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# Calibration and Metrological Test of the RadonEye Plus2 Electronic Monitor

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## Abstract

Consumer-grade electronic radon monitors are increasingly utilized by users and researchers. Fast and cost-effective procedures for their metrological assurance are necessary. The metrological characteristics of 20 RadonEye Plus2 monitors were investigated. The new monitors had low background of  $2.5 \pm 0.5$  Bq/m<sup>3</sup>. The precision error for the studied group was estimated at about 9 % and the biased error (accuracy) ranged from 3 % to 16 % for activities in the range 280 – 2900 Bq/m<sup>3</sup>. An excellent linearity of all monitors was observed in this range. The statistical fluctuations of the RadonEye Plus2 at 300 Bq/m<sup>3</sup> were estimated at 9% (relative standard deviation).

A simplified calibration procedure was successfully applied. The exposure was at activity concentration exponentially increasing with a small rate, being almost constant within a single measurement of the RadonEyes. The correction factors obtained with this procedure are in excellent agreement with those obtained through the standard procedure with exposure at different constant radon concentrations. The correction factors of the monitors ranged from 0.70 to 1.06 with an average of 0.880 and a standard deviation of 0.079. Overall, the results show that the metrological characteristics of RadonEye Plus2 are sufficient for measurements in dwellings and workplaces. However, the spread of their correction factors

highlights the importance of individual calibration when measurements are made for research, legislation compliance tests or decision making.

**Keywords:** RadonEye, electronic radon monitor, metrological characteristics, calibration

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## 1. Introduction

The accessibility of sensitive electronic radon monitors has opened new doors for research and practical solutions towards the reduction of radon-related risk. The risk for the general population is mainly formed by the exposure to  $^{222}\text{Rn}$  (radon) indoors. A statistically significant increase in the lifetime risk for lung cancer was found for people in homes with radon concentration in the range 100-199  $\text{Bq/m}^3$  in comparison to people in homes with radon below 100  $\text{Bq/m}^3$  (Darby et al., 2005). The World Health Organization (WHO) proposes a reference level for radon indoors of 100  $\text{Bq/m}^3$  (WHO, 2009). According to the European legislation (EC directive, 2013), the reference levels for the annual average radon activity concentration in air in dwellings and workplaces shall not be higher than 300  $\text{Bq/m}^3$ . Due to the large time variations of indoor radon, WHO recommends that the annual average concentration of radon is estimated by measurements continuing for at least three months and preferably longer (WHO, 2009). The commonly applied detectors for long-term radon measurements are diffusion chambers with solid state nuclear track detectors (SSNTD). Such detectors have been in use for several decades and procedures for their quality assurance have been established (Wasikiewicz, 2020).

In contrast, procedures for quality assurance of radon measurements in dwellings and workplaces by electronic radon monitors have not been established yet. The primary reason for this is that commercial devices with low-cost and sufficient sensitivity have only recently become available. Currently, electronic radon monitors are becoming more popular among end users and in some countries they are available for rent. Scientists also showed interest in the new information on the dynamics of radon (Sá et al., 2022). Electronic monitors were applied in the estimation of temporal correction factors, which are used to obtain the annual average radon concentration by measurements with duration of less than a year (Dicu et al., 2021). They could potentially help to improve the assessment of occupational exposure

(Turtiainen et al., 2021). Furthermore, it was proposed to use online data from electronic monitors in active radon mitigation systems that respond to current radon levels (Valcarce et al., 2022).

Metrological assurance of electronic radon monitors is of key importance both for measurements in dwellings and workplaces and for scientific studies. Recently, several studies on the performance of consumer-grade radon monitors have been conducted (Daraktchieva et al., 2019; Warkentin et al., 2020; Mitev et al., 2022; Sá et al., 2022; Dimitrova et al., 2023; Lalau et al., 2023, Rabago et al. 2024). It is shown that even the same type of devices may exhibit large differences in measured values (Daraktchieva et al., 2019; Dimitrova et al., 2023). Therefore, individual calibration of radon monitors is recommended, especially when they are used for testing the non-exceedance of the reference radon levels. It is also essential to investigate the linearity of response of the monitors in the range of activity concentrations typical in buildings. However, calibration and metrological tests of radon detectors are costly, since they are time-consuming and are carried out in specialized laboratories. The current calibration and test procedures are aimed at research-grade electronic monitors or passive radon detectors. The former should have excellent metrological characteristics, while the later require longer exposure times at higher activities. Such procedures might not be applicable to low-cost devices aimed at the wider market. Simplified calibration procedures should be tested, and the most important metrological characteristics should be outlined.

The current study involves calibration and basic metrological tests of 20 RadonEye Plus2 electronic monitors. In addition to the common exposure procedure, we tested a simplified and faster exposure regime that allows calibration and check of the linearity of response.

## **2. Materials and methods**

### **2.1. Experimental**

RadonEye Plus 2, developed by RadonFTLab in South Korea, is an electronic radon monitor based on a pulsed-ionization chamber. It records hourly averages in its memory and can report a 60-minute moving average over the WiFi every 10 minutes. The following specifications are given by the producer: sensitivity: 0.0135 cpm/(Bq/m<sup>3</sup>), range: 7 to 9,435 Bq/m<sup>3</sup>, reproducibility:  $< \pm 10\%$  at 370 Bq/m<sup>3</sup> and accuracy:  $< \pm 10\%$ .

Previous studies of this device indicated that the reproducibility of measurements with different RadonEyes was within 10%. However, their individual accuracy was often worse than 10% (Dimitrova et al., 2023). A non-linearity of

the signal was observed (Turtiainen et al., 2021, Dimitrova et al., 2023), but it was significant above 3500 Bq/m<sup>3</sup>. The background of new detectors was of the order of a few Bq/m<sup>3</sup> (Mitev et al., 2022). Different devices saturated at different levels, but in some, the saturation led to zero signal even below 6000 Bq/m<sup>3</sup> (Mitev et al., 2022). The response time of RadonEyes was estimated at 90 minutes for reaching 90% of their plateau (Dimitrova et al., 2023). They also had some sensitivity to thoron (Turtiainen et al., 2022).

