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Performance evaluation of radon active sensors and passive dosimeters at low and high radon concentrations

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A R T I C L E I N F O

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A B S T R A C T

Radon is a naturally occurring radioactive gas that has the potential to accumulate in buildings and over time, causes lung cancer in humans. Present methods for radon measurements are disparate, which pose challenges to benchmark radon concentrations and to accurately assess the population's received dose. This paper presents a comprehensive performance evaluation of radon dosimeters and three grades of active radon sensors: consumer-, medium- and research-grade. The measurements were performed at relatively low (300 Bq/m^3) and high (2′000–3′000 Bq/m^3) radon levels. Tests were conducted in an atomic shelter, with stable temperature and humidity conditions. The active sensors differed in absolute accuracy and dynamic performance (time-dependent correlations) according to their grade. Research-grade sensors performed marginally better than medium-grade sensors, and significantly better than consumer-grade sensors. Relative to the reference, the error (percentage difference between the reference and the sensors) was below 5 % for research- and medium-grade sensors, and nearly 10 % for consumer-grade sensors at high radon levels. Performance of sensors diminished at low radon levels, except for research-grade sensors. Passive dosimeters generally performed better at high radon levels than at low ones. Their longer exposure time was associated with increased measurement reliability. These results highlight the need for understanding the purpose of measurements in order to select an adequate radon detector, and ultimately, reduce measurement and interpretation errors. This study raises awareness among researchers, radon professionals and the general public regarding the performances of different active radon sensors and passive dosimeters. It also sheds light on their respective scope of application.

1. Introduction

People in developed countries spend ~90 % of their time indoors [1]. During this time, they are exposed to myriad of air pollutants, many of which are linked to deleterious health consequences. Among the over-abundance of substances present in indoor air, radon, a natural radio-active noble gas is a major public health concern [2,3]. Radon's lacks of color, odor and smell makes it imperceptible to building occupants [4]. World Health Organization (WHO) [4] provides guidelines for developing national action plans, with the most important measure being the establishment of a reference value of 100 Bq/m^3. If this level cannot be reached due to a higher radon prevalence, the reference value is set to 300 Bq/m^3. For instance, the arithmetic means of indoor radon levels in countries such as the Netherlands, Denmark, and Norway, are 16, 53 and 89 Bq/m^3, respectively, and are therefore using 100 Bq/m^3 reference level. Conversely, arithmetic means of radon concentrations in Switzerland, France and Brazil reach 75, 92 and 100 Bq/m^3, respectively, where the reference value is set at 300 Bq/m^3 [4,5].

Inhalation of radon and its progeny strongly affects the human respiratory system. With a half-live of 3.8 days, radon (^{222}Rn) undergoes in a very short time three alpha and two betas-minus decays to form solid daughters, known as inhalable daughters (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po, ^{210}Pb) [6]. Consequently, inhaling the air containing radon and its short-lived progeny result into an accumulation of solid radon daughters in the lungs. The energy released by radon decays in the human lungs damages cellular DNA, thereby promoting the development of

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cancerous cells [6,7]. Radon's radiation effects on cells are stochastic in nature [8], meaning that a higher dose is associated with a greater probability of cancer. Globally, radon is responsible for 3 %–14 % of all lung cancers, with this variability depending on the national average radon level and smoking prevalence [9]. It has been estimated that residential radon exposure was responsible for 84′000 deaths worldwide in 2019 [10]. The development of national radon action plans to lower population exposure, as seen in countries like Switzerland, Canada, and the USA, reflects the growing concern for this issue [2,11,12].

The market for indoor air quality (IAQ) measurement devices, including those for radon, has significantly evolved over the last decade [13,14]. Consequently, the disparity of radon measurement devices on the market is large in terms of the prices and methods of detection. This lack of harmonization in radon measurement approaches impedes our ability to perform cross-study comparisons, establish benchmark radon concentrations across different buildings, and accurately assess the effective dose absorbed by the population. Moreover, the market for both radon passive dosimeters and active radon sensors exhibit significant variability in terms of their detection methods and exposure times. Furthermore, passive radon dosimeters are widely used for official measurements in various countries, such as in Switzerland [15], Germany [16], and Canada [17]. In order to harmonize methods for benchmarking radon levels in buildings, there is a need for comprehensive and robust performance evaluation and comparison of existing radon measurement methods.

A review of the literature reveals that metrological institutes have employed cross-comparisons of radon sensors for decades to ensure quality controls and acceptable performance of tests and measurements. Notably, the MetroRADON project (2016–2020) sought to identify possible reasons for inconsistencies in radon sampling and measurement techniques [18]. Several recent studies attempted to compare the performance of consumer-grade and high-grade radon sensors [19–22]. Carmona et al. [19] tested different consumer-grade radon sensors, mainly available in the North American market. In a monthly experiment with radon levels ranging from 500 to 1′500 Bq/m^3, all tested devices performed within 20 % of the reference measurements. Similarly, Rabago et al. [21] found that over 80 % of the tested active radon sensors fell within the interval defined by the instrument's reference value and its standard deviation. However, it is worth noting that the examined radon concentrations during the experiment were unrealistically high, up to 30′000 Bq/m^3 [21]. Warkentin et al. [22] found that radon consumer-grade sensors perform better at higher radon levels than at levels close to the Canadian reference value (200 Bq/m^3). Dimitrova et al. [20] tested the behavior of consumer-grade radon sensors, specifically RadonEye Plus2, and demonstrated good results up to 3′500 Bq/m^3 with slight deviations at higher concentrations. Notably, at concentrations between 3′500 and 7′000 Bq/m^3, RadonEye Plus2 would, on average, underestimate the radon level by 12 %. Collectively, these studies demonstrate that the performance of consumer-grade radon sensors is generally within manufacturer-specified levels.

