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Diurnal, monthly, and seasonal variations of indoor radon concentrations concerning meteorological parameters

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Abstract

Indoor radon concentrations and meteorological parameters were measured in an office of the teaching staff at the Institute of Nuclear Sciences, Ege University. Data were collected hourly over 25 months (762 days). Raw data, diurnal, monthly, and seasonal variation of parameters were investigated separately. The results show that the average indoor radon concentration (18 Bq m^{-3}) is relatively lower than national and international reference values. Indoor radon concentrations showed an increasing and decreasing trend throughout the day. Radon concentrations are slightly higher in the morning (downtime and early hours of the day) and then reduced in the afternoon. This can be related to the daily routine usage of the office, which is affected by ventilation of the room, air temperature variations, etc.

Highlights

- Indoor radon concentrations are considerably lower than national and international reference values.
- Radon concentrations are slightly higher in the early hours of the day and then decrease in the afternoon.
- Indoor radon concentrations vary wider in autumn and winter than in other seasons (spring and summer).

Introduction

As an odorless, tasteless, colorless, radioactive, and noble gas, Radon (^{222}Rn) is formed by the decay of ^{226}Ra, a member of the ^{238}U decay chain. Radon is produced naturally within the earth's crust, moves to soil pores, and then migrates to the atmosphere from the earth's crust. This migration will be completed with the penetration of Radon into the building. Radon moves into dwellings through micro-cracks, voids, poorly isolated wall joints, and air-pressure differences (Tabar et al. 2013; Yarar et al. 2014; Günay et al. 2018; Park et al. 2018; Ülküm et al. 2018; Semwal et al. 2019; Hatungimana et al. 2020). Its noble gas character and radioactive decay properties make Radon a unique tracer for monitoring temporarily and periodic variations of natural processes (Steinitz et al. 2013). The average radon concentrations worldwide in outdoor and soil airs are 10 and 10.000 Bq m^{-3}, respectively (Podstawczyńska 2015).

It is a fact that Radon is one of the natural ionizing radiation sources, and by inhalation, it enters the human lungs and can lead to severe diseases such as lung cancer. Many studies have reported the relationship between indoor radon exposure and lung cancer, and it is estimated that exposure to high radon levels at least 10% of the lung cancer cases in the US. IARC has defined radon gas as a human carcinogen because its progeny emits radioactive alpha particles capable of causing lung cancer (Bräuner et al. 2012; Şen et al. 2013; Yarar et al. 2014). It is classified as the second cause of lung cancer after smoking (Baltrenas et al. 2020). In addition, Radon has been implicated as the primary cause of lung cancer in never-smokers (Di Carlo et al. 2019).

Populations of developed and developing countries spend 92% of their daily time indoors, so it is significant to determine the radon levels in the indoor environment (McGrath and Byrne 2021). It is reported that indoor radon concentrations exhibit significant spatial and time-scales variations. environmental factors (geological structure, radon concentrations of soil pores, permeability and porosity of soil, meteorological parameters) and factors related to buildings (building construction, ventilation system, occupants' activities – number of windows, periodicity of window and door opening/closing activities, etc.) have influence on radon variation characteristics (Murty et al. 2010; Podstawczyńska 2015; Ivanova et al. 2019; Baltrenas et al. 2020; Antignani et al. 2021). Air exchange between outdoor and indoor is a significant factor for indoor radon variations (Smetanová et al. 2017). Long-term indoor air Rn-222 concentration measurements are become very popular and well documented in the last decades. This study aimed to investigate the variability of hourly indoor air radon (Rn-222) concentration as the first approach between January 2019 to February 2021, considering diurnal, monthly, and seasonal variations of radon time series. For this purpose, the two-story university building in Bornova-İzmir/Turkey was investigated to assess the indoor radon risk.

Material And Methods

Description of the Building and Its Location

The two-story university building where we studied the indoor radon concentrations is in Bornova (Fig. 1), the third most populated metropolitan district of Izmir. It is located east of Izmir Bay. The total population of Bornova district is almost 450,000, while it is 4.5 M for Izmir city (ABPRS 2018; İçhedef 2019). The district's climate is entirely different from the İzmir city center because it is far from the seacoast and surrounded by mountains. The weather is dry and hot in the summer months, while the winters are harsh in Bornova.

