Coherent long-term average indoor radon concentration estimates obtained by electronic and solid state nuclear track detectors

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Abstract

Despite the rapid development of consumer-grade electronic radon monitors, their capabilities to assess long-term average radon concentrations are not systematically investigated. We present the results of a year-long measurement campaign in 32 dwellings and workplaces in two areas with typical and high radon concentrations in Bulgaria. A systematic comparison was made between electronic monitors and the gold standard – solid-state nuclear track detectors (SSNTDs). RadonEye Plus2 (RE) monitors were used, calibrated and metrologically tested at the three participating laboratories. Two SSNTD-based detectors were utilized: passive radon detectors (PRDs) developed by UKHSA, and CDs/DVDs, developed at SU. Two PRDs for quarterly radon measurements, a RE, a CD and a DVD were placed at each location. Additional old CDs/DVDs were collected for retrospective radon estimates. The results for the annual average radon concentrations, estimated by the four methods are presented. The average difference between the REs and PRDs estimate was 8% (median 4%), between the REs and CDs was 5% (median 0.4%) and between REs and DVDs was -10% (median-12%). The Z-score, representing the difference normalized

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to its uncertainty, in most cases fell within -1 and 1, indicating excellent agreement. The retrospective estimates also demonstrated excellent agreement with the other data. However, in some cases, small but statistically significant biases were identified between REs and SSNTDs or between different SSNTDs, requiring an inclusion of a reference instrument in future studies. Overall, the results imply that with sound metrological assurance, RadonEye Plus2 monitors can assess long-term average radon concentrations with sufficient accuracy.

Keywords: Indoor radon measurements, Long-term radon average, RadonEye Plus2 electronic detector, Radon SSNTDs, Diffusion chambers with PADC, Continuous radon monitors

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1. Introduction

The concentration of ^{222}Rn (radon) in air is a crucial indicator of the quality of the indoor environment. Radon is a radioactive gas originating from ^{226}Ra in rocks, soil, building materials and subterranean waters. Its accumulation indoors leads to exposure of the whole population and to an increased risk of lung cancer [1, 2, 3]. It was estimated that in the United States radon exposure leads to about 21000 deaths each year [4], surpassing other environmental sources of mortality. Global estimates of lung cancer mortality performed for 66 countries confirm that residential radon is responsible for a substantial proportion of lung cancer mortality worldwide with radon-attributable lung cancer deaths totaled 226,057 in 2012, representing a median of 3.0% of total cancer deaths [5]. Identifying buildings with elevated radon levels and implementing radon mitigation strategies helps to reduce health risks. The only reliable way to identify such buildings is by direct measurements of radon in the indoor air. Given the high temporal variations of indoor radon, the quantity considered representative for the risk is the annual average radon concentration [6]. It is estimated by long-term measurements for at least three months and preferably longer [6].

The most common devices for long-term radon measurements use solid-state nuclear track detectors (SSNTD) [7]. Alpha-particles emitted by radon and its progenies form latent tracks in the SSNTDs, which are developed and used to determine the integral of radon concentration over the exposure period. The low cost of such passive devices makes them appropriate for large measurement campaigns and long-term exposures [6]. The SSNTDs are considered the gold standard for long-term radon measurements, have been used for many years [8] and procedures for their quality assurance have been developed (e.g. [9, 10]).

On the other hand, continuous radon monitors (CRMs - electronic devices that conduct consecutive radon measurements) have seen limited usage in building assessments [7]. Due to their cost, they were mostly employed in short-term diagnostic measurements pre- and post-radon mitigation or as reference instruments in laboratory studies. However, this tendency is currently changing with the emergence of smaller consumer grade CRMs, which are targeted towards individual users like homeowners and employers. While their initial cost may exceed that of a single SSNTD measurement, their reusability, for instance across different rooms in a workplace, offers advantages. Notably, a library lending service for CRMs was found to increase radon testing in some communities in the US [11]. Users typically favor CRMs due to their real-time data display, eliminating the need to await laboratory results as with passive devices. Many CRMs also offer network connectivity, aligning with modern concepts for smart buildings [12] and air pollution monitoring by individual electronic sensors [13].

Furthermore, CRMs data on radon dynamics unlocks enhanced and new applications. It could lead to advanced approaches for the assessment of occupational radon exposure by accounting for temporal variations and actual working hours [14]. It enables assessment of seasonal correction factors, which are used in many countries to estimate the annual average radon concentration by several-month-long measurements [15]. CRMs could also be applied to study radon transport inside large, multi-level buildings [16]. Moreover, the accumulation of CRM data could boost investigations into emerging issues concerning indoor radon, including the impact of climate changes, building construction trends, and shifting lifestyles. These concerns have already been raised by the scientific community. For instance, elevated radon levels during the summer have been hypothesized to stem from increased building air tightness and greater use of air-conditioning [17]. Recent studies have indicated that energy-saving renovations of buildings result in heightened indoor radon levels [18, 19, 20, 21, 22, 23]. Additionally, a study on the changing of Canadian activity patterns since the COVID-19 pandemic revealed increased radon exposure for young people [24].

Despite their huge potential, the quality of radon measurements by consumer-grade CRMs is still under question. These affordable devices typically do not undergo individual calibration or metrological testing prior to sale. Recent laboratory studies have identified a variability in the performance among different models [25, 26, 27, 28, 29, 30, 31, 32, 33] and even within devices of the same type [29, 33]. However, long-term comparisons between CRMs and other detectors in real buildings remain scarce. Thus, despite the rapid development of consumer grade electronic radon monitors in the last decade, their capabilities to assess long-term average radon concentrations, such as annual or quarterly averages, are not systematically investigated.

The objective of this work is to address this gap, conducting a systematic year-long study of the performance of a consumer-grade CRM and two types of SSNTDs under field conditions. The RadonEye Plus2, hereafter called RadonEye(s) (RE), which demonstrated good characteristics in laboratory studies [26, 27, 29, 33], was employed as CRM and UK Health Security Agency (UKHSA) passive radon detectors (PRDs) and CDs/DVDs were employed as SSNTDs. The comparison involved 32 occupied homes and workplaces with indoor radon concentrations ranging from few tens to few thousands Bq/m^3.

2. Methods and materials

2.1. RadonEye+2 electronic monitors

The RE is an electronic radon monitor based on a pulsed ionization chamber. It is sensitive to the alpha particles emitted by radon and its decay products [34]. It is also sensitive to thoron (^{220}Rn) [35, 36] if present in indoor air. According to the producer [37], the ^{222}Rn measurement range of the instrument is from 7 to 9435 Bq/m^3, with a sensitivity of 0.014 cpm/Bq/m^3, and both accuracy and reproducibility are stated as 10%.

