Characterization of Commercially Available Active-Type Radon–Thoron Monitors at Different Sampling Flow Rates

Yuki Tamakuma 1,†, Chutima Kranrod 2,3,†, Yuto Jin 4, Hiromu Kobayashi 4, Eka Djatnika Nugraha 1, Aoi Sanpei 4, Mizuki Kiso 4, Hiroki Hashimoto 3, Ryoju Negami 1, Masahiro Hosoda 1,2,* and Shinji Tokonami 2,*

1 Graduate School of Health Sciences, Hirosaki University, 66-1 Honcho, Hirosaki, Aomori 036-8564, Japan; h19gg703@hirosaki-u.ac.jp (Y.T.); h20gg701@hirosaki-u.ac.jp (E.D.N.); h21gg206@hirosaki-u.ac.jp (H.H.);
2 Institute of Radiation Emergency Medicine, Hirosaki University, 66-1 Honcho, Hirosaki, Aomori 036-8564, Japan; kranrodc@hirosaki-u.ac.jp
3 Natural Radiation Survey and Analysis Research Unit, Department of Nuclear Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand
4 School of Health Sciences, Hirosaki University, 66-1 Honcho, Hirosaki, Aomori 036-8564, Japan; yutojin772008@outlook.jp (Y.J.); h.koba1222@gmail.com (H.K.); h18m2212@hirosaki-u.ac.jp (A.S.);
* Correspondence: tokonami@hirosaki-u.ac.jp; Tel.: +81-172-39-5404
† These authors made equal contributions to the paper.

Abstract: Recently, some commercially available active-type radon–thoron monitors were developed; however, their performance has not been characterized. This article presents the characteristics of three commercially available active-type radon–thoron monitors (RAD7, Radon Mapper, and AlphaGUARD) at different sampling flow rates. The thoron concentration measured by the monitors was compared with the reference value measured by a grab sampling method. As a result, the ratio of the measured concentration to the reference increased with flow rate for the RAD7 and the Radon Mapper although that of the AlphaGUARD decreased. The difference may be attributed to the coefficients used in the calculation and the measurement time scheme. The results indicate the importance of the sampling flow rate in thoron measurement. Monitoring of flow rate at the measurement and periodic calibration at multiple sampling flow rates should be conducted for quality assurance and quality control of the measurand.

Keywords: thoron; discriminative measurement; flow rate; performance test

1. Introduction

Lung cancer is one of the most common cancers in the world and there were more than 700,000 deaths due to lung cancer in Japan [1]. Radon and its progeny are well known as a large contributor to the annual effective dose by natural radiation (approximately 50%) and a secondary cause of lung cancer following smoking [2,3]. Radon has three radioisotopes: $^{222}\text{Rn}$ (radon), $^{220}\text{Rn}$ (thoron), and $^{219}\text{Rn}$ (actinon). From the viewpoint of radiation protection, actinon is neglected because of its quite short half-life (4.0 s). Historically, thoron was also ignored due to its short half-life (56 s). However, it was recently recognized that the contribution of thoron cannot be ignored because it may be high at some places in the world [4–11].

In radon measurements, an active-type radon monitor is generally used for an accurate measurement or a short-term survey. However, some researchers have reported that the measured radon concentration would have been influenced by the existence of thoron [12–14]. For thoron measurements, an electrostatic collection radon–thoron monitor, namely RAD7, has been used by many researchers [15–17]. Recently, some active-type radon–thoron monitors using a scintillation cell and an ionization chamber were developed.
and available for real-time radon and thoron measurements. So far, there is no publication describing their characteristics. Due to the short half-life of thoron, the sampling flow rate likely influences the measurement values. Thus, in the present study, a performance test related to the sampling flow rate was carried out to reveal the characteristics of the active-type radon and thoron monitors.

2. Materials and Methods

2.1. Radon–Thoron Monitors

In the present study, an electrostatic collection radon–thoron monitor (RAD7 (SN3154), Durridge Inc., Billerica, MA, USA) [18], a scintillation-cell-type radon and thoron monitor (Radon Mapper, Mi.am Srl, Piacenza, Italy) [19], and an ionizing-chamber-type radon and thoron monitor (AlphaGUARD, DF2000, Saphymo, Frankfurt, Germany) [20] were used for the performance test, as shown in Figure 1.