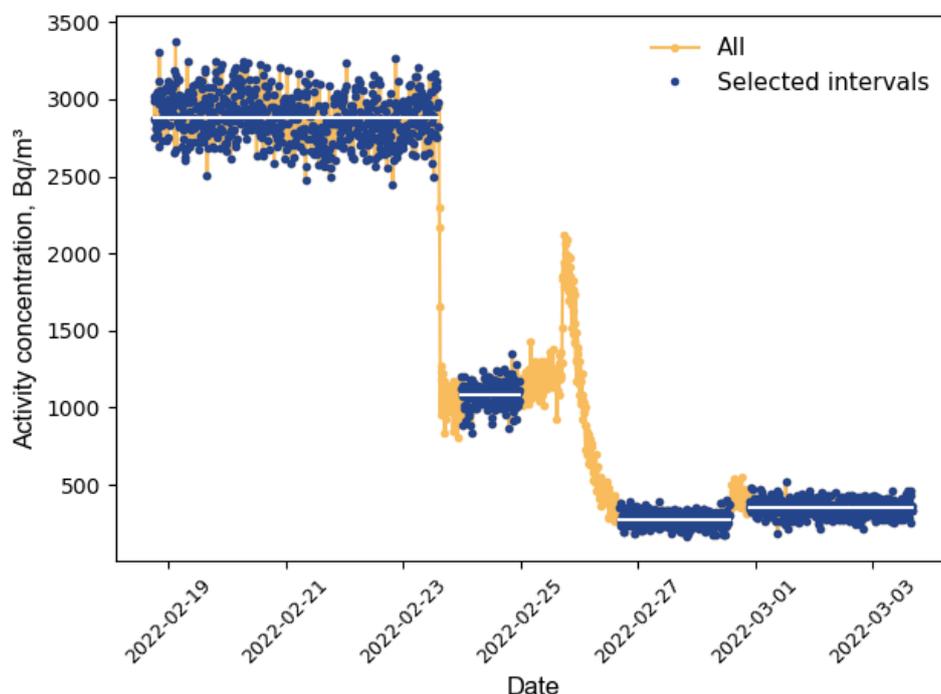
In the current study the RadonEye monitors were exposed in the radon chamber of the UK Health Security Agency (UKHSA), which is a walk-in chamber with a volume of 43 m<sup>3</sup>. The reference instrument used for control of the activity concentration in the chamber in the current study was Atmos 12 DPX. The instrument is regularly calibrated by radon sources traceable to a primary radon standard supplied by Laboratoire National Henri Becquerel, France (LNHB). The measurement of the volume used during the instrument calibration is traceable to the UK National Measurement Regulation Office. The uniformity of radon concentration has been evaluated using 5 groups of 10 passive radon detectors placed in 5 different locations inside the chamber. The one-way ANOVA method was used to determine the statistical difference between the means of these 5 groups. The hypothesis for homogeneity of radon concentration in the chamber cannot be rejected at significance level of 0.05. The UKHSA (formerly NRPB, HPA, PHE) has run an intercomparison program of radon detectors since 1982.

Twenty RadonEye Plus2 monitors were exposed to radon at UKHSA in two sessions. In the first session, four different constant activity concentrations were created (Fig. 1). The exposure session continued for two weeks to ensure long-enough intervals with constant activity. The UKHSA radon chamber was operated in a steady state, i.e. radon concentrations are stable when emanation from the sources is balanced by decay of the radon in the chamber atmosphere. Different activity concentrations were achieved by combining three sources of activity 98, 105 and 78 kBq. Between each exposure the sources were closed and the chamber partially vented to bring the radon activity concentration down quickly to its new lower concentration. In each interval, the average activity concentration and its standard deviation were estimated based on the records of each monitor. For the second session the chamber was resealed and all radon sources were used, allowing the radon concentration to rise. The increase of the activity could be fitted with an exponential function (Fig.2.) of the type:

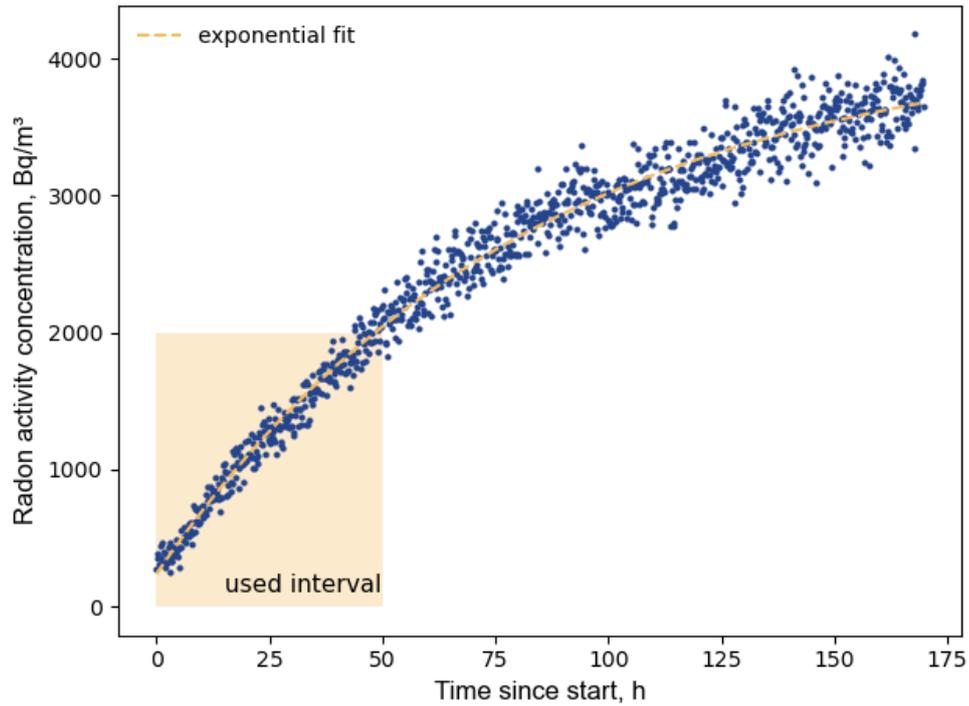
$$C_A = C_{max}(1 - (C_{max} - C_0)\exp(-\lambda t)), \quad (1)$$

