Applied Radiation and Isotopes 179 (2022) 109991

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Radiological assessment subjected to outdoor radon and thoron concentrations and terrestrial gamma radiation measurements in Perak Malaysia

Habila Nuhu [a,d,*], Suhairul Hashim [a,b], Mohamad Syazwan Mohd Sanusi [a], Muneer Aziz Mohammed Saleh [c]

[a] Department of Physics, Faculty of Science, Universiti Teknologi Malaysia, Johor, 81310, UTM, Skudai, Johor, Malaysia
[b] Ibnu Sina Institute for Scientific and Industrial Research (ISISIR), Universiti Teknologi Malaysia, Johor, 81310, UTM, Skudai, Johor, Malaysia
[c] Nuclear Engineering Programme, School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia
[d] Department of Science, School of Science and Technology, Plateau State Polytechnic Barkin Ladi, PMB 2023, Bukuru, Jos Plateau State, Nigeria

ARTICLE INFO

Keywords:
Activity concentration
Effective dose
Outdoor air
Radiation
Dose rate

ABSTRACT

The concentrations of radon, thoron and terrestrial gamma radiation were measured to evaluate the outdoor effective dose. The outdoor radon activity concentration ranged from 5.79 to 5110 ± 46.36 Bq m^{-3}, with a mean of 320.03 Bq m^{-3} which is higher than the EPA level of 14.8 Bq m^{-3}. The range of the thoron activity concentration outdoor was from 0.00 to 4226.7 ± 58.5 Bq m^{-3}, with a mean of 226.1 Bq m^{-3} which was above the UNSCEAR recommended level of 10 Bq m^{-3}. The terrestrial gamma radiation dose rates range was from 98.31 to 3769.71 nGy h^{-1} with a mean of 446.27 nGy h^{-1}. The effective dose contribution from radon exposures in the study was estimated to be 3.2 ± 0.5 mSv y^{-1} is about 84% total annual effective dose received by the population in those areas. The estimated thoron and gamma dose contributions (15%, and 1% respectively) were not significant. The outdoor doses for thoron and gamma were lower than the ICRP (2007) value of 1 mSv. The total annual outdoor effective dose with an occupancy factor of 1825 h (5 h day^{-1}) was estimated to be within the range of 0.30–551.41 ± 0.65 mSv, with a mean of 3.75 mSv which is a little higher than the world average of 2.4 mSv.

1. Introduction

Exposure of human beings to ionizing radiation from natural sources is a continuing and inescapable feature of life on earth. In daily living, people are exposed to naturally occurring radon gas present in the atmosphere. The most common isotopes of radon are radon (^{222}Rn) and thoron(^{220}Rn). Both are colorless, odorless, chemically inert, radioactive gases that are found at varying concentrations in outdoor air (UNSCEAR, 2006). ^{222}Rn is a product of Ra-226 (radium) in the Uranium (^{238}U) decay series. The abundances of the natural occurrence of ^{238}U in rocks and soils cause different ^{222}Rn radioactivity levels in the air. The ^{222}Rn concentrations in the air are measured in the number of radioactive decays per second per cubic meter of air (Bq m^{-3}) (Russell and Bradley, 2015). The latter isotope, ^{220}Rn is a daughter of Ra-228 from the thorium (^{232}Th) decay series. ^{232}Th also occurs naturally in the earth's crust, thus is responsible for ushering ^{220}Rn to the air in varying concentrations. Because, ^{222}Rn and ^{220}Rn are from different radioactive decay chains, their ratio or that of their decay products depends on the ratio of ^{238}U and ^{232}Th in rocks and soils of a location (UNSCEAR, 2000).

