Association between levels of radon and bioaerosols (bacteria and fungi) by living conditions

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Abstract

This study aimed to measure the levels of airborne radon (Rn) and bioaerosols—culturable airborne bacteria (CAB) and culturable airborne fungi (CAF)—in South Korea's residential environments, considering living conditions such as the number of ventilations, number of windows, floors, temperature, and relative humidity. These levels were evaluated for 32 houses of residents from the socially vulnerable class. Rn gas and bioaerosols were sampled twice: in fall and summer. A self-report survey gathered residents' information on their general characteristics (daily residence time, heating and cooking type, cleaning and washing cycle, etc.) and health condition scores (0–100 points) on the day of sampling. The range of Rn levels was 0.43–7.439 pCi/L with a median of 0.70 pCi/L. The CAB levels were 239–488 colony-forming unit (CFU)/m^3 with a median of 309 CFU/m^3, and CAF levels were 174–366 CFU/m^3 with a median of 233 CFU/m^3. Thus, this study found that semi-basement residential indoor environments negatively affected Rn and bioaerosol levels, and living in such residences resulted in high health condition scores.

1. Introduction

People spend most of their time in various types of indoor environments including COVID-19 which may have also increased the amount of time spending indoors, especially residential buildings. Exposure to indoor air pollutants impacts human health; there is considerable scientific evidence that chemical and biological factors affect indoor air quality, and inappropriate indoor air quality negatively affects human health (Hromadaka et al., 2017). The World Health Organization (WHO; 2014) reported that air pollution has caused the deaths of approximately 7 million people worldwide.

Of the various indoor air pollutants, exposure to radon (Rn) and bioaerosols can significantly influence human health. Rn is a radioactive gas containing carcinogens, and prolonged exposure to high levels of Rn gas can cause lung cancer (UNSCEAR, 1993). Similarly, increased levels of bioaerosols in the air are linked to a wide range of acute and chronic health problems such as allergies, asthma, rhinitis, sinusitis, and bronchitis (Heederik and Von Mutius, 2012).

Moreover, many studies have indicated that populations such as children, older people, and people with low-income and in the minority may be disproportionately impacted by Rn, mold, and other indoor pollutants in buildings where people live (EPA, http://epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality). Environmental diseases caused by indoor air pollution are feared to occur more frequently among socially vulnerable groups than among the general public. However, short-term and temporary disease treatment is unable to fundamentally improve these problems, and children of those raised in such environments may also be vulnerable to diseases from previous generations due to genetic exposure (Murrison et al., 2019). Therefore, there is a need for fundamental measures to address this issue. It has thus become urgent to grasp the current status of indoor air pollution by the type of residence of socially vulnerable groups.

This study aimed to measure the airborne Rn and bioaerosol levels in living environments of the vulnerable groups in South Korea, while considering living conditions such as the number of ventilations, number of windows, floors, temperature, and relative humidity (RH). As health effects from indoor air pollutants may be experienced soon after exposure, we also measured the self-health condition by using a scale from 0 to 100 on the day samples were measured. The aim was to determine the association between high levels of pollutants and the self-health condition. The closer the score was to 100, the higher was the health level.

2. Method

2.1 Selection of the socially vulnerable class and residential type

Data on the socially vulnerable class (current status and distribution, residential type, and welfare level) were collected from the Institute for Older Society in University located in Seoul. Accordingly, classification criteria for the socially vulnerable groups were established. Residential areas were selected through random sampling, but due to difficulties in conducting nationwide surveys, the survey was conducted in the Bucheon region, Gyeonggi province, with the help of Bucheon City Hall. Based on this information, we visited each house in the selected residential area to explain the purpose of this study, and finally 34 households were selected to confirm their consent to participate in this study.

2.2. Residential characteristics and surveys

Data on the types and characteristics of housing were collected to ensure data uniformity. A survey was designed for residents to self-report their general characteristics (daily residence time, heating and cooking type, cleaning and washing cycle, etc.) and health condition score (0–100 points) on the day of sampling. The questionnaire surveys were filled after the sample measurements was completed in their houses.