![Figure 1](image-url)

Figure 1. Illustration of (a) an electrostatic collection radon–thoron monitor (RAD7), (b) a single scintillation-cell radon and thoron monitor (Radon Mapper), and (c) an ionizing-chamber radon and thoron monitor (AlphaGUARD) used for the performance test in the present study.

The RAD7 collects the sample air using a pump and a column of dryer (Drierite, Drierite Company Inc., Xenia, OH, USA) because humidity would strongly affect the electrostatic collection. The sample air goes into the electrostatic collection cell after it is filtered at the inlet of the RAD7 to remove existing radon and thoron progenies. A silicon semiconductor detector is mounted in the cell, and separately detects alpha particles.
emitted from radon and thoron progenies, which are electrostatically collected on the detector surface. The RAD7 provides the radon and thoron concentrations calculated from the count rates of two regions of interest considering the spillover of the alpha particles from the other progenies [21].

The Radon Mapper has an optional measurement mode named “thoron cycle”, which can evaluate radon and thoron concentrations simultaneously with the time interval of 30 min. An inner pump works for 10 min after the beginning of measurement and counts at an interval of 3–10 min and recorded at 20–30 min. The radon and thoron concentrations are calculated by the counts at each interval. It has been reported that the detection efficiency at the flow-through condition varies with the flow rate because some of the radon and thoron progeny escape before attaching to a wall surface of the scintillation cell [22]. The efficiencies for radon and thoron, depending upon the sampling flow rate, are thus considered in the calculation. End users can adjust several parameters on the thoron measurement by operating a user interface: the sampling flow rate, efficiencies for radon and thoron depending on the flux, and the volume of Lucas cell.

The AlphaGUARD also offers another mode to simultaneously measure radon and thoron concentrations, namely, the “Rn/Tn mode”. In this mode, it operates the inner pump for 7 min, and records the counts in the time intervals of 0–3 min and 7–10 min. The sampling flow rate can be set from the preset flow rates of 1.0 and 2.0 L min\(^{-1}\). According to the manufacturer, the thoron concentration and the expanded uncertainty are provided by considering the decay of each radionuclide. As \(^{212}\)Po could affect the result, its influence on the measurement is also taken into account during the long-term measurement.

2.2. Performance Test

In order to investigate the influence of the sampling flow rate on the measurement result, performance tests were carried out using a thoron exposure system at Hirosaki University [23]. Figure 2 shows a schematic diagram of the thoron exposure system used in the present study. A stable and homogeneous thoron atmosphere was made in a 150 L stainless-steel chamber using lantern mantles as a thoron source. According to Sorimachi et al. [24], the amount of thoron gas released from the lantern mantle source depends on an absolute humidity because the water content facilitates the emanation of thoron from the source. In the present study, the thoron concentration was controlled by humidifying the source, and the monitors were tested at the thoron concentration of 10,540 Bq m\(^{-3}\) with a relative standard deviation of 14%. Thoron concentration in the chamber was monitored by a portable radon monitor (AB-5, Pylon Inc., Hong Kong, China) with a single scintillation cell (300A, Pylon Inc., Mississauga, ON, Canada) using a grab sampling method [25]. The method provides an instant sampling without a physical decay of thoron and its progeny and is generally used as a reference method of thoron measurement. The thoron concentration by grab sampling was thus assumed as the reference value in the thoron chamber to compare with the results of the tested monitors. The RAD7, the Radon Mapper, and AlphaGUARD were connected to the system to simultaneously measure the thoron concentrations. The measured values were corrected for the physical decay through the path to the chamber. The actual flow rate of each monitor was measured during the performance tests using a mass flow meter, which covers a range of 0–2.0 L min\(^{-1}\) (MF-FP10NH06-020-AI, HORIBA Inc., Kyoto, Japan).

For the RAD7, the sampling flow rate was set in the range 0.2–2.0 L min\(^{-1}\) at 0.1 L min\(^{-1}\) intervals using an external pump (MP-Σ30NII or MP-Σ300NII, SIBATA Scientific Technology Ltd., Tokyo, Japan). MP-Σ30NII and MP-Σ300NII were used for the flow rates of 0.2–0.5 and 0.5–2.0 L min\(^{-1}\), respectively. The flow rate for the Radon Mapper was set at 0.3, 0.5, 0.6, 0.9, 1.0 L min\(^{-1}\), and that for the AlphaGUARD was set at 1.0 and 2.0 L min\(^{-1}\). The flow rates of both monitors were set as default by the manufacturers. Grab sampling by AB-5 was conducted at least three times for all experiments while the thoron concentration was measured at least five times by the other monitors. Ratios of
the thoron concentration measured by the monitors to the reference value were calculated for comparison.