Passive radon dosimeters have undergone extensive comparisons in previous research studies [23–25], intergovernmental reports [26], and by governmental agencies. For instance, the Swiss metrology institute performs biennial assessment of recognized radon dosimeters to ensure the highest level of measurement reliability [27,28].

Beyond the studies listed above, our understanding of the overall performance of existing radon measurement methods and their comparative evaluations remains limited. Specifically, there is a lack of knowledge regarding 1) the comparative performance of the range of active radon sensors available on the market, including consumer-, medium- and research-grade sensors; 2) the dynamic performance of active radon sensors at varying radon concentrations commonly encountered in buildings; 3) a mutual comparison between active and passive detection methods at variable radon concentrations; 4) the reliability of passive dosimeters at different concentration levels, particularly those designed for short term measurements.

To address these gaps, this paper aims to answer the following research questions: 1) To what extent do radon consumer-grade, medium-grade and research-grade sensors differ in terms of accuracy at distinct radon levels? 2) To what extent do passive radon dosimeters' performances differ depending on exposure time and radon detection method? In this study, we compared the performance of both active and passive radon measurement tools at two distinct radon levels – 300 Bq/m^3 and 2000-3′000 Bq/m^3. We evaluated a total of 6 types of consumer-grade sensors from 5 brands, 4 types of medium-grade from 3 brands, and 2 types of research-grade active radon sensors from 2 brands. Additionally, we tested 6 different types of passive radon dosimeters from 4 brands, each for a minimum of 48 h. The results of this study are valuable for researchers, manufacturers, stakeholders, and the general public as they aid selection of radon evaluation methods that alight with real-world conditions and address measurement concerns.

2. Methods

2.1. Study site

The *Anthropole* Building of the University of Lausanne in Switzerland was used as a study site. The experiments were conducted in one of the atomic shelters located in the basement of the building. This study site has stable indoor air temperature and relative humidity conditions, as indicated in Table 1. These conditions are suitable for testing radon detection devices. The floor area of the study site is 40 m^2 with the volume of ~144 m^3. A table was positioned in the center of the room to accommodate radon active sensors and passive dosimeters. To ensure uniform radon concentrations throughout the space, fans were installed at each corner of the room. For a visual representation of the experimental setup, please refer to Fig. 1.

2.2. Experimental design

The experiments took place during the summer of 2021, characterized by high radon levels (Experiment I), and the autumn of 2022, marked by low radon levels (Experiment II). Fig. 2 illustrates the timeline of the two experiments.

First, we aimed to assess the performance of radon active sensors and passive dosimeters at relatively high radon levels, i.e., 2′000–3′000 Bq/m3. This range is occasionally encountered in residences [9] but is below the upper detection limits of several radon sensors. Active radon sensors were tested over periods ranging from 48 to 69 h (Table 1), subject to the availability of experimental facility (i.e. security restrictions). The passive dosimeters were tested for up to 3 months (Table 3). Additionally, passive dosimeters were also evaluated at radon levels close to reference value (300 Bq/m^3) recommended by WHO [4]. The second experimental campaign (autumn 2022) sought to compare the performance of radon active sensors, including consumer-grade, medium-grade, and research-grade sensors, under relatively low radon levels (300 Bq/m^3). This threshold value is established in several countries, including Switzerland, France, and Austria [5]. Since remediation works may be recommended if the reference value of 300 Bq/m^3 is exceeded in spaces with long-term stay, it is critical to assess sensors' performances at this radon level. Table 1 summarizes the total of 15 experiments: six performed during the first experimental campaign, and nine during the second experimental campaign.

2.3. Radon generation

Two highly active natural radon sources were employed to establish both high and low radon levels. To achieve high radon levels, we used the "Swiss Radon Mega Source Facility" consisting of a mobile lead and steel enclosure filled with 20 kg of high-grade uraninite (UO_2 + UO_3 85–94 %) bearing ore, in secular equilibrium, sourced from La Creusaz uranium mine in Valais, Switzerland [29]. For the low radon levels, we

Table 1
Summary of experimental design and associated mean ± standard deviation (SD) of associated environmental conditions. Means and standard deviations were computed on the time-series provided by the reference sensors for the specified durations.

Experimental campaign	Year	Radon level	Duration for active radon sensors	Number of active sensors[a]	Air temperature		Relative humidity		Radon	
					Mean	SD	Mean	SD	Mean	SD
			(h)	n	(°C)	(°C)	(%)	(%)	(Bq/m^3)	(Bq/m^3)
I	2021	High	48	25	20.9	0.24	60.5	1	2220	425
I	2021	High	48	25	21	0.26	59.5	0.31	2300	700
I	2021	High	48	25	21.6	0.28	59.8	0.32	2290	730
I	2021	High	48	25	21.5	0.28	61.2	0.71	2560	690
I	2021	High	48	–	21.5	0.22	60.8	0.32	2860	730
I	2021	Low	48	–	23.5	0.15	52.4	0.29	295	150
II	2022	Low	69	33	21.8	0.14	59.6	0.5	435	135
II	2022	Low	48	34	22	0.17	60.2	0.28	410	135
II	2022	Low	48	34	22	0.14	60.5	0.2	330	115
II	2022	Low	67	34	21.7	0.17	60	0.34	280	110
II	2022	Low	48	34	21.9	0.23	60.1	0.41	355	130
II	2022	Low	48	34	22.1	0.27	61.6	0.36	360	125
II	2022	Low	66	34	21.4	0.33	59.1	1.09	235	95
II	2022	Low	48	34	21.1	0.23	56.7	0.38	230	95
II	2022	Low	48	34	20.9	0.23	56.2	0.31	290	115

[a] Along with active sensors, experimental campaign I also included passive dosimeters (n = 12 per run). Duration of their exposure was longer (see Table 3), however, it also included radon levels defined during the experimental campaign I. For the remaining time, dosimeters were stored in another part of the shelter with similar environmental conditions (temperature and humidity) and radon levels.