The Institute of Nuclear Science was established in 1983 and moved to its new building in 2012. The building is a reinforced concrete construction, and it has two floors with a basement (Fig. 2). There are 11 storage on the basement floor, 32 rooms on the first floor (27 offices, 3 classrooms, 3 meeting rooms, and 2 student rooms), and 37 rooms on the second floor (27 laboratories, 3 offices, 1 waiting room, and 1 canteen). An office of Teaching Stuff located on the second floor was selected for indoor radon measurements. The cubic volume of the office is about 72 m^3 (24 m^2 floor area and 3 m height). It has three windows opened at least once a day to ventilate the room. The frequency of opening the windows varies depending on the season.

Measurements Of Indoor Radon And Meteorological Parameters

We performed 25 months (762 days) of indoor radon concentrations measurements, which began in January 2019 (01/01/2019) and ended in February 2021 (02/01/2021) and took place in the office of the teaching staff of the Institute of Nuclear Sciences, Ege University. 2 people occupied the office through the measurement period. The radon concentrations of the office were measured using a commercially available radon monitor (Airthings Corentium Plus). The radon detector was situated at 1 m, away from windows and doors remote from the direct impact of external air. The measurements were taken on an hourly basis. The detection limit of the radon monitor is between 6.5 and 50 kBq/m^3. Simultaneously, the environmental parameters were also recorded by the same device, i.e., the indoor temperature, with an accuracy of ± 1.0°C, indoor pressure, with an accuracy of ± 1kPa, and indoor relative humidity, with an accuracy of ± 4.5%.

Statistical Analysis

The workflow in Fig. 3 summarizes the statistical analysis stages of the obtained data. In the first step, raw data of Radon and meteorological parameters were collected. Then, data were analyzed in three-step: diurnal, monthly, and diurnal variations.

The statistical analysis was conducted in R and Rstudio (RStudio Team 2019; R Core Team R 2020) and figures were produced using the package ggplot2 (Wickham et al. 2019). Descriptive statistics for parameters (Radon, Indoor Air Temperature, Indoor Air Pressure, and Humidity) were given in Table 1. The missing data corresponds to measurements below the detection limit.

Results And Discussion

The frequency distribution of the indoor radon concentrations was given in Fig. 4. It is fitting to a lognormal distribution.

The present data analysis showed that the indoor radon activity concentration varied from 6.5-151.1 Bq m^{-3} with a mean value of 18 Bq m^{-3} during the study period (Table 1). UNSCEAR 2000 has reported 40 Bq m^{-3} as the arithmetic means for the distribution of indoor radon concentration. The European Commission proposed that the action level is 200 Bq m^{-3} for new buildings (Clouvas et al. 2011). Turkey Atomic Energy Authority published a directive on radiation safety which includes the action level of 400 Bq m^{-3} and 1000 Bq m^{-3} for houses and workplaces, respectively (TAEK 2000). It is seen that the radon data is lower than the national and international reference values. This may be because the building is newly built, the room is well ventilated during the day, and many other reasons. It is well known that the primary factors that affect indoor radon concentrations are ventilation, season, height, building, age, and building material (Nazaroff et al. 1989). The concentrations are expected to be relatively low since the office where the measurements are made is located on the second floor.

Table 1
Basic descriptive statistics for Radon and meteorological parameters

	^{222}Rn ($Bq\ m^{-3}$)	Temperature (°C)	Air Pressure (mbar)	Relative Humidity (%)
Total	18744	18744	18744	18744
Number of data	14652	18744	18744	18744
Missing	4092	-	-	-
Min	6.5	16.7	987.9	12.6
Median	13.9	23.7	1010.1	37.9
Mean	18.0	23.7	1010.1	37.8
Max	151.1	32.5	1034.0	66.0
Std. Dev.	12.23	2.0	10.5	5.9
Skewness	2.0	2.01	-0.82	0.18
Kurtosis	8.3	0.06	0.04	0.27

Diurnal Indoor Radon Variations

This section considers discussions on the diurnal variations of indoor radon concentration at the teaching staff office. The diurnal indoor radon concentrations vary from 3.3 to 37.7 Bq m^{-3}. In Fig. 5, a violin chart is plotted to show the variation of hourly radon concentrations. It is seen in the graph that the extreme values increase due to the emergence of outliers, especially in the morning hours. It was noteworthy that indoor radon concentrations changed at different times of the day.