In this study, thirty-two REs were used. After purchase, the detectors underwent metrological tests and calibrations performed at SU (all detectors) [27], the French primary metrology laboratory Laboratoire National Henri Becquerel (LNHB) (9 detectors), and the UK Health Security Agency (20 detectors). The results of these tests and calibrations are presented in [33] and indicate that the new monitors have a low background, with an average of 2.5(5) Bq/m^3. The precision error of the group studied at UKHSA was about 9%, and the biased error ranged from 3% to 16% for activities in the range of 280–2900 Bq/m^3. Excellent linearity of the readings for all monitors was observed in this range, with a slight deviation from linearity within 12% in the range of 3500–7000 Bq/m^3 [29]. However, a large individual bias in some monitors necessitated the determination of an individual calibration factors for each monitor, ranging from 0.70 to 1.06, with an average of 0.880(79) [33]. The data reported by all instruments in this study were corrected using individual calibration factors.

As per the producer's specifications, the RE performs measurements with a duration of 10 minutes and calculates the last 60-minute moving average. The result is reported on a 10-minute basis over the network when the monitor is connected to a Wi-Fi network. The data obtained in this mode is referred to as "WiFi data." The instrument also stores the running average for each hour in its internal memory. This data can be read via Bluetooth connection from a mobile phone and is referred to as "Bluetooth data." Unlike Bluetooth data, not all WiFi data readings are independent, because the result from one 10-minute measurement enters six moving averages within one hour. However, this type of data analysis and reporting allows for an improved time response of the instrument compared to Bluetooth data (one-hour measurement).

The response time of the monitors is quantified in terms of the characteristic times T_{50} and T_{90} representing the time needed for the signal to reach 50% and 90%, respectively, of its equilibrium activity after a step-like increase from zero.

The characteristic response times of the REs were determined in [29] and are approximately 40 minutes for reaching 50% and 90 minutes for reaching 90% of the plateau of a rectangular pulse.

To collect, store, visualize, and analyze the measurement data, a web-accessible database (further referred to as SPIRAD database) was created at Sofia University. The SPIRAD database allows for the collection and storage of WiFi data and manages active REs and their locations and status. The web interface of the database checks the real-time RE values (WiFi data) of the active detectors to identify problems with the Wi-Fi connection and stores the WiFi 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 they can be visualized, downloaded, and analyzed together or separately. More information about the functionality of the database is provided in [27].

2.2. UKHSA passive radon detectors

Passive detectors assembly includes a housing which acts as a diffusion chamber and a sensing element inside which is Poly Allyl Diglycol Carbonate (PADC) polymer produced by Mi-Net Technology Ltd., UK. After manufacture, sheets of plastic are kept for one month in radon proof pouches under ambient air to avoid the sudden drop in sensitivity reported by Portwood [38]. Then, sheets of PADC are cut and assembled into a standard detector housing. Each sheet is calibrated using the UKHSA 43 m^3 radon chamber with calibration traceable to the LNHB primary radon standard. The latent alpha tracks in PADC are revealed by chemical etching with NaOH (5 M) at a temperature of 75 °C for 18 h. Images of etched detectors are recorded by a Nikon LS5000ED slide scanner at the resolution of 4000 dpi. Subsequently, images are analysed and tracks calculated using the UKHSA in-house image analysis software [39, 40]. All the production processes undergo stringent quality protocol that are described in detail elsewhere [10]. Additionally, results precision and accuracy are checked by participation in intercomparisons organized internally [41] or internationally [42]

2.3. CDs and DVDs as passive detectors

Radon measurements by CDs or DVDs were proposed more than 20 years ago [43] as a retrospective method. Home-stored disks were used to estimate the average radon activity for a past period. Such measurements are possible because of the track-etch properties of the polycarbonate material of the disks [43, 44]. The alpha-particles of radon and its progeny form latent tracks in the material which can later be developed by chemical or electrochemical etching. In addition, the polycarbonate absorbs radon and thus tracks are also formed inside the volume of the disk. Research has shown that the track density at a depth exceeding 79 μm below the disk surface is unaffected by radon progeny in the air or plated on the disk's surface and correlates with the integrated radon activity concentration [43]. The signal at such depths is not influenced by the mode of disk storage [45]. Bare disks can be used as well as disks in jewel cases or envelopes. The applicability of the CD-method has been tested in laboratory studies [45, 46] and demonstrated in measurement campaigns [47, 48, 49].

Typically, tracks in the disks are developed through electrochemical etching [47], preceded by the removal of a surface layer of 79 μm or more via chemical pre-etching. After the tracks are developed, they are counted by a computer scanner and dedicated software [50].

To conduct retrospective measurements, used CDs or DVDs are gathered from the studied locations, ensuring they are at least one year old. Their age is estimated through interview with their owner or by the date of their records. The disks are developed and their track density is used to retrospectively estimate the average radon activity concentration for the period of their storage. An average calibration factor determined for a group of disks of various brands [47] can be used for the estimate. An a posteriori calibration is also possible by additional exposure of a piece of the used disk to known radon levels and estimation of the increase in the track density due to the exposure [46].

CDs and DVDs can also serve for prospective radon measurements. In this case they are used in the same way as PRDs. New disks are placed at the studied locations for a specified duration. Then they are collected and left for at least two weeks, so that radon absorbed inside them could fully decay. The tracks inside the disks (at a depth of 79 μm or more) are developed and counted. Generally, the sensitivity of disks is lower compared to conventional PRDs, necessitating exposure for at least one year to accumulate detectable signal at low radon levels. The background track density is determined by etching new disks from the same batch. The calibration factor is determined by exposure of identical new disks to controlled radon concentrations.

3. Experimental design

In order to compare electronic and SSNTDs detectors, a long-term radon measurement campaign was organized. The campaign encompassed two regions in Bulgaria: the Sofia region, known to have normal indoor radon concentrations [51], and the Buhovo region, a radon-prone area [49]. A previous study in the Buhovo region showed that there are dwellings with radon concentrations up to 8 kBq/m^3 [49], and some of these dwellings were deliberately included in this study. Attempts were made to place the detectors in both dwellings and workplaces, which were successful in the Sofia region and less successful in the Buhovo region.