where  $C_0$  is the initial activity in the chamber,  $C_{max}$  is the activity at infinity and  $\lambda$  is the effective constant with which radon activity decreases due to decay and airflow. The data was split in 3-hour intervals and the average and standard deviation of the monitors' readings were calculated for each interval. This was done to lower the influence of statistical fluctuations. Only data below 2000 Bq/m<sup>3</sup> (based on the referent monitor) was further used, so that the activities in the intervals were relatively equidistant, and the effect of saturation of the monitors was avoided.

Additional exposures at constant activity concentration were carried out in the radon chamber at Sofia University (SU) in Bulgaria. The chamber is a 200 L vessel in which the activity is supplied by a flow-through radon source (Dimitrova et al., 2023) with emanation rate of 788 Bq/h. Activity concentrations in the range 400 to 1800 Bq/m<sup>3</sup> were created by connecting the source and the chamber in an open system and continuously blowing air with a flow rate between 5 and 30 l/min (the theory is described in Pressyanov et al, 2017). The activity concentration inside the chamber is followed by an AlphaGUARD PQ2000 Pro Rn/Tn detector. These exposures were only used to study the statistical fluctuations of RadonEye readings (i.e. to estimate their standard deviation at constant activity).



**Fig. 1:** Data by the reference instrument Atmos in the first exposure session. In the selected 4 intervals RadonEye Plus2 monitors were exposed at constant activity concentration. The horizontal lines mark the average value. The shortest exposure interval was 24 h.



**Fig. 2:** Data by the reference instrument Atmos in the second exposure session with slowly increasing concentration. The dashed line marks a fit with the function in Eq.(1) with parameters:  $C_{max} = 4160 \pm 30 \text{ Bq/m}^3$ ,  $C_0 = 239 \pm 39 \text{ Bq/m}^3$  and  $\lambda = 0.01231 \pm 0.00023 \text{ h}^{-1}$ . The region below  $2000 \text{ Bq/m}^3$  was used, in which RadonEye Plus2 was shown to be linear and the points were well spread.

## 2.2. Metrological characteristics and correction factor

For each RadonEye monitor the background, linearity and statistical fluctuations were studied and an individual correction factor was estimated.

The performance of the group of 20 RadonEye monitors was evaluated according to the Performance Ranking Scheme, developed by the Health Protection Agency (a predecessor of UK Health Security Agency) (Daraktchieva et al., 2012). The performance parameters are called % biased error and % precision error. The % biased error which measures accuracy is the relative percent error of the mean radon concentration measured by the group of instruments and the reference radon concentration. The % precision error is the relative standard deviation of the radon values measured by the group of the instruments. The % measurement error is the combined error calculated by the square root of the sum of the squares of the above two parameters:

$$\% \textit{ precision error} = 100 \frac{\textit{Standard deviation}}{\textit{Measured mean}} \quad (2)$$

$$\% \textit{ biased error} = 100 \frac{(\textit{Measured mean} - \textit{Reference value})}{\textit{Reference value}} \quad (3)$$

$$\% \textit{ measurement error} = \sqrt{\% \textit{ biased error}^2 + \% \textit{ precision error}^2} \quad (4)$$

The measurement error could be low only if both the biased and the precision error are low. The biased error is intrinsic to the detector type or the batch of detectors and cannot be corrected for. On the other hand, the precision error is a systematic error and can be corrected for. The precision error should correspond to the reproducibility and the biased error to the accuracy declared by the producer. Based on the measurement error the performance of the device is classified from A to F (A – measurement error < 10%, B – 10 % < measurement error < 20%, C – 20 % < measurement error < 30%, D – 30 % < measurement error < 40%, E – 40 % < measurement error < 50%, F – measurement error ≥ 50 %).

The background signal ( $B$ ) is the reading when no radon is present in the ambient atmosphere. The background of the studied RadonEyes was estimated by a 10-day exposure in a nitrogen atmosphere at UKHSA. For each monitor the value of  $B$  was estimated as an average of the 1-hour measurements during the exposure.

The linearity was evaluated by testing the linear dependence between the net radon activity concentrations measured by the RadonEye and by the reference instrument. A good linear dependence has a correlation coefficient close to 1 and no systematic change of slope. The linearity was studied in the range 280 – 2900 Bq/m<sup>3</sup>.

The conducted exposures at UKHSA were used to calibrate the RadonEYE detectors. An individual correction factor was estimated for each monitor. The correction factor is defined as:

$$R_i = \frac{C_{A,ref,net}}{C_{A,i,net}} = \frac{C_{A,ref} - B_{ref}}{C_{A,i} - B} \quad (5)$$

where  $C_{A,ref}$  is the activity concentration determined by the referent monitor,  $B_{ref}$  is the background of the referent monitor,  $C_{A,i}$  is the activity concentration estimated by the RadonEye's readings and  $B$  is the average background of the RadonEyes. The values of  $R_i$  were estimated as slopes of the linear fits of the function  $C_{A,ref,net}(C_{A,i,net})$ . The correction factor is used to correct for the individual response of the corresponding monitor by multiplying its readings.