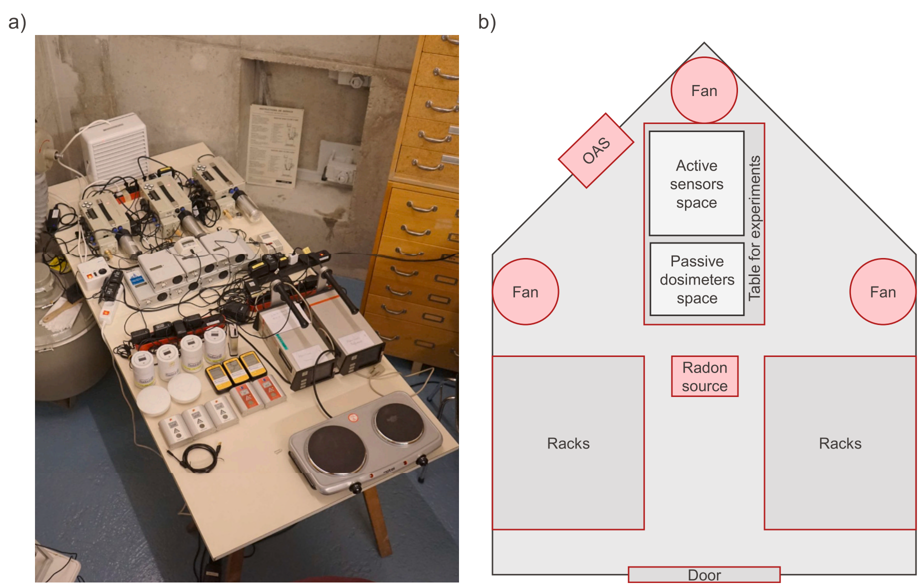


Fig. 1. Example image of the experimental setup (a); and schematic layouts of the shelter with the location of measurement devices and the different elements (OAS: Outdoor air supply) at two studied radon levels (b). Note that the example image (a) presents one out of several investigated experimental scenarios, as reported in Table 1.

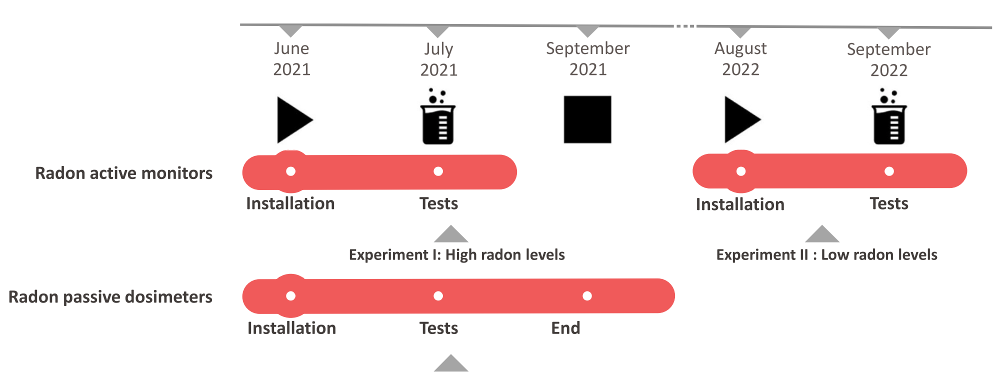


Fig. 2. Stages of the measurement campaigns, along with their associated timelines for active sensors and passive dosimeters.

Table 2
Names and technical specifications of the three grades of active radon sensors[a]. More information available in Table S1.

Model	Brand	Country	Grade	Sampling interval (min)	Detection range (Bq/m^3)	Other parameters measured	NHL	NLL
AER	Algade	France	C	2880	No data	T; RH	3	0
AER+	Algade	France	C	15	No data	T; RH	2	6
RadonEye RD200	Radon FTLab	South Korea	C	60	1–3′700	–	4	5
RadonScout Home	Sarad	Germany	C	240	1–1′000′000	T; RH; CO_2	0	1
Ramon	GT-Analytic KEG	Austria	C	2880	0–9′999	–	1	1
Wave Plus	Airthings	Norway	C	60	0–20′000	T; RH; P; CO_2; TVOC	2	2
AlphaE	Bertin SA	France	M	10	20–10′000′000	T; RH; P	1	1
Corentium Plus	Airthings	Norway	M	60	0–50′000	T; RH; P	3	3
RadonScout Plus	Sarad	Germany	M	10	1–10′000′000	T; RH; P	7	6
RadonScout Pro	Sarad	Germany	M	10	1–1′000′000	T; RH	1	1
AlphaGUARD	Bertin SA	France	R	10	2–2′000′000	T; RH; P	2	3
Radonmapper	Tecnavia SA	Switzerland	R	1	10–3′000′000	T; RH; P; CO_2	3	5

[a] (C: Consumer-grade; M: Medium-Grade; R: Research-grade; T: Air Temperature; RH: Relative Humidity; P: Atmospheric Pressure; TVOC: Total Volatile Organic Compounds; NHL: Number of sensors at high radon levels; NLL: Number of sensors at low radon levels).

