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Effects of air conditioning, dehumidification and natural ventilation on indoor concentrations of ^{222}Rn and ^{220}Rn

Thomas K.C. Lee[a], K.N. Yu[b,*]

[a]Environmental Management Division, Hong Kong Productivity Council, HKPC Building, 78 Tat Chee Avenue, Kowloon, Hong Kong

[b]Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon Tong, Hong Kong

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Abstract

A bedroom was selected for detailed measurements on ^{220}Rn and ^{222}Rn concentrations and environmental parameters including CO_2 concentration, temperature and relative humidity. To simulate different sealing conditions, five conditions were artificially created in the sampling period of 25 consecutive days. It was concluded that natural ventilation is the most efficient way to lower the ^{222}Rn levels, while air conditioning is the next. Dehumidification provides only a marginal reduction of ^{222}Rn levels. The ^{220}Rn concentrations are not affected by natural ventilation, air conditioner or dehumidification, and were all around 10 Bq m^{-3}. There are no significant correlations between the ^{220}Rn and ^{222}Rn concentrations and environmental conditions such as CO_2 concentrations, temperature, relative humidity and pressure. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

With regard to the natural radiation dose, the contribution from indoor ^{222}Rn is the most important (UNSCEAR, 1993). There is also increasing attention being given problem of ^{220}Rn (Bigu, 1986). Although the half-life of ^{220}Rn is short and it is

* Corresponding author. Tel.: + 852-2788-7831; fax: + 852-2788-7830.
E-mail address: peter.yu@cityu.edu.hk (K.N. Yu)

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believed that only a small portion of ^{220}Rn can ultimately enter the indoor environment, the high concentrations of ^{232}Th in building materials employed in Hong Kong imply that indoor concentrations of ^{220}Rn may not be negligible (Yu, Guan, Stokes & Young, 1992a). Recently, there are surveys of indoor concentrations of ^{222}Rn and progeny and ^{220}Rn progeny in Hong Kong (Yu, Young, Stokes, Luo & Zhang, 1992b, Yu, Young & Li, 1996a,b, Yu, Young, Stokes, Guan & Cho, 1997, Yu, Young, Stokes & Tang, 1998) which have demonstrated the extent of exposure to ^{222}Rn and ^{220}Rn, and in particular the unexpected importance of dose due to ^{220}Rn. It is imperative, therefore, to identify effective ways to mitigate ^{222}Rn and ^{220}Rn dose to people

In this work, a bedroom was selected for detailed measurements of ^{222}Rn and ^{220}Rn concentrations under different sealing conditions, and environmental parameters including CO_2 concentration, temperature and relative humidity were also measured in order to identify their possible relationships with the ^{222}Rn and ^{220}Rn concentrations.

2. Experimental

2.1. Measurement devices

In the present study, the instrument RAD7 (model 710 version 2.5: Niton Corporation, Bedford, MD, USA) was used to measure concentrations of ^{220}Rn and ^{222}Rn. RAD7 employs a solid state α detection chamber for measurements and can produce α energy spectra in the range of 0–10 MeV with a resolution of 0.05 MeV which differentiates α particles emitted from the progeny of ^{220}Rn and ^{222}Rn.

Eight energy ranges, called windows A–H, are defined in the spectrum for data analysis, and three of them are relevant to our measurements. Window A collects α particles from ^{218}Po decay (6.00 MeV), which is used for the determination of ^{222}Rn. Window B collects α particles from ^{216}Po decay (6.78 MeV), which is used for the determination of ^{220}Rn. Window C collects α particles from ^{214}Po decay (7.69 MeV), which can also be used for the determination of ^{222}Rn. The spillover of α particles from Window C can interfere with the counts of Window B, which should be corrected. To determine the correction factor, test cycles are conducted in a closed loop environment so that no new ^{220}Rn can enter the loop. Since the half-life of ^{220}Rn is 55.6 s, ^{220}Rn in the loop effectively vanished in the first 10 min, so all counts in Window B are then spillovers from Window C.

