ORIGINAL ARTICLE

Recent work with electronic radon detectors for continuous Radon-222 monitoring

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Abstract

Background: Sensitive electronic radon detectors can be an advantageous solution for continuous monitoring of radon dynamics in dwellings and workplaces. In order to investigate their applicability, such detectors must be subjected to adequate metrological assurance, and their performance in field conditions must be tested and evaluated.

Objectives: To perform laboratory and field tests in order to evaluate the applicability of RadonEye^{+2} instruments for continuous radon monitoring.

Results: In this work, we have performed laboratory tests of 36 RadonEye^{+2} detectors, which appear to have linear response for ^{222}Rn concentrations below 3.5 kBq/m^3 and a non-linear response (<15%) in the interval from 3.5 to 7 kBq/m^3. Their response to ^{222}Rn at 4.7 kBq/m^3 is within 15% to the reference. In experiments with sharp variation of the ^{222}Rn concentration, the detectors show fast response within 2 h. For the application of the detectors in dwellings and workplaces, we have developed a database, which collects, stores and visualises the RadonEye data. The database proved to be very useful tool, not only for data analysis but also for the identification of interruptions in the detectors operation and/or their connection to the internet. In a pilot 10-month-long study with three detectors located in different dwellings, we have observed more than 91% uptime of the online data collection from the detectors and more than 96% uptime of the data recording in the internal memory of the instruments.

Conclusions: Overall, the results show that the RadonEye^{+2} instruments are very suitable for continuous radon monitoring and may be useful for follow-up of radon dynamics in long-term measurement campaigns in homes and workplaces.

Keywords: *indoor radon; continuous monitoring; electronic radon detectors*

A significant number of electronic radon monitors have emerged in the last two decades. These detectors offer an interesting possibility for continuous radon monitoring in dwellings and workplaces. In principle, they can provide useful information for the assessment of indoor ^{222}Rn dynamics. However, prior their wide-scale usage, the electronic radon detectors should be a subject of sound metrological assurance, in which many aspects of their performance should be tested. Amongst these are as follows: calibration factor, linearity of response, temporal response, thoron cross-interference, etc. In a previous study, the thoron cross-interference of various electronic detectors has been studied systematically (1). During these tests, the RadonEye^{+2} (RE) electronic radon detectors (2) demonstrated excellent sensitivity to ^{222}Rn and quick temporal response, which outlined them as good candidates to be tried out in campaigns for continuous ^{222}Rn monitoring. This type of detector has been preferred also for improving the assessment of indoor exposure to radon in workplaces (3).

In this work, we present results from metrological tests of the calibration factor, linearity of response and temporal response of 36 RadonEye^{+2} radon detectors, which were performed in the Sofia University (Bulgaria) and in the French primary metrology laboratory LNE-LNHB (Laboratoire National Henri Becquerel). To facilitate the monitoring of indoor ^{222}Rn dynamics with these detectors, we developed a database for storage, online visualisation and analysis of the radon data gathered by them. The features of the database and the applicability of the electronic detectors for field studies are discussed. Pilot results from the applications of such detectors in radon surveys in dwellings and workplaces are presented and discussed.

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Methods and materials

This study employed 36 RadonEye detectors purchased in 2020 from FTLab corporation. The detectors come with common calibration certificate, which states that the RadonEye^{+2} has been individually calibrated by equipment traceable to international standards and has been inspected. The declared specifications are given in Table 1.

According to the producer, the detectors perform radon activity concentration measurements on a 10-min basis, calculate the 60-min moving average every 10 min and report its value. The detectors store the data in the internal memory every hour (i.e. each sixth reading is stored), and this data can be read via Bluetooth connection from a mobile phone (hereafter the data collected in this way is referred to as Bluetooth RE data). When the REs are connected to the Wi-Fi network, every 10 min they broadcast the result (the 60-min moving average) over the Internet, and this data can be collected (these data are referred as Web RE data). Thus, the Bluetooth RE data contain records on hourly basis, and the Web RE data contain records on 10-min basis.

Table 1. RadonEye specifications as declared by the producer (2)

Radon activity concentration (measurement range)	4–9,435 Bq/m^3
Temperature (operating range)	10–40°C
Relative humidity (RH) (operating range)	<80%
Sensitivity	0.5 cpm/pCi/L (~20 cpm/Bq/m^3)
Precision (reproducibility) at 370 Bq/m^3	<10%
Accuracy at 370 Bq/m^3	<10% (min. error < 0.5 pCi/L)

The application of the RadonEye^{+2} detectors for radon surveys and studies of the radon dynamics require suitable tool that allows gathering and storage of the measurement data. As the RadonEyes are not initially designed for this use, such tool, to the best of our knowledge, is not available even by the producer. Therefore, we have developed a web accessible database (further referred to as SPIRAD, see Fig. 1), which has the following functionality: collects and stores the Web RE data and manages active REs (which were set-up to stream data over Wi-Fi) and their locations. Previous locations and their time intervals are listed for quick reference during data analysis. The web interface of the database also shows real-time RE values of the active detectors to identify problems with the Wi-Fi connection and response of devices and can visualise the RE data (^{222}Rn concentration, temperature and humidity vs. time). The records of an individual detector or a selected group can be exported in convenient format: the record (written in a CSV-file) can include the whole measurement data, or it can be restricted to a certain period of time and can include certain type of measurement (e.g. radon concentration and/or temperature and/or humidity) and/or other available data. The Bluetooth RE data can also be stored in the database by uploading it via the web interface. The Web and Bluetooth RE data are stored under different flags, so that it can be visualised, downloaded and analysed together or separately. Examples of the interface to the database and its visualisation capabilities are given in Fig. 2. Hereafter, in the tables and in the figures in this manuscript, the RadonEye detectors are noted either by their product number (e.g. PE22101200007) or our internal laboratory number (e.g. RE07).