The statistical fluctuations of each monitor were evaluated in terms of the standard deviation of the 1-hour measurements during exposure at constant radon activity concentration. Seven exposures in the range 160 – 1800 Bq/m<sup>3</sup> were conducted at UKHSA and at Sofia university and each lasted at least 12 hours. Since RadonEyes do not report the single measurement uncertainty or the number of counts, the obtained values were compared to a simplified formula. The expected statistical fluctuations  $\sigma_{stat}$  can be obtained assuming that the measured activity concentration  $C_A$  is proportional to a certain number of counts  $N$  that follow a Poisson distribution. Background correction and other corrections that might be done during the signal processing are neglected. Then:

$$\sigma_{stat}(C_A) = C_A \cdot \delta_{stat} = \frac{C_A}{\sqrt{N}} = \frac{C_A}{\sqrt{k \cdot C_A \cdot \Delta t}} = \sqrt{\frac{C_A}{k \cdot \Delta t}}, \quad (6)$$

where  $\delta_{stat} = 1/\sqrt{N}$  is the relative uncertainty the number of counts,  $k = N/(\Delta t \cdot C_A)$  is the detector sensitivity in cpm/(Bq/m<sup>3</sup>) and  $\Delta t$  is the duration in minutes of the measurement interval (60 minutes for RadonEye Plus2). The statistical fluctuations of the individual measurements can be neglected when estimating long-term averages of the radon concentration. However, when a monitor is used to trigger threshold alarms or to control the operation of a radon mitigation systems, the range of statistical fluctuations should be known. It is also important for studies on the dynamics of indoor radon.

### 3. Results

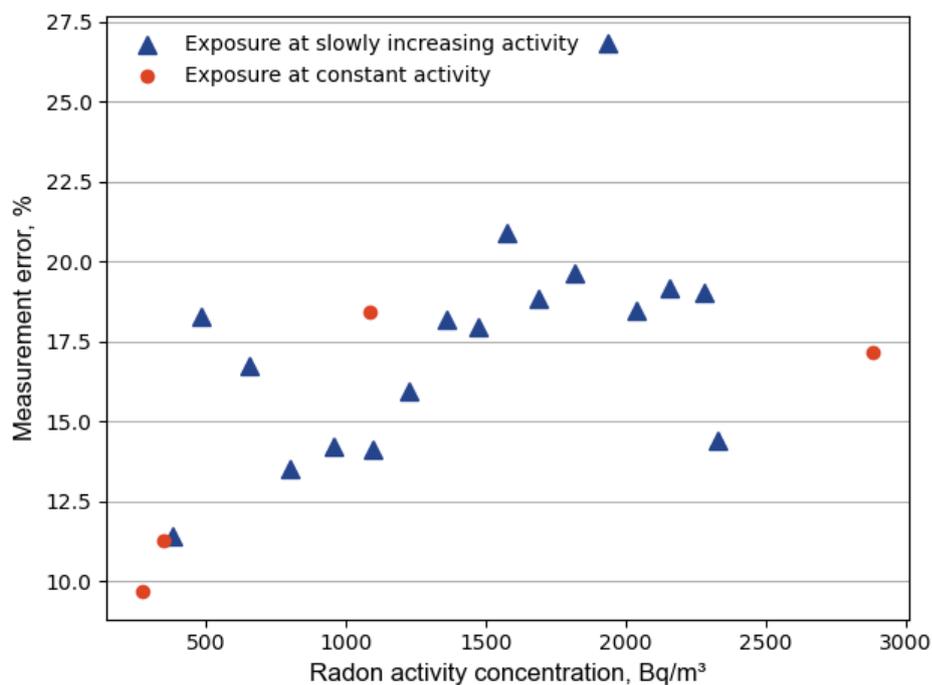
The results for the precision and bias errors estimated by exposure at constant radon concentrations (Fig.1) are presented in Table 1. As seen, the precision error is consistent, while the biased error is higher at higher radon concentrations. In the studied range, the measurement error is below 20%.

The same estimates could be applied to the results from the exposure session in Fig.2 by splitting it to 17 3-hour intervals and using the average radon activity concentrations reported by the 20 RadonEyes in each interval. Indeed, the radon concentration during the 3-hour intervals was not constant, but all detectors were exposed under the same conditions. The standard deviation and the mean value of the 20 detectors were estimated for each interval and used to estimate the precision error by Eq (2). The average activity concentration reported by the reference instrument in each interval was used to estimate the measurement error by Eq (3). In Fig.3 the results for the measurement error obtained

for the exposures at constant and at slowly increasing radon concentration are compared. The results for the measurement error agree very well. In all cases the precision error was 9 – 10 %. The estimate based on shorter intervals is more prone to random fluctuations of the biased error.

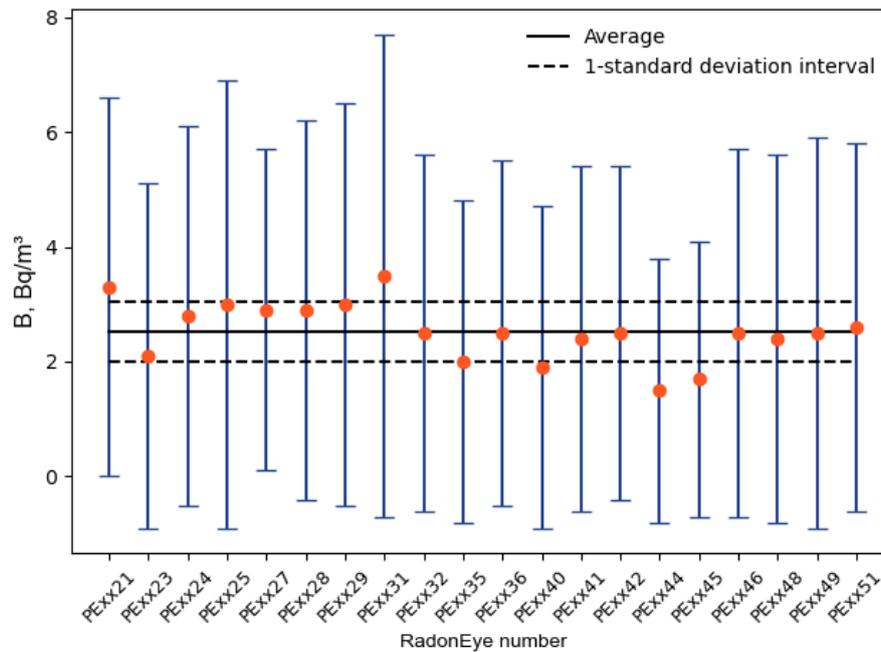
Referent activity, Bq/m <sup>3</sup>		Measured activity, Bq/m <sup>3</sup>		Precision error, %	Biased error, %	Measurement error, %	Performance class
average	st. dev.	average	st. dev.				
276	50	283	26	2.8	9.2	9.7	A
347	53	372	33	7.1	8.8	11.3	B
1084	87	1258	113	16.1	9.0	18.4	B
2879	153	3295	307	14.4	9.3	17.2	B