2.3. Sampling of airborne Rn and bioaerosols

Rn gas and bioaerosols were sampled for 34 residential facilities twice—first, in the fall season, when ventilation and living conditions are relatively good and, second, in summer (after the rainy season) when RH was high. Rn and bioaerosols (culturable airborne bacteria [CAB] and culturable airborne fungi [CAF]) samples were collected mainly from single houses, multi-family houses, and townhouses (Table 1). A continuous Rn monitor sampler of model 1027 (SUN NUCLEAR Corporation, USA) was utilized for 48-h periods, based on a Korean indoor air quality monitoring procedure using the SARA-4100 sampler (KEMIC Company Inc., Korea). In the case of CAB and CAF, the total collection flow rate was set to 200 to 1,000 L, which was captured by the collision method, and the tryptone soya agar and sabouraud maltose agar mediums were used for bacteria monitoring. The collected samples were brought to the laboratory and incubated at room temperature for three days before counting the number of colonies to calculate the concentration. Temperature and RH were also measured inside the houses during the survey and sampling.

Table 1
Information on residential type, number of facilities, and definition of residential type.

Type	No. of facilities	Definition
Single house	14	Single residential form
Multi-family housing	14	Many generations living in one residential form
Town house	6	Multi-family housing with four or more floors in the building

2.3. Statistical analyses

Statistical analyses were conducted using R software. Nonparametric analysis was performed to determine the relationships between airborne Rn and bioaerosol levels, including the indoor temperature and RH. Note that this approach was used because the Rn and bioaerosol values were not distributed normally or log-normally, according to the Shapiro-Wilk test. The distribution of discrete or continuous variables was summarized by the median and interquartile range. The distribution of categorical variables was reported as counts and percentages. The association between floor-level residents and other variables was tested using the Kruskal-Wallis test and Fisher's exact test. The correlation between environmental factor variables was computed. The significance level cut-off was set at $p < 0.05$.

3. Results

Table 2 presents information of the households' general characteristics such as age, sex, RH, temperature, levels of Rn, bioaerosol level, self-reported health score, and living conditions (number of ventilations, number of windows, and apartment floor) in indoor residences. Rn gas levels were 0.43–7.439 pCi/L with a median of 0.70 pCi/L. CAB levels were 239–488 colony-forming unit (CFU)/m^3 with a median of 309 CFU/m^3, and CAF levels were 174–366 CFU/m^3 with a median of 233 CFU/m^3 (Table 2).

Table 2
Characteristics of variables in indoor residences

Variables	**Median (range)**
Relative humidity (%)	65.5 (61.5–69.0)
Temperature (°C)	28.6 (27.7–30.2)
Rn (pCi/L)	0.70 (0.43–0.80)
Culturable airborne bacteria (CFU/m^3)	309 (239–488)
Culturable airborne fungi (CFU/m^3)	233 (174–366)
Self-reported health score	60.0 (40.0–80.0)
Variables	Number (%)
Sex	
Male	10 (29.4%)
Female	24 (70.6%)
Number of ventilations	
4≥	6 (17.6%)
4<	28 (82.4%)
Number of windows	
3≥	15 (44.1%)
3<	19 (55.9%)
Apartment floor	
Semi-basement	6 (17.6%)
First floor	16 (47.1%)
Higher than first floor	12 (35.3%)
Note: CFU: colony-forming unit.	

Rn gas was monitored in the semi-basement, first floor, and higher than first floor (Table 3). Among the three floor levels, Rn levels were highest in the semi-basement at 0.80 pCi/L (median) and lowest in the level higher than the first floor, with a median of 0.40 pCi/L ($p < 0.001$). CAB and CAF levels showed the same pattern as Rn levels, although there was no significant difference ($p > 0.05$) between the semi-basement, first floor, and higher than the first floor.