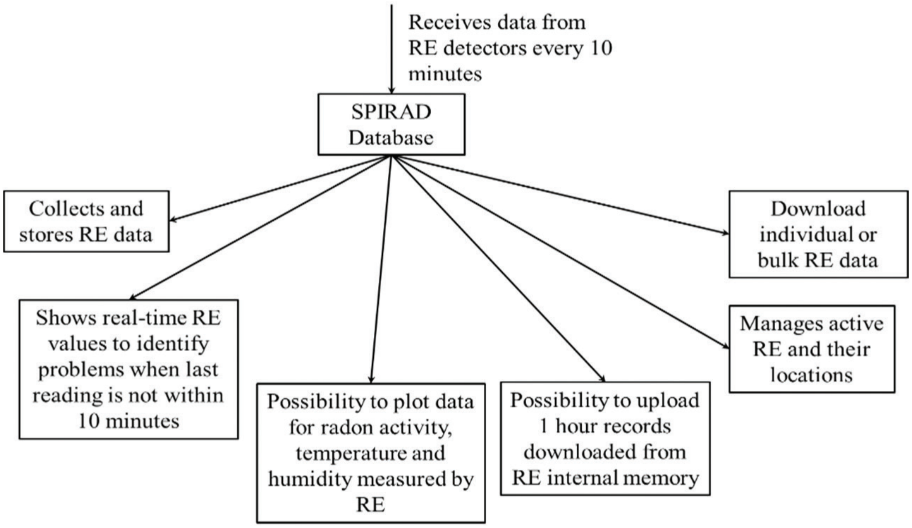

Fig. 1. Schematic representation of the SPIRAD database and its functionality.

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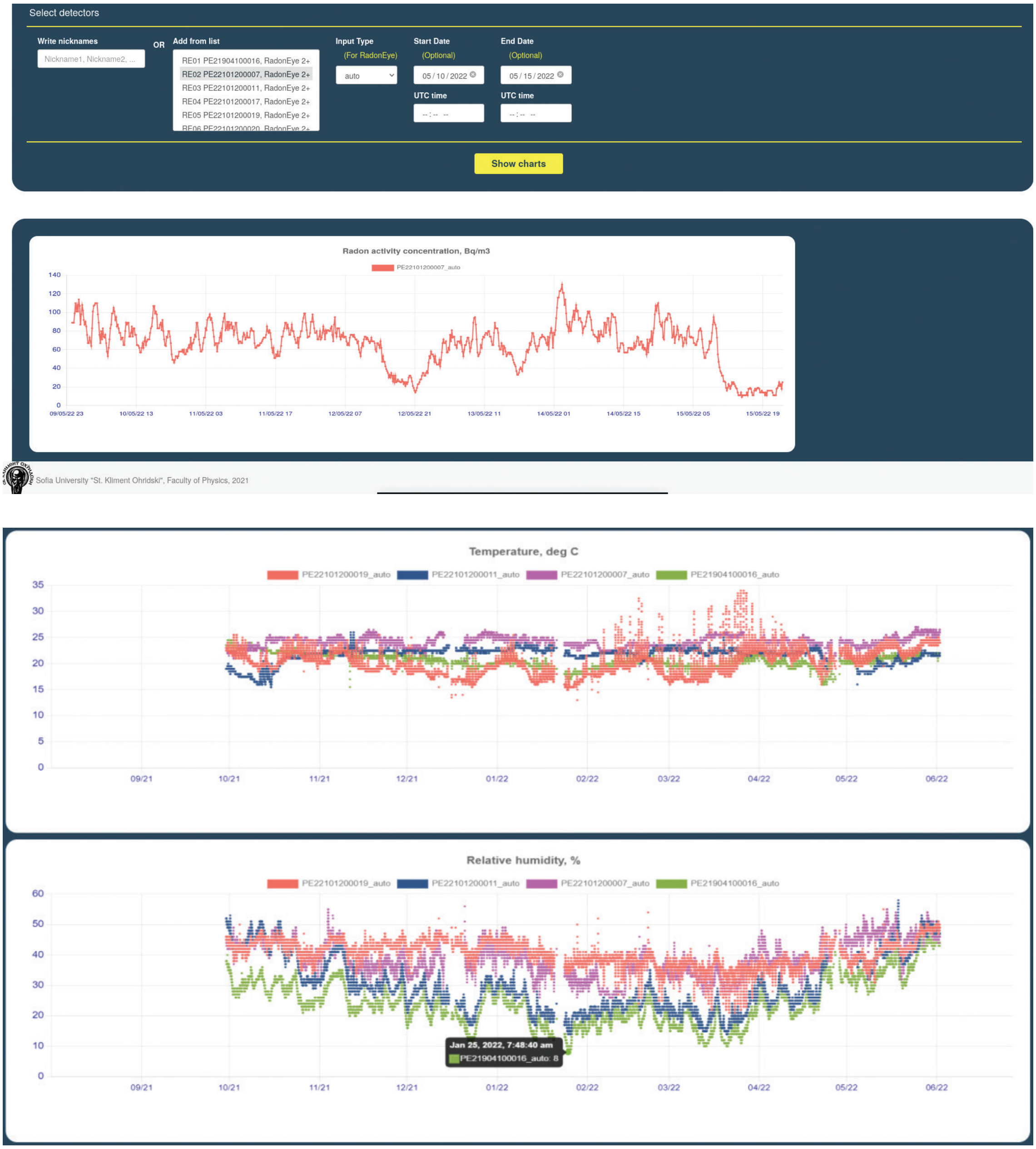

