one-month exposure periods, respectively. These values exceeded the reference level of 300 Bq/m<sup>3</sup> for annual average indoor radon, as recommended by the EU Council Directive (EU Council Directive, 2014). Generally, such elevated indoor radon levels can be attributed to a combination of factors, including local bedrock geology, building characteristics, and the specific ventilation regime (Vuchkov et al., 2013). Location L7 is a small, single-story house without a basement, characterized by a low ventilation rate during the study. The building serves as a weekend house from late spring to early winter; consequently, it remained unoccupied and largely sealed throughout the measurement period. Doors were opened only briefly during detector installation in the first two months, and just once weekly during the final month, preventing any significant air exchange. It can be inferred that the building's construction facilitates the emanation of radon from the underlying soil



**Figure 1.** Diffusion chamber, image of alpha track marks recognized on the detector's chip surface, and Radosys reading system

into the living space, while the lack of ventilation further promoted the accumulation of high radon activity concentrations [Alhamdi, 2024; Baskaran, 2016; Seo et al., 2018].

Research results from Łódź in Central Poland, (Podstawczyńska, 2015) led to the conclusion that limited ventilation in the unoccupied house can cause rapidly increase of indoor radon levels up to 5 times higher values than the average level. That implies that for location L7, the lack of ventilation was the main cause of indoor radon accumulation. It must be emphasis that accumulated radon in indoor environments lead to significant exposure through inhalation and, consequently, a higher radiation dose.

Estimation of the annual effective dose received from radon inhalation is based on the radon activity concentration in air, occupancy time, and dose coefficient. According to the calculations by ICRP (International Commission on Radiological Protection) the reference level of  $300 \text{ Bq/m}^3$  represents the annual effective dose approximately of  $10 \text{ mSv}$  (WHO, 2009). For homes with the annual average radon activity concentrations above the reference level, remediation measures are always recommended or required. The values obtained in our study for location L7 exceed the reference level by a factor of 2. If estimated, the annual effective dose in the Phase 3M would be higher than in the Phase 1M by a factor of 1.5. This requires appropriate radon remediation measures. According to Environmental Protection Agency Guide remedial measures may include installing radon sump under the floor, increasing under-floor ventilation, positive pressurisation, sealing of gaps and cracks in the floor and walls, and increased indoor ventilation (Environmental Protection Agency, EPA, 2019; Durrani and Ilić, 1997). Recommendations for the necessary measures for location L7 should take into account the conditions under which the

measurements were made, and especially the usage and time of occupancy of the house. When estimating the annual effective dose it is commonly assumed that people spend 80% of their time inside house (UNSCEAR Report, 2000). For location L7, the indoor occupancy factor must be taken below 0.8, considering that people were not staying in the house during the measurements. During the final month, average radon activity concentration was lower by a factor of 1.5 compared to the three-month measurement results. Based on this, it can be concluded that even one weekly door opening during the final month contributed to reduction of indoor radon accumulation. Therefore, the first measure in reducing the radon accumulation would be to recommend ventilation the house by opening windows and doors, enabling exchanging indoor air.

If the measurement results from location L7 are excluded, the mean values for Phase 3M, Phase 2M, and Phase 1M drop to  $27.1$ ,  $30.3$  and  $35.6 \text{ Bq/m}^3$ , with ranges  $6.0\text{--}58.1 \text{ Bq/m}^3$ ,  $10.1\text{--}61.1 \text{ Bq/m}^3$  and  $15.1\text{--}71.2 \text{ Bq/m}^3$  for the Phase 3M, Phase 2M and Phase 1M, respectively. These values are well below the recommended reference level of  $300 \text{ Bq/m}^3$ .

A paired-sample *t*-test was used to determine whether there were significant differences in radon activity concentrations across the exposure periods. The significance level for the *t*-test was set at 0.05 ( $p < 0.05$ ). The results indicated no statistically significant difference between concentrations measured during Phase 2M and Phase 3M measurements ( $t(19) = 0.58$ ,  $p > 0.05$ ). The 95% confidence interval of the difference in means was  $[-87.21, 97.69]$ . The null value that is included in the confidence interval indicates that difference in mean values is not statistically significant. Also, no significant differences were found between Phase 1M and Phase 3M

**Table 1.** The results of the radon activity concentration measurement at location sites for three exposure periods (Phase 3M – three months, Phase 2M – two months and Phase 1M – one month)