Figure 2. Schematic diagram of the thoron exposure system at Hirosaki University used for the performance tests.

3. Results

The relationships between the setting and actual flow rates are shown in Figure 3. Here, the uncertainty for a setting flow rate of the pump was assumed to be 5%. According to the manufacturer of the flow meter, the accuracy ranges from 3% to 100% depending on the flow rate. Thus, the uncertainty for a mass flow meter is assumed to be 10% at less than 1.0 L min\(^{-1}\) and 5% in the range 1.0–2.0 L min\(^{-1}\). The actual flow rate measured was slightly larger than the setting flow rate in the range over 1.0 L min\(^{-1}\), although the others were in good agreement.

Figure 4 shows the ratios obtained at each setting flow rate using the three monitors. For the RAD 7, the ratio rapidly increased at flow rates between 0.3 and 0.6 L min\(^{-1}\), and then stabilized with a fluctuation around 1.0 in the range over 0.6 L min\(^{-1}\). The ratio for the Radon Mapper gradually increased with the flow rate; it also appeared to be stable at 1.0. For the AlphaGUARD, the ratios at 1.0 and 2.0 L min\(^{-1}\) were evaluated to be 1.66 and 1.26, respectively, indicating the measured value by the AlphaGUARD is higher than the reference concentration.
1.26, respectively, indicating the measured value by the AlphaGUARD is higher than the reference concentration.

Figure 3. Relationship between the setting flow rate and actual flow rate measured by a mass flow meter.

Figure 4. Relationship between the setting flow rate and the measured ratio. The ratio is defined as the thoron concentration measured by each monitor divided by the reference value. The uncertainties are expressed as an expanded uncertainty (i.e., $k = 2$). The reference value is defined as the thoron concentration measured by the grab sampling method with the AB-5 and the scintillation cell.

4. Discussion

The ratios of thoron concentration measured by the monitors to the reference value had characteristics unique to each monitor, as shown in Figure 4. However, the cause of the tendencies could not be revealed because the equations to derive the thoron concentration are not open to the users. The authors infer that one possible cause may be the coefficient...
used in the calculation. Machaj et al. [26] reported the simultaneous measurement method of radon and thoron using a single scintillation cell. They theoretically calculated and used the coefficients for 1.0 L min\(^{-1}\), which are the total alpha activity in a certain interval when unit activity of radon or thoron flows through the cell. If the coefficients in the calculation are fixed for a certain flow rate in the devices, the measured thoron concentrations would be changed by flow rates. For the RAD7 and according to the user manual, the thoron concentration is calculated based on the count rate of \(^{216}\)Po, which is the first decay product of thoron [21]. It indicates that the measured thoron concentration varies with the \(^{216}\)Po concentration in the internal cell, which is in equilibrium with thoron. To confirm the relationship, the thoron atom concentration in the cell is theoretically calculated by the following differential equation:

\[
\frac{dN}{dt} = C_0v - \lambda N - \frac{N}{V}v
\]  

(1)

where \(N\) is the atom number of thoron in the internal cell, \(C_0\) is the atom concentration of thoron at the outside of the cell (m\(^{-3}\)), \(\lambda\) is the decay constant of thoron (s\(^{-1}\)), \(V\) is the volume of the cell (m\(^3\)), \(v\) is the flow rate (m\(^3\) s\(^{-1}\)), and \(t\) is the elapsed time after the start of sampling (s). This differential equation indicates the time variation of the atom number of thoron in the internal cell. The first term on the right side of the equation shows the inflow of the thoron atoms. The second term indicates the physical decay of thoron, and the third term shows the outflow of the thoron atoms from the internal cell. If \(t \rightarrow \infty\), the equation is expressed as below:

\[
N = \frac{C_0v}{\lambda V - v}
\]  

(2)

