Short-term variations of indoor and outdoor radon concentrations in a typical semi-arid city of Northwest China

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Abstract

To obtain basic data for adverse effects of radon (Rn) on human health, indoor and outdoor Rn concentrations were measured using a RAD7 Rn detector from Oct 2015 to Jun 2016 in Xi'an, China. The effects of air quality and ventilation conditions on the short-term variation of Rn concentrations were evaluated in detail. The results show that the outdoor Rn concentrations increased with the increase in degree of air pollution, and the indoor Rn concentrations decreased with the increase in ventilation rate under different airflow patterns. Some effective measures are proposed to reduce the effect of Rn exposure.

Keywords Radon · Indoor and outdoor · Air quality · Ventilation

Introduction

Over the last few decades, air pollution problems have attracted increasing interest with rapid urbanization and industrialization in China. In addition to conventional chemical and biological air pollutions, radiation pollution induced by radioactive substances imposes a considerable threat to human health. Radon (^{222}Rn) is ubiquitous in nature; it is one of the decay products of a long decay chain of uranium. Rn is found in trace amounts in most soil and construction materials [1, 2]. Rn and its short-lived decay products (radioactive daughters) can be deposited in the respiratory tract and lungs, damaging the surrounding cells. Therefore, the World Health Organization (WHO) has concluded that Rn is harmful to human; Rn is also a major contributor to lung, skin, and leukemia cancers after smoking [3, 4]. Therefore, it is essential to improve the control and prevention of Rn pollution.

Spatial–temporal distribution of Rn concentration indoor and outdoor has been extensively studied. Atmospheric Rn concentration depends on the amount of ^{226}Ra in the underlying soils and/or rocks and their type, porosity, humidity, and temperature [5–10]. The concentration of Rn clearly varies from region to region. For example, the annual average activity of Rn in India was 12.01 ± 0.66 Bq/m^3 [11], whereas that in Hong Kong was 8.3 Bq/m^3 [12]. Moreover, Rn in atmosphere rapidly dissipates due to atmospheric dispersion which is strongly influenced by weather conditions such as precipitation and haze. Therefore, the outdoor Rn level depends on weather conditions. However, most previous studies on outdoor Rn concentration were performed on clear sunny days, and no data is available for special weathers such as haze. Therefore, more studies are needed.

In an indoor space, Rn accumulates easily. Indoor Rn concentrations are generally much higher than outdoor Rn concentrations, especially under poor ventilation conditions. In Riyadh, Saudi Arbia, the indoor Rn concentrations ranged from 1 to 195 Bq/m^3, with a mean value of 24.68 Bq/m^3 for 786 dwellings [13]. In Switzerland, a nationwide Rn survey indicated that the mean Rn level in 32,151 houses was 189 ± 439 Bq/m^3 [14]. The indoor Rn concentration is strongly influenced not only by the Rn

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concentration in building materials, but also by the ventilation rate, i.e., the exchange rate of indoor air with outdoor air naturally or artificially [15]. Many experiments concerning the natural ventilation rates in houses have been carried out. However, sufficient quantitative data are not available for different ventilation rates. In particular, the effect of airflow pattern on indoor Rn concentration has not been reported.

Some studies also reported that the Rn concentration varied with seasons with the highest concentration generally in the winter months. A study in Iran concluded that the average Rn concentration for 650 homes was higher in winter (36.95 Bq/m^3) than summer (27.20 Bq/m^3) [16]. Similarly, a study in Italy reported that the ratio of average Rn concentration of 5631 dwellings from winter to summer was 1.41 [17]. The outdoor Rn concentrations are often the maximum during the winter months. The average outdoor Rn concentration was reported to be 5 Bq/m^3 in summer and 15 Bq/m^3 in winter [18]. The similarity in seasonal behavior of outdoor Rn concentration was also observed in Japan [19], where the outdoor Rn concentration ranged from 0.5 to 2.6 Bq/m^3 in summer, lower than 2.8 Bq/m^3 in winter. However, short-term variations in Rn concentration have been rarely reported. Kolarž measured the air-ion and Rn concentrations in residential buildings and showed that the outdoor and indoor changes had similar trends with the maximum values at dawn and lower in afternoon [8].

This study was carried out in a typical semiarid city to fill our knowledge gap. The indoor and outdoor Rn concentrations under different weather conditions were monitored using a Rn monitor RAD-7. Short-term variations in Rn concentrations were also analysed. The influencing factors were identified, and a correlation between Rn concentrations and air quality and ventilation conditions was established.

Methodology

Description of measurement sites

The Rn concentrations were measured at two different sites in the urban area of Xi'an, China, as shown in Fig. 1. As the largest city in northwestern China, Xi'an (34°26′N, 108°94′E, and 424 m above the sea level) is located in the center of Guanzhong Plain with a large population of over 8.468 million and an area of 39,064 km^2 surrounded by the Loess Plateau and Qinling Mountain. As a typical semiarid inland city, Xi'an has four distinct seasons with long summer and winter and short spring and autumn. In general, the climate in Xi'an is rainy and humid in summer and cold and dry in winter with an annual average temperature of 13.0–13.4 °C and annual precipitation of 558–750 mm.