Filters are installed on the top of the sampler of RAD7 to screen off the progenies of ^{220}Rn and ^{222}Rn, so that only the gas concentrations are measured. A desiccant drying tube containing anhydrous $CaSO_4$ hammond is also installed to maintain a relative humidity of the incoming air below 10% during measurements, which is monitored by a humidity sensor. The sensitivity of the α particle detector will be lowered significantly when the relative humidity is too high. The RAD7 was sent back to and calibrated by the manufacturer annually.

Another instrument called Q-Trak (model 8550: TSI Incorporated, Shoreview, MN, USA) was used to measure environmental parameters including CO_2 concentrations, temperature and relative humidity. The Q-Trak was also sent back to and calibrated by the manufacturer annually. Daily data on outdoor atmospheric pressure measured at the Hong Kong Observatory were also used for subsequent data analysis.

2.2. Sampling

All tests were conducted in a bedroom of a residential unit, which is located on the middle floors of a building and is about 30 m above the ground level. The building is a 27-storeyed building about 6 years old. The bedroom has a floor area of 5.6 m^2, a gross volume of 13.9 m^3 and a net volume of about 10.5 m^3 (obtained by subtracting the volume occupied by fixtures). The windows of the room are normally kept closed especially when it is unoccupied. This is also a common practice in other residential units in Hong Kong.

The sampling probes of the instruments were placed on the top of a desk 0.4 m away from the nearest wall and 1.2 m above the floor, i.e. in the breathing zone of a seated person. Since ^{220}Rn levels depend remarkably on the sampling position (Katase, Matsumoto, Sakae & Ishibashi, 1988; Doi, Fujimoto, kobayashi & Yonehara, 1994), the sampling inlet of RAD7 was fixed at a point on the desk throughout the present work.

During the test period, four sealed conditions and one unsealed condition were maintained to provide various environmental conditions, which included the operation of an air conditioner and a dehumidifier, and opening of windows and door. These conditions are defined in Table 1. The air conditioner is a window unit with a capacity of 750 W, and with the temperature set to lowest, the fan set to low and the vent closed during operation. The dehumidifier is a heavy-duty floor top unit, and was operated to its full loading. For sealed conditions, the windows and the door of the room were kept closed, and there were no entries except for the operation of the instruments. When the dehumidifier or air-conditioner was employed for the sealed conditions in Days 6–15, it was switched on about 2 h before the measurements.

The measurements for the present work can be divided into two major parts. In the first part, i.e. from Days 1 to 15, ^{220}Rn and ^{222}Rn measurements were only taken daily from 20:00 to 24:00. The objective was to compare the levels of ^{220}Rn and ^{222}Rn in sealed and unsealed conditions. During the 15 days, the room was kept in sealed conditions except from 22:00 to 24:00 every day, which is a simulation of realistic situations. In the second part, i.e. from Days 16 to 25, ^{220}Rn and ^{222}Rn measurements were taken 24 h a day to obtain the diurnal variations during different sealed

Table 1
Definition of sealing conditions

Sealing condition	Operation of air conditioner	Operation of dehumidifier	Windows and door
A	No	No	Closed
B	No	Yes	Closed
C	Yes	No	Closed
D	Yes	Yes	Closed
E	No	No	Open

Table 2
Sampling schedule

Day	Measurement	Condition of the room
1–5	*RAD7*: 20:00–24:00 every day *Q-Trak*: round the clock starting from 20:00 of Day 1	Door/windows closed except 22:00-24:00 every day
6–10		Door/windows closed except 22:00–24:00 every day Dehumidifier operated during 18:00–22:00 every day
11–15		Door/windows closed except 22:00–24:00 every day Air-conditioner operated during 18:00–22:00 every day
16–17	*RAD7 and Q-Trak*: round the clock starting from 08:00 of Day 16	Door/windows closed except 22:00–24:00 every day
18–19		Door/windows closed except 22:00–24:00 every day Dehumidifier operated when door/windows closed
20–21		Door/windows closed except 22:00–24:00 every day Air-conditioner operated when door/windows closed
22–23		Door/windows closed except 22:00–24:00 every day Air-conditioner and dehumidifier operated when door/windows closed
24–25		Door/windows opened round the clock