Location	Phase 3M		Phase 2M		Phase 1M	
	Exposure period (days)	$C_{Rn}$ (Bq/m <sup>3</sup> )	Exposure period (days)	$C_{Rn}$ (Bq/m <sup>3</sup> )	Exposure period (days)	$C_{Rn}$ (Bq/m <sup>3</sup> )
L1	94	25.3 ± 5.7	63	24.1 ± 5.9	31	20.0 ± 6.3
L2	94	8.8 ± 2.5	63	22.4 ± 5.6	31	21.2 ± 6.5
L3	94	16.5 ± 4.0	63	21.3 ± 5.4	31	23.7 ± 7.0
L4	93	37.1 ± 7.8	62	31.7 ± 7.4	31	35.2 ± 9.4
L5	93	14.6 ± 3.7	62	16.9 ± 4.5	31	15.1 ± 5.2
L6	93	12.5 ± 3.2	62	20.2 ± 5.2	31	20.0 ± 6.3
L7	93	727 ± 133	62	561 ± 103	31	480 ± 92
L8	93	43.7 ± 9.1	62	37.5 ± 8.4	31	42.5 ± 10.8
L9	93	57.0 ± 11.5	62	54.1 ± 11.5	31	62.5 ± 14.6
L10	93	24.6 ± 5.5	62	30.2 ± 7.1	31	18.2 ± 6.0
L11	93	17.4 ± 4.2	62	15.6 ± 4.3	31	39.3 ± 10.5
L12	93	12.4 ± 3.3	62	17.5 ± 4.6	31	27.5 ± 7.8
L13	93	16.2 ± 4.0	62	17.5 ± 4.6	31	21.2 ± 6.5
L14	93	12.1 ± 3.2	62	10.1 ± 3.1	31	23.7 ± 7.0
L15	93	43.3 ± 9.0	62	40.4 ± 9.0	31	48.7 ± 12.0
L16	93	49.6 ± 10.1	62	45.0 ± 9.8	31	50.3 ± 12.3
L17	94	35.4 ± 7.5	63	24.2 ± 5.9	33	44.6 ± 11.0
L18	94	23.9 ± 5.4	63	28.9 ± 6.8	33	28.2 ± 7.8
L19	94	6.0 ± 1.9	60	61.1 ± 12.9	31	71.2 ± 16.2
L20	94	58.1 ± 11.7	60	56.8 ± 12.0	31	62.5 ± 14.7
Range		6.0 - 727		10.1 - 561		15.1 - 480
Mean value		62.1		56.8		57.8

( $t(19) = 0.32$ ,  $p > 0.05$ ), not between Phase 1M and Phase 2M ( $t(19) = 0.20$ ,  $p > 0.05$ ). The 95% confidence interval of the difference in means were [-83.11, 91.68] and [-72.19, 74.11] for Phase 1M and Phase 3M, and Phase 1M and Phase 2M, respectively. These findings were expected, given the closely aligned mean radon concentrations observed across all three exposure durations.

To assess the strength of the linear relationship between the measurement phases, the Pearson’s correlation coefficient ( $r$ ) was calculated. The correlation between Phase 3M and Phase 2M was 0.995, which indicates a very strong positive correlation. This relationship is statistically significant at a 95% confidence level ( $p < 0.05$ ). Similar results were obtained for the relationship between Phase 3M and Phase 1M ( $r = 0.991$  with  $p < 0.05$ ), and between Phase 2M and Phase 1M ( $r = 0.996$  with  $p < 0.05$ ).

To establish the relationship between the results of the two-month (Phase 2M) and three-month (Phase 3M) exposure periods, a linear

regression analysis was performed. From this, a linear model with corresponding regression coefficients was developed, as shown in Equation 2

$$C_{Rn}(3M) = 1.309 \cdot C_{Rn}(2M) - 12.321 \quad (2)$$

where:  $C_{Rn}(3M)$  and  $C_{Rn}(2M)$  refer to the radon activity concentration for Phase 3M and Phase 2M, respectively. The model yielded an exceptionally high coefficient of determination,  $R^2 = 0.99$ .

The standardized residuals for the linear regression analysis are presented in Figure 2. As shown in the plot, one observation stands out as an outlier, with its standardized residual exceeding the absolute threshold of 3. Even with a more stringent threshold of 2, this point remains an outlier. For the 18 observations, the absolute values of the standardized residuals were less than 1. This distribution indicates that the developed linear model provides a robust prediction of

three-month radon activity concentrations based on two-month measurement results.