Select detectors

Write nicknames: Nickname1, Nickname2, ...

OR

Add from list:
- RE01 PE21904100016, RadonEye 2+
- RE02 PE22101200007, RadonEye 2+
- RE03 PE22101200011, RadonEye 2+
- RE04 PE22101200017, RadonEye 2+
- RE05 PE22101200019, RadonEye 2+
- RE06 PE22101200020, RadonEye 2+

Input Type (For RadonEye): auto

Start Date (Optional): 05 / 10 / 2022

UTC time: -- : -- --

End Date (Optional): 05 / 15 / 2022

UTC time: -- : -- --

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Fig. 2. An example of the control and visualisation capabilities of the SPIRAD database.

The tests of the response of the RE were performed at the ^{222}Rn/^{220}Rn laboratory facility at Sofia University (Fig. 3). This facility can create ^{222}Rn and/or ^{220}Rn concentrations with a predefined temporal pattern (4). In this work, the facility was upgraded with a larger (200 L) exposure volume to allow testing more detectors simultaneously. The 200 L volume has hermetic power supply and USB plug-ins. This allows to conduct experiments with longer duration and to read the detectors at any time. The 200 L volume also has several inlets and outlets with hermetic valves. The facility was also upgraded using a pump with adjustable flow-rate up to 30 L/min. This allows to create low level (about 350 Bq/m^3) constant ^{222}Rn concentrations in a flow-through mode (Fig. 4, second exposure) and to conduct calibrations and studies of detectors at concentrations closer to the typical indoor radon. The high flow-rate of the pump allows faster homogenisation of the activity in the beginning of the experiment and reduces the duration of the transient processes. The reference radon monitor used at Sofia University is an AlphaGUARD PQ2000 PRO.

For this experiment, 35 REs, one AlphaGUARD and two other radon monitors (AlphaE and RAD7) were arranged in the 200 L volume, and all the detectors were

Fig. 3. The ^{222}Rn/^{220}Rn laboratory facility at Sofia University (left). Centre: the new 200 L exposure chamber. Right: the exposure chamber filled with radon detectors.

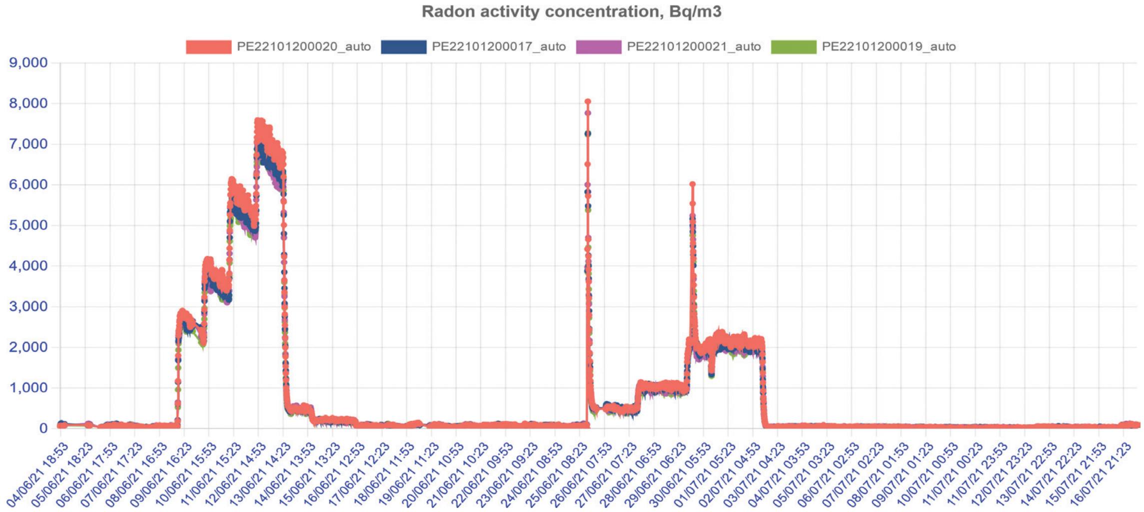

Fig. 4. Examples of two exposures (first: 08/06/21 – 16/06/21; second: 25/06/21 – 03/07/21) of ^{222}Rn measurement instruments at Sofia University. All the readings are from the four RadonEye instruments.