The three sites are situated between the 2nd and 3rd ring roads in Xi'an. The distance of sites from nearby major roads is about 200 m. The sites are surrounded by trees, greenbelts, commercial and residential buildings, and school buildings. There is no specific industrial pollution source around the site. Therefore, the data obtained from these sites can well represent the urban air quality of Xi'an.

One of two indoor sites is a first-floor single room in an old building with a brick-concrete structure named as room A. Room A has one door and one window. Measurements were performed in room A to determine the daily variations in Rn concentrations. Moreover, the effect of natural ventilation on Rn level was evaluated by opening and closing the door and window in room A. The other indoor site is named as room B; it is a single room of a new building with wooden floors and walls. The Rn concentrations in room B were measured to evaluate the effects of mechanical ventilation. In room B, the air change rate and airflow patterns were altered in this experiment. The three airflow patterns used in this study were (a) lateral air supply and bottom air exit (LSBE), (b) lateral air supply and top air exit (LSTE), and (c) lateral air supply and exit (LSLE), as shown in Fig. 2. The ventilation rate was denoted as ACH (air change rate per hour, unit 1/h), which is defined as a ratio of the flow rate of inlet air (m^3/h) to room volume (m^3).

Rn measurements

All the Rn concentrations were measured by RAD-7 (Durridge, USA), which is a real-time continuous Rn detector. The air inlet of detector was placed at a height of 0.7 m above the ground. The equipment was regularly checked, and the filter desiccant was replaced before each experiment. RAD7 is a sniffer that detects the 3-min α-decay of a Rn daughter without interference from other radiations. It also detects the instantaneous α-decay of a thoron daughter for rapid thoron measurements. Its detection range is 3.7–74,000 Bq/m^3, and the accuracy is ± 5%. At the end of each run, the detector prints out a complete report. According to the accuracy requirements, the Rn concentration sampling under mechanical ventilation conditions was set to the suction monitoring mode, whereas the other samplings were set to the automatic mode. The measurement interval was 6 min.

To obtain a clear picture of variations of outdoor Rn concentration under different weather conditions, the Rn concentration in ambient air was measured on clear sunny days (5 days), hazy days (5 days), and rainy days (2 day) from Oct 2015 to Apr 2016. During the sampling period, the concentration of fine particulate matter (PM$_{2.5}$) and meteorological data such as ambient temperature, relative humidity (RH), atmospheric pressure were simultaneously

Fig. 1 Location of sampling sites at the south of downtown of Xi'an, China
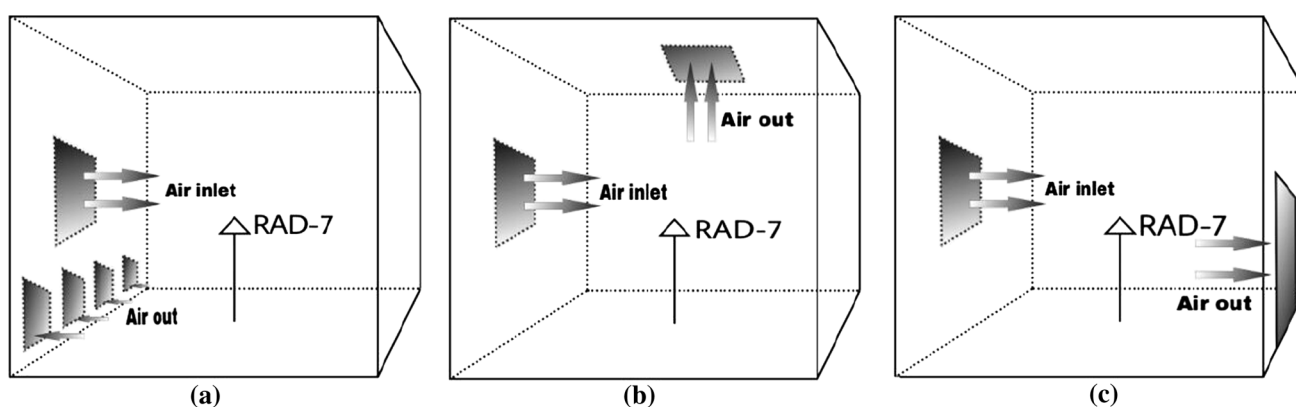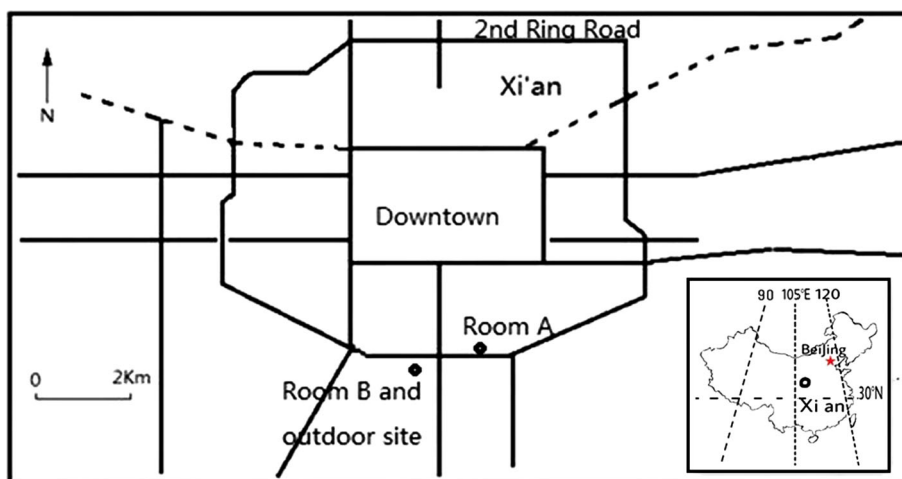
Fig. 2 Sketch of different airflow patterns in room B with mechanical ventilation **a** lateral air supply and bottom air exit (LSBE), **b** lateral air supply and top air exit (LSTE), and **c** lateral air supply and exit (LSLE)