Table 3
Characteristics of variables by floors in indoor residences

	Semi-basement	First floor	Higher than first floor	P-value
	N = 6	N = 16	N = 12	
Age	74.0 (61.8–76.5)[a]	58.5 (47.2–77.2) [a]	51.0 (42.8–74.5) [a]	0.297
Sex				0.041
Male	0 (0.00%)	8 (50.0%)	2 (16.7%)	
Female	6 (100%)	8 (50.0%)	10 (83.3%)	
Temperature (℃)	29.0 (27.8–31.2) [a]	28.6 (27.8–29.7) [a]	29.4 (27.6–30.6) [a]	0.709
Relative humidity (%)	66.5 (60.2–71.2) [a]	66.0 (62.5–69.2) [a]	65.5 (62.2–67.0) [a]	0.981
Radon (pCi/L)	0.80 (0.72–0.95) [a]	0.70 (0.67–0.83) [a]	0.40 (0.30–0.50) [a]	< 0.001
CAB (CFU/m^3)	397 (301–738) [a]	320 (232–518) [a]	262 (208–426) [a]	0.250
CAF (CFU/m^3)	271 (158–366) [a]	241 (200–432) [a]	225 (164–252) [a]	0.604
Self-reported health score	50.0 (42.5–57.5) [a]	65.0 (37.5–82.5) [a]	80.0 (60.0–80.0) [a]	0.204
Number of ventilations				0.634
4≥	0 (0.00%)	3 (18.8%)	3 (25.0%)	
4<	6 (100%)	13 (81.2%)	9 (75.0%)	
Number of windows				0.203
3≥	4 (66.7%)	8 (50.0%)	3 (25.0%)	
3<	2 (33.3%)	8 (50.0%)	9 (75.0%)	

Notes: [a]Range. CFU: colony-forming unit; CAB: culturable airborne bacteria; CAF: Culturable airborne fungi.

Correlation analysis showed a positive association between Rn and CAB levels ($r = 0.479$, $p < 0.01$), Rn and CAF levels ($r = 0.441$, $p < 0.01$), and CAB and CAF levels (Fig. 1). To evaluate the difference in Rn levels from the semi-basement to higher than the first floor, we divided Rn levels into three groups based on the floor (Fig. 2). Rn levels were higher in the semi-basement than in the level higher that the first floor

($p < 0.01$). We also confirmed that Rn levels were higher when there were less than three windows in the semi-basement, first floor, and higher than the first floor (Fig. 3).

4. Discussion

Many socially vulnerable people in South Korea live in semi-underground housing types. However, there is lack of research on hazardous environmental conditions in such housing. This study conducted Rn and bioaerosols exposure assessments of these vulnerable residential environments. The median level of Rn in the houses was 0.7, ranging from 0.43 to 0.80 in this study.

In comparison, the average level of Rn was 1.13 pCi/L in basement parking lots of six governorates of Kuwait in summer (Bu-Olayan and Thomas, 2016), 0.30 pCi/L in the Tokyo subway in Japan (Doi and Kobayashi, 1996), and 0.81 pCi/L in Caracas city subway in Venezuela (Liendo et al., 1997). Moreover, most residential areas in Arab countries have lower Rn on the ground level than basements and areas involved in industrial activities (Alkan and Karadeniz, 2014). Similarly, higher Rn levels were found in basements compared with the first or second floors of buildings (Alkan and Karadeniz, 2014; Abel Ghany, 2008). These results are in line with the current study (Table 3), and they can be attributed to the ventilation and air-conditioning systems, poor building maintenance on the ground floor, and so on (Bu-Olayan and Thomas, 2016).

However, we did not find an association between the number of ventilations, time of ventilation, and Rn levels. The possible reason is that the numbers of ventilations and ventilation times surveyed on the day of sampling were not based on the sampling day but the memory of the residents. A previous study found that increasing ventilation rates by 3–10 times than the natural ventilation rate at home by controlling outdoor air ventilation helped reduce indoor emissions (Hospodsky et al., 2015). Therefore, high ventilation rates are effective in reducing Rn levels.