power-supplied via the plug-in available (Fig. 3). The REs were connected to a Wi-Fi router installed close to the 200 L vessel, whilst the AlphaGUARD was connected to a computer via the USB plug-in. A certified radon source was connected to the pump described above and was fed to an inlet of the 200 L volume, and the outlets were opened. This open-loop system allows to create different low radon concentrations (down to 350 Bq/m^3) by varying the flow-rate of the pump (Fig. 4). Due to the heat generated by the power supply adaptors of the detectors, two fans (available in the 200 L vessel) were switched-on to ensure air circulation. The walls of the vessel were cooled by a conventional room air conditioner, which ensured the efficient cooling of the whole system in an open loop with an increase of the temperature in the chamber within 1–2°C (no more than 20 monitors can be efficiently cooled in a closed system).

The exposures at LNHB were performed at the recently developed noble gas reference system shown in Fig. 5. The system allows quick and sharp changes of ^{222}Rn concentrations, exposures to ^{222}Rn-free air, ^{222}Rn transfer from the ^{222}Rn primary standard of LNHB (5) and measurements with reference ^{222}Rn measurement instruments (6). Due to the smaller volume of the exposure chamber in LNHB, only nine REs were exposed (these nine REs were exposed also in Sofia University). In the current experiments, the reference radon instrument was the AlphaGUARD PQ2000 PRO, which is the well characterised ^{222}Rn reference instrument of IRSN. The two AlphaGUARD monitors (the one of the Sofia University and the one of IRSN) were successfully compared in the frame of a recent intercomparison carried out in IRSN (7).

In order to quantify the performance of the REs, we use the response factor (R), defined in this work as

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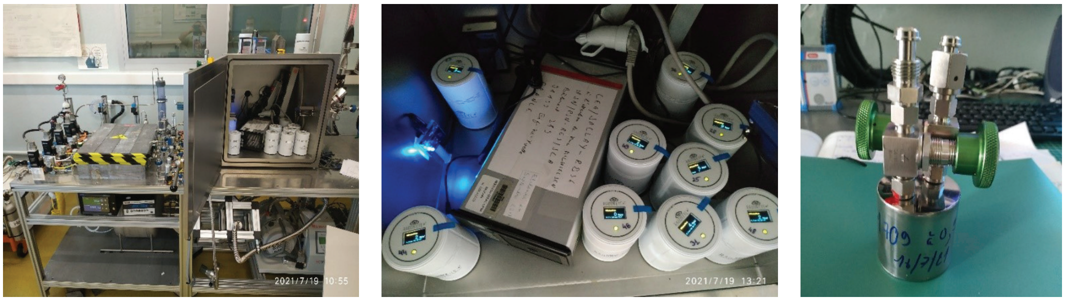

Fig. 5. The ^{222}Rn/^{220}Rn laboratory facility at LNHB (left). Centre: the REs in the system together with the reference instrument AlphaGUARD. Right: the volume used to transfer the radon in the system from the primary ^{222}Rn standard.

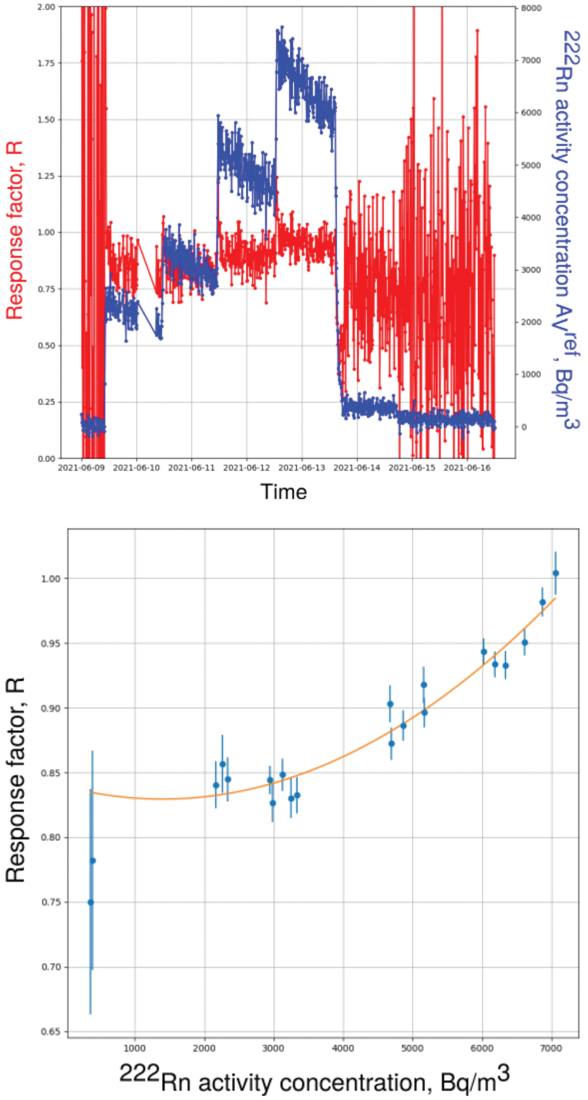

Fig. 6. Up: example of the results of the exposure performed at Sofia University. The blue line indicates $A_V^{ref}(t)$, and the red line indicates the observed response factor for one of the instruments. Down: example of the observed non-linearity of the response of REs. The uncertainty bars on the right figure indicate the overall estimated statistical uncertainty of the response factor.