Linear regression analysis was also conducted to establish the relationship between the results of the one-month (Phase 1M) and three-month (Phase 3M) exposure periods. The resulting model, presented in Equation 3 and illustrated in Figure 2b, yielded a coefficient of determination of  $R^2=0.98$ . In this model,  $C_{Rn}(1M)$  represents the radon activity concentration for Phase 1M. Similar to the previous analysis, a single outlier was

identified, corresponding to the same observation (location L19 in Table 1).

$$C_{Rn}(3M) = 1.548 \cdot C_{Rn}(1M) - 27.352 \quad (3)$$

The regression analysis model for the Phase 2M and Phase 1M is defined by Equation 4, with the corresponding standardized residuals illustrated in Figure 2c. The coefficient of determination for this relationship  $R^2 = 0.99$ .

$$C_{Rn}(2M) = 1.183 \cdot C_{Rn}(1M) - 11.525 \quad (4)$$

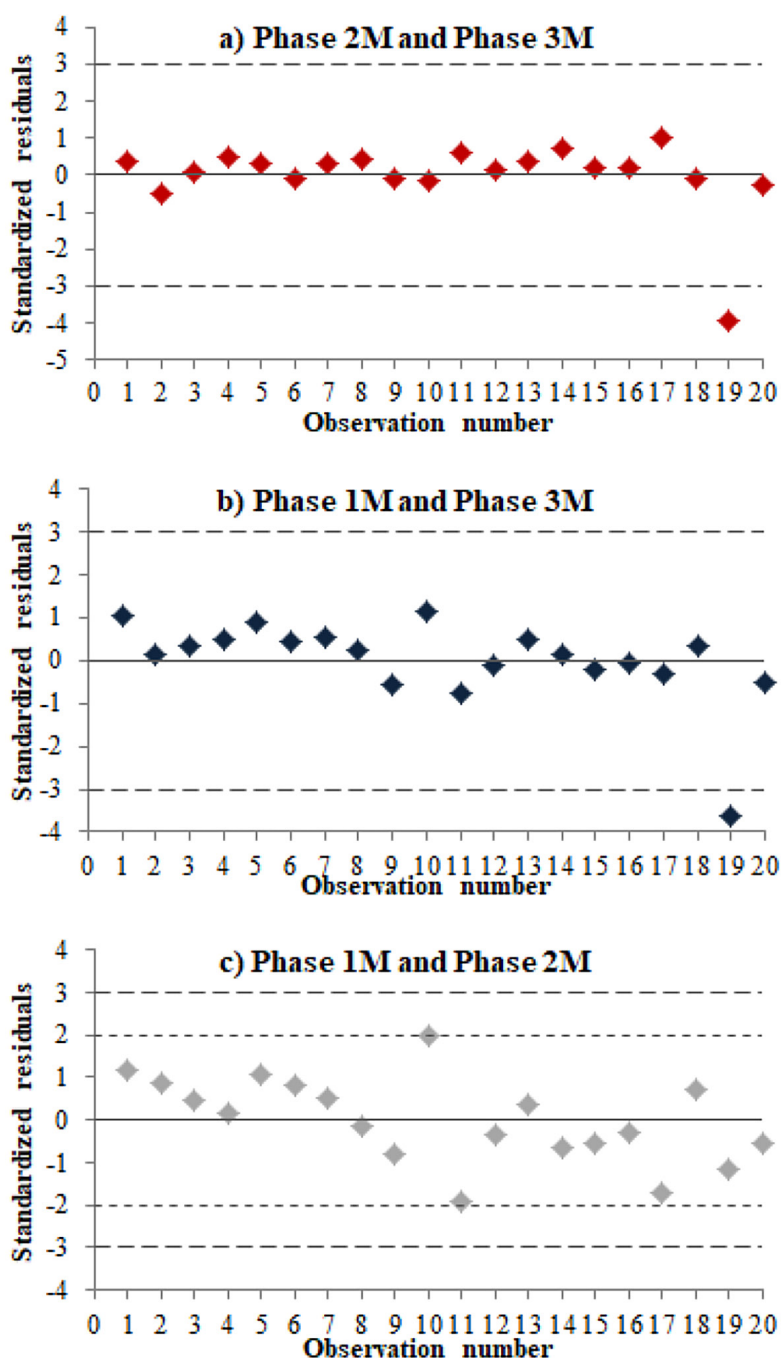


Figure 2. Standardized residual plots for the linear regression models for different measurements phases

In this model, no outliers were identified using a threshold of 3; however, when the threshold was lowered to 2, one observation was identified as an outlier (location L10, Table 1).