**Table 1:** Precision, biased and measurement errors and the corresponding performance class for a group of 20 RadonEye Plus2 monitors.



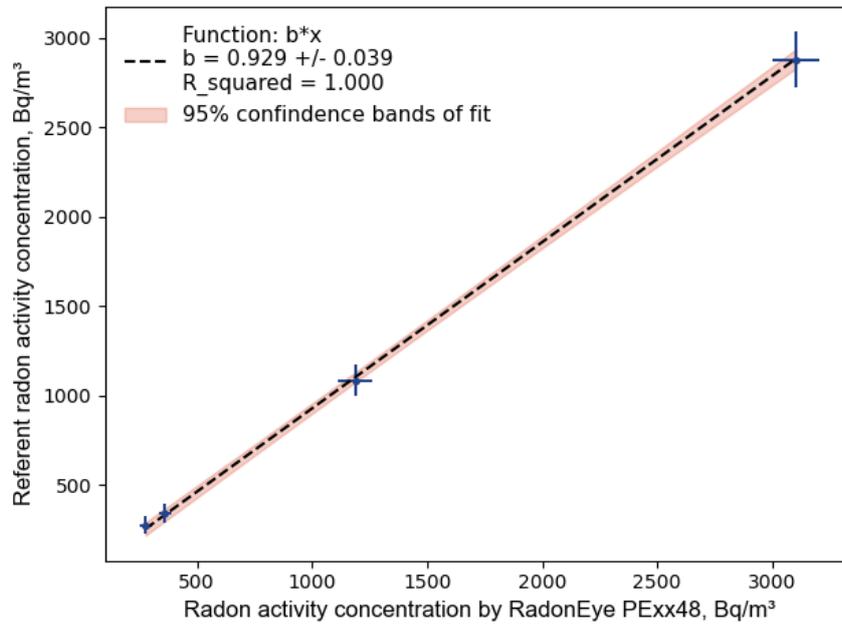
**Fig 3:** Comparison of the measurement errors in the two calibration regimes.

Results for the background signal are shown in Fig. 4. Different monitors had very similar background with a standard deviation comparable to the average value. The average of the background of the 20 monitors was  $2.5 \text{ Bq/m}^3$  with a standard deviation of  $0.5 \text{ Bq/m}^3$ .

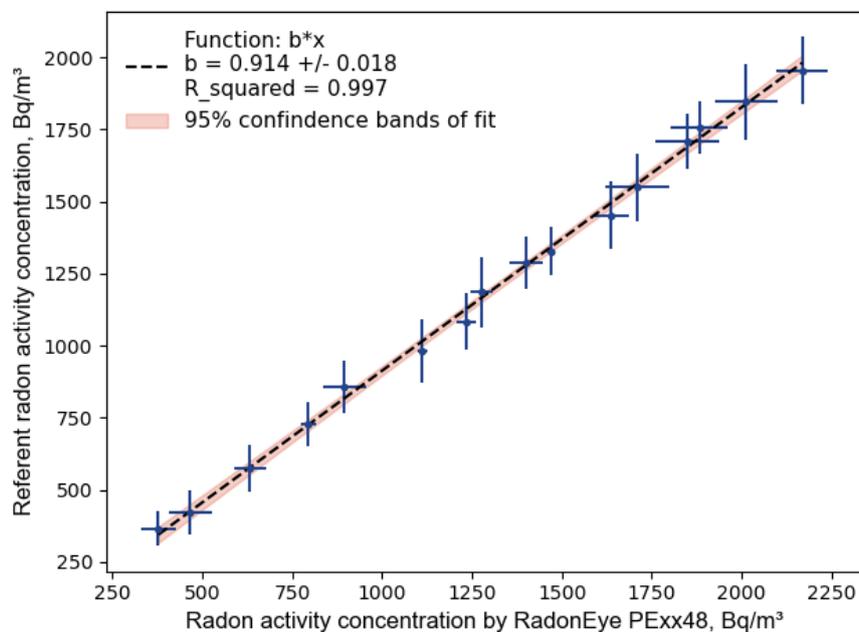


**Fig. 4:** Average and standard deviation (error bars) of the 10-day-long background signal ( $B$ ). Different data points correspond to different new RadonEye monitors.

The linearity of the monitors' response in the studied interval was tested by studying the correlation of the results of the referent monitor Atmos and of each RadonEye monitor. For all detectors in the two exposure modes excellent correlations were found with correlation coefficients above 0.99. Examples are shown in Fig. 5 and Fig. 6. Overall, an excellent linearity was observed in the range below  $3000 \text{ Bq/m}^3$ .



**Fig. 5:** Radon activity concentration by the Atmos and one of the RadonEyes. The datapoints are averages for the intervals in Fig.1 and the error bars are the standard deviations. A linear fit through zero is shown, where the slope  $b$  and the squared correlation coefficient are given. The 95% confidence bands of the fit are shaded.