Table 3
Names and specifications of the studied passive radon dosimeters[a].

Model	Brand	Country	Exposure duration	Radon detection method	Detection range (Bq/m^3)	NHL[a]	NLL[a]
Radtrak2	Radonova	Sweden	3 months	Alpha track	15–25′000	10	2
Duotrak	Radonova	Sweden	10 days	Alpha track	50–150′000	10	2
Rapidos	Radonova	Sweden	7 days	Alpha track	60–150′000	10	2
RSKS	RadoSys Ltd.	Hungary	3 months	Alpha track	No data	10	2
Radout	Mi.am	Italy	3 months	Alpha track	0–9′000	10	2
E-Perm	Mi.am	Italy	48 h	Electret ion chamber	No data	10	2

[a] (NHL: Number of sensors at high radon levels; NLL: Number of sensors at low radon levels).

utilized a fragment of pure uraninite, specifically the "pitchblende" variety ($UO_2 + UO_3$ 87–93 % - 550 g), also in secular equilibrium, obtained from the historic Mine of La Crouzille-Bessine in Limousin, France [30].

High radon levels were achieved by releasing radon at the beginning of the experiment, resulting in a rapid increase in radon concentration. After approximately 15 min, the source was moved outside the shelter, leading to a gradual decrease in over the course of the experiment. In contrast, throughout the experiments at low radon levels, the uraninite source remained within the shelter, maintaining a relatively stable radon concentration.

2.4. Active radon sensors

As shown in Table 2, we assessed the performance of 12 sensor types from 7 different brands, resulting in a total of 28 sensors tested at high radon levels and 34 sensors tested at low radon levels. Whenever possible, the same sensors were tested at both high and low radon levels (more details in Table S1). This selection is intended to be representative of the European radon sensor market. We categorized the sensors into three grades based on their selling price as follows: 1) Consumer-grade, priced below 950 USD; 2) Medium-grade, ranging from 950 to 5000 USD, and 3) Research-grade, priced at over 5000 USD.

2.5. Passive radon dosimeters

We tested 6 different radon dosimeter types manufactured by four prominent European brands. These sensors differ in terms of their detection method and exposure duration. Table 3 lists the investigated passive dosimeters and their specifications.

2.6. Radon reference measurements

To facilitate cross-comparison, we used Radonmapper as the reference sensor. During both experiments, an AlphaGUARD served as a backup reference instrument in case of failure of the Radonmapper. These devices were chosen due to their recent calibration and because of accreditation of their performance by METAS (Federal Office of Metrology, Switzerland). The average uncertainty of radon measurement, defined by the confidence interval at 95 %, ranged between 15.1 and 26.8 Bq/m^3 at high radon levels, and between 3 and 5.4 Bq/m^3 at low radon levels.

2.7. Data analysis

To assess performances of the examined devices, we carried out data analyses involving ratios and correlation coefficients. For statistical analyses and graphical productions, we used the R language (Version 4.3.0 for Windows) [31] and RStudio (Version 1.4.1717) [32] software, respectively. Graphics and figures were created using the ggplot2 system installed as a package within RStudio [33].

2.7.1. Ratios

Ratios are defined as the average concentration measured by a sensor divided by the average of the reference sensor for the same experiment. Ratios allow cross-comparisons among sensors or dosimeters within the same experiment, as well as comparisons across different experiments. This type of analysis has previously been used to assess the performance of radon sensors [24,34,35].

The radon time-series acquired by active radon sensors are described by Equation (1), where X represents the sensor, and t represents the time-series:

$$Ratio_X = \overline{X}_t / \overline{REF}_t \quad (1)$$

Furthermore, we calculated the absolute percentage difference APD for a sensor X as follows (Equation (2)):

$$APD_X = 100 * |Ratio_X - 1| \quad (2)$$

Absolute percentage difference (APD) was then averaged to obtain the absolute mean difference (AMD) for a group of sensors. The AMD represents the accuracy of the tested sensors relative to the reference sensor.

2.7.2. Correlation coefficient

The Pearson correlation coefficient was used to assess the correlation between time-series data from active radon sensors. The Pearson correlation coefficient, denoted as ρ, was calculated between a sensor's time-series data and its corresponding reference data (*REF*), as shown in Equation (3), where σ represents the standard deviation:

$$\rho_{X_t,REF_t} = cov(X_t, REF_t) / \sigma_{X_t}\sigma_{REF_t} \quad (3)$$

Subsequently, an average value of the correlation coefficients was computed to obtain the mean correlation coefficient (*MCC*). The MCC serves to highlight the dynamic response of the tested sensors relative to the reference data.

2.8. Quality assurance

The reference instruments were high-grade sensors with a stable calibration, accredited by METAS [36,37]. To the extent possible, we used multiple sensors of the same kind in our experiments. Among all the active radon sensors, only AlphaE, RadonScout Pro, RadonScout Home, and Ramon underwent single testing. Most of active radon sensors (i.e., AER, AER+, AlphaE, RadonEye RD200, RadonScout Home, Ramon, Wave Plus, RadonScout Pro and AlphaGUARD) were provided by different institutions from Switzerland and France, implying variations in their utilization history. To minimize differences between sensors of the same type, all sensors were powered on one week prior to the commencement of the experiments. Furthermore, all sensors were deployed in accordance with the manufacturer-specified recommendations. Finally, the experimental protocol was strictly followed to reduce the measurement uncertainty, thus maximizing the quality assurance and repeatability of the results.