The high coefficients of determination obtained in this study are consistent with findings reported by Stojanovska et al. (2016), who observed a high coefficient of determination between indoor radon concentrations measured over two different long-term periods (12 and 9 months). Similarly, a high coefficient of determination ( $R^2=0.92$ ) was also reported in another study (Stojanovska et al., 2017), where a linear regression model was used to determine annual radon concentrations based on short-term (winter) measurements.

According to the results in this study, it can be noticed that for 19 of the 20 locations radon activity concentrations not exceeded  $100 \text{ Bq/m}^3$ . This implies that observed correlation and a high coefficient of determination can only refer to the range of low radon concentrations. Therefore, it is difficult to conclude whether a similar correlation between the measurements with different exposure periods would be maintained for radon

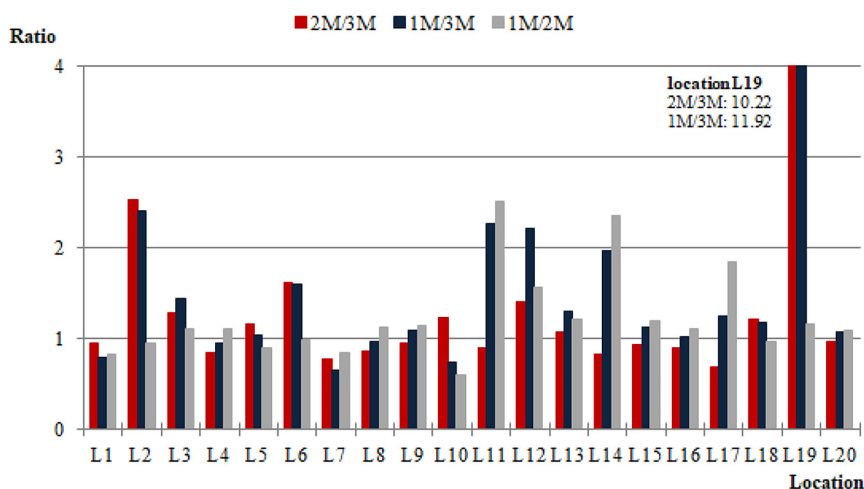
concentrations on the order of several hundred or several thousand  $\text{Bq/m}^3$ .

The ratios of radon activity concentrations between the different measurement phases were determined and are presented for all locations in Table 2 and at Figure 3. The ratio of the Phase 2M to Phase 3M measurements ranged from 0.68 to 10.22, with an overall mean value of 1.57. At 11 locations (55%) this ratio was below 1, with a mean of 0.87. In addition, at seven locations (35%) the ratio fell between 1 and 2, with a mean of 1.28. At two locations (L2 and L19) the ratio exceeded 2, reaching values of 2.54 and 10.22, respectively.

The ratios between Phase 1M and Phase 3M yielded a mean value of 1.85, ranging from 0.66 to 11.92 (Table 2 and Figure 3). At 11 locations (55%), the ratio fell between 1 and 2 (mean = 1.28), while at five locations (25%), it was below 1 (mean = 0.82). At three locations, the ratio exceeded 2 (mean = 2.29), whereas location L19 showed an extreme ratio of 11.92. Location L19 was identified as an outlier in the established linear regression models. This is attributed to the fact that a significantly lower radon

**Table 2.** Ratios of radon activity concentration ( $C_{Rn}$ ) measurements and relative bias for different exposure periods (3M – three months, 2M – two months and 1M – one month)