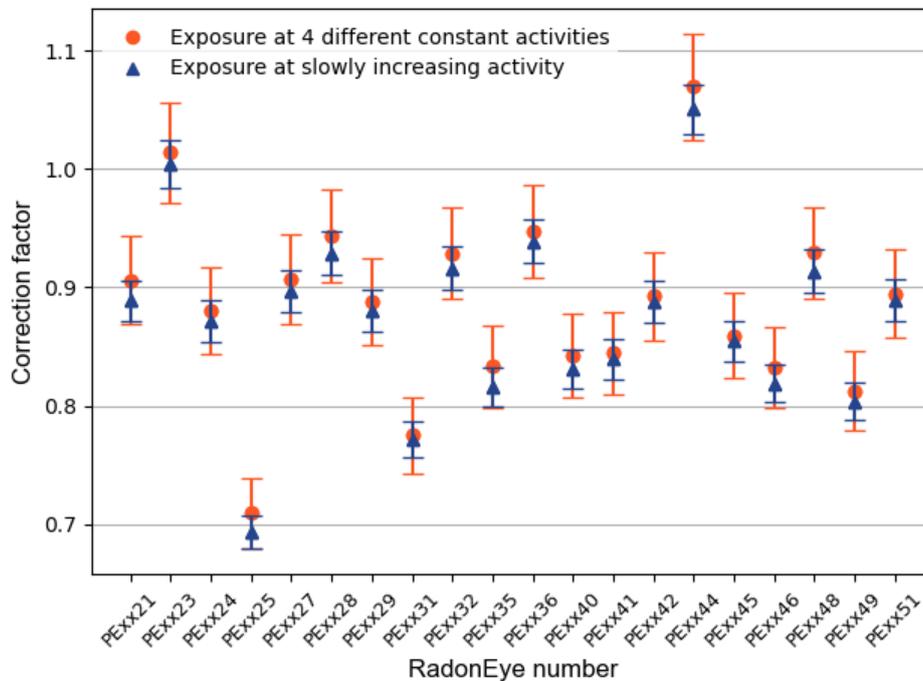
**Fig. 6:** Radon activity concentration by the Atmos and one of the RadonEyes. The datapoints are 3-hour averages for the interval below 2000 Bq/m<sup>3</sup> in Fig. 2 and the error bars are the standard deviations. A linear fit through zero is shown, where the slope  $b$  and the squared correlation coefficient are given. The 95% confidence bands of the fit are shaded.

The excellent correlations between the net signal of the referent monitor Atmos and of the RadonEye monitors were used to estimate  $R$  by the slopes of the linear fit through the origin (see Fig. 5 and Fig. 6). This was done separately for the two exposure sessions.

For all 20 studied monitors the correction factors in the two exposure modes agreed within the statistical uncertainties. A comparison is shown in Fig. 7. The final estimate of  $R$  was made as an average of the two. An uncertainty budget is provided in Table 2. The obtained correction factors for the 20 studied RadonEye Plus2 monitors ranged from 0.70 to 1.06 with an average of 0.880 and a standard deviation of 0.079.

As can be seen in Fig. 7, almost all correction factors were below 1, indicating that the studied monitors overestimate the activity concentration. For half of the monitors, the overestimation exceeded 10 %.

The same detectors had been previously exposed in the radon chamber at SU (Dimitrova et al., 2023). For all but two devices the values of the correction factor obtained at SU were the same as those obtained at UKHSA within the uncertainties (see Fig. 8). The two cases with higher difference can be attributed to the worse fits obtained for the exposures at SU.

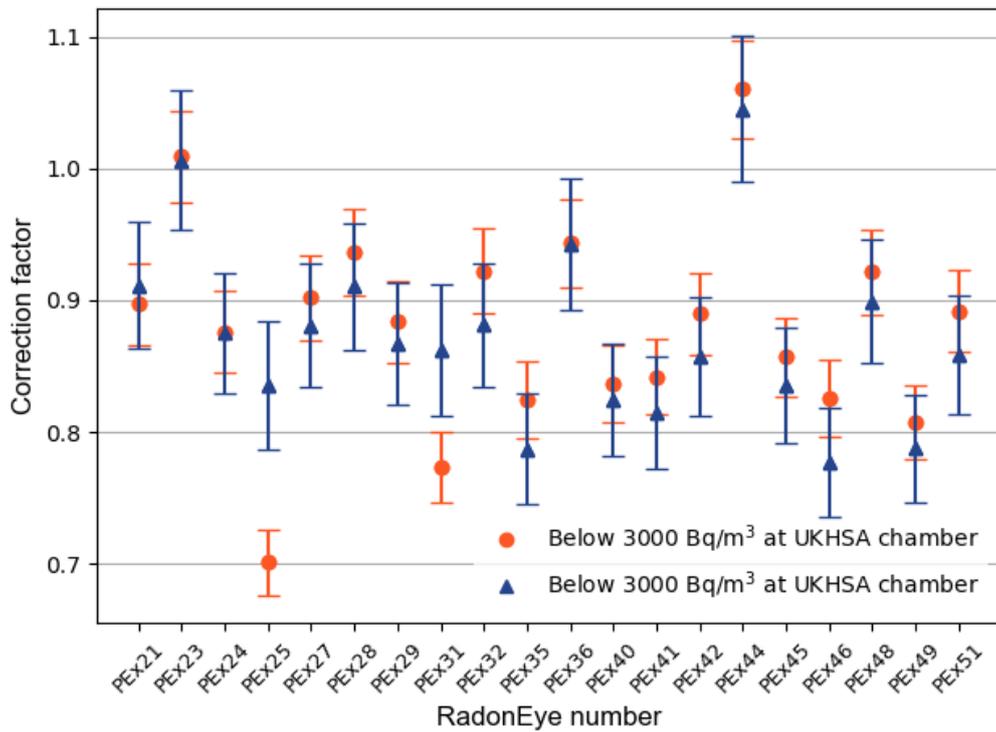


**Fig. 7:** Comparison of the correction factors obtained by exposure at intervals with constant  $C_A$  (Fig. 1) and at slowly increasing  $C_A$  (Fig.2). The error bars represent the uncertainty at the level of  $1\sigma$ , which includes only the uncertainty in the fit parameters.