Additionally, concentrations are measured slightly higher in the morning (downtime and early hours of the day) and then decreased in the afternoon. On the other hand, it can be seen from the graph that the distributions differ significantly at different times of the day. The shape of the violin becomes thinner and longer between 3 and 9 am, while at other hours, the shape of the violin becomes more rounded. This difference may be due to office hours. The office remains closed at night and midnight without any regular ventilation, and radon concentrations are likely to be measured over a broader range. Pant et al. (2016) reported an increase in radon concentration from evening to early morning until it reaches its maximum value. Murty et al. (2010) mentioned that radon concentrations are higher in the early morning hours and decrease after that and reach the minimum value during early afternoon hours. Moreover, they pointed out that Radon is strongly dependent on atmospheric pressure, relative humidity, and air temperature.

The median and mean values were not equal for most of the hours. The distribution spread with the increase of outliers, especially in the morning hours. The slow variation of indoor radon (higher in downtime, and early hours of the day and then decreased in the afternoon) throughout the measured period shows similarity to the results of some researchers (Murty et al. 2010; Pal et al. 2015; Chen et al. 2016; Pant et al. 2016; Xie et al. 2017). This variation may be affected by the ventilation differences and the gap between indoor and outdoor temperatures.

Monthly Variations Of Indoor Radon And Meteorological Parameters

The monthly average of indoor radon concentrations, air temperature, relative humidity, and air pressure obtained within the 25 months are presented in Table 2. The monthly variations of each parameter were calculated by calculating the average of total monthly data. As can be seen from Table 2, indoor radon concentrations decrease in the spring and summer months of both years (2019 and 2020). This decline is apparent in June and July. It is thought that air circulation in the room increases with air conditioners in the office with the increasing temperatures. This view is consistent with the fact that there is no significant increase in office temperatures as in outdoor temperatures. Likewise, the humidity values measured inside the room during these months also increase.

On the other hand, concentrations are higher in November and December compared to other months. During these periods, the lack of air conditioners, the fact that the office's central heating starts to work, and the fact that the doors and windows are less open may be the high levels. Researchers suggest that the seasonal patterns of Radon might change depending on the location of the measurements and their surroundings (Hirsikko et al. 2007; Victor et al. 2019).

Table 2
The monthly average of indoor Radon and meteorological parameters

	^{222}Rn (Bq m^{-3})	Temperature (°C)	Humidity (%)	Pressure (mbar)
January 2019	19.1	24.7	25.8	1007.8
February 2019	15.7	24.3	25.5	1014.4
March 2019	14.6	24.3	26.8	1012.1
April 2019	16.0	23.9	28.7	1010.9
May 2019	14.5	23.7	36.2	1008.6
June 2019	14.9	22.3	47.9	1007.3
July 2019	16.6	22.7	45.4	1004.6
August 2019	15.4	23.9	45.9	1005.8
September 2019	14.1	24.3	45.7	1009.0
October 2019	20.1	22.5	52.6	1012.2
November 2019	17.9	22.9	46.7	1012.6
December 2019	16.2	24.0	33.8	1012.4
January 2020	17.8	23.7	23.8	1018.0
February 2020	15.0	23.9	27.4	1013.9
March 2020	18.9	22.8	29.8	1010.9
April 2020	22.5	19.3	37.6	1009.8
May 2020	21.4	23.9	41.2	1010.6
June 2020	15.8	27.2	40.7	1006.2
July 2020	15.0	26.9	42.7	1004.1
August 2020	17.6	24.3	48.3	1004.2
September 2020	15.3	24.7	53.7	1008.4
October 2020	27.1	22.6	50.9	1011.9
November 2020	23.6	23.3	31.3	1016.3
December 2020	21.3	24.0	32.6	1013.8

Seasonal Variations Of Indoor Radon And Meteorological Parameters

Since the study began in January, the 2019 winter season was calculated by taking the average of January and February. Similarly, the winter season of 2021 is calculated by taking the average of December 2020 and January 2021. Therefore, two-month data were made for winter season calculations for 2019 and 2021. The other seasons were calculated using the three months' data that formed those seasons. The seasonal variation of indoor radon concentrations is figured in a ridgeline chart (Fig. 6) which allows for studying the distribution of a numeric variable for several groups.