The measurement campaign lasted about one year, divided into four quarters as described in Table 1. A standardized set of detectors was placed in each location, consisting of: 2 UKHSA PRDs for quarterly measurements, 1 RadonEye Plus2, one new CD and one new DVD for yearly radon measurement (Table 1). The detectors were positioned close to each other in locations convenient to the inhabitants (see the example in Fig. 1). At the end of each quarter, the locations were visited, and the 2 UKHSA PRDs were replaced with new ones. The exposed PRDs were then sent to UKHSA for analysis. During these visits, measurements stored in the RadonEye's internal memory were downloaded via Bluetooth connection and uploaded to the SPIRAD database (Bluetooth data).

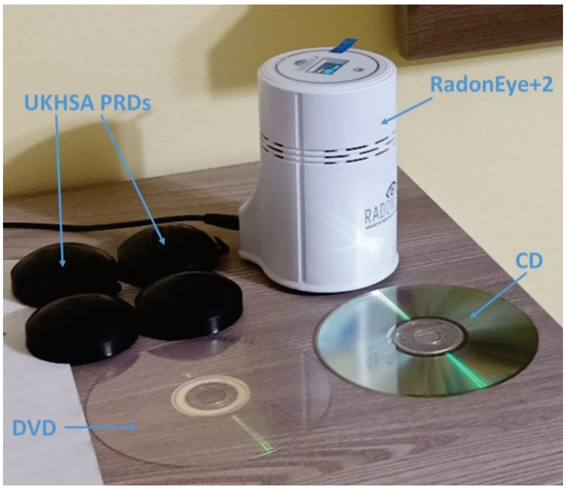

Figure 1: Typical placement of the detectors used in the campaign

Additionally, in some locations, retrospective radon measurements were conducted by old CDs that had been kept in the location for a known period. The age of the disks ranged from 3 to 20 years. It should be noted that the exposure periods of the disks for prospective measurements and the other detectors do not overlap. The old disks were collected just at the start of the campaign. Some of them had been kept in a room different from the one in which the other detectors were exposed. Furthermore, in selected locations, we placed 5 weather stations with inside and outside modules for temperature and humidity measurements.

Label	Period	Duration, mo	Season in Bulgaria	Detectors placed in each location particularly for the period
Q1	from 11 Oct 2022 to 25 Jan 2023	3.5	Autumn/Winter	2 UHKSA PRDs
Q2	from 25 Jan 2023 to 15 May 2023	3.7	Winter/Spring	2 UHKSA PRDs
Q3	from 15 May 2023 to 21 Aug 2023	3.2	Spring/Summer	2 UHKSA PRDs
Q4	from 21 Aug 2023 to 13 Nov 2023	2.8	Summer/Autumn	2 UHKSA PRDs
Full period	from 11 Oct 2022 to 13 Nov 2023	13	all seasons	1 RadonEye, 1 CD and 1 DVD

Table 1: Summary of the exposure periods in the radon measurement campaign.

Figure 2 shows examples of the data obtained with the RadonEyes during the measurement campaign. The Wi-Fi and Bluetooth data were collected, as well as data for the ambient temperature and humidity at the location (not shown).

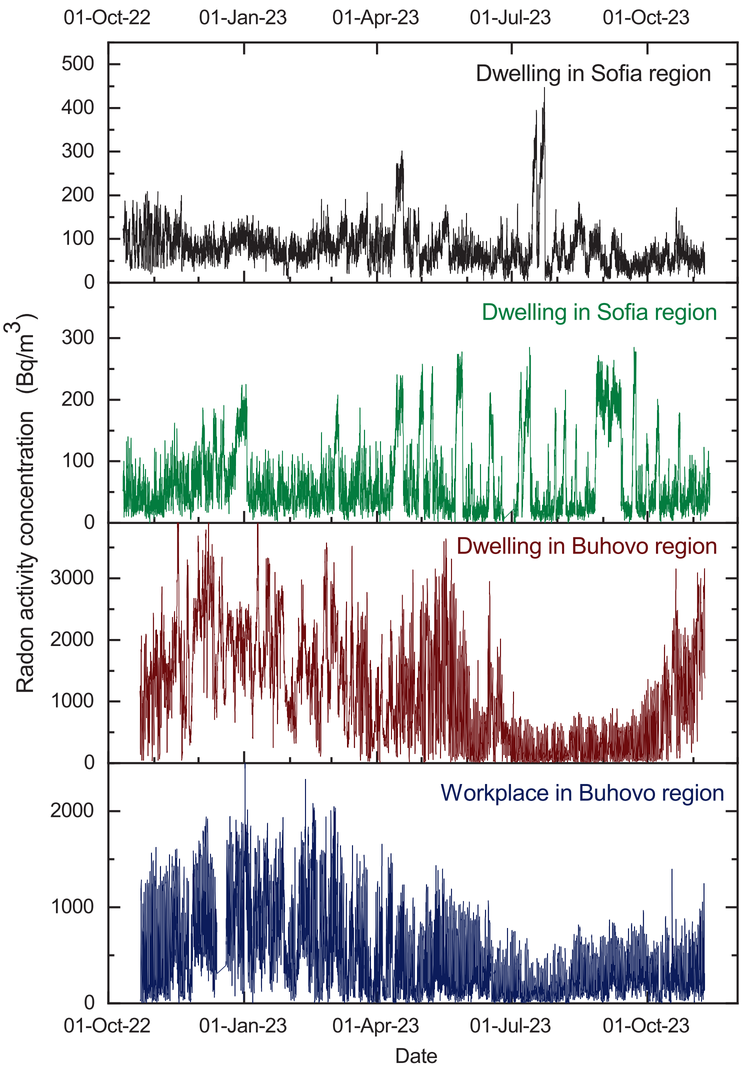

Figure 2: Examples of RE Bluetooth data acquired during the campaign in the regions of Sofia and Buhovo.

The records of RadonEyes were integrated for the whole exposure period and two separate estimates were obtained for the Bluetooth data and the Wi-Fi data. The average radon activity concentration was estimated as:

$$C_{RE} = R_{cal}\left(\frac{\sum_{i=1}^{N} C_i \Delta t}{\sum_{i=1}^{N} \Delta t} - C_{bg}\right) = R_{cal}\left(\frac{\sum_{i=1}^{N} C_i}{N} - C_{bg}\right) \quad , \tag{1}$$

where R_{cal} is the individual calibration factor of the RadonEye detector, Δt is the duration of the RadonEye measurement interval and C_{bg} =2.5 Bq/m^3 was the average background estimated for 20 RadonEyes before the measurement campaign. The sum in Eq.1 was over all intervals in which RadonEyes reported a value. The uncertainty in C_{RE} was dominated by the uncertainty in the calibration factor R_{cal} which was between 3.5% and 6.8%.