recorded using a portable automatic meteorological station (JLC-QGL, China). The height of mixing layer was calculated by CALPUFF model by inputting a series of meteorological parameters.

Table 1 shows the meteorological parameters and AQI (PM$_{2.5}$) levels during the sampling period. The AQI value of PM$_{2.5}$ is generally used to characterize the air quality level, and air quality is considered as haze pollution when AQI (PM$_{2.5}$) is > 100 in China [20]. Three air quality levels were used for this evaluation: clean days (0–100), polluted days (101–200), and severely polluted days (> 200). The Rn concentrations at different air quality levels were compared to establish a relationship between Rn concentration and air quality.

Under different ventilation types, the indoor Rn concentrations were measured at 0.7 m height above the ground for nine clear sunny days in Apr 2016. During the entire measuring period, the meteorological conditions were moderate and calm, and no human activities bothered the experiments.

Data analysis

SPSS 19.0 was used to conduct statistical analysis of data. Spearman correlation analysis was used to establish the relationship between Rn concentrations with meteorological parameters and atmospheric environmental indices. An ANOVA test was carried out to measure the difference in Rn concentrations under different air quality levels. A p value of less than 0.05 was considered as a statistically significant difference at a confidence level of 95%. Moreover, principal component analysis (PCA) was used to cluster several factors into small groups known as components to explain the observed variability. PCA is a statistical dimension-reduction procedure that converts s set of observations of possibly correlated variables into several linearly uncorrelated variables known as principal components. It shows the internal structure of data and explains the variance in the data.

Table 1 Meteorological parameters and AQI (PM$_{2.5}$) levels during the sampling period

Date	Temperature (°C)	RH (%)	Wind speed (m s^{-1})	Height of mixing layer (m)	Pressure (kPa)	AQI (PM2.5)	Weather
2015-10-20	24.69 ± 2.16	51.91 ± 27.36	1.67 ± 1.14	487	758.9	202	Hazy
2015-10-21	23.22 ± 2.37	62.16 ± 9.55	1.06 ± 1.28	481	760.6	165	Hazy
2015-11-01	10.56 ± 2.54	71.10 ± 16.69	1.83 ± 0.74	718	771.3	49	Nonhazy (sunny)
2015-11-02	10.43 ± 2.13	61.49 ± 16.69	1.41 ± 0.98	684	766.4	63	Nonhazy (sunny)
2015-11-03	9.77 ± 1.62	71.26 ± 12.45	1.43 ± 0.96	734	763.9	104	Hazy
2016-01-01	2.19 ± 2.59	77 ± 7.21	0.83 ± 0.21	339	768.1	468	Hazy
2016-01-02	− 3.79 ± 3.21	64.24 ± 11.90	1.19 ± 0.78	403	765.4	345	Hazy
2016-04-15	15.5 ± 3.29	73.75 ± 21.13	3.61 ± 7.31	837	756.1	55	Nonhazy (rainy)
2016-04-16	17.75 ± 5.39	83 ± 7.64	2.78 ± 3.09	1061	755.2	33	Nonhazy (rainy)
2016-04-18	16.77 ± 0.89	67.88 ± 10.53	1.67 ± 2.76	913	769.3	70	Nonhazy (sunny)
2016-05-24	25.16 ± 0.57	68.54 ± 6.55	2.22 ± 1.46	784	768.5	30	Nonhazy (sunny)
2016-06-17	27.25 ± 0.61	49.00 ± 6.77	1.67 ± 1.97	956	768.3	36	Nonhazy (sunny)