The determination of the outdoor concentration of ^{222}Rn, ^{220}Rn, and their decay products in the lower layers of the atmosphere is not easy, because of the influence of atmospheric factors (Place, time, height above the ground, and meteorological conditions). The determination of the outdoor concentration levels of ^{222}Rn and ^{220}Rn also provides a baseline for indoor levels respectively (UNSCEAR, 2006). Extensive studies have been done on indoor ^{222}Rn activity concentration and the associated health risks (UNSCEAR, 2006). Meanwhile, data on ^{220}Rn activity in the study area is scanty from literature, which could be because of its short half-life (56s). However recent studies have shown that ^{220}Rn can also be a potential health risk at ^{232}Th rich locations, thus making its determination important (UNSCEAR, 2006; Zunic et al., 2009). Large volumes of air with a high concentration of ^{222}Rn and

* Corresponding author. Department of Physics, Faculty of Science, Universiti Teknologi Malaysia, Johor, 81310 UTM, Skudai, Johor, Malaysia.
E-mail address: habilanuhu@yahoo.com (H. Nuhu).

https://doi.org/10.1016/j.apradiso.2021.109991
Received 8 March 2021; Received in revised form 3 May 2021; Accepted 19 October 2021
Available online 23 October 2021
0969-8043/

^{220}Rn releases into the outdoor atmosphere could cause high health risks to the public, as they eventually enter indoors (Ramola et al., 2008; UNSCEAR, 2000).

The world annual average of effective dose is estimated to be of the order of 2.4 mSv out of which 1.1 mSv is from the inhalation of ^{222}Rn and its decay daughters which are alpha emitters (Durrani and Ilic, 1997; UNSCEAR, 2006). Generally, the dose rate due to occupancy outdoor is less compared to those indoor. Nevertheless, outdoor data are equally important for the estimation of doses to humans, particularly in a region with high naturally occurring radiation (UNSCEAR, 2006). Our study location is to a great extent rich in both ^{238}U and ^{232}Th which are the parent radionuclides of both ^{222}Rn and ^{220}Rn respectively. Thus, because of the long half-life of the parent radionuclides, ^{222}Rn and ^{220}Rn would always be ushered into the atmosphere (Nursama et al., 2013). In the study area, the measurement of ^{222}Rn and ^{220}Rn in outdoor air is limited.

The goal of our measurement is to determine the ^{222}Rn and ^{220}Rn concentration in outdoor air, as well as the terrestrial gamma radiation dose rate and estimate the corresponding doses received by inhabitants and assess the significance of any health hazards. The results of this study will benefit in establishing the database of outdoor radiation exposure issues, especially to inhalation of ^{222}Rn and ^{220}Rn in the study area.

2. Materials and method

2.1. The study area and sampling

The study area is located between latitudes 3.50° to 5.35° North, and longitudes 100.00° to 101.75° East, in Northern Peninsular Malaysia, within an area of 21,006 km2 (Director of National Mapping, 1989; Nursama et al., 2013). The area is located on the main granite range of Peninsular Malaysia and is divided into four major geological contexts as follows: Quaternary (Comprise of marine and continental deposits, such as clay, silt, sand, peat with minor gravel and basalt of early Pleistocene age) covering 24% of the study area; Triassic-Jurassic (Sedimentary rocks of marine origin and form a wide belt. They entail shale, mudstone, siltstone, sandstone, and minor limestone lenses. Interbeds of tuff are common within this openly crumpled sequence) which covers 15% of the study area; Silurian (consists of tightly compressed consolidated shale, slate, argillite, metasandstone, phyllite, and schist) covering 16% of the study area, and Intrusive rocks (Mainly undifferentiated igneous rocks of granitic origin) which cover 45% of the study area (Director-General of Geological Survey and Malaysia, 1988; Omar et al., 2006). Seventy (70) locations were sampled based on the geological formations surrounding the sampling site, to investigate the variability of ^{222}Rn and ^{220}Rn in outdoor air.