3. Results

3.1. Performance assessment of active sensors

In this section, we describe the results of the cross-comparison among consumer-, medium- and research-grade sensors at high and low radon concentrations. The sensors were evaluated in terms of their absolute accuracy and dynamic performance. Fig. 3 shows that the performance of active sensors scaled with their grades. Notably, the consumer-grade exhibited the lowest relative performance (AMD = 9.28; σ = 5.85), while both medium- and research-grade sensors achieved higher performance levels, typically with an AMD of less than 5 %. Surprisingly, medium-grade sensors demonstrated similar performance (similar AMD) to consumer-grade sensors under the low radon conditions, but they matched research-grade sensors under high radon levels.

To ascertain the statistical distinctions between distributions of AMD and MCC, we employed pairwise Kolmogorov-Smirnov tests. Table 4 summarizes the results and their corresponding P-values. It is noteworthy that all distributions (AMD and MCC) showed in Fig. 3 mutually had statistically significant differences, both at high and low radon levels, with P-values consistently lower than 0.05.

Dynamic performance comparison at high radon levels highlighted exceptional results for research-grade sensors (MCC = 0.96), followed by slightly lower scores for medium-grade sensors (MCC = 0.8), and finally, lower performance for consumer-grade sensors (MCC = 0.64). Furthermore, the standard deviation exhibited a significant increase, rising from 0.05 for research-grade sensors to 0.47 for consumer-grade sensors. This variance underscored important variability in the results for medium- and consumer-grade sensors. At low radon levels, research-grade sensors demonstrated high performance (MCC = 0.76), while both medium- and consumer-grade sensors had similar, comparatively lower MCC values, specifically 0.44 and 0.42, respectively. Pairwise Kolmogorov-Smirnov tests (Table 4) revealed that all distributions had statistically significant differences, with P-values consistently below 0.01.

Fig. 4 presents the distribution of the ratio and correlation coefficient of the consumer-, medium- and research-grade radon active sensors. The intersection between the red lines represents the ground truth data recorded by the reference instrument. Notably, at both high and low radon levels, the distribution of coefficients associated with consumer-grade sensors was more spread relative to medium- and research-grade sensors, indicating lower ratio values (see also Table 4). Interestingly, distributions were more scattered for all the three sensor grades at low radon levels compared to high radon levels. This observation is further supported by the higher values of standard deviation at low radon levels, as depicted in Fig. 3.

Table 5 summarizes performance data of individual sensors belonging to the three studied grades. Research-grade active radon sensors, represented by AlphaGUARD and Radonmapper, demonstrated strong consistency in terms of accuracy and dynamic performance across the different experiments. This is evident from the maximum standard deviation of 0.18 recorded for dynamic performances at low radon levels. Medium-grade sensors, regardless of the sensor type, yielded consistent results in terms of accuracy at high radon levels. However, their performance was somewhat less consistent at low radon levels. The average ratio by sensor type ranged from 0.98 to 1.02 at high radon

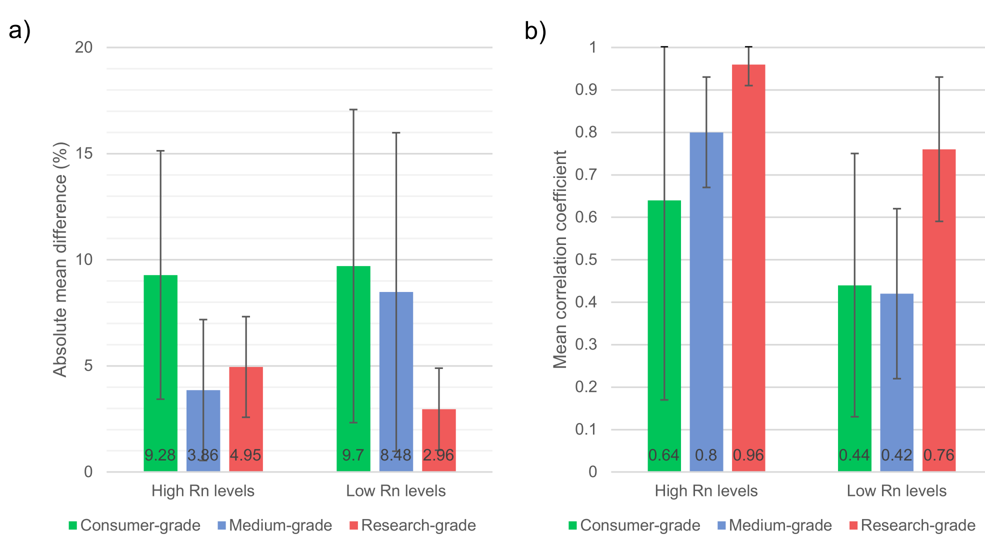


Fig. 3. Absolute mean difference (a) and mean correlation coefficient (b) and their relative standard deviations of consumer-, medium- and research-grade radon sensors at high (3'000 Bq/m^3) and low (300 Bq/m^3) radon concentrations.

Table 4
P-values of Kolmogorov-Smirnov tests associated with active sensors of different grades. Significance is presented as follows: * p-value <0.1; ** p-value <0.05; *** p-value <0.001.