$$R = \frac{A_V^{ref}(t)}{A_V^{RadonEye}(t)}, \tag{1}$$

where $A_V^{ref}(t)$ is the ^{222}Rn activity concentration measured by the reference instrument at a moment t and $A_V^{RadonEye}(t)$ is the ^{222}Rn reading of the RE instrument at the same moment t. The response factor R is determined in simultaneous exposures of the reference instrument and the REs in the exposure facilities.

Results

The response factor of an RE estimated in one of the exposures at Sofia University is shown in Fig. 6 (left). The detectors were exposed to different activity concentrations up to 7 kBq/m^3. A non-linearity of the response of the REs was observed – a typical example is shown in Fig. 6 (right). From these results, it appears that the response of the instruments seems linear up to 3.5 kBq/m^3 and has a slight non-linearity (<15%) in the range 3.5–7 kBq/m^3. The variation of the estimated response factor is due to variations in the response of the tested instrument (RE) and the variations of the response of the reference instrument (AlphaGUARD PQ2000 PRO). At low radon activity concentrations (<300 Bq/m^3), both instruments contribute to the variation of R, and further studies are planned in order to evaluate the intrinsic variation of the response of the RE instrument.

During the acceptance tests of the REs, we observed differences in the maximum range of the readings of different detectors. This situation is illustrated in Fig. 7, where one of the detectors (RE36) saturates at 5,900 Bq/m^3 and the other (RE22) saturates at about 6,300 Bq/m^3, whilst the others continue to operate normally, and their readings are close to the reference monitor. One misleading feature of the REs is that when they saturate at high activity concentration, they start to record zeroes as measurement results (Figs. 7 and 8). This aberration can cause bias because such saturation can occur in dwellings and workplaces (e.g. underground or spa workplaces). In cases with zero readings in the RE data, the database of stored

Fig. 7. Examples for saturation of the detectors. When saturated, the detectors record 0 Bq/m^3 – RE36 (orange line) in the left graph and RE50 (green line) in the left graph. The time format on the abscissa is 'Month-day hour'.

RE data can be used for recovery of the exposure history. Due to the different saturation levels of the detectors, the maximum activity concentration used in this study was set at 7 kBq/m^3.

Figure 9 depicts the data obtained from the exposures at LNE-LNHB. Two spikes with ^{222}Rn were performed: one short (~5 h) spike with small activity and a long one (30 h) with higher activity (4.7 kBq/m^3). The objective of the first spike was to test the time response of the detectors and how quickly they return to their background levels after the end of the exposure, when the system was flushed with ^{222}Rn-free air. Therefore, the activity concentration (of the order of 1 kBq/m^3) was not controlled during the first spike. In these experiments, the data from the REs were collected through the Bluetooth connection, and, thus, it was stored in the device each hour. Overall, we observe a quick response of the REs and a quick return to their baseline levels (<10 Bq/m^3) within 2 h after the end of the exposure. The response factors determined in this exposure are given in Table 2. The background signal of the REs obtained in a 24-h exposure in radon-free air is also shown in Table 2.

The information from the REs can be obtained by two modes: by Bluetooth connection (Bluetooth RE data, recorded each hour) or by Wi-Fi – connection to the internet (Web RE data, broadcasted every 10 min). In order to compare the types of data harvesting, we performed pilot, long-term exposures of the REs in several locations in Bulgaria, as summarised in Table 3. An example of the data collected from such exposures (duration 10 months) is shown in Fig. 10. The data in Fig. 10 show that there are some gaps in the Web RE data, which are probably caused by interruptions of the RE connection to the web. However, the internal memory data (the blue line) are available during these interruptions. Table 3 shows some statistics of the ^{222}Rn data harvesting from the pilot experiments with several detectors in dwellings and workplaces.

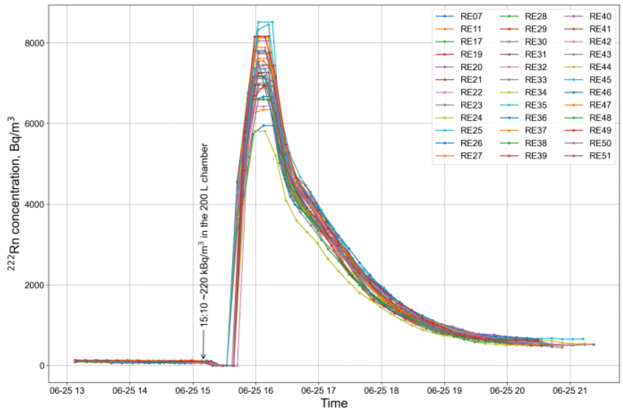

Fig. 8. After high activity spike, all detectors record zeroes. Immediately after flushing the exposure chamber with clean air, there is significant difference between the detector readings, whilst they return to their working range. The time format on the abscissa is 'Month-day hour'.