conditions and the unsealed condition. Similar to the first part, the door and the windows were kept open during 22:00 to 24:00 from Days 16 to 23, while the door and windows were kept open for 24 h during Days 24–25. At other times, the room was kept in sealed conditions with or without the operation of the dehumidifier and/or the air-conditioner. The sampling schedule is summarized in Table 2. In addition, 16 test cycles described above were conducted to determine the correction factor for spill-overs from Window C during ^{220}Rn measurements.

3. Results and data analysis

3.1. Correction factor for ^{220}Rn *measurements*

The correction factor for ^{220}Rn measurements (R) was obtained from 16 test cycles to be 0.082 ± 0.026 (range: 0.04–0.12), which means that about 8% of counts in

Window C will spillover to Window B. This correction factor was used to correct all results of ^{220}Rn measurements.

3.2. Correlation among measured parameters

The five parameters obtained, namely ^{220}Rn concentration (Bq m^{-3}), ^{222}Rn concentration (Bq m^{-3}), CO_2 concentration (ppm), temperature (°C) and relative humidity (%) were analyzed to investigate their interdependence. In the present work, a total of 150 sets of data of the above parameters were obtained. From Days 1 to 15, 2 sets of data were obtained daily, while 12 sets of data were obtained daily thereafter. Each set of data contains the 2-h averages of the five parameters. The correlation coefficients of the following combinations were calculated: ^{220}Rn concentration with ^{222}Rn concentration, CO_2 concentration, temperature and relative humidity, ^{222}Rn concentration with CO_2 concentration, temperature and relative humidity.

In addition to the five measured parameters, the daily atmospheric pressure data (in Pa) were obtained from Hong Kong Observatory. Additional correlation tests were conducted to check the correlation between the daily atmospheric pressure and the ^{220}Rn or ^{222}Rn levels during 22:00–24:00 from Days 1 to 25. There were in total 25 sets of data available for this additional parameter.

The significance for correlations was tested with the Fisher's Z transformation of the correlation coefficient (r), which produces a statistical variable $Z = 0.5\ln[(1 + r)/(1 - r)]$ that distributes normally. The Z scores were then checked by the confidence level of the normal distribution. When a 95% confidence level is adopted, Z needs to be greater than 1.64 to show a significant correlation.

3.3. ^{220}Rn and ^{222}Rn measurements

Although RAD7 can provide ^{220}Rn and ^{222}Rn levels over cycles as short as 1 min, the test cycle was set to 2 h to obtain a greater number of counts in Windows A and B to provide better statistics. A total of 150 sets of 2-h average of ^{220}Rn and ^{222}Rn levels were collected during the sampling periods.

Two groups of results for ^{220}Rn and ^{222}Rn measurements are presented. In the first part of the measurements (i.e., Days 1–15) the main objective was to identify the differences of ^{220}Rn and ^{222}Rn levels for different sealing conditions. For this purpose, a part of the results in the second series of measurements (i.e., results for 20:00–24:00 of Days 16–23) were also included. A total of 46 sets of data from 23 days are obtained, which are summarized in Table 3. From these results, it is seen that ^{220}Rn levels did not vary so much for different sealing conditions. The ^{220}Rn levels were all maintained at around 10 Bq m^{-3}. On the other hand, ^{222}Rn levels varied significantly, showing the lowest values under condition E and the highest under condition A.

The second part of the measurements (i.e., continuous measurements) started from Day 16 and were completed on Day 25. 12 sets of 2-h averages were obtained daily for 10 days and there were in total 120 sets of data. Five sealing conditions were set for the 10-days of continuous measurements, being 2 days for each condition from A to E.