Results and discussion

Variation in outdoor Rn concentrations on hazy days

Figure 3 shows that the diurnal variation of outdoor Rn concentration on clear sunny and hazy days. Note that the
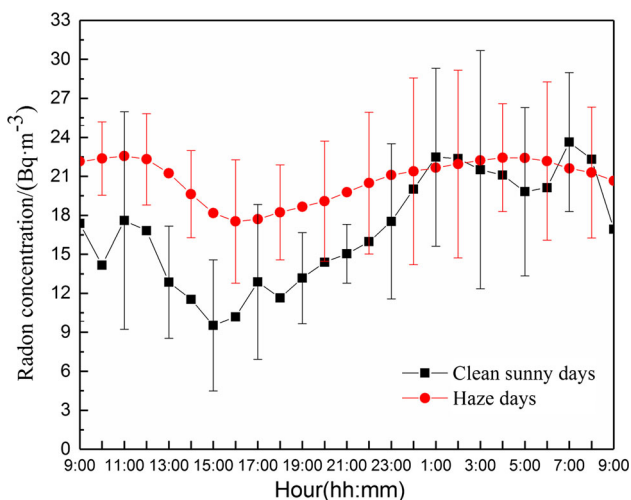
Fig. 3 Diurnal variation of Rn concentrations on clear sunny and hazy days

concentration is an hourly average of sampling days of each weather. The Rn concentration was higher at night and lower during the day under both weather conditions. Generally, the Rn concentration reached a maximum at 7:00 and then decreased to a minimum in afternoon, 14:00–17:00.

A similar diurnal behavior was also observed worldwide by other studies. Nagaraja reported the maximum Rn concentration during early morning hours (4:00–7:00) and a minimum during afternoon hours (12:00–16:00) at Pune, India [7]. Kolaržalso observed most of the Rn peaks at dawn and minimal Rn concentrations during the afternoon at Belgrade, Serbia [8]. According to the correlation analysis, the trend of diurnal variation can be mainly attributed to atmospheric turbulent diffusion caused by temperature change. During the night, temperature inversion generally occurs near the surface, suppressing the turbulent movement of lower atmosphere and preventing the vertical diffusion of Rn. As a result, the radioactive gases emanating from soil accumulate closer to the Earth's surface and thus cause higher Rn concentrations. During the day, heating of the earth surface by sunlight causes warm air to move upward, and inversion layer disappears, decreasing the Rn concentration level.

In addition, there is a hint that the Rn concentration in clean days is lower than that of hazy days. On clear sunny days, the concentration range and average value were 4–32 and 16.8 ± 6.9 Bq/m^3, respectively, whereas those on hazy days were 10–33 and 21.2 ± 5.7 Bq/m^3, respectively. This may also be explained by atmospheric diffusion conditions. According to Wang [21], double or even multiple inversion often occurred in Xi'an during the hazy days (Dec 16–25, 2013), and the thickness of low-altitude temperature inversion layer was in the range 50–430 m on hazy days. In this study, lower surface wind speeds (less than 2 m/s) and lower mixed-layer heights (356–778 m) were observed during the hazy days. Therefore, the existence of near-ground inversion stabilized the atmospheric stratification, indicating that the horizontal transport and vertical mixing of lower atmosphere were too weak to dilute Rn. This weather condition would be favorable for the near-ground accumulation of air pollutants as well as radioactive gas Rn.

Variation in outdoor Rn concentrations on rainy days

To evaluate the effect of rainfall on Rn concentration, a continuous 24-h measurement was performed on a rainy day. Figure 4 shows the variation of Rn concentration on the rainy day. In this study, the rainfall period was divided into four stages: before rain, light rain, moderate rain, and after rain. Obviously, the Rn concentration slowly decreased from 8:00 a.m. to 12:00 p.m. before rain, and this trend was consistent with the diurnal variation on clear sunny days as discussed above. When it rained, the concentration of Rn significantly decreased, reaching a minimum at about 18:00–19:00. Afterwards the Rn
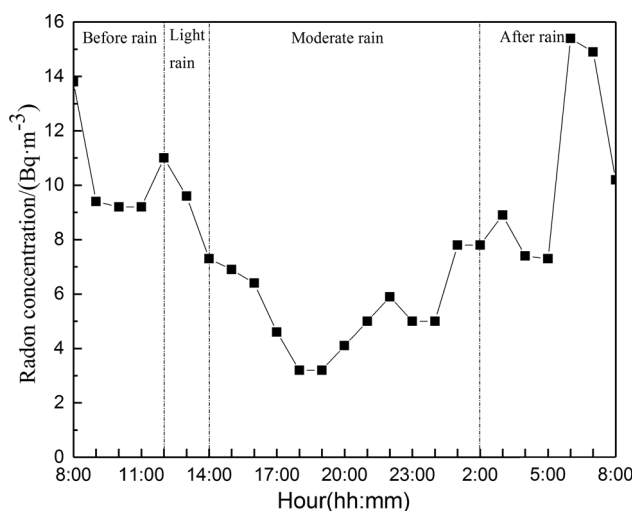
**Fig. 4** A continuous 24-h variation in outdoor Rn concentration during a rainfall period

concentration gradually increased, followed by returning to normal daily variation after the rain. The range of Rn concentration during this rainfall period was 3.2–11.0 Bq/m^3 with an average of 6.2 ± 2.3 Bq/m^3.