Since the different sampling methods and conditions of meteorological variables of bioaerosols make level comparisons difficult, we compared only approximate levels of bioaerosols for the indoor environments. In previous research, the levels of bioaerosols sampled in indoor environments such as lecture theaters at universities in China (Dexing et al., 2015) ranged from 7.8 to 1,460 CFU/m^3, the mean at an elderly care facility was 310.5 ± 221.3 CFU/m^3, and that at a postnatal care center was 302.2 ± 69.4 CFU/m^3 (Hwang et al., 2018). These results are fairly close to the range of bioaerosol levels observed in this study. However, in another study, airborne bacteria measured in child day-care centers ranged from 249.6 to 19,000 CFU/m^3, with a median of 2,566 CFU/m^3 (Hwang et al., 2017), which is higher than any of the values measured in this study. When we compared the same residential indoor environments from other countries, levels of bioaerosols in different Portuguese homes ranged from 350 to 1,618 CFU/m^3 with a median of 684 CFU/m^3 for CAB, and 119 to 566 CFU/m^3 with a median of 250 CFU/m^3 for CAF (Madureira et al., 2015).

Despite such results, guidance on bioaerosols has not yet been established by international organizations or agencies in other countries such as the WHO, the United States Environmental Protection Agency, and American Conference of Governmental Industrial Hygienists due to limited data (WHO, 2009; Kim et al., 2018). On the other hand, South Korea established a quantitative guideline of 800 CFU/m^3. It should be noted that the average level of bioaerosols (CAB and CAF) did not exceed these guidelines for indoor air quality in this study (Ministry of Environment of Korea. 2014). However, the mean level of CAB was the highest at 609 CFU/m^3 in semi-basement houses compared to 1st-floor houses (398 CFU/m^3 and 314 CFU/m^3, respectively), even though the temperature and RH conditions were similar. These characteristics were similar to a prior research finding that the deeper the underground station platform, the higher the levels of CAB, even in the same underground subway environment (Hwang et al., 2010).

Regarding the ventilation effect on the houses, Kwan et al. (2020) suggested that ventilation was not a significant factor controlling bacterial and fungal levels at homes; they reported that in occupied homes, the average amount of bacteria and fungi in indoor air that is controlled by outdoor air ventilation was less than 10%. With these results, even if the number of ventilations was surveyed on the day of sampling in this study, there might not have been a significant relation between the bioaerosol level and number of ventilations; however, this cannot be guaranteed because the results may vary by region, climate, and residential environments of the countries.

Meteorological parameters and building structures are also important factors that may affect the seasonal variation of Rn levels in indoor environments (Xie et al., 2015). For northern climates, Rn concentration was previously reported to be the highest in winter and lowest in summer (Mose et al., 1992; Lee et al., 2017). This is because the dwellings' doors and windows remain closed through most of the winter, compared with summer; hence, the ventilation is poor in winter (Duggal et al., 2014). In winter, higher levels of Rn gas develop in indoor environments because of their lower pressure compared to the exterior (Sahoo et al., 2007). Regardless of the season, high Rn levels in semi-basements can be attributed to the entry of Rn through cracks or crevices from the surrounding soil, low temperature, and high RH from outdoor environments (UNSCEAR, 2006).

In this study, the Rn level was significantly correlated with levels of CAB ($r = 0.33$, $p < 0.01$) and CAF ($r = 0.22$, $p < 0.01$); the correlation between these three variables is visualized using color in Fig. 1. Lee et al. (2020) reported that Rn radiation could instigate microbial metabolic activity depending on the Rn levels when they were exposed, which indicates that the threshold concentration present in the ecosystem is relevant to both microbial diversity and population density. Mumataz et al. (2013) also found that microbes could grow in mediums containing a high concentration of uranium in the Ranger Uranjum mine. Moreover, microbial density and dehydrogenase activity, such as of *Bacillus* sp., *Brevibacillus* sp., *Lysinbacillus* sp., and *Paenibacillus* sp., increased as they came closer to the natural Rn source (Lee et al, 2020).