Table 3
^{220}Rn and ^{222}Rn levels

Day	Time	Sealing condition	Concentration ($Bq\ m^{-3}$) [average]	
			^{220}Rn	^{222}Rn
1–5, 16–17	20:00–22:00	A	0–32 [12]	220–474 [320]
6–10, 18–19	20:00–22:00	B	0–28 [10]	162–346 [261]
11–15 20–21	20:00–22:00	C	6–28 [14]	112–187 [150]
22–23	20:00–22:00	D	9–12 [11]	112–122 [117]
1–23	22:00–24:00	E	0–34 [11]	20–87 [45]

Table 4
Summary of results for continuous measurements of ^{220}Rn and ^{222}Rn levels

Day	Time	Sealing condition	Concentration ($Bq\ m^{-3}$) [average]	
			^{220}Rn	^{222}Rn
16–17	24 h starting from 08:00	A	0–41 [13]	44–474 [298]
18–19		B	0–37 [14]	36–390 [199]
20–21		C	0–31 [12]	20–185 [119]
22–23		D	0–28 [11]	41–262 [132]
24–25		E	0–22 [9]	9–57 [29]

The results are summarized in Table 4. It can be seen that the ^{220}Rn and ^{222}Rn levels are similar to those shown in Table 3.

A total of 46 sets of ^{220}Rn data and 46 sets of ^{222}Rn data collected during Days 1–23 were used for *t*-tests. The data were categorized into 5 sealing condition groups. Each of the conditions A–C contains 7 sets of data, condition D contains 2 sets, and condition E contains 23 sets. There are in total 10 combinations of conditions for both ^{220}Rn and ^{222}Rn. In all *t*-tests, 95% confidence levels were adopted. The null hypothesis can be rejected if the *p*-value is found to be less than 0.025. The results are tabulated in Table 5.

Table 5
Results of *t*-tests for ^{220}Rn and ^{222}Rn levels (Days 1–23)

Comparison of conditions	*p*-Value	
	^{220}Rn	^{222}Rn
A–B	0.70	0.20
A–C	0.76	0.0022
A–D	0.72	0.0011
A–E	0.84	0.0002
B–C	0.47	0.0042
B–D	0.89	0.0016
B–E	0.79	0.0002
C–D	0.41	0.0380
C–E	0.53	0.0000
D–E	0.80	0.0077

Table 6
Results of *t*-tests for ^{220}Rn and ^{222}Rn levels (Days 16–25)

Comparison of conditions	*p*-Value	
	^{220}Rn	^{222}Rn
A–B	0.87	0.0024
A–C	0.57	0.0000
A–D	0.40	0.0000
A–E	0.12	0.0000
B–C	0.44	0.0001
B–D	0.29	0.0008
B–E	0.069	0.0000
C–D	0.77	0.27
C–E	0.26	0.0000
D–E	0.40	0.0000

It is clearly shown in Table 5 that all *p*-values of ^{220}Rn and the *p*-values of ^{222}Rn in A–B and C–D combinations were much greater than 0.025. The levels of ^{220}Rn were not significantly different among different sealing conditions and the levels of ^{222}Rn were not significantly different for A and B. On the other hand, all *p*-values of ^{222}Rn, except those for A–B and for C–D combinations, were less than 0.025, so the ^{222}Rn levels for these combinations are significantly different. From the *t*-test, ^{222}Rn levels for both A and B were significantly higher than those for C, D and E; and those for C and D significantly higher than those for E.

Similarly, *t*-tests were performed for all the ^{220}Rn and ^{222}Rn data collected during Days 16–25. A total of 120 sets of ^{220}Rn data and 120 sets of ^{222}Rn data were used. The results are summarized in Table 6. Again, all *p*-values of ^{220}Rn comparisons were found to be much greater than 0.025. In addition, the *p*-value of ^{222}Rn comparison for C–D was also found to be much greater than 0.025, while that for A–B was barely smaller than 0.025. Therefore, ^{220}Rn levels were not significantly different amongst the different sealing conditions and the ^{222}Rn levels were not significantly different between C–D and only barely different between A and B.