Figure 3 illustrates the uptime statistics observed in this campaign, which is an important indicator of the RadonEyes' capability to provide data for assessing the yearly average radon concentration. The Bluetooth data from all 32 monitors used in this study covered more than 98% of the time, with 26 of them achieving a coverage of more than 99.5%. Additionally, Wi-Fi data from 29 out of the 32 detectors covered more than 80% of the measurement time. In 2-3 isolated cases, the Wi-Fi connection to the REs in the location was very poor. This resulted in scarce Wi-Fi data, which prevented the calculation of the yearly average radon concentration in this mode.

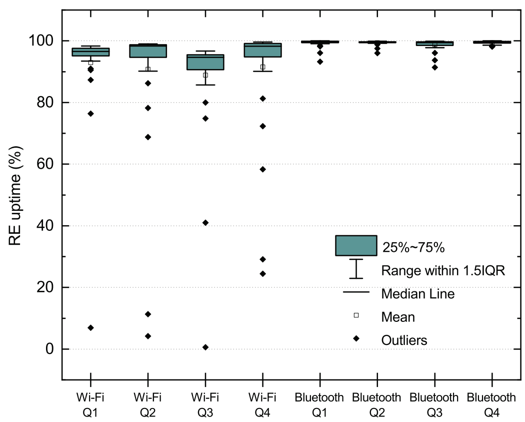

Figure 3: Uptime of REs by yearly quarters during the campaign

Figure 4 depicts the correlation between yearly average radon concentrations estimated from Bluetooth and Wi-Fi data. An excellent linear correlation is observed between the two sets of data, with a slope of 1.0006(48) and an intercept of -0.14(21). This indicates that Bluetooth and Wi-Fi data yield the same C_{RE} results. Therefore, only the Bluetooth data will be used hereafter in the comparisons.

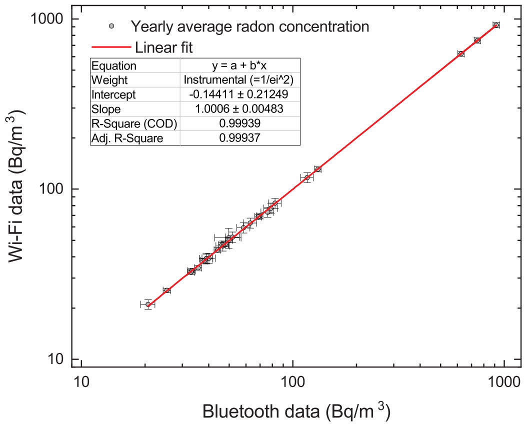

Figure 4: Correlation between yearly average radon concentrations estimated from RadonEyes' Bluetooth and Wi-Fi data

The average activity concentration by the UKHSA PRDs was estimated as:

$$C_{PRD} = \frac{n - n_{bg}}{CF_{PRD}.\Delta t}, \quad (2)$$

where n is the observed track density or area covered by tracks at higher exposures as tracks overlap makes counting of individual tracks impossible, n_{bg} is the background track density or area covered by tracks, Δt is the duration of the exposure period and CF_{PRD} is a calibration factor determined for each individual sheet of detectors as described elsewhere [10]. For all sets of UKHSA PRDs, transit exposure was estimated by 10 identical PRDs travelling with them. At the UKHSA all new PRDs were packed in radon-proof plastic foil. The PRDs designated for transit exposure estimation remained sealed in the foil until the other PRDs from the same batch were exposed and collected. Then, the unexposed PRDs were opened and repacked in the same way as the exposed detectors. The PRDs were returned together for track development and analysis at the UKHSA radon laboratory. In all cases, the transit exposure was negligible compared to the signal of the exposed chambers. The results from all couples of PRDs exposed together coincided well withing the declared uncertainties. The average result of the two PRDs was further used in the comparisons.

The average activity concentration for the whole period was estimated by the PRDs exposed in the four consecutive periods as:

$$C_{PRD} = \frac{\sum_{i=1}^{4} C_{PRD,i} \Delta t_i}{\sum_{i=1}^{4} \Delta t_i} \,. \tag{3}$$

where $C_{PRD,i}$ is the annual average radon concentration for the i^{th} period (calculated by Eq. 2) and Δt_i is its duration. The average activity concentration for each CD and DVD was estimated as:

$$C_{disk} = \frac{n - n_{bg}}{CF.\Delta t} \,, \tag{4}$$

where n is the observed track density, n_{bg} is the background track density, Δt is the duration of the exposure period and CF is a calibration factor, separate for CDs and DVDs. The relative uncertainty of the activity concentration $\delta(C_{disk})$ was estimated as:

$$\delta(C_{disk}) = \sqrt{\frac{\sigma^2(n) + \sigma^2(n_{bg})}{(n - n_{bg})^2} + \frac{\sigma^2(CF)}{CF^2} + \frac{\sigma^2(\Delta t)}{\Delta t^2}} \,, \tag{5}$$

where σ denotes the absolute standard uncertainty of the corresponding value. The uncertainty of the observed track density is found assuming a Poisson distribution of the observed tracks N in a field of the disk with area S, hence $\sigma(n) = \sqrt{n/S}$. The background was estimated at n_{bg} =10.0 ± 2.9 cm^{-2} for the new CDs and n_{bg} =3.4 ± 1.5 cm^{-2} for the new DVDs. For the retrospective measurements n_{bg} =6.3 ± 2.4 was used, estimated previously for a group of various new disks [47]. In some of the studied buildings with low radon levels, the observed track density in the new CDs was statistically the same as the background track density. In these cases the minimum detectable activity concentration was reported as a measure of the maximum value that can lead to this signal. The uncertainty in the duration of the exposure $\sigma(\Delta t)$ is negligible for the new disks exposed in the campaign. For the old disks collected for retrospective measurements $\sigma(\Delta t)$ was estimated individually based on interview with the disk owner. The calibration of the new disks used in the current study was conducted by the exposure system described in [52].

4. Results

4.1. Comparison between all detectors

In order to compare the results obtained by different types of detectors, we first compare the annual average radon concentration estimated from their readings in each location. The comparison includes annual average activity concentrations obtained by: RE Bluetooth data (see Eq. 1); four UKHSA PRD pairs, each pair exposed for 3 months (see Eq. 3); DVDs and CDs (Eq. 4). The results for the annual average radon concentrations are shown in Tables 2 and 3 (Sofia and Buhovo regions, respectively) and are illustrated in Figures 5, 6, and 7. Note that the values shown in brackets in all the tables in this work represent the standard estimated uncertainty ($k = 1$), expressed by the notation defined in paragraph 7.2.2 point 2 in [53] .