Location	Ratio of the $C_{Rn}$			Relative bias (%)		
	2M/3M	1M/3M	1M/2M	(2M-3M)/3M	(1M-3M)/3M	(1M-2M)/2M
L1	0.95	0.79	0.83	-4.61	-21.02	-17.20
L2	2.54	2.40	0.95	153.98	140.35	-5.37
L3	1.29	1.44	1.11	29.15	43.62	11.20
L4	0.85	0.95	1.11	-14.54	-4.96	11.22
L5	1.16	1.04	0.90	15.81	3.66	-10.49
L6	1.62	1.60	0.99	61.74	60.00	-1.08
L7	0.77	0.66	0.86	-22.81	-33.98	-14.48
L8	0.86	0.97	1.13	-14.29	-2.86	13.33
L9	0.95	1.09	1.15	-5.18	9.49	15.47
L10	1.23	0.74	0.60	22.91	-25.72	-39.56
L11	0.90	2.26	2.52	-10.16	126.41	152.00
L12	1.41	2.21	1.57	40.63	120.98	57.14
L13	1.08	1.31	1.21	7.69	30.77	21.43
L14	0.83	1.97	2.36	-16.66	96.55	135.85
L15	0.93	1.12	1.21	-6.69	12.50	20.56
L16	0.91	1.02	1.12	-9.24	1.55	11.89
L17	0.68	1.26	1.84	-31.70	25.86	84.28
L18	1.21	1.18	0.97	20.91	17.87	-2.51
L19	10.22	11.92	1.17	922.17	1091.70	16.58
L20	0.98	1.08	1.10	-2.22	7.62	10.06



**Figure 3.** Ratios of radon activity concentrations for different detector exposure periods (Note: The values for location L19 are out of scale in order to improve the graph view)

concentration was determined for Phase 3M at this site. Specifically, the detector registered a very low track density, which was inconsistent with its three-month exposure duration, suggesting a potential measurement anomaly or localized condition during that period.

Regarding the comparison between Phase 1M and Phase 2M, the ratio of radon activity concentrations ranged from 0.60 to 2.52, with a mean value of 1.24. At 35% of the locations, the ratio was below 1 (mean = 0.87), while at 55% of the sites, it fell between 1 and 2 (mean = 1.25). At two locations, the ratios exceeded 2, specifically 2.52 and 2.36. On average, the ratio of shorter to longer exposure periods ranged from 1.24 to 1.85; however, when the outlier at location L19 was excluded, this range narrowed to 1.11–1.32.

For comparison, a study conducted in the UK (Ibrahimi and Miles, 2009) found that three-month long-term measurement results were approximately 85% of the 14-day short-term results. Similarly, the findings from our study indicate that the three-month exposure results were 83% of those obtained from the one-month exposure detectors.

To quantify the discrepancies between the three-month exposure results and those from the two-month and one-month periods, the relative bias (relative difference) was calculated. The relative bias is expressed as a percentage, where the Phase 3M results serve as the reference (or ‘true’) values for radon activity concentration. The relative percentage difference (RPD) was estimated using Equation 5 for the Phase 2M measurements, and analogous calculations were performed for

Phase 1M (Stojanovska et al., 2016). These results are summarized in Table 2. Additionally, the relative bias was evaluated for the one-month measurements (Phase 1M) in comparison to the two-month measurements (Phase 2M).

$$RPD = \frac{C_{Rn}(2M) - C_{Rn}(3M)}{C_{Rn}(3M)} \cdot 100 \% \quad (5)$$

The estimated relative percentage difference (RPD) between Phase 2M and Phase 3M ranged from –31.70% to 922.17%. However, when the outlier at location L19 was excluded, the range narrowed to –31.70% to 153.98%. A histogram of the absolute RPD values is presented in Figure 4. Based on Table 2 and Figure 4, it can be concluded that for 75% of the locations, the absolute relative difference was below 30%, with 55% of the locations showing values below 20%. Comparing Phase 1M and Phase 3M, the RPD ranged from –33.98% to 1091.70% for all locations, and from –33.98% to 140.35% when L19 was excluded. At 55% of the locations (11 sites), the absolute value was below 30%, and for 40% (8 sites), it was below 20%. Further analysis between Phase 1M and Phase 2M showed that the absolute RPD was below 20% for 13 locations, with an overall range of –39.56% to 152.00%.