Table 2. Response factors (R) at 4.7 kBq/m^3 and background signal estimated from the exposures at LNE-LNHB

RadonEye #	Response factor *R*	Background signal, Bq/m^3
PE22101200023	1.210 (66)	2.7 (20)
PE22101200025	0.876 (56)	3.8 (39)
PE22101200028	1.155 (70)	3.6 (24)
PE22101200031	0.959 (52)	3.0 (31)
PE22101200036	1.138 (63)	3.4 (26)
PE22101200044	1.306 (74)	2.3 (23)
PE22101200046	1.025 (54)	2.9 (30)
PE22101200048	1.159 (61)	2.6 (19)
PE22101200049	0.976 (55)	2.2 (21)

Note: The numbers in the brackets indicate the estimated standard uncertainties of R or the standard deviation of the background signal. The average response factor, averaged over all nine instruments, is $\bar{\bar{R}}$ = 1.09 (14).

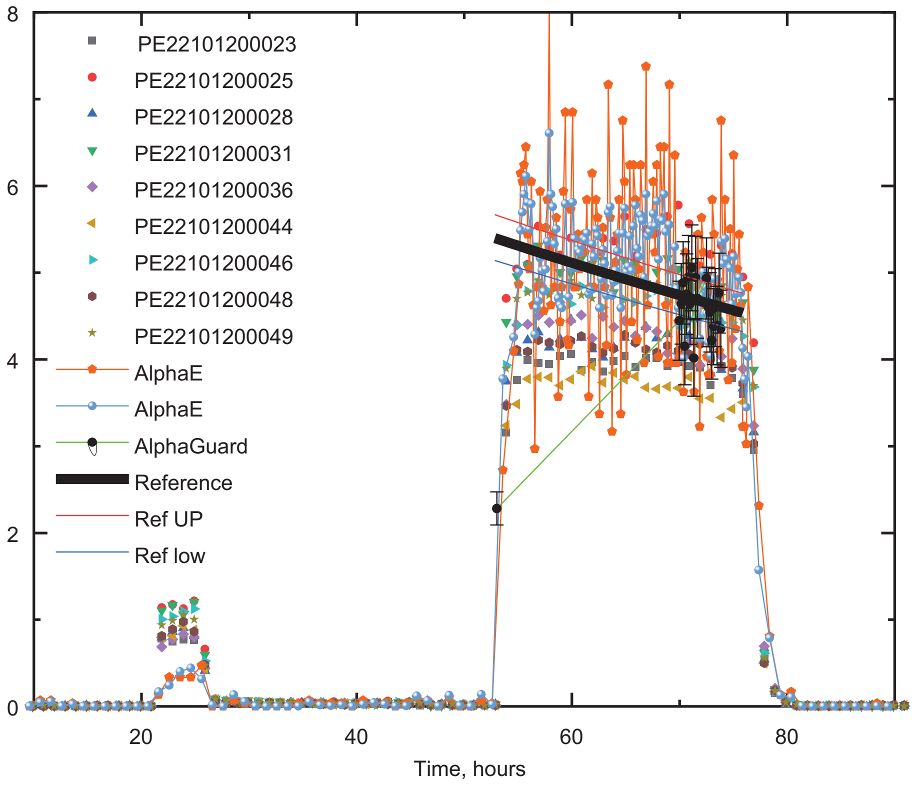

Fig. 9. Exposure of the instruments at LNE-LNHB. The black dots show the readings of the Reference instrument. The black solid line (Reference) shows the reference ^{222}Rn activity concentration $\left(A_V^{ref}(t)\right)$ during the exposure. The lines 'Ref UP' and 'Ref low' show the one-sigma interval around the reference activity concentration $\left(A_V^{ref}(t) \pm \sigma A_V^{ref}(t)\right)$.

Table 3. Summary of the data collection statics from the pilot exposure of detectors at dwellings and workplaces and a description of the studied locations

Data collection mode	Detector ID /location type	Building type, floor	Uptime	Downtime	Uptime, %
Web RE data	RE07 Dwelling	Four-floors block of flats, 1	263 days 20:21:37	23 days 10:37:39	91.8
	RE11 Workplace	Four-floors building, 1	264 days 23:17:55	21 days 06:54:43	92.6
	RE16 Workplace	Four-floors building, 1	314 days 23:03:15	19 days 07:30:10	94.2
	RE19 Dwelling	House, 1	272 days 22:46:30	14 days 05:47:23	95.0
	RE33 Dwelling	Six-floors block of flats, 5	272 days 01:00:43	14 days 05:38:42	95.0
	RE34 Dwelling	House, 1	75 days 23:44:43	6 days 08:53:51	92.3
Bluetooth RE data	RE07 Dwelling	Four-floors block of flats, 1	270 days 03:41:22	10 days 20:07:50	96.2
	RE11 Workplace	Four-floors building, 1	285 days 13:24:31	0 days 14:57:11	99.8
	RE33 Dwelling	Six-floors block of flats, 5	285 days 16:26:00	0 days 10:53:24	99.8