	Ratios			Correlation coefficients		
	High radon levels					
	Consumer	Medium	Research	Consumer	Medium	Research
Consumer	–	–	–	–	–	–
Medium	0.46***	–	–	0.45***	–	–
Research	0.44**	0.42**	–	0.53***	0.85***	–
	Low radon levels					
	Consumer	Medium	Research	Consumer	Medium	Research
Consumer	–	–	–	–	–	–
Medium	0.45***	–	–	0.25***	–	–
Research	0.53***	0.85***	–	0.5***	0.7***	–

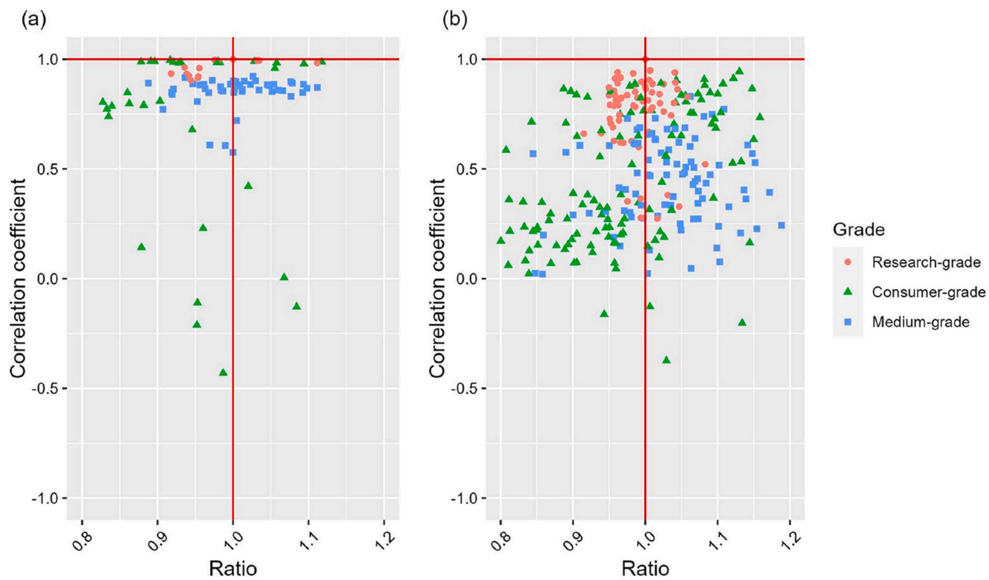


Fig. 4. Consumer-, medium- and research-grade active radon sensors distributed according to their ratio and correlation coefficient at high (3′000 Bq/m^3) (a) and low (300 Bq/m^3) (b) radon levels.

Table 5
Mean and standard deviation (σ) of ratio and correlation coefficient for each type of consumer-, medium- and research-grade active radon sensors at high (3′000 Bq/m^3) and low (300 Bq/m^3) radon levels.

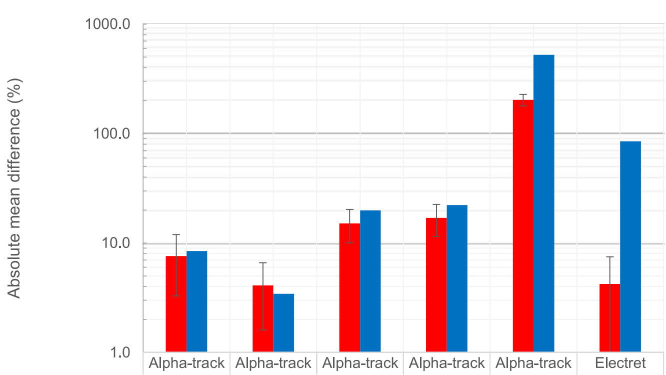
Model	Grade	High radon levels				Low radon levels			
		Ratio		Correlation coef.		Ratio		Correlation coef.	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ
AER	C	0.96	0.1	–	–	–	–	–	–
AER+	C	0.86	0.03	0.74	0.13	0.9	0.06	0.19	0.1
RadonEye RD200	C	0.98	0.08	0.96	0.08	1.03	0.07	0.74	0.15
RadonScout Home	C	–		–		0.8	0.16	0.35	0.27
Ramon	C	0.97	0.03	–	–	1.07	0.19	–	–
Wave Plus	C	0.93	0.11	−0.08	0.33	0.96	0.13	0.31	0.38
Overall	**C**	**0.94**	**0.09**	**0.64**	**0.47**	**0.95**	**0.11**	**0.44**	**0.31**
AlphaE	M	0.99	0.02	0.56	0.17	1.16	0.04	0.34	0.11
Corentium Plus	M	0.98	0.07	0.81	0.14	0.9	0.13	0.29	0.17
RadonScout Plus	M	1.02	0.05	0.82	0.09	1.04	0.05	0.49	0.18
RadonScout Pro	M	1	0.01	0.83	0.09	1	0.03	0.45	0.18
Overall	**M**	**1**	**0.05**	**0.8**	**0.13**	**1.02**	**0.11**	**0.42**	**0.2**
AlphaGUARD	R	0.94	0.01	0.92	0.04	0.97	0.03	0.68	0.18
Radonmapper	R	1.01	0.04	0.99	0.01	1	0.03	0.82	0.18
Overall	**R**	**0.98**	**0.05**	**0.96**	**0.05**	**0.99**	**0.03**	**0.76**	**0.17**

levels but varied from 0.9 (Corentium Plus) to 1.16 (AlphaE) at low radon levels. In contrast, the differences in dynamics performance were more pronounced at high radon levels, with mean correlation coefficients ranging from 0.56 (AlphaE) to 0.83 (RadonScout Pro) compared to a range of 0.29 (Corentium Plus) to 0.49 (RadonScout Plus) at low radon levels. Finally, consumer-grade sensors exhibited the highest variability, showcasing a wide range of performances. In terms of accuracy, consumer-grade sensors seemed to be consistent at both high and low radon levels. However, dynamic performances varied significantly at the different levels tested. For instance, at high radon levels, Wave Plus and RadonEye RD200 exhibited mean correlation coefficients of −0.08 and 0.96, respectively. At low radon levels, AER+ and RadonEye RD200 displayed mean correlation coefficients of 0.19 and 0.75, respectively.