The equation shows the thoron atom number in the internal cell of the RAD7. Thus, the thoron activity concentration in the cell \(A_i\) can be expressed as follows:

\[
A_i = \frac{\lambda C_0v}{(\lambda V - v)V}
\]  

(3)

The relationship between the calculated thoron concentration and the ratio with flow rate is shown in Figure 5. The thoron concentration was calculated assuming \(C_0\) is 1 m\(^{-3}\), \(V\) is 7.5 \times 10\(^{-2}\) m\(^3\), and \(\lambda\) is 1.2 \times 10\(^{-4}\) s\(^{-1}\). There was a difference between tendencies of the ratio and the calculated thoron concentration at high flow rate. This may be because of the relative counting efficiency depending on the flow rate [22,26]. If the flow rate increases, the relative efficiency decreases since some of radon, thoron, and their progenies would escape before being counted. Thus, a magnitude of increase of the calculated thoron concentration at the range of high flow rate could become lower by the correction of the relative counting efficiency. It indicates good agreement of the tendencies of the ratio and the thoron concentration. This would be the reason for the ratio characteristics for the RAD7.

In addition, the sampling and measurement time scheme might have an influence on the measurement accuracy. For the Radon Mapper and the AlphaGUARD, they do not have capability for energy discrimination; thus, they should use a method similar to the decay method reported by many researchers [27–30]. Wang et al. [31] reported that the time scheme for the sampling and measurement affects the uncertainty. Although they are the methods for radon and thoron progeny measurement, the principle would be same as that for radon and thoron concentration. Tokonami et al. [25] simulated relative standard deviations of radon and thoron for several timetable patterns for their grab sampling measurement method. In addition, the balance of both concentrations would also have an influence on the accuracy of each other because one becomes the background to the other.

These results indicate that the flow rate is an important parameter in the thoron measurement using an active-type radon and thoron monitor. For quality assurance and quality control of the measurand, the actual flow rate at the measurement should be monitored to ensure a constant flow. Additionally, there may be a discrepancy in sensitivity
to thoron between models of the same device. In the same way, we tested another serial number of the RAD7 (SN775). The ratio at 1.0 L min$^{-1}$ of the SN775 was estimated to be 1.59 while that of the SN3154 was 0.94, as shown in Figure 4. Furthermore, the decrease of the flow rate of the inner pump may occur as time passes because the inner pump could be exhausted. If the characteristic with different flow rates at some points is already known by a calibration, the measured value could be corrected. Thus, the authors propose that a periodic calibration at multiple sampling flow rates for thoron should be conducted.

![Figure 5. Relationship between the calculated thoron concentration and the ratio with flow rate.](image)

In the measurement of the radon and thoron exhalation rate, the flow rate must be as low as possible because the pumping effect would occur depending on the pressure difference between in-air and in the accumulation chamber [32]. The results show that the lower flow rate could lead to an incorrect result; for example, in case of the RAD7, the estimated thoron concentration at 0.2 L min$^{-1}$ could be five times higher than that measured at the default flow rate (approximately 0.65 L min$^{-1}$) [21].

5. Conclusions

This article addressed the characteristics of commercially available active-type radon–thoron monitors at different sampling flow rates. The performance was carried out using a thoron exposure system at Hirosaki University, Japan. Three types of monitors were used for the performance tests: an electrostatic collection monitor (RAD7), a scintillation-cell-type monitor (Radon Mapper) and an ionizing-chamber-type monitor (AlphaGUARD). The ratios of the measured thoron concentration by each monitor to the reference value measured by a grab sample were evaluated. The ratio for the RAD7 and the Radon Mapper increased with the flow rate while that of the AlphaGUARD decreased. The results show that the thoron concentration measured may differ greatly depending on the flow rate; for example, the lower flow rate led to a thoron concentration that was five times smaller. It indicates the importance of the sampling flow rate in thoron measurement using an active-type radon and thoron monitor. The authors propose that the monitoring the flow rate and the periodic calibration at multiple sampling flow rates should be conducted for quality assurance and the quality control of the measurand.