3.4. CO_2, temperature, relative humidity and pressure

Over 7000 sets of data of 5-min averages of CO_2, temperature, relative humidity and pressure were collected during the sampling periods. The results for these three parameters are summarized in Table 7. There was a sudden humidity rise in the afternoon of Day 23, because the dehumidifier automatically stopped when its condensate container was full. The atmospheric pressure levels were not fluctuating very much during the sampling period. The highest pressure was 1.022×10^5 Pa, recorded on Day 8, while the lowest pressure was 1.012×10^5 Pa, recorded on Day 24. To identify the parameters which might be related to the levels of ^{220}Rn and ^{222}Rn, the correlation coefficients of the relationships were determined and their significance was evaluated by the Fisher's Z transformation. The results are tabulated in Table 8. Since all Z scores were between -1.64 and 1.64, no significant correlations were found between ^{220}Rn and ^{222}Rn concentrations and these parameters in this work.

3.5. Air exchange rate

The air exchange rates under sealed conditions of the room were determined using the 5-min averages of CO_2 and the indoor pollution model suggested by ASTM (1993) which can only apply for sealed conditions. Fig. 1 shows five duplex peaks of CO_2

Table 7
Results of CO_2 level, temperature, and relative humidity

Day	CO_2 Level (ppm) [average]	Temperature (°C) [average]	Relative humidity (%) [average]
1–5	402–1166 [547]	19.3–25.2 [21.1]	69.6–87.3 [75.4]
6–10	405–1239 [555]	19.4–26.3 [22.1]	51.3–81.1 [68.5]
11–15	406–1239 [591]	19.2–26.3 [22.8]	49.5–87.3 [74.3]
16–17	427–968 [546]	24.1–26.4 [25.1]	68.9–78.7 [73.4]
18–19	415–1116 [532]	24.8–30.4 [28.9]	36.7–72.1 [43.4]
20–21	389–878 [458]	18.9–25.9 [19.9]	38.9–83.4 [68.0]
22–23	368–872 [480]	18.8–24.7 [20.2]	40.8–93.4 [52.9]
24–25	406–475 [473]	26.2–27.1 [27.2]	66.1–78.2 [78.8]

Table 8
Correlations among measured parameters

Correlation	Correlation coefficient (r)	Z
^{220}Rn–^{222}Rn	0.109	0.109
^{220}Rn–CO_2	0.136	0.137
^{220}Rn–Temperature	0.064	0.064
^{220}Rn–Relative Humidity	– 0.088	– 0.088
^{222}Rn–CO_2	0.124	0.125
^{222}Rn–Temperature	0.11	0.110
^{222}Rn–Relative Humidity	– 0.302	– 0.312
^{220}Rn–Pressure	– 0.034	– 0.034
^{222}Rn–Pressure	– 0.397	– 0.420

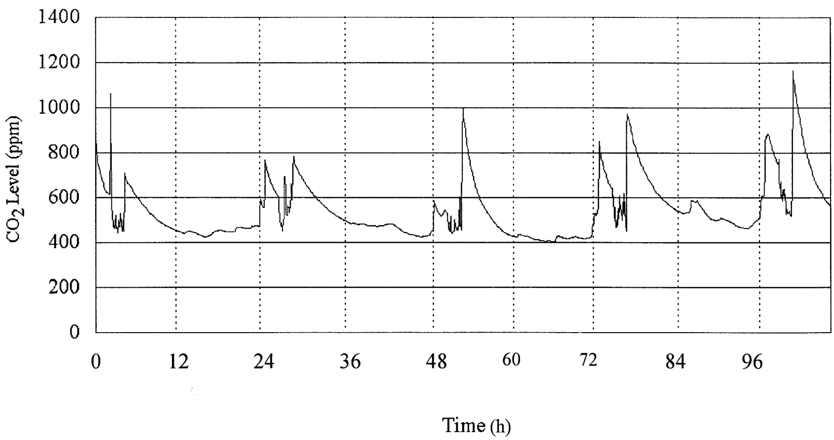

Fig. 1. Time variation of CO_2 levels for Days 1–5.

level for Days 1–5. The peaks recorded the occupation of the room by a person for operation of the instrument, once before the start of measurement and once at the end. As no occupancy was recorded after the second peak, the CO_2 concentration decreased towards the outdoor level of about 400 ppm. The CO_2 data between 1:00–5:00 were used to determine the air exchange rates (hour^{-1}) for Days 1–23, which are shown in Table 9.