3.2. Performance assessment of passive dosimeters

Fig. 5 compares the performance of tested brands of passive radon dosimeters with diverse exposure times and method of detection at high and low radon levels. The figure suggests that exposure time was the most influential factor affecting the absolute mean difference (AMD), independently of the radon concentration. The AMD relative to the reference value decreased as the exposure time increased. Radtrak2 and RSKS dosimeters delivered the highest performance at low and high radon levels, with AMD ranging from 3.4 % to 8.5 %. Although Radout dosimeters were exposed for a 3-month period, their performance was inferior to those of other dosimeters with equivalent exposure time, with AMD values of 15.1 % and 19.9 % at high and low radon levels, respectively. Shorter exposure times, as seen with Duotrak and Rapidos dosimeters, resulted in higher. Furthermore, in the case of Miam electret dosimeters exposed to high radon levels for 48 h, the absolute mean difference was as low as 4.2 %, a result comparable to the best performances achieved by the Radosys dosimeter with a 3-month exposure time operating with alpha-track detection method. Contrary to our findings, we observed an influence of radon levels on the precision of electret dosimeters. Their performances were less consistent (AMD = 85.3 %), especially at low radon levels. Since the measurement range is not provided by the manufacturer [38], we may hypothesize that these sensors (i.e., E-Perm SST system with a small chamber and a ST electret, designed for a 2–7 days exposure) are not designed to detect low radon levels.

In general, alpha-track dosimeters exhibited more robust performance at higher radon levels, although the primary source of error was linked to exposure time. In contrast, the investigated Miam electret dosimeters showed a substantial difference between low (85.3 %) and high (4.2 %) radon levels in terms of absolute mean difference. In this exceptional case, the detection method was more influential parameter



	Alpha-track 3-months Radtrak2	Alpha-track 3-months RSKS	Alpha-track 3-months Radout	Alpha-track 10-days Duotrak	Alpha-track 7-days Rapidos	Electret 2-days E-Perm
High Rn Levels	7.6	4.1	15.1	17	203.6	4.2
Low Rn Levels	8.5	3.4	19.9	22.2	525.4	85.3

High Rn Levels   Low Rn Levels

n = 10   n = 2

Fig. 5. Absolute mean difference (AMD) (%) and their relative standard deviations of passive dosimeters according to their type, exposure time and method of detection at high (3′000 Bq/m^3) and low (300 Bq/m^3) radon levels. Standard deviations at low radon levels were not computed due to the small sample size.

relative to exposure time. Finally, we detected large performance differences provided by the Radonova 7-days dosimeter at both low and high radon levels.

4. Discussion

Our study suggests that the accuracy of sensor reading was directly proportional to the grade (cost) of the measuring device. These findings align with those reported by Carmona et al. [19], where they found that the majority of active radon sensors fell within a 20 % from the reference values. Additionally, in line with the findings of Warkentin et al. [22], we highlighted performance differences between high and low radon levels, especially for consumer-grade radon sensors. Their study demonstrated that the higher the radon levels, the lower the measurement error for consumer-grade sensors, with error ranges of 4.95–20.75 %, 8.98–21.98 %, and 7.33–16.83 % at 200, 600, and 1′000 Bq/m^3, respectively. Our study confirmed these previous findings showing that the absolute mean difference and, especially, the mean correlation coefficient demonstrated lower performance at low radon levels.

Nevertheless, our results extend beyond previous studies by highlighting the dynamic performance of radon sensors. Short-term radon variations, such as sudden increases in radon concentration, were effectively captured by all high-grade sensors and some medium-grade sensors, whereas consumer-grade sensors took longer to detect these variations. This observation may be explained by the fact that some of consumer-grade sensors do not provide an instantaneous measurement, but rather a rolling average data. This leads to smoother time-series, thus erasing short-term radon variations. These results are illustrated through the average values of Pearson's correlation coefficients for each sensor grade (see Figs. 3 and 4). Furthermore, depending on the radon level, medium-grade sensors matched the performance of both high-grade and consumer-grade sensors. This observation emphasizes the overall reliability of medium-grade sensors while highlighting an inherent variability in their performance. Consequently, it is recommended for indoor air quality consultants utilizing medium-grade sensors for radon assessments to exercise caution when interpreting results. This underscores the need for more comprehensive testing and evaluation of the medium-grade radon sensor category.

The assessment of passive radon dosimeter performance highlights two main points. Firstly, with some exceptions, longer exposure times of dosimeters generally led to higher measurement precision. This suggests that shortening the duration of measurements with passive dosimeters might increase measurement uncertainty. This finding is supported by the results obtained with the 7-day dosimeters. Despite being developed for short exposure times [39], these dosimeters exhibited high discrepancies relative to the reference data. Future developments are needed to improve the precision of passive measurement techniques based on short exposure times. Secondly, the radon level did not influence the performance of alpha-track dosimeters, except for electret dosimeters. This confirms that most passive detectors maintain strong stability regardless of the radon level, highlighting their ability to assess radon in various indoor environments. These results are in line with previous research studies [23–25] and reports published by intergovernmental [26] and governmental agencies [27,28].