Location	Type	Annual average radon activity concentration (Bq/m^3) Oct 2022 - Nov 2023				
		PRDs annual	RE Bluetooth	RE WiFi	DVD	CD
1	home	59.0(25)	78.8(60)	77.2(56)	126(66)	79(32)
2	home	50.7(22)	46.6(34)	46.4(31)	65(22)	46(30)
3	home	82.1(35)	82.3(58)	82.8(56)	124(26)	77(34)
4	home	22.5(10)	20.6(16)	21.0 (14)	no*	no*
5	home	34.1(15)	33.2(13)	33.2(11)	30(20)	<75**
6	home	38.1(16)	38.9(28)	39.1(26)	65(38)	<79**
7	workplace	139.0(60)	128.8(89)	114.3(78)***	177(30)	135(73)
8	home	67.7(29)	76.0(53)	73.2(50)	108(26)	45(35)
9	home	24.0(10)	35.6(14)	34.5 (11)	34(18)	<61**
10	home	44.0(19)	44.0(16)	43.9(15)	66(27)	<93**
11	home	60.0(26)	58.4(42)	59.3(40)	95(26)	53(30)
12	home	69.5(30)	69.6(25)	69.5(24)	94(31)	<77**
13	home	126.6(54)	131.3(47)	131.0(46)	150(32)	106(35)
14	workplace	38.8(17)	49.7(71)	51.8(70)	76(23)	<83**
15	workplace	66.9(29)	49.7(71)	51.8(70)	76(23)	<83**
16	home	49.5(21)	47.8(18)	47.4(16)	77(23)	<95**
17	workplace	34.6(15)	33.0(13)	32.5(11)	50(20)	<55**
18	workplace	43.7(19)	46.2(18)	47.2(16)	45(20)	47(29)
19	workplace	33.9(15)	38.0(15)	38.0(13)	28(18)	<44**
20	workplace	24.0(10)	25.4(11)	25.4(8)	31(18)	<44**
21	workplace	41.3(18)	38.9(28)	38.9(26)	25(15)	61(26)
22	home	38.4(16)	40.1(29)	39.3(26)	26(17)	54(31)
23	home	57.6(25)	66.6(24)	61.0(21)***	62(21)	44(34)
25	home	88.2(38)	116.8(81)	117.0(80)	103(27)	77(33)
26	home	49.3(21)	62.9(44)	63.3(43)	44(21)	<63**
31	home	44.4(19)	51.8(40)	52.2(38)	no*	74(33)
32	home	43.5(19)	49.9(19)	50.1(17)	51(21)	81(35)

* The disks were lost.

** The minimum detectable activity concentration is given.

*** The uptime of the WiFi signal is less than 80%.

Table 2: Annual average radon activity concentrations and their estimated uncertainties by detector type for Sofia Region

Location	Type	Average radon activity concentration (Bq/m^3) Oct 2022 - Nov 2023				
		PRDs annual	RE Bluetooth	RE WiFi	DVD	CD
27	home	884(38)	917(32)	920(32)	1010(120)	830(140)
28	home	747(32)	747(26)	748(26)	831(99)	820(120)
29	home	3460(150)	>2380*	>2700*	3660(420)	3060(580)
30	home	578(25)	624(22)	624(22)	711(89)	700(110)
33	home	223.1(96)	235.1(83)	–	254(41)	196(66)

*RadonEye is saturated during many of the measurements.

Table 3: Annual average radon activity concentrations and their estimated uncertainties by detector type for Buhovo Region.

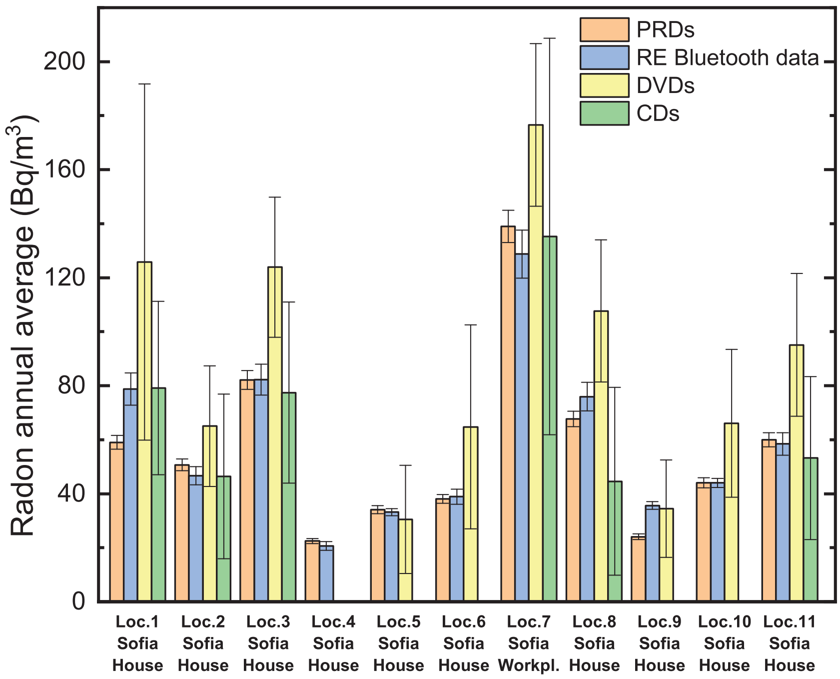

Figure 5: Annual average radon concentration measured by various detectors across locations 1-11

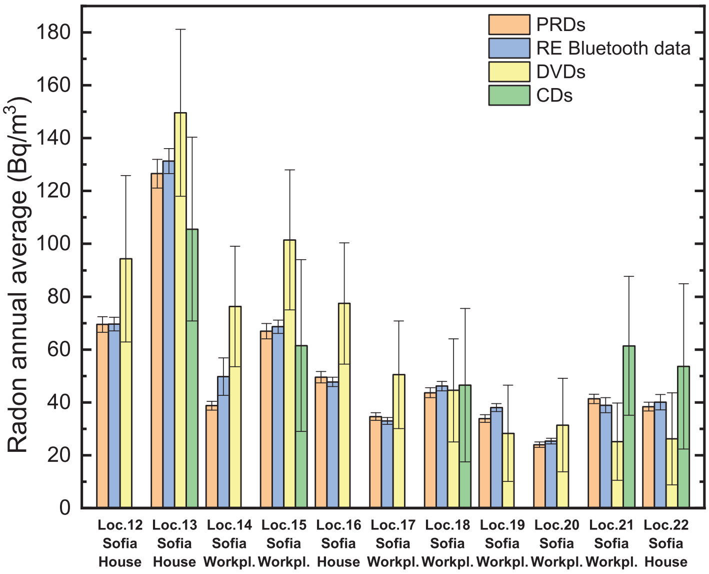

Figure 6: Annual average radon concentration measured by various detectors across locations 12-22