2.2. Measurement of ^{222}Rn and ^{220}Rn concentration in the air

Fig. 1 displays the setup of the RAD 7 detector which is an alpha detector that was used for the measurement of ^{222}Rn and ^{220}Rn concentration in outdoor air in the study area. It has a very low intrinsic background of 0.2 Bq m^{-3} and was calibrated by the manufacturer Durridge company in the USA, The detector is designed to measure in the range of 4 and 750,000 Bq m^{-3} (Durridge Company RAD7 User Manual, 2015) The procedure involves setting the RAD 7 to THORON protocol. In the THORON protocol, the detector measures both ^{222}Rn and ^{220}Rn concentrations. This protocol uses 5-min in four (4) cycles and prompts the RAD7 to print both ^{222}Rn and ^{220}Rn concentrations (in pCi L^{-1} or Bq m^{-3} depending on the unit chosen) at the end of every cycle. THORON protocol also directs the automatic pump setting to continuous pump operation to ensure a fresh sample. For ^{222}Rn, the first two cycles should be ignored while the ^{220}Rn reading reaches equilibrium. The ^{220}Rn reading will be valid for all except for the first cycle (Durridge Company RAD7 User Manual, 2015). For accurate ^{220}Rn measurement, the same sample taking configuration/setting should be used always. Many difficulties impede the accurate measurement of ^{220}Rn gas. For example, the presence of ^{222}Rn gas (often found together with ^{220}Rn) can interfere with the measurement. The short half-life of ^{220}Rn gas makes some aspects of the measurement easier (quickly and in rapid succession) but makes the sampling method a critical issue because of its variation, depending on air motion (Durridge Company RAD7 User Manual, 2015).

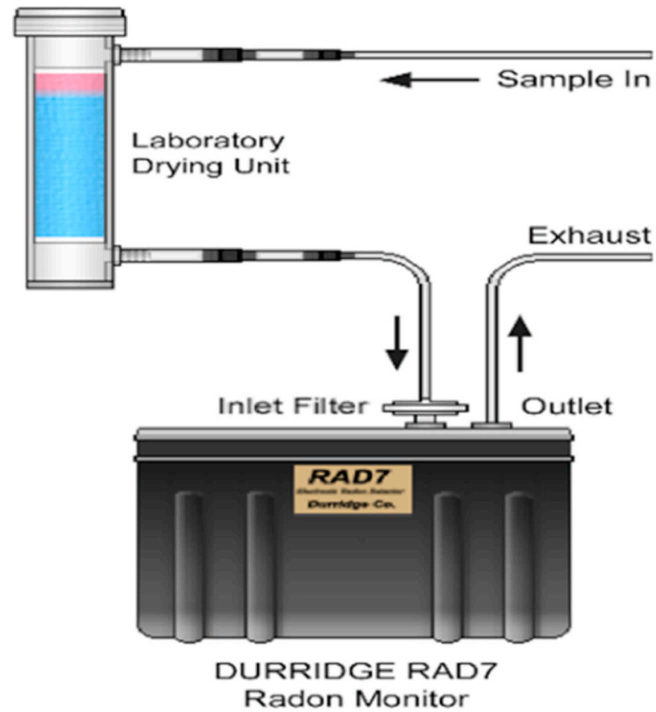

Fig. 1. RAD7 Detector (Durridge company RAD7 User Manual, 2015).

2.3. Estimation of the annual effective dose of ^{222}Rn and ^{220}Rn

The estimation of annual effective dose (H_{air}) from the inhalation of ^{222}Rn and ^{220}Rn is carried out using equation (1), based on the mean activity concentration as follows:

$$H_{air} = C_r \times F_r \times T \times DCF_r \times 10^{-6} \quad (1)$$

where: H_{air} is an effective dose. C_r is the mean ^{222}Rn or ^{220}Rn activity concentration (Bq m^{-3}). F_r is the equilibrium factor outdoors (for radon and progeny the equilibrium factor is 0.6–0.8 of which 0.6 was used in this paper, while the equilibrium factor for thoron is 0.003), T is the time of exposure in hours with an average of 7000 h yr^{-1}. DCF_r is the dose conversion factor [9 nSv Bq^{-1} equivalent equilibrium concentration (EEC) h m^{-3} for ^{222}Rn and 40 nSv Bq^{-1} EEC h m^{-3} for ^{220}Rn] (ICRP, 1993; UNSCEAR, 2000a, 2006). These values were used in the estimation of annual effective dose (H_{air}) from the inhalation of ^{222}Rn and ^{220}Rn respectively.