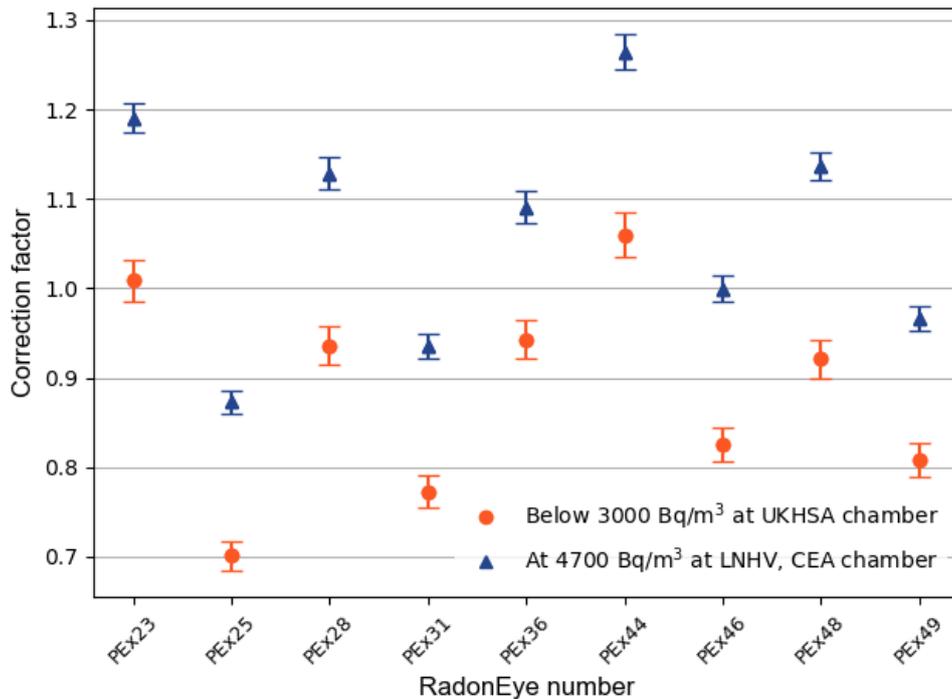
<b>Quantity</b>	<b>Components</b>	<b>Method</b>	<b>Relative standard uncertainty, %</b>
<b>Referent <math>C_A</math> by Atmos</b>	Efficiency of referent monitor, including uncertainty of radon gas standard, calibration volume and statistical counting uncertainty	By standard calibration certificate, calculation of the volume uncertainty and statistics of measurements	2.7
<b>RadonEye response</b>	Statistical counting uncertainty	Uncertainty of the slope of the linear fit, assuming normal distribution of the residuals	2.3
<b>Combined standard uncertainty of <math>R</math></b>			3.5 (k=1)

**Table 2:** Uncertainty budget of the estimated correction factors for the RadonEye monitors.

Nine of the monitors had been previously exposed in the LNHB's noble gas reference system (Sabot et al, 2020). The radon volume activity in the chamber was derived from the  $^{222}\text{Rn}$  primary standard of LNHB. The exposure was carried out at activity concentration of  $4702 \pm 61 \text{ Bq/m}^3$ . The correction factors for the RadonEyes are compared with those obtained at UKHSA in Fig. 9. The significantly higher correction factors obtained at LNHB, corresponding to lower reading of the RadonEyes, can be attributed to the non-linearity of RadonEyes at higher activity concentrations observed previously (Turtiainen et al., 2021, Dimitrova et al., 2023). The lower readings of the RadonEye at higher activity concentrations are probably due to saturation. The effect becomes significant at values higher than  $3500 \text{ Bq/m}^3$  (Dimitrova et al., 2023). One can try and correct for the non-linearity (Dimitrova et al., 2023), but should be careful since different RadonEye monitors can saturate at different levels, sometimes even below  $6000 \text{ Bq/m}^3$  (Mitev et al., 2022). A drawback of the RadonEyes is that when saturated, they record zeros in their memory.



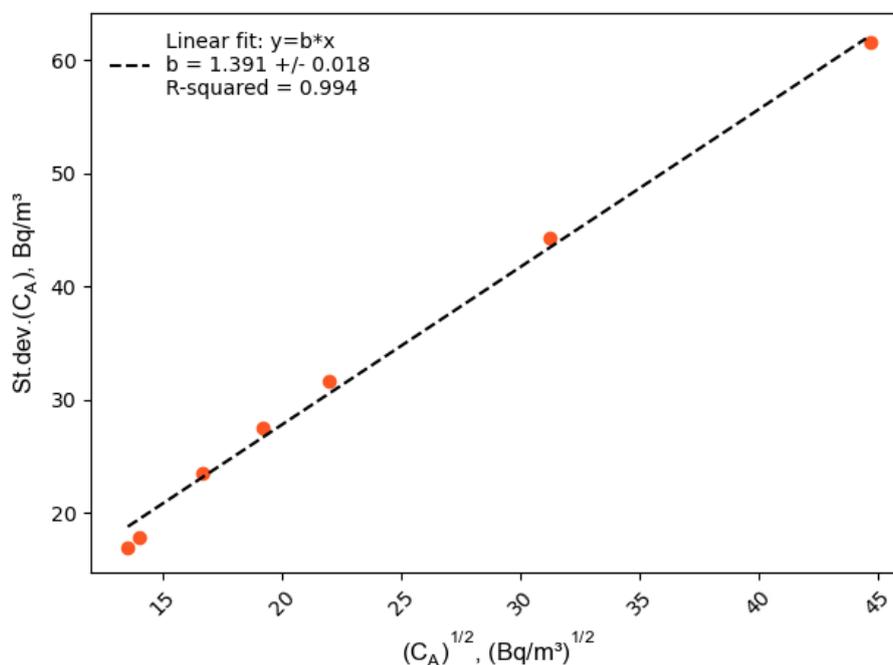
**Fig. 8:** Comparison of the correction factors  $R_i$  obtained by exposures at UKHSA and SU. The error bars represent the combined uncertainties at the level of  $1\sigma$ .