The Rn concentration in ambient air depends not only on atmospheric dispersion, but also on the amount of Rn exhaled from ground. On rainy days, the moisture in soil increases, and the channel of Rn movement is blocked, decreasing soil porosity and permeability. In addition, the atmospheric pressure on rainy days was lower than that on sunny days, as shown in Table 1. Accordingly, the pressure difference between soil and atmosphere decreased on rainy days, consistent with a study in Hungary [22]. According to Darcy's law, the exhalation flux of Rn from the soil decreases as the pressure gradient decreases, and thus a lower Rn concentration can be expected during rainfall. A statistically negative correlation between atmospheric pressure and outdoor Rn concentration also supported these results, as shown in Fig. 5a.

Another reason for a low Rn concentration during a rainfall can be attributed to a high humidity. Figure 5b shows the correlation between RH and hourly outdoor Rn concentration during the rainfall. The Rn concentration decreases with the increase in RH. On rainy days, the moisture in soil increases, and the channel of Rn movement is blocked, decreasing soil porosity and permeability. Besides, a decrease in gas diffusion coefficients has been reported at higher water fractions, and it became particularly pronounced when the soil was saturated with water [23]. Thus, the outdoor Rn concentration was lower during the rainfall.

Outdoor Rn concentrations at various air quality levels

Figure 6 shows the effect of different AQI values of PM$_{2.5}$ on outdoor Rn concentration during nonrainy days. The average Rn concentrations on clean, polluted, and severely polluted days were 14.66, 16.44, and 24.65 Bq/m^3, respectively. A Spearman's correlation analysis showed that the correlation coefficient between AQI (PM$_{2.5}$) and Rn concentration was 0.357, indicating no statistically significant correlation between them. Even so, the Rn concentration increased with the increase in AQI (PM$_{2.5}$). Moreover, the Rn concentration on severely polluted days was significantly higher than that on clean days ($p < 0.01$). Similarly, the Rn concentration on severely polluted days was also statistically significantly higher than that on polluted days ($p < 0.01$). The ratio of Rn concentration on severely polluted days to that on polluted days was about 1.68. Generally, the higher value of AQI (PM$_{2.5}$) reflects better atmospheric stability, contributing to the accumulation of Rn.
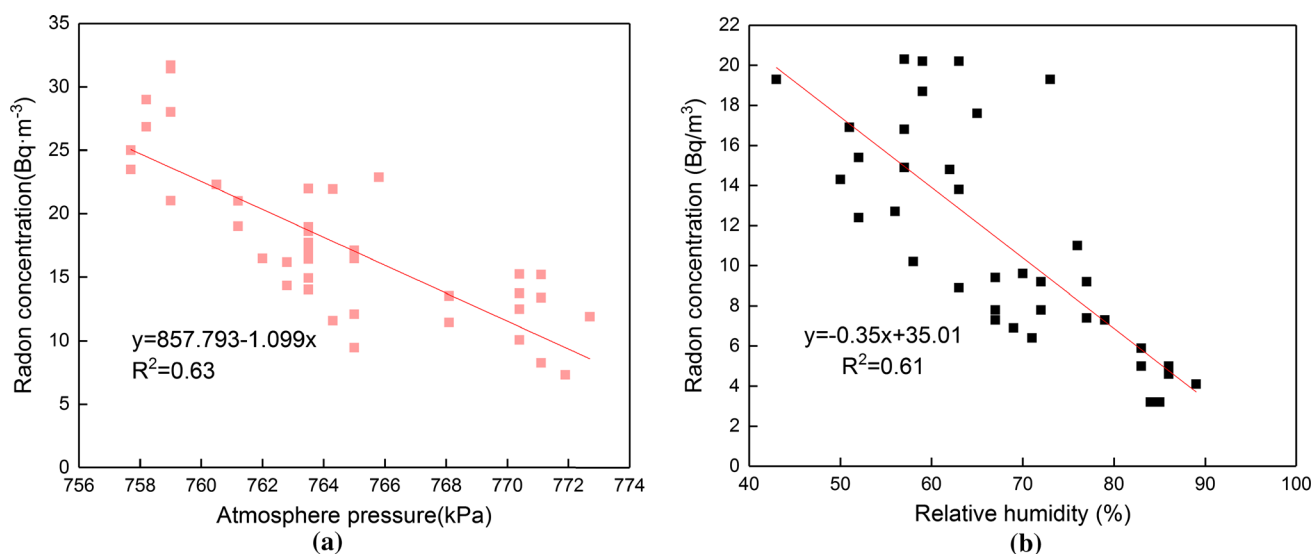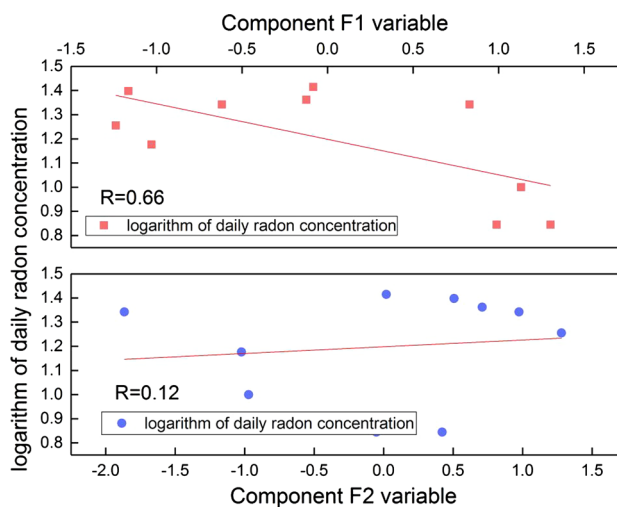
Fig. 5 Correlation between hourly Rn concentration and **a** atmosphere pressure and **b** RH during precipitation
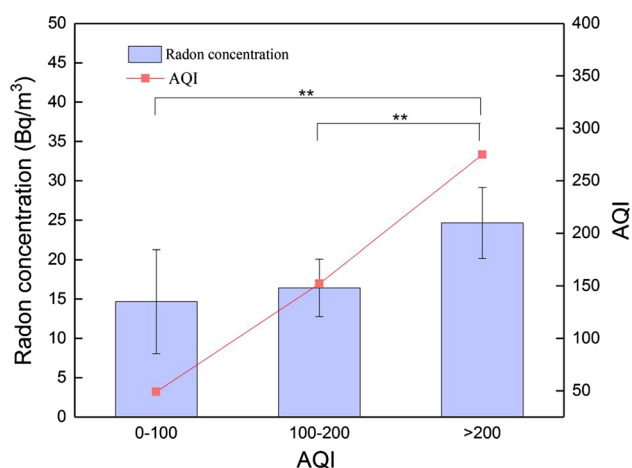
Fig. 6 Effect of different air quality levels on outdoor Rn concentration. Notice that ** means a significant difference when the confidence level is 0.01