2.4. Terrestrial gamma (γ) radiation dose (TGRD) measurement

The γ - dose rate was measured by using the Analogue Survey Meter Ludlum model 9. It is an ion chamber that reads in units of μR h^{-1} on a scale that ranges from 0 to 5. A switch selects between multipliers of 1, 01, 100, and 1000 of the scale reading, leading to detection ranges of 0–5, 0–50, 0–500, and 0–5000 μR h^{-1}. The survey meter has a provision that enables an audible indication of the detection of gamma radiation {George et al., 2006}. The γ - dose rate was measured at one (1) meter above the ground. At least 3 stable readings were taken at each sampling point and the average values converted into dose rate in the air (unit-nGy h^{-1}) by multiplying the measured exposure rate in μR h^{-1} into 8.7 (Martin et al., 2012). The geological background of each measurement was recorded to investigate the relationship between ^{222}Rn, ^{220}Rn, and geological features. The external gamma radiation dose rate outdoor was determined using equation (2) below.

$$H_{\gamma-rad}(mSv) = D\left(nGy\ h^{-1}\right)\ \times 8760\ h\ \times 0.2\ \times 0.7\ Sv\ Gy^{-1}\ \times\ 10^{-6} \quad (2)$$

where $H_{\gamma-rad}$ = effective dose, D = measured gamma dose rate, 0.2 = outdoor occupancy factor and 0.7 = conversion coefficient from absorbed dose in air to human effective dose equivalent (UNSCEAR, 2006).

The total outdoor effective dose is obtained from equation (3) below.

$$H_{Total} = H_{\gamma-rad} + H_{222Rn} + H_{220Rn} \quad (3)$$

where H_{Total} is the total annual effective dose, $H_{\gamma-rad}$ is the effective gamma radiation dose, H_{222Rn} is the effective radon dose and H_{220Rn} is the effective thoron dose, in outdoor air.

3. Results

3.1. ^{222}Rn activity concentration measurements result in outdoor air

Displayed in Fig. 2 is the histogram of the ^{222}Rn activity concentration in outdoor air and summarized in Table 1 is the descriptive statistics of the results of ^{222}Rn activity concentration measurements in outdoor air. The values of the ^{222}Rn concentration ranged from 5.79 to 5110 Bq m^{-3} with an arithmetic mean of 320.03 ± 46.36 and median of 67.2 Bq m^{-3} respectively. The mean value is higher than the USEPA recommended outdoor ^{222}Rn level of 14.8 Bq m^{-3} (0.4 pCi L^{-1}).

3.2. ^{220}Rn activity concentration measurements result in outdoor air

Elucidated in Fig. 3 is the Histogram of the activity concentration of ^{220}Rn distribution in outdoor air while displayed in Table 2 is a summary of the descriptive statistics of the ^{220}Rn activity concentration measurements. The results obtained were in the range of 0.00–4226.7 Bq m^{-3}. The arithmetic mean was 226.12 ± 58.5 Bq m^{-3}, with a median of 69.75 Bq m^{-3}. The mean ^{220}Rn concentration outdoor was higher than the UNSCEAR (2006) recommended value of about 10 Bq m^{-3} with a range of 1–100 Bq m^{-3}.

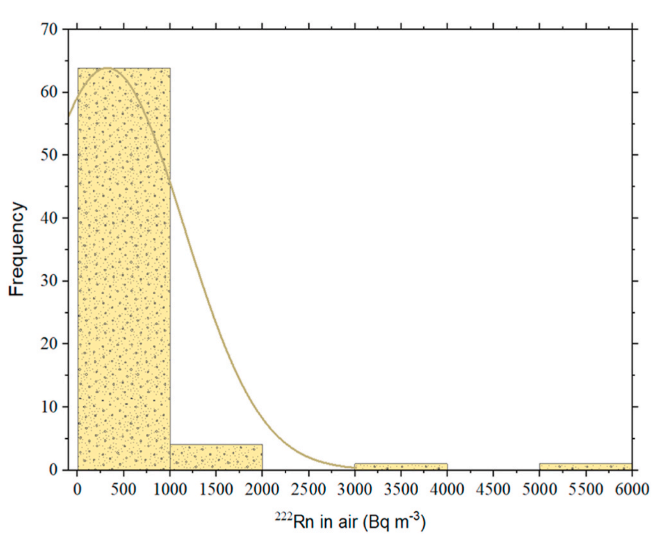

Fig. 2. Histogram of the data distribution of ^{222}Rn activity concentration in outdoor air.