Moreover, this study found that CAF levels correlated with the levels of CAB and RH. A recent study analyzed the correlation between bacteria and fungi in sugarcane tops silage before and after aerobic exposure, finding that *Pichia* was positively correlated with genera *Lactobacillus* and *Pediococcus*, but negatively with genera *Acinetobacter*, *Citrobacter*, and *Serratia* (Zhang et al., 2019). This indicates that the correlation between CAF and CAB levels depends on the species of microorganisms. Unfortunately, this study could not identify the bioaerosols, making it difficult to explain the correlation between CAF and CAB. Moreover, RH is known to affect the correlation among microorganisms in various studies (Takahashi, 1997; Tang, 2009; Hwang et al., 2018;). The current study showed that among other environmental factors, such as illumination, height, and temperature, RH had the greatest impact on fungal richness (Li et al., 2020).

There was no correlation between the levels of Rn and the residences' temperature in this study ($r = 0.08$, $p > 0.05$; Fig. 1). This result was the same as that reported by Xie et al. (2015), who found no clear correlation between indoor Rn levels and indoor temperature. A previous study reported that this may be because variations in indoor temperature in the premises were substantially lower than variations in outdoor temperature, and indoor Rn levels strongly depend on outside temperature (Baltrenas et al., 2020). We noticed that the correlations between indoor Rn levels and RH in this study were not significantly different, in line with a previous study (Baltrenas et al., 2020), but RH was still an important factor that could be correspondingly high with increasing Rn levels (El-May et al., 2004; Schnell et al., 2012).

Another factor that can influence indoor Rn levels is the underlying geology. A significant positive correlation was found between indoor Rn levels and the geological composition of the ground (Je et al., 1999; Sundal et al., 2004; Moreno et al., 2008). A previous study reported that high Rn levels are present in underground station platforms based on granite areas compared with those based on non-granite areas (Hwang et al., 2018).

Further, we found that people living in semi-basements had higher health condition scores than those living in ground residences (Table 3). This result reveals that people living in semi-basements have weaker health conditions with relatively higher levels of Rn exposure compared with ground living residents. Modern construction practices have produced many buildings that capture, contain, and concentrate Rn to unsafe levels (Cholowsky et al., 2021). This continues to worsen as newer residential buildings are constructed, increasing the innate risks of producing high Rn levels, which are disproportionately impacting younger individuals with children (Gogna et al., 2019; Lorenzo-Gonzalez et al., 2019). Recently, the WHO emphasized that Rn levels are higher indoors and in areas with minimal ventilation, with the highest levels found in places such as caves and mines; this is especially true for some homes where people spend much of their time, thus risking significant exposure to Rn (WHO, 2021). According to WHO (2021), some common ways to reduce Rn levels are increasing under-floor ventilation and sealing floors and walls.

The present study has several limitations. First, the assessment period covered only the summer and the fall seasons because of resource limitations. Thus, evaluation of the influence of seasonal differences, such as those during the winter season, is required to identify seasonal variations in Rn levels in underground environments. Second, air samples of Rn and bioaerosols were not collected outside the residences for comparison between indoor and outdoor levels. Third, we could not identify the specific bioaerosols for CAF and CAB. Thus, further studies should concentrate on the types of bioaerosols that could affect the levels of Rn in residential environments. Despite these limitations, this study found a correlation between the levels of bioaerosols and Rn, although further large-scale studies are needed.

5. Conclusion

This study measured the airborne Rn and bioaerosol levels in living indoor environments with living conditions such as the number of ventilations, number of windows, floors, temperature, and RH in the houses of socially vulnerable classes in South Korea. Semi-basement residential indoor environments negatively affect Rn and bioaerosol levels, and living in such residences resulted in higher health condition scores in this study. In conclusion, we found that residents living in a semi-basement are more vulnerable to Rn exposure than those living in ground residences.