To better understand the variation in Rn concentrations under various weather conditions, a PCA was performed to identify the main components affecting outdoor Rn concentration. All the data obtained during the nonrainy days were analyzed in this study. Five different meteorological factors recorded in nonrainy days were attributed into two groups including component F1 (temperature, wind speed, and height of mixing layer) and component F2 (RH and atmospheric pressure). F1 reflects the transmission and diffusion of Rn, whereas F2 affects the exhalation of Rn in soil. The principal components F1 and F2 accounted for 49.801 and 34.524% of the variance, respectively, indicating that diffusion affected outdoor Rn concentration more strongly.

Moreover, a linear regression was conducted between the components and Rn concentration, and the effect of each factor on Rn concentration in the atmosphere was also analyzed by Spearman's correlation analysis. As shown in Fig. 7, the correlation between F1 and Rn concentration was more significant than that between F2 and Rn concentration, indicating that air diffusion factors strongly affected the air Rn concentration than Rn rate exhalation from soil, dominating the source of outdoor Rn. Among these meteorological factors, the higher the temperature, wind speed, and height of mixing layer, the more favorable it was for Rn to be diffused and transmitted. Therefore, it is not surprising that component F1 has a significantly clear


Fig. 7 Correlation between principal components F1 and F2 variables and logarithm of daily Rn concentration during nonrainy days (Component F1, F2 variable means regenerated dimensionless value representing the variables in F1 and F2 group, respectively)

negative relationship with outdoor Rn concentration. As discussed above, the atmospheric pressure and RH mainly effect the soil Rn exhalation. The exhalation of soil Rn is linked to not only several weather conditions, but also the properties of soil such as its radium content and texture. This is probably why F2 does not affect Rn concentration as significantly as F1. Compared with rainy days, Rn concentrations were slightly affected by RH and air pressure. This can be attributed to a higher change in airflow during the rainy days.

Variation of indoor Rn concentration under natural ventilation

To evaluate the daily variation of indoor Rn level and the effect of natural ventilation, a 30-h continuous measurement for indoor Rn concentration was carried out in room A. According to the national standard of China [24], one door and one window in room A should be closed for at least 12 h before the measurement. This short-term measurement had three stages: stage 1 at which the door and window were closed from 8:00 on the first day to 7:00 on the second day, stage 2 at which the door and window were full opened from 7:00 to 17:00 on the second day, stage 3 at which the door and window were again closed from 17:00 on the second day to 13:00 on the third day. No human activities occurred during the measurement except for opening/closing the door and window. Figure 8 shows the variation in Rn concentration during this period.

Similar to the Rn variation in ambient air, the indoor Rn concentration also showed a daily change trend with maximum values at dawn and lower during the afternoon,
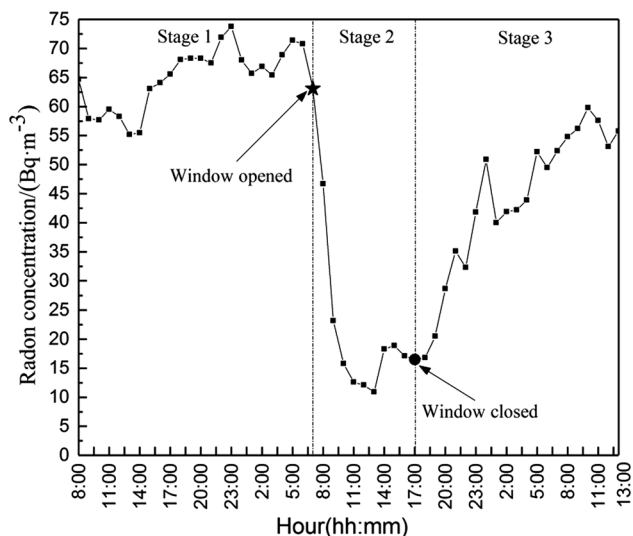
Fig. 8 Variation in Rn concentration under natural ventilation condition ★ represents when the window was opened and ● represents when the window was closed