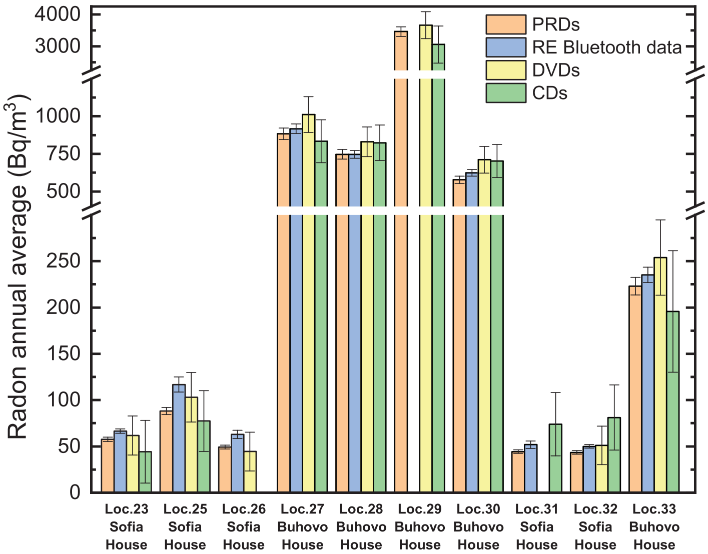

Figure 7: Annual average radon concentration measured by various detectors across locations 23-33

In order to compare the results from the electronic detectors (REs) and the SSNTDs, we define the relative difference as:

$$\Delta_{RE-SSNTD,i} = \frac{C_{RE,i} - C_{SSNTD,i}}{C_{SSNTD,i}} 100\% \,, \tag{6}$$

where $C_{RE,i}$ is the average radon activity concentration estimated from the RE readings and $C_{SSNTD,i}$ is the average radon activity concentration estimated from the SSNTD measurements at the ith location. SSNTD in this case can be: UKHSA PRDs, CDs or DVDs. The results from the statistical analysis of the relative differences across all locations are shown in Table 4. The highest relative differences were obtained when the results by DVDs are taken as referent. The lowest were obtained when the results by the PRDs are taken as referent. The highest relative differences were in buildings with radon below 100 Bq.m^{-3}. In all buildings with radon above 200 Bq.m^{-3} the relative differences were between -12% and 20%. Overall, the results are coherent between the detector types and in most cases agree within the estimated uncertainties.

Methods	Δ average	Δ median	Δ min all	Δ max all	Δ min high	Δ max high
RE Bluetooth to PRDs	8 %	4 %	-8%	48 %	0.01%	8 %
RE Bluetooth to DVD	-10 %	-12 %	-40 %	55 %	-12 %	-7 %
RE Bluetooth to CD	5 %	0.4 %	-38 %	70 %	-11 %	20 %

Table 4: Statistics for the relative difference Δ (Eq. 6) of the RadonEye estimate and the SSNTDs estimate of the annual average radon activity concentration. The extremal values are estimated for all locations (Δ min all and Δ max all) and for locations with radon above 200 Bq.m^{-3} (Δ min high and Δ max high).

In order to bring the comparison one step further and include in it the uncertainties of the estimated average radon concentrations, we define the Z statistics as the difference between the average radon activity concentrations at a given location normalized by its uncertainty. For instance, the Z_j statistics for the measurement by CDs and DVDs on the jth location is defined as:

$$Z_j = \frac{C_{CD,j} - C_{DVD,j}}{\sqrt{\sigma^2_{C_{CD,j}} + \sigma^2_{C_{DVD,j}}}} \tag{7}$$

where $C_{CD,j}$ is the estimated average radon activity concentration from the measurements by the CD method in the jth location, and $\sigma_{C_{CD,j}}$ is its estimated uncertainty. Similarly, $C_{DVD,j}$ is the estimated average radon activity concentration from the measurements by the DVD method in the jth location and $\sigma_{C_{DVD,j}}$ is its estimated uncertainty. Furthermore, we perform statistical analysis on the series of data Z_j (with $j = 1, \ldots, M$, where M is the number of locations for which there are estimates of C with both radon measurement methods). Ideally, for a perfectly agreeing data by two methods, the mean and median of the Z-scores should be 0 and most of the Z-scores data should be located symmetrically between -1 and 1.

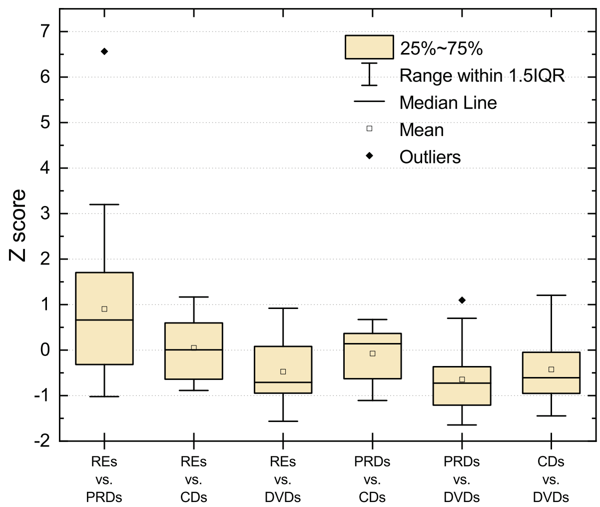

Figure 8: Statistical Analysis of Z-Scores for Various Method Pairs

The results of the Z-score analysis are depicted in Fig. 8, indicating a very good agreement between the different techniques, with most of the Z-scores lying between -1 and 1. An excellent agreement is observed between the RadonEyes Bluetooth data and the four quarters' UKHSA PRDs, with mean, median, and the majority of Z-scores falling between -0.5 and 1.5 (see RE vs. PRDs). Similar excellent agreement is also noted for the yearly average radon estimates between: RadonEyes and CDs (see REs vs. CDs); the four quarters' UKHSA PRDs and

CDs (PRDs vs. CDs) and the CDs and DVDS (CDs vs. DVDs). Very good agreement, with mean, median, and the majority of Z-scores between -1 and 0, is observed for the yearly average radon estimates between: RadonEyes and DVDs (see RE vs. DVD) and the four quarters' UKHSA PRDs and DVDs (PRDs vs. DVDs). In order to obtain a deeper insight into the comparison between the techniques, correlation analysis is further performed on selected pairs of methods.