Overall, the results for different exposure periods agreed within ±20% at approximately 53% of the locations. This represents a higher level of consistency than the study by Vaupotič and Kobal (2002), in which long-term track detector results (two months) were compared with short-term continuous recordings (7–10 days),

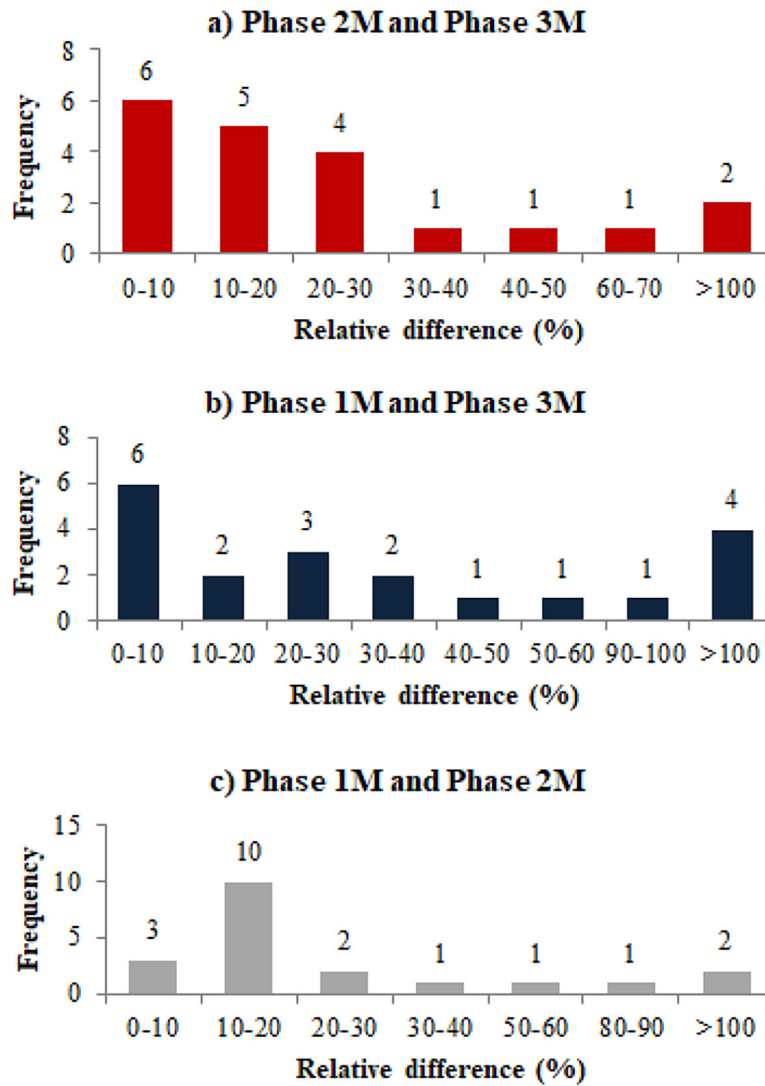


Figure 4. Histograms of the absolute values of the estimated relative percentage differences for different exposure periods

yielding agreement within  $\pm 20\%$  in only about one-third of the cases.

## CONCLUSIONS

In this study, indoor radon activity concentrations were measured at 20 locations using passive CR-39 detectors across three distinct exposure periods. At one specific location (L7), significantly elevated concentrations exceeding the EU Directive 2013/59/Euratom reference level of  $300 \text{ Bq/m}^3$  were recorded across all phases. These high values were attributed to specific building construction characteristics and a total lack of ventilation during the measurement period. It must be emphasized that there was no risk to human health

because there were no occupants in the house during the measurement.

Statistical analysis using a paired-sample t-test showed no significant differences between the radon concentrations across the different exposure durations. Furthermore, Pearson correlation coefficients ( $r$  was 0.995, 0.991 and 0.996) demonstrated an exceptionally strong relationship between the phases. Linear regression models further confirmed this consistency, although one specific observation (L19) consistently emerged as an outlier with standardized residuals exceeding the threshold of 3. This refers to the regression functions between measurements period of three months and two months, and three months and one month. These findings suggest that the exposure period for CR-39 detectors can be reduced to less than three months,

when a rapid assessment of radon exposure is required. However, it is important to note that this study was limited to a single season (January to April). Also, according to the obtained range of radon activity concentrations the determined correlations from this study maintain in the low concentration range, below 100 Bq/m<sup>3</sup>. Whether a similar correlation between the measurements with different exposure periods would hold for higher radon concentrations cannot be concluded on the obtained results.

The analysis of relative bias, using Phase 3M as the reference, indicated that the two-month exposure period provides a better agreement with the three-month standard than the one-month period. Specifically, the results remained within ± 20% of the reference at 55% of the locations for the two-month phase and 40% for the one-month phase.

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