It is well established that dosimeters require longer exposure durations to yield reliable measurements. However, the modern construction industry increasingly demands swift radon diagnosis, particularly in scenarios such as real estate purchase or renovation. Such situation prompts an important question: Can active radon sensors (consumer or medium grade) be sufficient for reliable and rapid radon diagnostic needs? A reasonable approach might involve employing active sensors for a short-time period to obtain a preliminary assessment of radon levels at a specific location and time. To ensure a high level of reliability in these expedited measurements, it is imperative to develop robust protocols which delineate the purpose of the measurement, its required duration, the performance criteria for sensors, and the specific environmental conditions under which the measurements should be conducted.

Our study points toward an interpretation that cheaper, consumer-grade, sensors could be associated with increased measurement errors and interpretation errors. Consequently, it is essential to assess the effectiveness of consumer-grade sensors in practical applications. We deem that the suitability of these sensors depends on the specific purpose of the measurement. For example, in residences, consumer-grade radon sensors can be used by property owners as a tool to make informed decisions regarding radon management. Our study shows that most active sensor grades can detect high radon levels with an error of at most ±10 %. This suggest that consumer-grade radon sensors could be an effective tool for radon management in buildings. On the other hand, if the objective is to precisely measure radon levels and their dynamics, it is necessary to use sensors capable of capturing these variations. This includes research-grade sensors and some medium- and consumer-grade sensors. In fact, medium- and consumer-grade sensors, such as AER+, RadonScout Home, Wave Plus, AlphaE, and Corentium Plus, often had low correlation coefficients at low radon levels (and also at high radon levels for the Wave Plus), while RadonEye RD200 had correlation coefficients similar to those of research-grade sensors at both high and low radon levels.

At present, there is no universally defined acceptable error for radon detection. In addition to measurement precision (accuracy and dynamic performance), consideration should also be given to measurement duration and cost. Among the investigated sensors, it appears that some consumer-grade sensors strike an optimal balance among precision, time and cost. Thus, manufacturers of consumer-grade sensors should transparently communicate about their sensors' capabilities and potential applications to the general public. Furthermore, national regulatory authorities should establish a clearer legal framework by precisely formulating performance requirements of these sensors. In this regard, the research presented in this paper should be considered by regulatory authorities to develop the most up-to-date measurements protocols, ensuring the highest precision in indoor radon assessment.

4.1. Study limitations

Our results were obtained in laboratory environments under stable conditions. However, these controlled settings may not be representative of wide spectrum of indoor climate conditions encountered in real-world buildings. Consequently, these experiments should be replicated in real-life conditions, such as households, workplaces, and schools, to challenge and validate the present results. Regarding the examined sensors, two limitations should be acknowledged: 1) some sensors were tested as only a single device without duplicates; and 2) sensor conditions varied; they were not all brand new at the beginning of the experiments. Due to budget and time constraints, passive dosimeters were tested in five experiments at high radon levels and in only one experiment at low radon levels. Finally, these experiments were relatively short, which means we lack information about the durability and consistency of the sensors over extended periods. Notwithstanding these limitations, the robust and comprehensive experimental design presented here allowed for the most extensive performance investigation of radon active sensors and passive dosimeters performed to date.

5. Conclusions

Our study offers a useful dataset related to the accuracy and cost-effectiveness of different methods and grades of radon measurements. We performed a comprehensive performance assessment of both active radon sensors and passive dosimeters across two distinct radon concentration levels.

The sensors differed both in terms of accuracy and dynamic performance according to their grade. Research-grade sensors performed better than medium-grade sensors, and substantially better than consumer-grade sensors, at both high and low radon levels. At high radon levels, research- and medium-grade radon sensors had an absolute mean difference (AMD) lower than 5 %, whereas consumer-grade had an AMD of 10 %. At low radon levels, AMDs were approximately 9.5 %, 8.5 %, and 3 % for consumer-, medium- and research-grade sensors, respectively. In terms of dynamic performance, research-grade radon sensors performed systematically better than medium- and consumer-grade sensors (with mean correlation coefficient (MCC) of 0.96 at high radon levels and 0.76 at low radon levels), while medium- and consumer-grade sensor performances dropped at low radon levels, with MMCs of 0.42 and 0.44, respectively. Furthermore, among the different grade categories, consumer-grade sensors exhibited the highest variability. For instance, the RadonEye RD200 performed similarly to research-grade radon sensors, whereas the Wave Plus had the lowest dynamic performance at both high and low radon levels.

Our findings underline the importance of defining the performance needs based on the specific purpose of the measurement. This process can significantly reduce measurement and interpretation errors. It is critical for manufacturers of consumer-grade sensors to improve communication regarding their sensors' performance and applications, and for public authorities to establish precise and binding legal framework. Moreover, given the differences observed among the different sensor grades, consistent standards and guidelines for sensors testing are necessary to reduce measurement and interpretation errors in the long term.

The recent raise in public awareness regarding indoor air quality, including indoor radon, has resulted in a growing demand for consumer-grade radon sensors. Although this awareness is positive from the public health perspective, it underscores the need for public authorities to gain knowledge about emerging radon sensors and to ensure their quality. Continuous research and evaluation of emerging radon monitoring devices by researchers are essential to provide up-to-date guidelines for radon assessment.

CRediT authorship contribution statement

Joan F. Rey: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicolas Meisser:** Writing – review & editing, Supervision, Resources. **Dusan Licina:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Joëlle Goyette Pernot:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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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Appendix A. Supplementary data

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