Author Contributions: Conceptualization, Y.T., C.K., M.H. and S.T.; methodology, Y.T., M.H. and S.T.; validation, C.K., Y.J., H.K., E.D.N., A.S., M.K., H.H. and R.N.; formal analysis, Y.T., Y.J. and H.K.; investigation, Y.T., C.K., Y.J., H.K., E.D.N., A.S., M.K., H.H. and R.N.; resources, M.H. and S.T.; data curation, Y.T.; writing—original draft preparation, Y.T. and C.K.; writing—review and editing, Y.T., C.K., E.D.N., M.H. and S.T.; visualization, Y.T.; supervision, C.K., M.H. and S.T.; project
administration, M.H. and S.T.; funding acquisition, C.K., M.H. and S.T. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was partially supported by Japan Society for the Promotion of Science KAKENHI, grant number 20H00556, Hirosaki University Institutional Research Grant, and Hirosaki University Female Researcher Recruitment and Development Support Grant.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data set available on request to corresponding authors.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. National Research Center Cancer Registry and Statistics. Cancer Information Service, (Vital Statistics of Japan). Available online: https://ganjoho.jp/data/reg_stat/statistics/dl/cancer_mortality(1958-2019).xls (accessed on 6 June 2021).
2. United Nations Scientific Committee on the Effect of Atomic Radiation (UNSCEAR). UNSCEAR 2006 Report to the General Assembly, with Scientific Annexes; United Nations: New York, NY, USA, 2006; Volume II.
3. World Health Organization (WHO). WHO Handbook on Indoor Radon—A Public Health Perspective; WHO: Geneva, Switzerland, 2009.
4. Tokonami, S. Why is $^{220}\text{Rn}$ (thoron) measurement important? Radiat. Prot. Dosim. 2010, 141, 335–359. [CrossRef]
5. Pereira, C.E.; Vaidyan, V.K.; Chougaonkar, M.P.; Mayya, Y.S.; Sahoo, B.K.; Jojo, P.J.; Indoor radon and thoron levels in Neendakara and Chavara regions of southern coastal Kerala, India. Radiat. Prot. Dosim. 2012, 150, 385–390. [CrossRef]
6. Kudo, H.; Tokonami, S.; Omori, Y.; Ishikawa, T.; Iwaoka, K.; Sahoo, S.K.; Akata, N.; Hosoda, M.; Wanabongse, P.; Pornnumpa, C.; et al. Comparative dosimetry for radon and thoron in high background radiation areas in China. Radiat. Prot. Dosim. 2015, 167, 155–159. [CrossRef]
7. Omori, Y.; Prasad, G.; Sorimachi, A.; Sahoo, S.K.; Ishikawa, T.; Sagar, D.V.; Ramola, R.C.; Tokonami, S. Long-term measurements of residential radon, thoron, and thoron progeny concentrations around the Chhatrapur placer deposit, a high background radiation area in Odisha, India. J. Environ. Radioact. 2016, 162–163, 371–378. [CrossRef]
8. Omori, Y.; Tokonami, S.; Sahoo, S.K.; Ishikawa, T.; Sorimachi, A.; Hosoda, M.; Kudo, H.; Pornnumpa, C.; Nair, R.R.; Jayakrishn, P.A.; et al. Radiation dose due to radon and thoron progeny inhalation in high-level natural radiation areas of Kerala, India. J. Radiol. Prot. 2017, 37, 111. [CrossRef]
9. Hosoda, M.; Kudo, H.; Iwaoka, K.; Yamada, R.; Suzuki, T.; Tamakuma, Y.; Tokonami, S. Characteristics of thoron ($^{220}\text{Rn}$) in environment. Appl. Radiat. Isot. 2017, 120, 7–10. [CrossRef]
10. Omori, Y.; Hosoda, M.; Takahashi, F.; Sanada, T.; Hirao, S.; Ono, K.; Furukawa, M. Japanese population dose from natural radiation. J. Radiol. Prot. 2021, 40, 99–140. [CrossRef]
11. Tokonami, S. Characteristics of thoron ($^{220}\text{Rn}$) and its progeny in the indoor environment. Int. J. Environ. Res. Public Health 2021, 17, 8769. [CrossRef]
12. Kochowska, E.; Kozak, K.; Kozłowska, B.; Mazur, J.; Dorda, J. Test measurements of thoron concentration using two ionization AlphaGUARD vs. radon monitor RAD7. Nukleonika 2009, 54, 189–192.
13. Yasuoka, Y.; Sorimachi, A.; Ishikawa, T.; Hosoda, M.; Tokonami, S.; Fukuhori, N.; Janik, M. Separately measuring radon and thoron concentrations exhaled from soil using AlphaGUARD and liquid scintillation counter methods. Radiat. Prot. Dosim. 2010, 141, 412–415. [CrossRef]
14. Iwaoka, K.; Negami, R.; Tamakuma, Y.; Hosoda, M.; Palad, L.J.H.; Tokonami, S.; Feliciano, C.P.; Kanda, R. Evaluation of the influence of thoron on portable radon measurement devices. Philipp. J. Sci. 2021, 150, 257–261.
15. Sorimachi, A.; Ishikawa, T.; Janik, M.; Tokonami, S. Quality assurance and quality control for thoron measurement at NIRS. Radiat. Prot. Dosim. 2010, 141, 367–370. [CrossRef]
16. Csixig, I.; Szabó, Z.; Szabó, C. Experimental technique to measure thoron generation rate of building material samples using RAD7 detector. Radiat. Meas. 2013, 59, 201–204. [CrossRef]
17. Sumesh, A.; Kumar, A.V.; Tripathi, R.M.; Nair, R.N.; Puranik, V.D. Impact of flow rate sensitivity of semiconductor type thoron monitor. Radiat. Meas. 2013, 59, 241–244. [CrossRef]
18. Durrridge Inc. RAD7 Radon Detector. Available online: https://durrridge.com/products/rad7-radon-detector/ (accessed on 9 June 2021).
19. Mi.am Srl. Radon Mapper. Available online: https://miam.it/en/radon-mapper/ (accessed on 9 June 2021).
20. Bertin Technologies SAS. AlphaGUARD—Radon Monitor. Available online: https://www.bertin-instruments.com/product/radon-professional-monitoring/radon-alphaguard/ (accessed on 9 June 2021).
21. Durrridge Inc. RAD7 RADON DETECTOR User Manual; DURRIDGE Company Inc.: Boston, MA, USA, 2012.
22. Sakoda, A.; Meisenberg, O.; Tschiersch, J. Behavior of radon progeny produced in a scintillation cell in the flow-through condition. Radiat. Meas. 2015, 77, 41–45. [CrossRef]
23. Pornnumpa, C.; Oyama, Y.; Iwaoka, K.; Hosoda, M.; Tokonami, S. Development of radon and thoron exposure systems at Hirosaki University. *Radiat. Environ. Med.* **2018**, *7*, 13–20.