Table 1
Descriptive statistics of ^{222}Rn concentration in the outdoor air.

Statistical Indicators	^{222}R in outdoor air (Bq m^{-3})
Number of Measurements	70
Arithmetic Mean	320.03 ± 46.36
Standard deviation	8.16
Median	67.2
Geometric mean	0.08
Range	5.79–5110

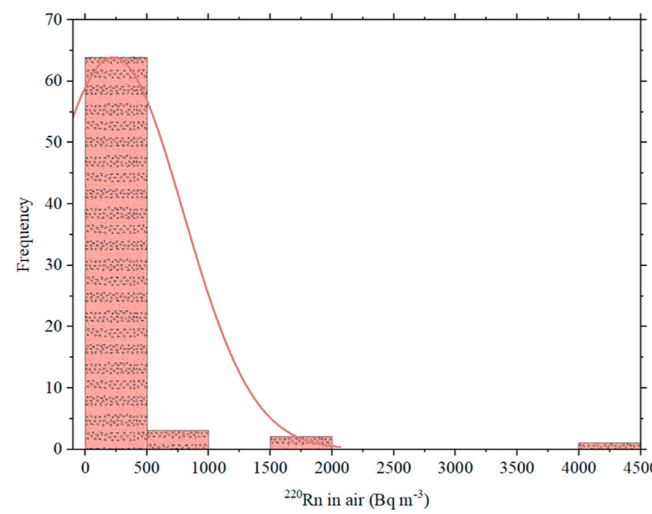

Fig. 3. Histogram of the data distribution of ^{220}Rn activity concentration in outdoor air.

Table 2
Descriptive statistics of ^{220}Rn concentration in the outdoor air.

Statistical Indicators	^{220}Rn in outdoor air (Bq m^{-3})
Number of Measurements	70
Arithmetic Mean	226.1 ± 58.5
Standard deviation	0.124
Geometric mean	0.084
Range	0.00–4226.7

3.3. Gamma dose rate results of the field measurements

Fig. 4 depicts the Histogram of the gamma dose rate in outdoor air while Table 3 displays the descriptive statistics of the gamma dose rate results of the field measurements. The range of the values was from 98.31 to 3769.1 nGy h^{-1}. The arithmetic mean was 446.27 ± 98.62 and median value of 217.5 nGy h^{-1} respectively, with a standard deviation of 825.1 nGy h^{-1}.

3.4. The outdoor annual effective doses for ^{222}Rn, ^{220}Rn, and gamma

The effective doses outdoor for ^{222}Rn, ^{220}Rn, were computed using equation (1), while the gamma effective dose and the total effective dose outdoor were obtained from equations (2) and (3) respectively. The result of the annual outdoor effective dose with an occupancy factor of 1825 h (5 h day^{-1}) is elucidated in Table 4. The estimated values were in the range of 0.30–51.41 mSv, with a mean of 3.75 mSv, which is higher than the world average of 2.4 mSv. The ^{222}Rn dose contributed most (84%) of the total effective dose outdoor of the study location. The ^{220}Rn and gamma dose contributions outdoor were visibly lower, 15%, and 1% respectively as displayed in Fig. 5. The outdoor doses for ^{220}Rn and gamma were lower than the ICRP (2007) value of 1 mSv, while the ^{222}Rn dose was higher than the ICRP value. The calculations assumed a

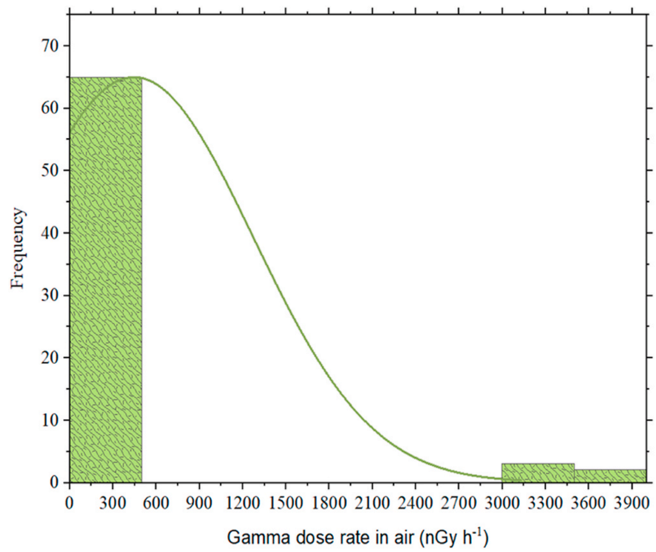

Fig. 4. Histogram of the gamma dose rate in outdoor air.