The Ridgeline chart shows that indoor radon concentrations vary in the broader range in autumn and winter than in other seasons. Maximum radon levels in spring and summer do not exceed 100 Bq m^{-3}. It can be seen from the graph that the seasonal distributions are almost similar, but the distributions do not fit the normal distribution. In addition, the distributions from a fluctuating graph consist of several peaks and different distributions overlapping. An exciting outcome of this chart is a comparison of the consecutive years. Although the concentration ranges and the shapes of the distributions are similar, radon concentrations showed sudden increases and decreases in 2020. Therefore, in 2020, it was observed that the distribution did not have a single peak but more than 4 small peaks. This dynamism continued in the winter season of 2021 as well.

Conclusion

The current study reports the results of indoor radon level dependencies on various indoor parameters for an office of a two-story university building. We focused on interpreting diurnal, monthly, and seasonal variations of a radon time series. Diurnal variations of indoor radon concentrations are measured slightly higher in the morning (downtime and early hours of the day) and then decreased in the afternoon. Monthly average radon concentrations declined in the June and July of both years (2019 and 2020). The opposite results were obtained in November and December. Seasonal indoor radon concentrations varied more extensively in autumn and winter than in other seasons. It is also noted that seasonal distributions are almost similar, but they do not fit the normal distribution. The study is preliminary work on clarifying indoor radon variations and meteorological parameters. Results revealed that it is essential to assess variations of indoor Radon and the effect of environmental factors. We plan to expand this study, take long-term measurements in more rooms and different floors, and interpret the results.

Declarations

Authors' contributions

Conceptualization, M.I.; methodology, M.I., and C.T.; data collection C.T.; statistical analysis M.I.; writing-original draft preparation, M.I.; writing and editing, M.I. and M.M.S.; supervision, M.M.S. The authors have read and agreed to the published version of the manuscript.

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Figures

Figure 1

Measurement location, Institute of Nuclear Sciences, Ege University Campus, Bornova, İzmir (is indicated by the red arrow).

Figure 2

The sketch of the Institute of Nuclear Sciences and the location of the studied office (red dot) in the second-floor plan