4.2. Comparison between REs and UKHSA PRDs

The correlation between annual average radon concentrations estimated by RadonEyes (REs) and the UKHSA PRDs is shown in Fig. 9. Excellent correlations are observed between both estimates with correlation coefficient R^2=0.99143. The linear fit has a slope of 0.984(17) and an intercept of 0.056(34), indicating a perfect agreement between the two techniques. In view of the perfect agreement between the RE and PRD estimates of the annual average radon concentration, it is interesting to compare the two techniques per 3-month exposure periods (quarters).

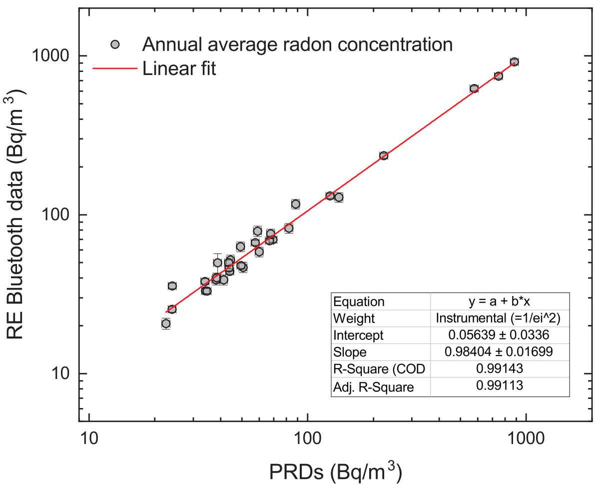

Figure 9: Correlation between yearly average radon concentrations estimated from the measurements with REs and UKHSA PRDs

In Q1 the average results by the REs were higher than these by PRDs (Fig.10). In the region of Buhovo the average relative difference was 7% and in the region of Sofia it was 39%. In Q2 the average results by the REs agreed very well with these by PRDs (Fig.11). In the region of Buhovo the average relative difference was 0.5% and in the region of Sofia it was 5%. In Q3 the results by the two types of detectors again agreed well with the results by the electronic monitors being slightly higher (Fig.12). The average relative difference was 17% for the region of Buhovo and 11% for the region of Sofia. In the final measurement period Q4 the agreement between the results from the PRDs and the RadonEyes was very good (Fig.13), but the results by the RadonEyes were slightly lower. The average relative difference was -7% for the region of Buhovo and -15% for the region of Sofia.

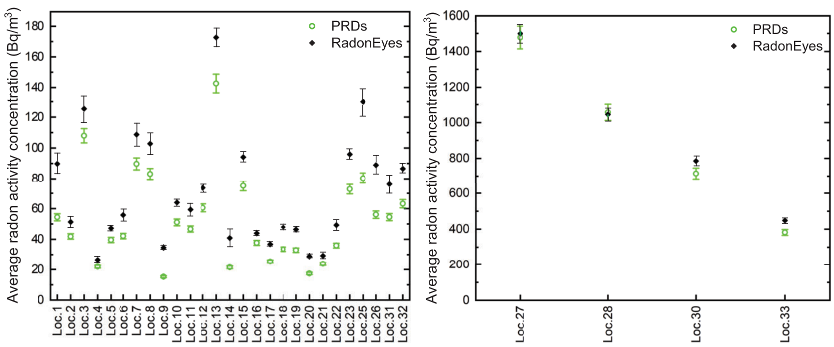

Figure 10: Comparison of Q1 average radon concentration estimates by PRDs and REs for locations in the Sofia (left) and Buhovo (right) regions.

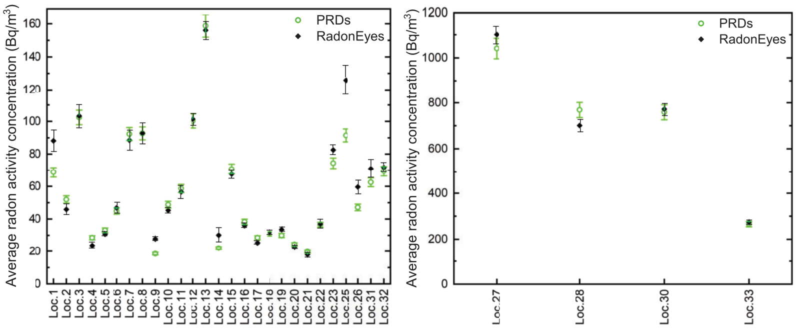

Figure 11: Comparison of Q2 average radon concentration estimates by PRDs and REs for locations in the Sofia (left) and Buhovo (right) regions.

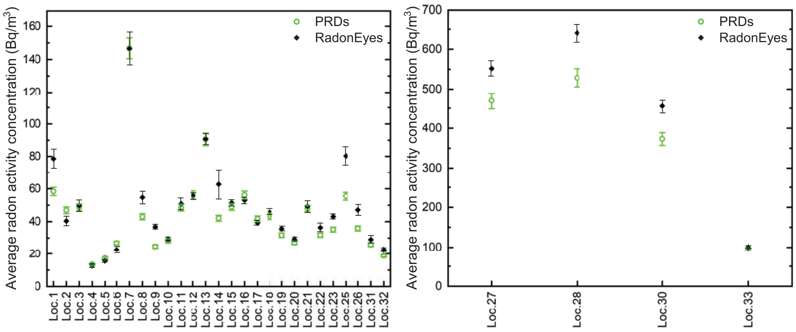

Figure 12: Comparison of Q3 average radon concentration estimates by PRDs and REs for locations in the Sofia (left) and Buhovo (right) regions.

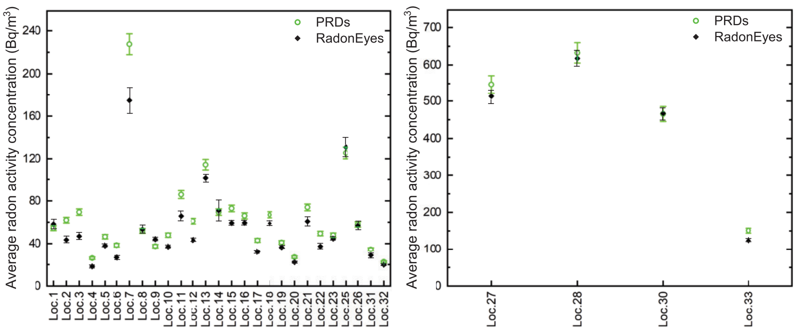

Figure 13: Comparison of Q4 average radon concentration for estimates by PRDs and REs locations in the Sofia (left) and Buhovo (right) regions.