24. Sorimachi, A.; Sahoo, S.K.; Tokonami, S. Generation and control of thoron emanated from lantern mantles. *Rev. Sci. Instrum.* **2009**, *80*, 015104. [CrossRef] [PubMed]

25. Tokonami, S.; Yang, M.; Yonehara, H.; Yamada, Y. Simple, discriminative measurement technique for radon and thoron concentrations with a single scintillation cell. *Rev. Sci. Instrum.* **2002**, *73*, 69. [CrossRef]

26. Machaj, B.; Urbanski, P.; Bartak, J. Measurement of radon (222Rn) and thoron (220Rn) concentration with a single scintillation cell. *Nukleonika* **2007**, *52*, 167–171.

27. Thomas, J.W. Modification of the Tsivoglou method for radon daughters in air. *Health Phys.* **1970**, *19*, 691. [PubMed]

28. Cliff, D.K. The measurement of low concentrations of radon-222 daughters in air, with emphasis on RaA assessment. *Phys. Med. Biol.* **1978**, *23*, 55–65. [CrossRef]

29. Busigin, A.; Phillips, C.R. Uncertainties in the measurement of airborne radon daughters. *Health Phys.* **1980**, *39*, 943–955. [CrossRef]

30. Scott, A.G. A field method for measurement of radon daughters in air. *Health Phys.* **1981**, *41*, 403–405.

31. Wang, Y.; Sun, C.; Zhang, L.; Guo, Q. Optimized method for individual radon progeny measurement based on alpha spectrometry following the Wicke method. *Radiat. Meas.* **2021**, *142*, 106558. [CrossRef]

32. Hosoda, M.; Ishikawa, T.; Sorimachi, A.; Tokonami, S.; Uchida, S. Development and application of a continuous measurement system for radon exhalation rate. *Rev. Sci. Instrum.* **2011**, *82*, 015101. [CrossRef]