Declarations

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Conflict of interest

The authors declare that they have no known conflicts/competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and material

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval

No approval of research ethics committees was required to accomplish the goals of this study.

Author contribution statement

Sungho Hwang was involved in conceptualization, data analysis and interpretation, manuscript preparation, and review process; Jong-Uk Won and Hyo Soung were involved in methods validation and manuscript verification; Sangwon Lee was involved in experimental works, data analysis and interpretation ; and Wha Me Park was involved in methods elaboration and validation, manuscript verification and corrections, and review process.

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Figures

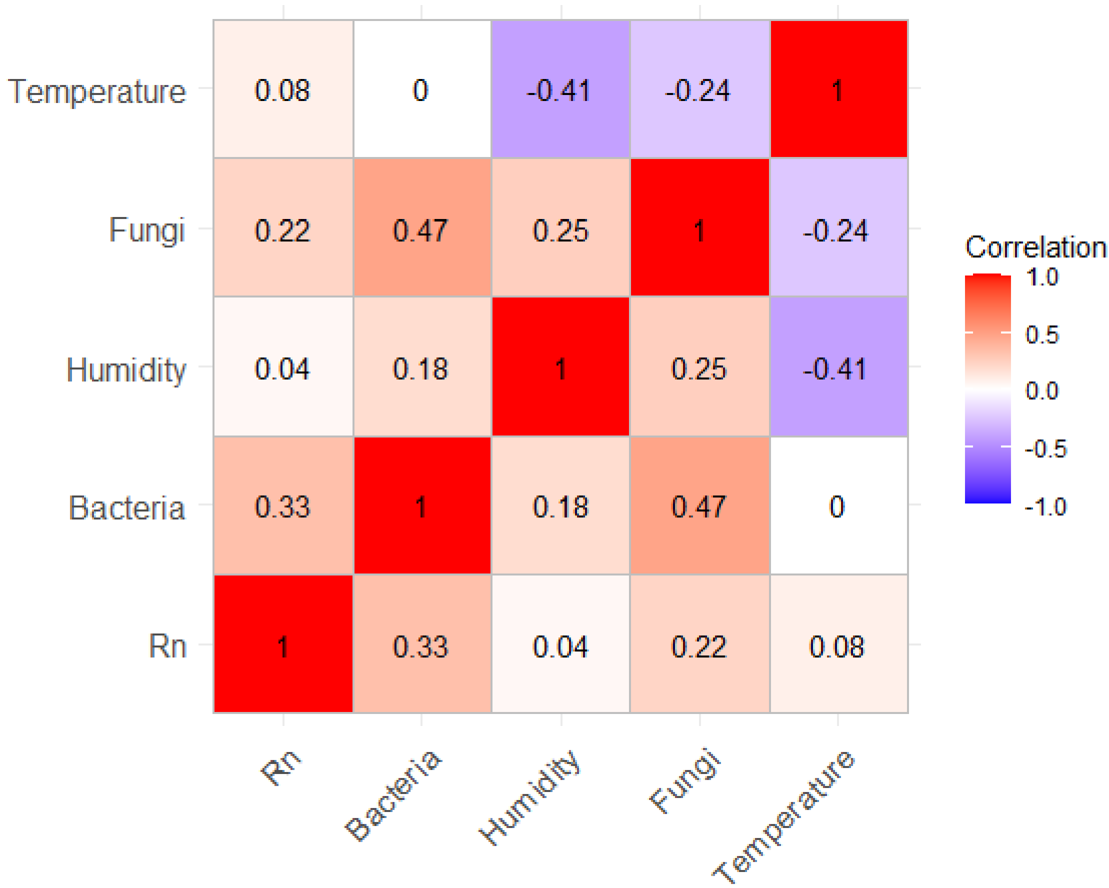

Figure 1

Correlations between indoor environmental variables such as temperature, relative humidity, bioaerosols, and radon (Rn)