4.3. Comparison between RE and CDs and DVDs

The correlations between annual average radon concentration estimated by REs and the CD and DVD measurements are shown in Fig. 14. Good correlations are observed between REs and both CD and DVD data. The linear fit of the REs vs. CD data has a slope of 0.92(11) and an intercept of 1.2(83), indicating a perfect agreement between the two techniques. The linear fit of the REs vs. DVD data has a slope of 0.724(59) and an intercept of 6.3(37), indicating a bias between the techniques.

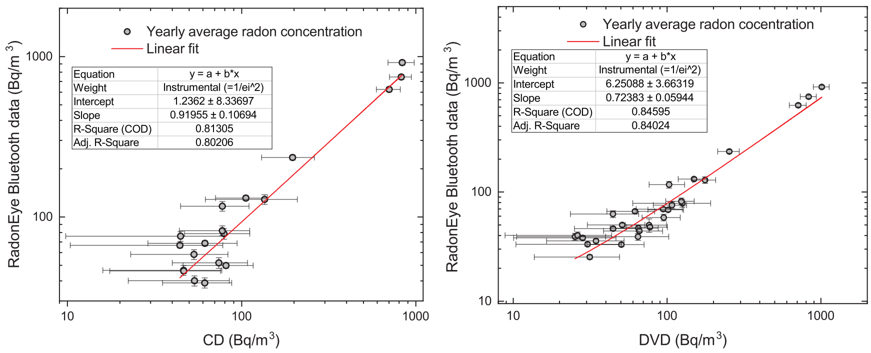

Figure 14: Correlation between annual average radon concentrations estimated from REs and CD (left) or DVD (right) measurements

4.4. Comparisons with retrospective CDs/DVDs

At the beginning of the survey participants were asked to provide "old" CDs/DVDs for retrospective radon measurements and 11 of them complied. Information was gathered concerning the age of the discs and any historical changes that might impact radon levels, such as building reconstructions or alterations in living habits and ventilation practices. The results from the retrospective measurements are shown in Table 5.

In two locations (Location 12 and 28, see Table 5) where the owners reported changes, significant differences between the retrospective and prospective measurements were observed. In Location 12, an active radon mitigation system was built at the beginning of the campaign, resulting in radon reduction. In Location 28, the measurements indicate an increase in radon concentration. About two years before the campaign, the occupants had a baby and significantly reduced the frequency and duration of ventilation by opening the windows, which could explain the rise in indoor radon.

Overall, the comparison between the retrospective and the prospective measurements shows very good agreement for locations where no reconstructions or alterations in habits occurred in the past.

Location	Retrospective		Average radon activity concentration (Bq/m^3)				
City	exposure description		CD/DVD	RadonEye	PRDs	DVDs	CDs
Type	Changes	Duration (y)	Retrospective	Bluetooth	annual	Prospective	
1 Sof./H	no	4.4(2)	92(23)	78.8(60)	59.0(25)	126(66)	79(32)
4 Sof./H	no	20(2)	30(7)	20.6(16)	22.5(10)	–	–
6 Sof./H	no	12.5(25)	50(14)	38.9(28)	38.1(16)	65(38)	<79*
9 Sof./H	no	18.0(5)	28(6)	35.6(14)	24.0(10)	34(18)	<61*
10 Sof./H	no	13.5(5)	51(11)	44.0(16)	44.0(19)	66(27)	<93*
11 Sof./H	no	11.3(2)	50(10)	58.4(42)	60.0(26)	95(26)	53(30)
12 Sof./H	YES**	15(2)	202(48)	69.6(25)	69.5(30)	94(31)	<77*
16 Sof./H	no	7.5(5)	35(8)	47.8(18)	49.5(21)	77(23)	<95*
17 Sof./WP	no	7.5(5)	23(6)	33.0(13)	34.6(15)	50(20)	<55*
21 Sof./WP	YES**	14.0(5)	25(6)	38.9(28)	41.3(18)	25(15)	61(26)
28 Buh./H	YES**	10.0(5)	480(100)	747(26)	747(32)	831(99)	820(120)

* The minimum detectable activity concentration is given.

** Location 12. Mitigation by active anti-radon system was performed just before the survey

** Location 21. Window frames change 9 years ago.

** Location 28. Habits change 2 years ago: the ventilation was reduced

Table 5: Comparison of the retrospective radon measurements by home-stored CDs/DVDs with the prospective measurements.

5. Conclusions

In this work, a year-long radon survey was organized and conducted with the aim of evaluating the applicability of continuous electronic radon monitors for estimating long-term average indoor radon concentrations. The comparison between RadonEye Plus2 CRMs and two types of SSNTDs – UKHSA's PRDs and CDs and DVDs – was conducted through parallel measurements in 32 homes and workplaces with largely varying radon concentrations.

Detailed results for the estimated yearly average radon concentrations by the different methods, examples of continuous radon measurements in dwellings and workplaces, and statistics on the data coverage by the electronic detectors during the campaign are provided.

The results of the study demonstrate that the annual average radon concentrations estimated by CRMs measurements are in agreement with the SSNTDs. The average difference with the RE estimates for the three independent SSNTD estimates of the yearly average concentration ranged between -10% and 8%, with median within -12% and 4%. A comparison of the methods, considering the uncertainty of the yearly average estimates was performed. The difference between the methods' results normalized to its estimated uncertainty (Z-score), were analyzed and the results indicate good agreement between the methods, within the estimated uncertainties, with most of the Z-scores lying between -2 and 2.

The correlation analysis of the annual average estimates by REs and SSNTDs demonstrates very good correlations between the different techniques. Small but significant biases were identified in some cases, which were observed between REs and SSNTDs, as well as between the estimates of the SSNTDs. These biases indicate the importance of conducting another study in the future, incorporating a reference instrument at designated locations.

Overall, it is implied by the results of this study that with sound metrological assurance, the RadonEye Plus2 electronic radon monitor can be used to assess long-term average radon concentrations with sufficient accuracy. The technical developments used in this study, such as the Wi-Fi data collection approach and the developed database, were proved to be useful tools for data analysis. This study represents a step towards the use of electronic radon detectors for active radon monitoring and the creation of intelligent systems to reduce human exposure to radon.

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.

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Declaration of interests

☒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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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