as shown in stage 1 in Fig. 8. The variation range of indoor Rn concentration was 55.2–71.4 Bq/m^3 with a mean value of 64.9 ± 5.3 Bq/m^3. Statistically, the mean value of indoor Rn concentration was significantly higher than outdoor ($p < 0.05$). With door and window opening during stage 2, the indoor Rn concentration rapidly decreased to the lowest value at 12:00. After the room was completely ventilated, the average Rn concentration was 16.3 ± 2.5 Bq/m^3, close to the outdoor level. Once the window and door were closed again during stage 3, the Rn concentration started to rise. After 17 h, it eventually returned to the concentration level before ventilation.

Clearly, the effect of natural ventilation on indoor Rn concentration was noticeable. Before the ventilation, the indoor Rn concentration was high, mainly due to poor air dispersion. After the ventilation, the indoor–outdoor air exchange promoted indoor air convection and dispersion. Therefore, the Rn concentration rapidly decreased. Another interesting result was observed in Fig. 8. The decreasing rate of Rn concentration after the door and window were opened was faster than the increasing rate after the door and window were closed again. This can be attributed to diurnal changes in Rn exhalation and a longer time required for accumulation [9].

Variation in indoor Rn concentration under mechanical ventilation

To further evaluate the effect of ventilation on indoor Rn concentration quantitatively, mechanical ventilation experiments were carried out with different airflow patterns in room B. In this study, test cases with six mechanical ventilation rates (ACH = 0, 0.5, 1, 2, 4, and 8 h^{-1}) and three airflow patterns were investigated. As shown in Fig. 8, some time is required to establish a balance between outdoor and indoor Rn concentrations. Therefore, before each measurement for different cases, all the air inlets and outlets were closed for at least 24 h to stabilize the initial Rn concentration. Nevertheless, the initial concentrations were slightly different due to varying outdoor Rn concentration. Therefore, two normalized values, the ratio of indoor to initial concentration and the ratio of indoor to outdoor concentration were used to show the variation in indoor Rn concentration with ventilation rate under different airflow patterns, as shown in Fig. 9. The measurement time was about 10–12 h, and the final stable Rn concentration was obtained for each case. Moreover, the outdoor Rn concentration was also measured for comparison.

The Rn concentration decreased with the increase in ventilation rate for all the three airflow patterns. When the ventilation rate was small, the Rn concentration rapidly decreased. The decreasing rates of the three airflow
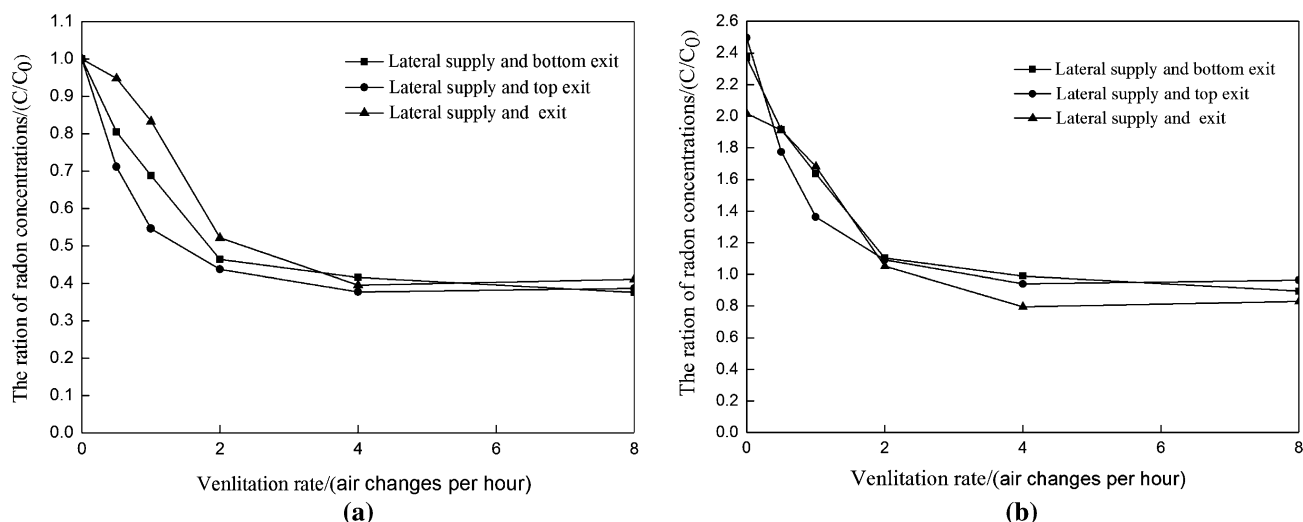
Fig. 9 Variation in Rn concentration under different airflow patterns. **a** Ratio of indoor to initial concentration and **b** ratio of indoor to outdoor concentration

patterns were slightly different, following the order of LSTE > LSBE > LSLE. When the ventilation rate was more than 4 h^{-1}, no significant change in Rn concentration was observed, and the difference in Rn concentration among the three airflow patterns was negligibly small. Baeza also reported that indoor Rn concentrations decreased with increasing air exchange rates [25]. The results obtained in this study further indicate that the effect of mechanical ventilation on indoor Rn concentration was related to the airflow patterns, especially for small ventilation rates.