**Fig. 9:** Comparison of the correction factors  $R_i$  obtained by exposures at UKHSA and LNHB. The error bars represent the combined uncertainties at the level of  $1\sigma$ .

The applicability of Eq.(6) for estimation of the statistical fluctuations was tested in the exposures at constant activity concentration. The standard deviation (as an estimate for  $\sigma_{stat}$ ) and the average ( $C_A$ ) of the readings of each monitor at the given radon concentration were calculated. For each of the 20 monitors linear fits of  $\sigma_{stat}$  as a function of  $\sqrt{C_A}$  were made with zero intercept. The coefficient of determination (COD,  $R^2$ ) was estimated for each fit. Its values ranged from 0.66 to 0.99. An example with excellent correlation is illustrated in Fig. 7. The fit slopes allowed to estimate an average value of  $k = 0.0069 \pm 0.0011$  cpm/(Bq/m<sup>3</sup>). This shows that if the sensitivity provided by the producer of 0.0135 cpm/(Bq/m<sup>3</sup>) was used in Eq. (4), the statistical fluctuations would be underestimated.

The conducted exposures were at activity concentrations between 160 and 1800 Bq/m<sup>3</sup>, which includes the typical recommended threshold of 300 Bq/m<sup>3</sup>. The results indicate that in the studied range the simplified relation given by Eq.(6) with an experimentally determined value of  $k$  is applicable. However, exposures at lower radon concentration are necessary to test if the dependence can be extrapolated downwards.



**Fig. 10:** Example of good correlation between the standard deviation (st. dev.) of  $C_A$  and the square root of the average concentration ( $C_A^{1/2}$ ) for exposures at constant activity concentration in the range 160 – 1800 Bq/m<sup>3</sup>. The dashed line represents a linear fit with zero intercept and its slope  $b$  and COD (R-squared) is given.

#### 4. Discussion

The results from the current study demonstrate that the RadonEye Plus2 monitor has metrological characteristics sufficient for measurements in dwelling and workplaces. It has low background, sufficient precision and accuracy and excellent linearity in the range below 3000 Bq/m<sup>3</sup>. However, the wide range of individual correction factors (from 0.70 to 1.06) highlights the importance of individual calibration, especially if the results are used in decisions-making or research.

The availability of data on radon concentrations in time gives new options for calibration of the electronic monitors. Our results show that successful calibration and linearity test could be done in a single exposure with slowly changing radon concentration. The same regime can even be used for evaluation of the precision and accuracy of the monitors. The change in activity should be relatively small in comparison to the duration of a single measurement and to the response time of the monitor. In our case, the measurement duration of RadonEyes is 60 minutes and their response time is about 90 minutes for reaching 90% of their plateau when exposed to rectangular activity pulses (Dimitrova et al., 2023). During the exposure (shown in Fig.2) the change of radon concentration in 60 minutes was 20% in the first hour, less than 10% after the first 6 hours and less than 5% after the first 14 hours. The removal of the first 6 hours did not improve the correlations between the RadonEye values and the referent activity concentration and did not lead to significant change in the slopes of the fits (see Fig. 6). It should be noted that at the beginning of the conducted exposure (Fig.2) there was residual activity in the chamber which led to smaller relative increase of the activity in the first hours compared to the case with no initial activity.

This exposure regime can save time in calibration of consumer-grade radon monitors, since it does not require reaching and maintaining stable radon concentrations. Furthermore, it can cover the range of low activity concentrations most typical for buildings. It is also interesting to note that a similar exposure regime (exponentially increasing radon concentration) can be achieved by simply opening a radium source with no or low initial activity of radon and letting radon exhalate in a closed volume. In this case the activity would rise with the build-up of radon with  $\lambda = 0.007554 \text{ h}^{-1}$  (corresponding to the half-life of radon of  $91.76 \pm 0.02 \text{ h}$  reported by Be et al. (2008)). Such a system can be easily created. In fact, a system with a source with small and known radon exhalation rate in a portable vessel

with certified volume can potentially serve for in-situ calibration. This could prove useful for calibration of monitors used in public buildings and workplaces.

## **5. Conclusions**

The metrological characteristics of 20 RadonEye Plus2 monitors were investigated. The newly bought monitors had low background with average of  $2.5 \text{ Bq/m}^3$  and a standard deviation of  $0.5 \text{ Bq/m}^3$ . The precision error for the studied group was estimated at about 9 % and the biased error ranged from 3 % to 16 % for activities in the range 280 – 2900  $\text{Bq/m}^3$ . An excellent linearity of the readings of all monitors was observed in this range. A simplified formula for evaluation of the statistical fluctuations of the single measurement values was tested. It predicts 9 % for the relative standard deviation of the RadonEye Plus2 measurements at  $300 \text{ Bq/m}^3$ , which agrees with the experimental results.

Due to the large individual bias of some of the monitors, the correction factor was estimated for each monitor. It ranged from 0.70 to 1.06 with an average of 0.880 and a standard deviation of 0.079. This highlights that individual calibration is advisable if measurements are made for research, legislation compliance tests or decision making.

During the calibration a simplified exposure regime was tested along with the standard regime. The excellent agreement between the results from the two approaches shows that the new regime could be successfully used for simultaneous calibration and linearity tests of the RadonEye Plus2 monitors. In this regime the activity concentration increases exponentially with a small rate, so that it is almost constant within the duration of a single measurement. Moreover, similar exposure regimes can be achieved with just a radon source with known exhalation rate and a certified volume. This mode allows fast and simple calibration and testing of consumer-grade radon monitors and can potentially serve for in-situ calibration. Such techniques will be necessary in context of the wider spread of radon monitors and their provisioned application in smart and energy- efficient solutions for air quality control.

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## 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.

## Data availability

Data will be made available on request.

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