Table 3
Descriptive statistics of gamma radiation dose rate measurements in air.

Statistical Indicators	Gamma dose rate (nGy h^{-1})
Number of Measurements	70
Arithmetic Mean	446.27 ± 72.65
Standard deviation	825.1
Median	217.5
Geometric mean	29.58
Range	98.31–3769.71

Table 4
Estimated outdoor annual effective dose (H).

	Effective doses (mSv)	
	Range	Mean
$H_{(222Rn)}$	0.06–50.40	3.2 ± 0.5
$H_{(220Rn)}$	0.0–0.93	0.05 ± 0.02
$H_{(gamma)}$	0.12–4.62	0.55 ± 0.09
$H_{(Total)}$	0.30–51.41	3.75 ± 0.65

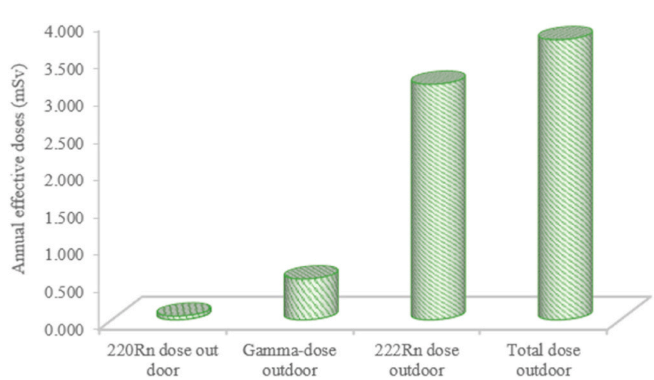

Fig. 5. Total annual effective dose for the study location.

uniform distribution of ^{220}Rn and ^{222}Rn which might not be the case due to the short half-life and environmental factors.

4. Discussion

The correlation between ^{222}Rn and ^{220}Rn from the results of the study is presented in a scatter diagram in Fig. 6. The following results were obtained from the regression equation: $R^2 = 0.90$, Intercept = 18.15, p = 0.01. The correlation coefficient R = 0.95 indicates a positive correlation of ^{222}Rn and ^{220}Rn in the air in the study area. The ratio of ^{222}Rn to ^{220}Rn concentration in the air tends towards a higher prevalence of ^{220}Rn. This was expected because the soil of the study area has been reported to be rich in ^{232}Th by Nursama et al. (2013).

The ^{222}Rn and ^{220}Rn activity concentrations in outdoor air from this study and different studies in Malaysia are compared in Table 5. The result of the mean ^{222}Rn activity reported in this study is higher than most of the radon levels reported in other parts of Malaysia, but it is lower than the one reported by Gillmore et al. (2005). The mean ^{220}Rn activity result reported here is very much higher than the one reported by Sulaiman et al. (1994). The high values can be attributed to the geological formation of the study area, which lies on the main granite range of peninsular Malaysia and covering 45% of the study location. According to UNSCEAR (2000), granites are relatively rich in radioactive minerals and contribute to higher background radiation. The results of this study form part of the baseline data for outdoor ^{222}Rn and ^{220}Rn measurements, because of the scanty data that are available from literature for the study area and Malaysia in general.

The outdoor ^{222}Rn and ^{220}Rn values for other countries and this study are compared in Table 6. The results of ^{222}Rn values for this study are seen to be extremely higher than those from Norway, China, and Romania. The mean ^{222}Rn result is generally higher than those reported for other countries. The ^{220}Rn results for this study are higher than those reported for Norway. The ^{222}Rn and ^{220}Rn results for this study are generally higher than those reported for other countries.