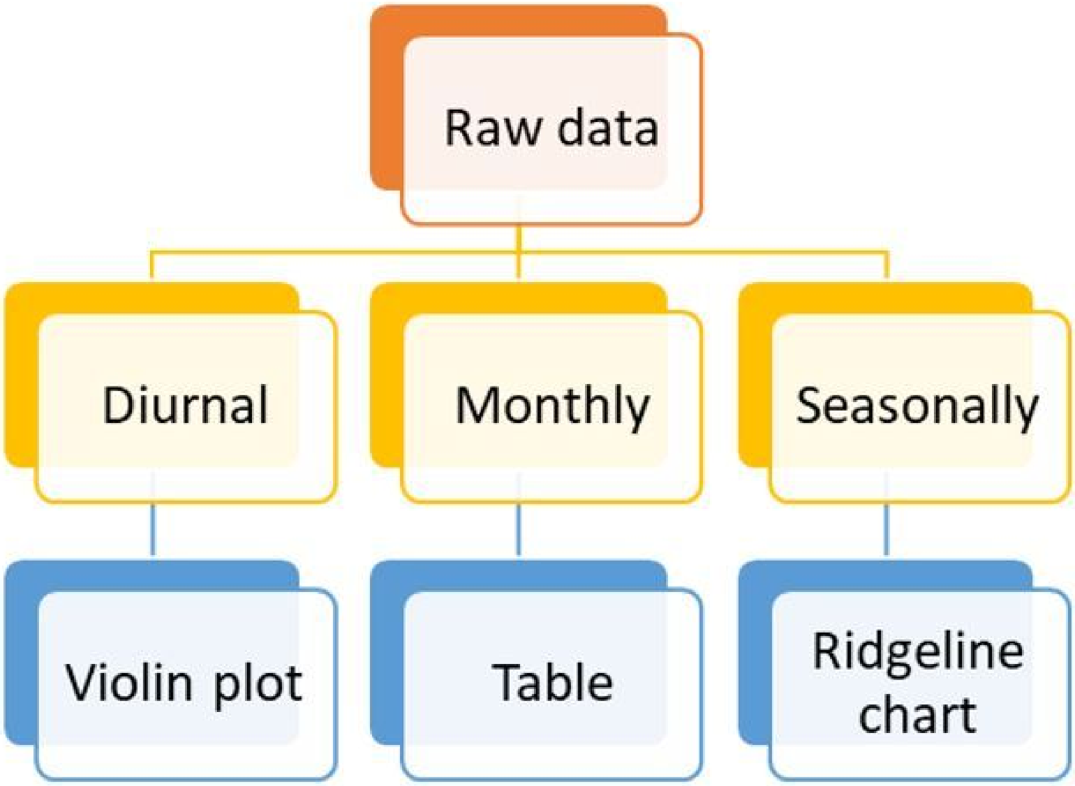

Figure 3

Scheme for preparing the dataset of measured parameters.