Table 4. Comparison of ^{222}Rn estimates calculated from the Web and Bluetooth data

Variable	Detector RE07		Detector RE11		Detector RE33	
	Web RE data (10 min cycle)	Bluetooth RE data (1 h cycle)	Web RE data (10 min cycle)	Bluetooth RE data (1 h cycle)	Web RE data (10 min cycle)	Bluetooth RE data (1 h cycle)
Mean ^{222}Rn concentration (Bq/m^3)	42.5	42.6	33.8	33.3	73.7	74.2
Standard deviation (Bq/m^3)	22.9	22.9	21.6	21.4	49	49.5
Median ^{222}Rn concentration (Bq/m^3)	39	39	27	27	63	63
Median absolute deviation (Bq/m^3)	12	12	11	11	28	28

Table 5. Estimation of seasonal ^{222}Rn fluctuations

Variable	RE07 (10 months in a dwelling, Bluetooth data)				RE16 (11 months in a workplace, WiFi data)				RE33 (10 months in a dwelling, Bluetooth data)			
	AUT	WINT	Full period	AUT/full period	AUT	WINT	Full period	AUT/full period	AUT	WINT	Full period	AUT/full period
Mean ^{222}Rn concentration (Bq/m^3)	41.8	35.1	42.5	0.984	38.4	19	40.5	0.948	68.4	65.7	73.7	0.928
Standard deviation (Bq/m^3)	15.3	11	22.9		27.1	10.8	30.1		40.3	29.1	49	
Standard deviation of the mean (Bq/m^3)	0.1	0.1	0.1		0.2	0.1	0.1		0.4	0.3	0.2	
Median ^{222}Rn concentration (Bq/m^3)	41	35	39	1.051	31	17	31	1.000	59	63	63	0.937
Median absolute deviation (Bq/m^3)	10	7	12		14	7	16		26	20	28	

Note: The data used for RE07 and RE33 are shown in Fig. 10.