Generally, the doses outdoor for this study were mostly below the ICRP public exposure average dose constraint of 1 mSv y^{-1}. Spatial variations (UNSCEAR, 2000) were not considered in this paper, this could result in the values obtained being higher or lower. If the exposure time outdoors is reduced (2 h day^{-1}), the dose from the study area will be lower. However, if a higher equilibrium factor (F = 0.1) is used for the calculation, higher outdoor dose values will be obtained with elevated uncertainties. The equilibrium factor value has been published globally in the range of 0.003–0.1(Chen et al., 2011; UNSCEAR, 2006).

5. Conclusion

In this study, outdoor radiation has been assessed in Granitic regions of Perak state Malaysia. The results indicate that the mean ^{222}Rn and ^{220}Rn activity concentration outdoor in the study location were both significantly high, respectively. The high values could be credited to the

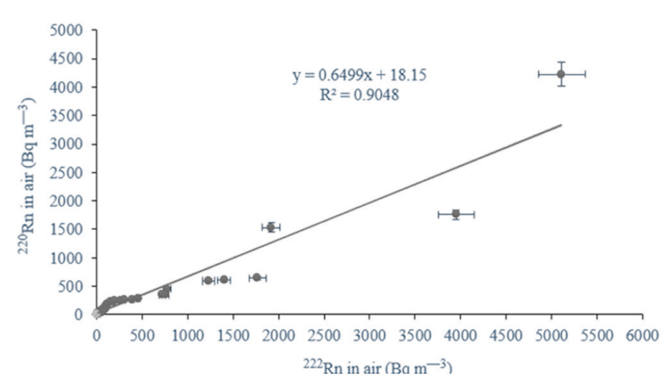

Fig. 6. Correlation between ^{222}Rn and ^{220}Rn in outdoor air.

Table 5
The comparison of radon and thoron concentration in outdoor air with previous measurements from different locations in peninsular Malaysia.

Location	^{222}Rn (Bq m^{-3})		^{220}Rn (Bq m^{-3})		References
	Range	Mean	Range	Mean	
Peninsular Malaysia		22		6.8	Sulaiman et al. (1994)
Niah, Sarawak	100–3075	608			Gillmore et al. (2005)
Peninsular Malaysia	8.51–41.07	–			Saat et al. (2010)
Sarawak, Sabah	–	Sarawak 1.5 Sabah 0.3			Sulaiman and Omar (2010)
Perak state Malaysia	5.79–5110	320.03	0.00–4226.7	226.1	(Present work)

Table 6
^{222}Rn and ^{220}Rn activity concentration in outdoor air in different countries.

Country	^{222}Rn (Bq m^{-1})		^{220}Rn (Bq m^{-1})		References
	Range	Mean	Range	Mean	
Norway	0–82	–	0–1786	–	Popic et al. (2012)
Romania	15–28	23.1	–	–	Calin et al. (2019)
Missouri, USA	11–111	–	–		Barros et al. (2015)
China	3–30	14			Wu et al. (2016)
Perak state Malaysia	5.79–5110	320.03	0.00–4226.7	226.1	(Present work)

bedrock of the study area, which is underlined with granite rocks covering 45% of the study location. Granites are relatively rich in radioactive minerals (UNSCEAR, 2000), and contribute to higher background radiation. The activity concentrations of ^{238}U and ^{232}Th from the study location were reported by Nursama et al. (2013) to be higher than the world average respectively. Ramli et al. (2016) also reported terrestrial gamma radiation doses from Perak state that were higher than the UNSCEAR 2000 reference values. Thus, high ^{222}Rn and ^{220}Rn activity concentrations outdoor in the study location were obtained as expected. The overall mean annual effective dose due to exposure outdoor 1825 h (5 h day^{-1}) was evaluated to be 3.75 ± 0.65 mSv y^{-1}. The results of the regression analysis hinted at a significant prevalence of outdoor ^{220}Rn.

Additional ^{222}Rn and ^{220}Rn concentration surveys are required to ascertain their overall contribution to an individual's outdoor exposure. The authors also recommend a seasonal study of the study area to cater for the variation of ^{222}Rn and ^{220}Rn due to atmospheric conditions, which will thus reduce uncertainties in the results of measurements.