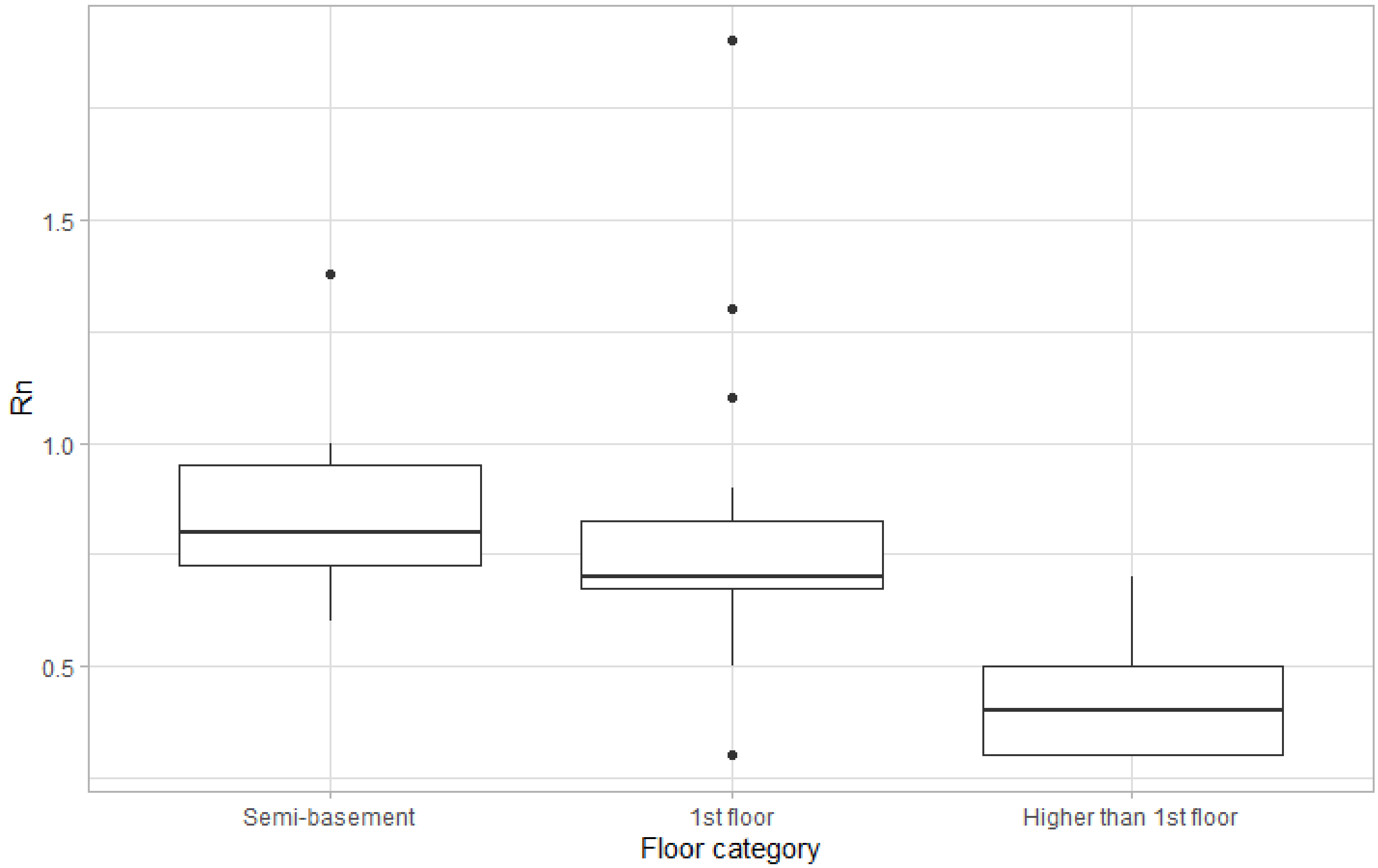

Figure 2

Boxplot between the semi-basement, first floor, and levels higher than first floor by radon (Rn) levels ($p < 0.01$)