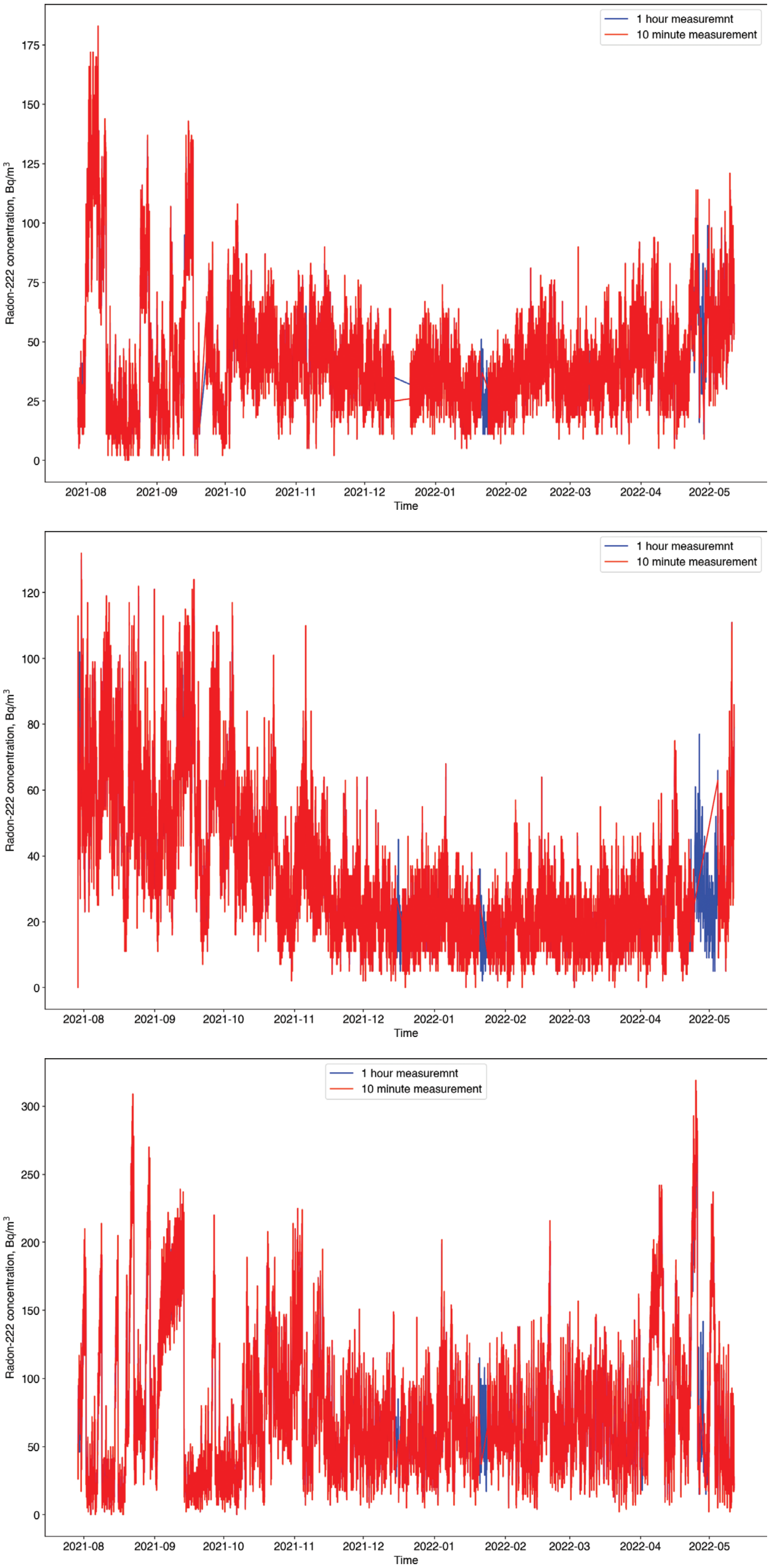

Fig. 10. Data collected from 10-month exposure of RE07-dwelling (top), RE11-workplace (middle) and RE33-dwelling (bottom) detectors. The red line indicates the Web ^{222}Rn data collected over the Internet (Wi-Fi connection of the instrument to the Web), and the blue line indicates the Bluetooth RE data. The data are used to calculate the quantities shown in Table 4.

The statistics in Table 3 shows very good data collection efficiency both with the Web and Bluetooth RE data with no differences between workplaces and dwellings. The Bluetooth RE data show more than 96% uptime for a 10-month period, with the downtime periods being attributed to moments with electricity breakdown or failure of the RadonEyes^{+2} to resume measurements after an electricity breakdown. We identified seldom cases, in which after electricity recovery, the RadonEyes^{+2} turn themselves on and seem to be operational, but failed to broadcast data and record it in their memory. It should be noted that one of the workplaces is the Faculty of Physics of Sofia University, and the other is another scientific institution. During the COVID-19 quarantine periods, they operated mostly in remote-work regime. Additionally, the studied 10-month period covers the summer season. These are prerequisites for significant changes in the building exploitation habits (e.g. power supply or WiFi shut-down when the building is not occupied). Nevertheless, we observe high efficiency of both data collection methods, which implies high data collection efficiency in other workplaces. However, to be more conclusive, more data have to be collected, including from other workplaces.

To get the comparison between the Web and Bluetooth collection methods one step further, we analyse the radon activity concentration data obtained from long-term measurements with three REs (shown in Fig. 10). Table 4 shows a comparison of the mean, standard deviation, median, and median absolute deviation values calculated from the data shown in Fig. 10. An excellent agreement between the Web and Bluetooth data is observed for all the three detectors. This indicates that both data collection methods give coherent results and can be used for ^{222}Rn estimates.

As a pilot test, the results of the RE07, RE33 (shown in Fig. 10) and RE16 were used to test an evaluation of seasonal ^{222}Rn fluctuations. The results are shown in Table 5. Overall, the results in Table 5 suggest that technically, the RE detectors can be used to study the seasonal ^{222}Rn fluctuations. However, a large number of such measurements are required in order to obtain reliable estimates.

Discussion

The results of this study imply that the RadonEye^{+2} instruments are suitable for continuous monitoring of radon dynamics in dwellings and workplaces. The RadonEyes appear to be linear below 3.5 kBq/m^3, and a non-linearity below 15% is observed for radon concentrations in the interval from 3.5 to 7 kBq/m^3. The response to ^{222}Rn at 4.7 kBq/m^3 was within 15% to the reference. As the radon data collected from the REs allow to apply an a posteriori correction to the radon readings, we plan to study in more details and characterise better their response in the entire activity range.

The developed software tools for web collection of RE data and the database appear to be very useful for large-scale continuous ^{222}Rn monitoring. They allow unambiguous data collection and storage and raise warnings when there are problems in receiving data from the detectors. These warnings are very useful for ensuring the collection of reliable long-term ^{222}Rn data. We observed excellent data collection efficiencies with more than 91% uptime for online data collection and more than 96% uptime with data collection from the internal RE memory. The software tool is also very suitable for finding 'zero'-records in case of detector saturation, which is very important for the correct exposure estimation in dwellings or workplaces (e.g. underground workers) with very high radon concentrations. It could also be set to raise warnings when the detector is operated outside the producer defined operating range that could be a reason for detector failure (e.g. RH above 80% – e.g. in spas or caused by rapid drop of temperature; temperature outside the range 10–40°C or other improper use). The results of this work support the results obtained in (3) and the idea for the application of RadonEyes for continuous ^{222}Rn monitoring in workplaces proposed there. The RE detectors combined with the software and the database provide reliable data for indoor radon dynamics, which may be useful for various purposes like evaluation of yearly average radon concentration, evaluation of exposure in workplaces based on occupancy factors, evaluation of seasonal correction factors, radon correlation with environmental factors, and evaluation of radon exposure in smart, energy efficient buildings that change their ventilation/air conditioning according to their occupation.

Conflict of interest and funding

The authors declare no conflict of interests.

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