The air exchange rates for conditions A–D were defined as follows: that for condition A as the average for all the data for Days 1–5 and Days 16–17, while those for conditions B–D as values calculated only for the periods of Days 18–19, Days 20–21 and Days 22–23, respectively, since the dehumidifier and/or air conditioner was in operation when the air exchange rates in these periods were determined. As mentioned above, the air exchange rate for condition E could not be determined by this method. The air exchange rates were found to be quite different amongst the different sealed conditions. The average air exchange rates for conditions A, B, C and

Table 9
Results for air exchange rate per hour (ACH) (r^2 is the square of the correlation coefficient)

Day	r^2	ACH (h^{-1})	Day	r^2	ACH (h^{-1})
1	0.999	0.18	13	0.996	0.11
2	0.999	0.15	14	0.998	0.17
3	0.991	0.34	15	0.987	0.22
4	0.996	0.18	16	0.992	0.16
5	0.992	0.26	17	0.997	0.14
6	0.986	0.17	18	0.996	0.27
7	0.976	0.17	19	0.973	0.28
8	0.993	0.24	20	0.979	0.44
9	0.991	0.18	21	0.914	0.26
10	0.987	0.15	22	0.985	0.39
11	0.991	0.18	23	0.964	0.26
12	0.955	0.10			

D were estimated to be 0.20 ± 0.07, 0.27 ± 0.01, 0.35 ± 0.13, and 0.33 ± 0.09 h^{-1}, respectively.

The results are as expected. Condition A was the stuffiest because there was no air current at all in the room. Condition B was found less stuffy than condition A. The running dehumidifier enhanced the air current in addition to the reduction of the relative humidity, which increased the infiltration rate of outdoor air and thus the air exchange rate. The air exchange rates for conditions C and D were very similar to each other. The operation of the air conditioner enhanced the difference between the indoor and outdoor pressure and thus the air exchange rate.

On the other hand, since ^{220}Rn has a short half-life, its concentration is confined to small distances from walls (about 20 cm) for static conditions, but tends to even up with turbulent flows (Ma, Yonehara, Aoyama, Doi, Kobayashi & Sakanoue, 1997). In this way, the ^{220}Rn concentrations at positions away from the walls will increase for a higher air exchange rate. This effect only applies to ^{220}Rn but not ^{222}Rn due to the much shorter half-life of the former. This effect will counterbalance the dilution effect, which explains the comparable ^{220}Rn levels for different conditions.

4. Conclusions

In this work, a bedroom was selected for detailed measurements of ^{222}Rn and ^{220}Rn concentrations under different conditions. The conclusions are as follows:

(1) Four sealed conditions and one unsealed condition were arranged to provide various environmental conditions. It was found that natural ventilation is the most efficient way to lower the ^{222}Rn levels, while air conditioning is the next most efficient method. Dehumidification provides only a marginal reduction of ^{222}Rn levels. The ^{220}Rn concentrations are not affected by natural ventilation, air

conditioning nor dehumidification. These are reasonable observations because a higher air exchange rate introduces more outdoor air with low ^{222}Rn concentration into the inside of the flat and thus lower the indoor ^{222}Rn concentrations. The exchange rates in conditions A–D were found to be 0.15, 0.28, 0.35, and 0.33 hr^{-1}, respectively.

(2) CO_2 concentration, temperature and relative humidity were measured and atmospheric pressure data were obtained in order to identify their possible relationships with the ^{222}Rn and ^{220}Rn concentrations. No significant correlations were found between the ^{222}Rn and ^{220}Rn concentrations and these parameters in this work.

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