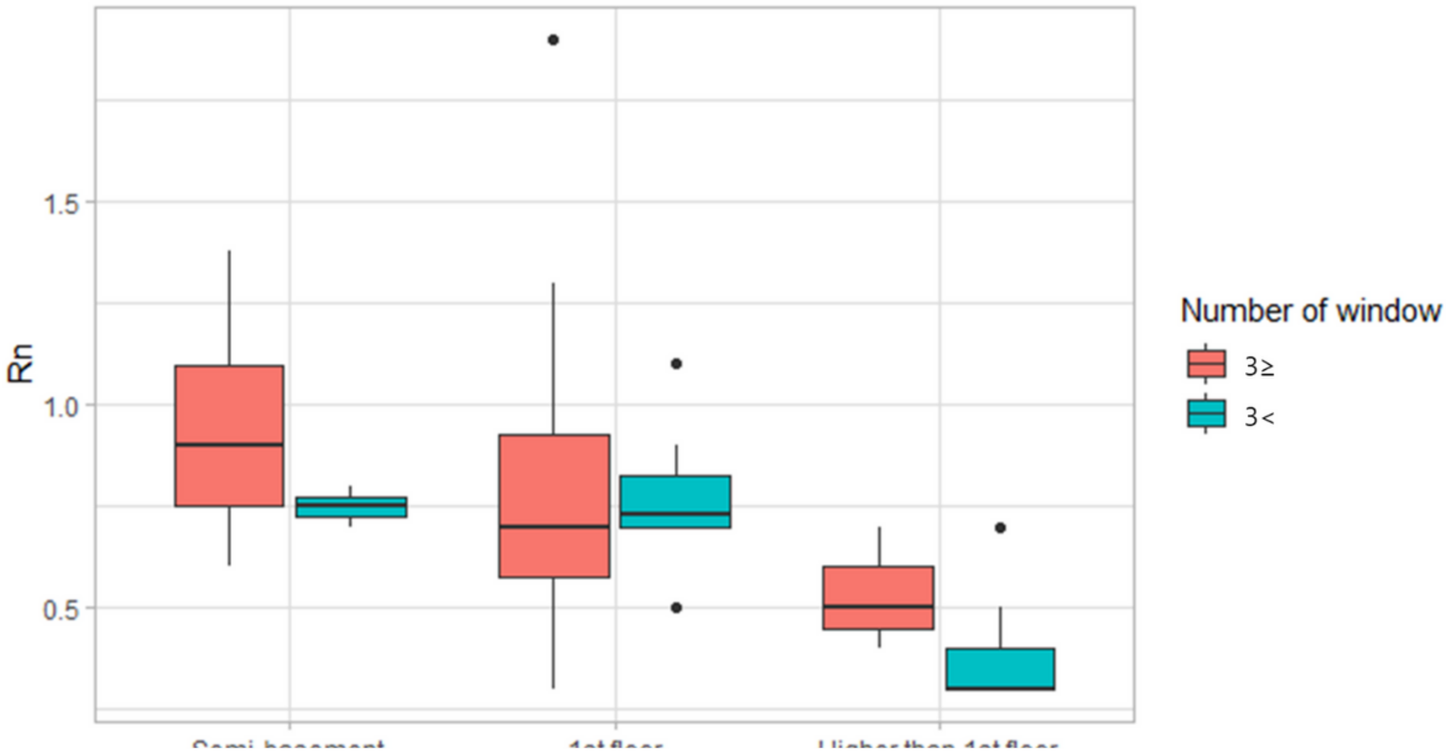

Figure 3

Comparison of radon (Rn) levels by the number of windows in the semi-basement, first floor, and levels higher than first floor