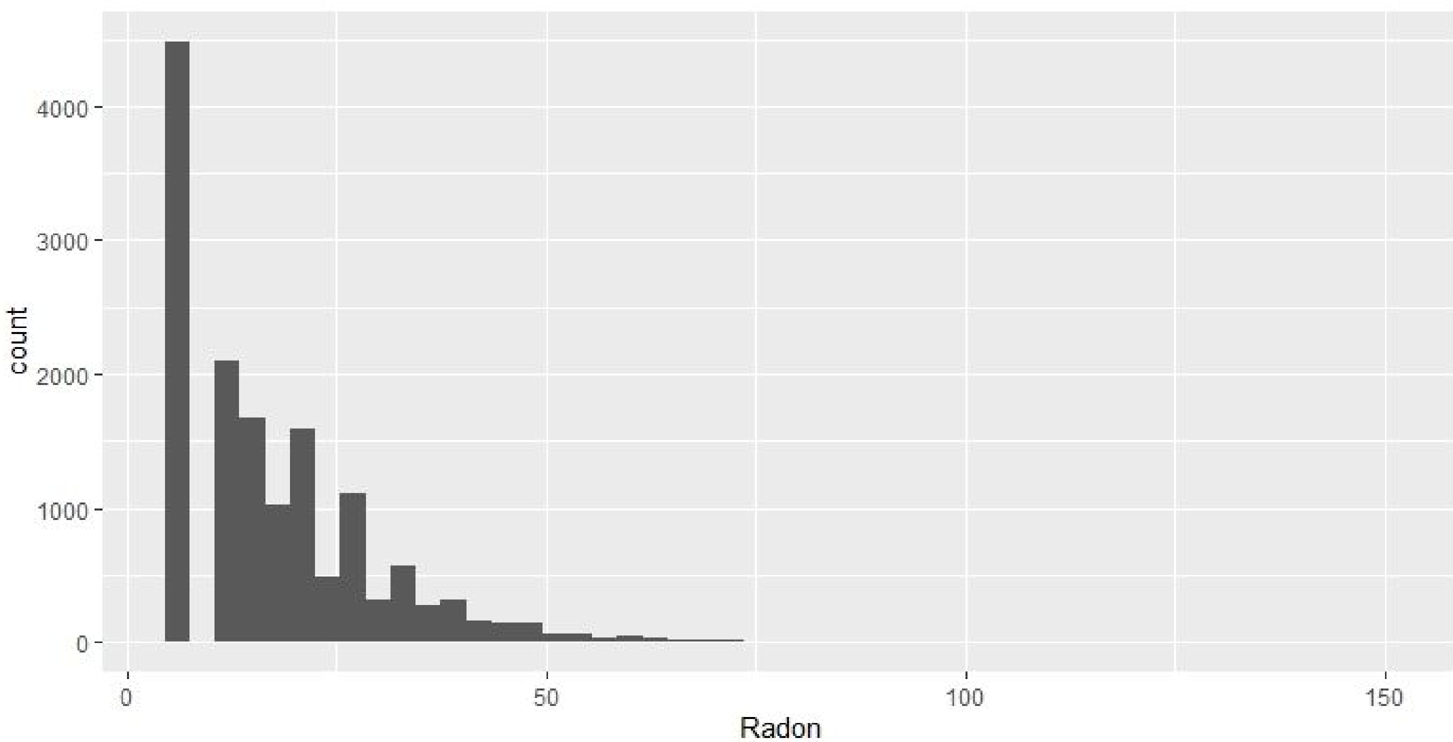

Figure 4

Frequency distribution of indoor radon concentrations

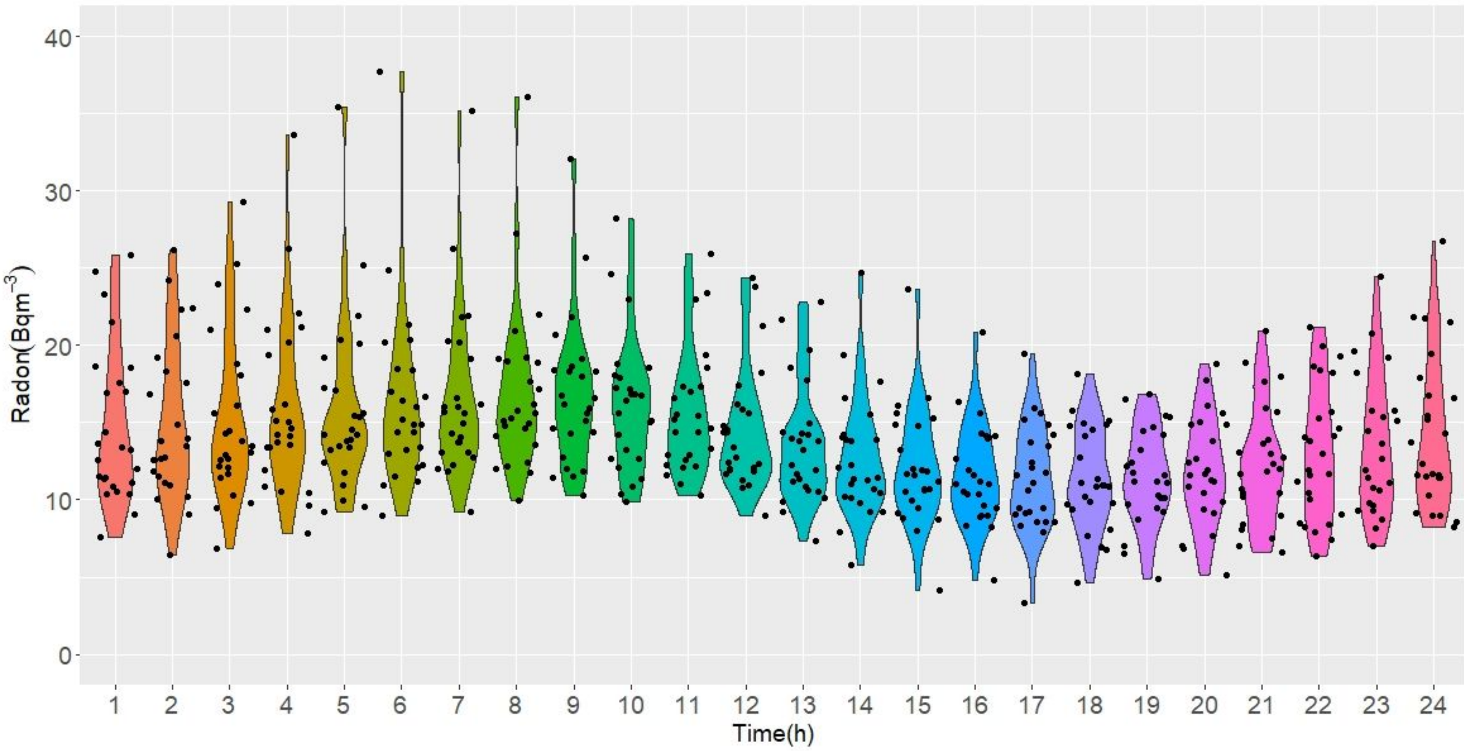

Figure 5

Diurnal variations of monthly average indoor radon concentration in the office (The x-axis shows the time of day, and each violin contains 25 data)