In addition, the ratio of Rn concentration between indoor and outdoor was the highest at ACH = 0 h^{-1}. When the ventilation rate was higher than 2 h^{-1}, the ratio of indoor to outdoor concentration was close to 1, indicating that the indoor Rn concentration was almost equal to the outdoor concentration. This indicates that with the increase in ventilation rate, a lot of fresh outdoor air entered into the room continuously. The indoor Rn accumulation can be diluted by mechanical ventilation; therefore, the indoor Rn concentration was close to the outdoor concentration.

Comparison of indoor and outdoor Rn concentrations worldwide

Table 2 shows a comparison of indoor Rn concentration in different regions worldwide. The level of indoor Rn concentration detected in Xi'an was higher than that in most regions in the world except in Switzerland. Moreover, UNSCEAR also reported that the world average Rn concentration in outdoor atmosphere is 10 Bq/m^3 [26], lower than that on the hazy days (16 and 21 Bq/m^3, respectively) and higher than that on rainy days (6 Bq/m^3) in the present outdoor environments. It is well known that the amount of

Rn exhaled depends on the amount of ^{226}Ra in the ground, type of ground cover, and porosity, humidity, and temperature of soil. In Switzerland, the geological composition of dominated granite and carbonate rocks should be responsible for such a considerable high Rn level [14]. As mentioned above, Xi'an is located in a semiarid or arid continental climate area surrounded by the Loess Plateau and Qinling Mountain. The drying weather and a high porosity may facilitate the exhalation of Rn gas. According to Zhuo [27], the Rn flux from soil in Xi'an varied from 27 to 35.7 mBq m^{-2} s^{-1}, slightly higher than the world average value (26 mBq m^{-2} s^{-1}). Additionally, the outdoor Rn concentration also depends on the diffusion condition. As an inland city surrounded by mountains, frequent inversions and stable stratification prevent the dispersion of air, resulting in easy accumulation of Rn in near-ground atmosphere in Xi'an. Therefore, it is not surprising that a relatively high Rn concentration was observed in Xi'an compared with other regions worldwide.

Owing to potential risk of human exposure to cumulative Rn in indoor environments, it is essential to evaluate the Rn concentration in indoor spaces. Several national or international permissible exposure levels are regulated. The WHO recommended an action reference level of 100 Bq/m^3 to minimize the health hazards due to indoor Rn exposure. The Chinese national reference level was regulated as 100 Bq/m^3 for new homes and 200 Bq/m^3 for old and existing homes. Although the indoor Rn concentration in Xi'an is lower than the Chinese permissible standard, it is much higher than the world average level. Therefore, some appropriate actions should be taken to control the adverse effects of indoor Rn exposure. According to the results obtained in this study, strengthening indoor ventilation, selecting appropriate airflow pattern, and improving

Table 2 Comparison of indoor Rn concentrations in different regions worldwide

Regions	Monitoring period	Mean concentration (Bq/m^3)	References
Xi'an, China	2015.11–2016.06	66.7	Present study
Xiamen, China	2008–2009	31.1	[28]
Pune, India	1997.12–2000.12	9.70	[7]
Switzerland	Over the last 30 years	189 ± 439	[13]
Riyadh, Saudi Arbia	2012.01–2012.12	24.7	[14]
Sivas, Turkey	2006	93.5	[29]
Valencia, Spain	2009.01	24	[30]
All over the world		40.0	[3]

air quality are all effective measures to reduce the Rn concentration.

Conclusion

This paper presents the results obtained from field measurements and experimental studies on variations in outdoor Rn concentration in various weathers and indoor Rn concentration under different ventilation conditions focusing on air quality and health risk. Weather conditions and air quality significantly affect the outdoor Rn concentration. The outdoor mean Rn concentration decreased in the following order: hazy days > clear sunny days > rainy days. Interestingly, the outdoor Rn concentration increased with the decrease in air quality. With increasing ventilation rate, the indoor Rn concentration decreased. The airflow patterns produced by mechanical ventilation are also important, especially for small ventilation rates. Moreover, the mean values of outdoor and indoor Rn concentrations were 16.8 ± 6.9 and 64.9 ± 5.3 Bq/m^3 in Xi'an, respectively, much higher than the world average level. These results provide basic data for the evaluation of adverse effects of Rn on human health. The results also encourage to take appropriate actions to decrease the Rn levels if necessary.

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