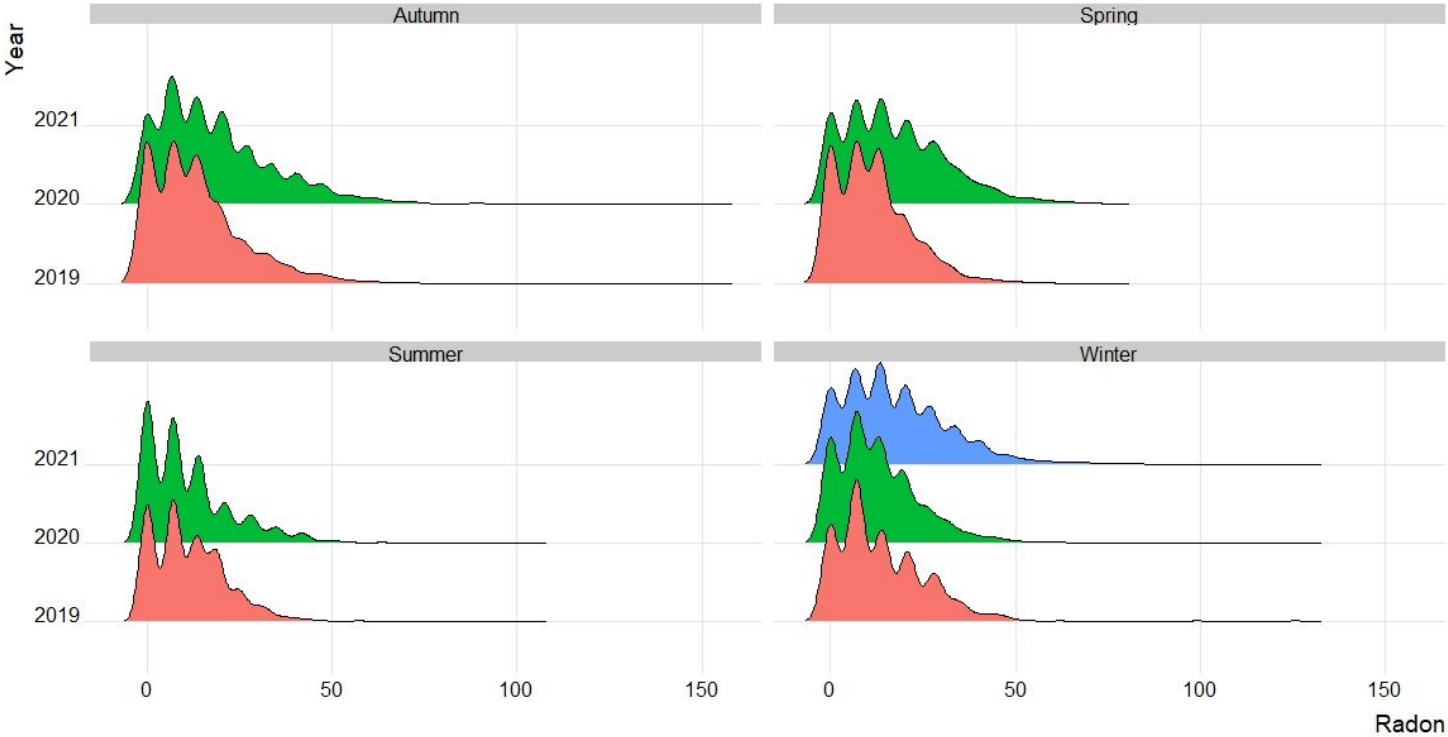

Figure 6

Ridgeline chart of seasonal variation of indoor radon concentrations in Bq m^{-3}.