Declaration of competing interest

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

Acknowledgment

We acknowledged the financial support from the Ministry of Higher Education Malaysia and Universiti Teknologi Malaysia through UTM-SHINE Signature Grant (No. 07G82 and 07G90). This study was also partially funded by a contract research DTD grant from Intech Scientific Sdn. Bhd. (R.J130000.7617.4C403). We would like to express our special gratitude to the Department of Mineral and Geoscience Malaysia under the Ministry of Energy and Natural Resources for approving our request to use the Geological Maps of Perak.

References

Barros, N., Field, D.W., Steck, D.J., Field, R.W., 2015. Comparative survey of outdoor, residential, and workplace radon concentrations. Radiat. Protect. Dosim. 163, 325–332. https://doi.org/10.1093/rpd/ncu185.
Calin, M.R., Ivan, C., Dragusin, M., Radulescu, I., 2019. Measurement and assessment of Radon gas concentration in IFIN-HH and ELI-NP using the active method. Rom. J. Phys. 64, 1–12.
Chen, J., Moir, D., Sorimachi, A., Tokonami, S., 2011. Characteristics of thoron and thoron progeny in Canadian homes. Radiat. Environ. Biophys. 50, 85–89. https://doi.org/10.1007/s00411-010-0338-5.
Director-General of Geological Survey, Malaysia, 1988. Map of Mineral Resources in Peninsular Malaysia ([Geological Survey Malaysia]).
Director of National Mapping, Malaysia, 1989. *Topographic Map Of Perak State* Ipoh Malaysia, Director of National Mapping.
Durrani, S.A., Ilic, R., 1997. Radon measurements BY etched track detectors: APPLICATIONS IN radiation protection. Singapore. In: Earth Science and the Environment, World Scienfic, first ed.
Durridge Company RAD7 User Manual, I., 2015. RAD7 Radon detector. User manual. http://www.durridge.com/documentation/RAD7.
George, X., Peter, C., Mark, F., 2006. Radiological Engineering Lab Manual. Spring, 2006.
Gillmore, G., Gilbertson, D., Grattan, J., Hunt, C., McLaren, S., Pyatt, B., Banda, R., Barker, G., Denman, A., Phillips, P., Reynolds, T., 2005. The potential risk from 222 radon posed to archaeologists and earth scientists: reconnaissance study of radon concentrations, excavations, and archaeological shelters in the Great cave of Niah, Sarawak, Malaysia. Ecotoxicol. Environ. Saf. 60, 213–227. https://doi.org/10.1016/j.ecoenv.2003.12.014.
ICRP, 1993. Publication 65: protection against ^{222}Rn at home and at work. Ann. ICRP 23, 32.
ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection, vol. 103. ICRP publication (Ann, ICRP).
Martin, A., Harbison, S., Beach, K., Cole, P., 2012. AN INTRODUCTION TO RADIATION PROTECTION, sixth ed. Hodder Arnold.
Nursama, H.A., Ramli, A.T., Sutisna, 2013. Activity concentration of 238U, 232Th, and 40K based on soil types in Perak state, Malaysia. Earth Sci. Res. 2, 122–127. https://doi.org/10.5539/esr.v2n2p122.
Omar, M., Hassan, A., Sulaiman, I., 2006. Radiation exposure during travelling in Malaysia. Radiat. Protect. Dosim. 121, 456–460. https://doi.org/10.1093/rpd/nc1060.
Popic, J.M., Bhatt, C.R., Salbu, B., Skipperud, L., 2012. *Outdoor ^{220}Rn, ^{222}Rn, and terrestrial gamma radiation levels: investigation study in the thorium rich Fen Complex, Norway*. J. Environ. Monit. 14, 193–201. https://doi.org/10.1039/c1em10726g.
Ramola, R.C., Choubey, V.M., Negi, M.S., Prasad, Y., Prasad, G., 2008. Radon occurrence in soil-gas and groundwater around an active landslide. Radiat. Meas. 43, 98–101. https://doi.org/10.1016/j.radmeas.2007.05.054.
Russell, K.H., Bradley, J.R., 2015. In: INTERMEDIATE PHYSICS for MEDICINE and BIOLOGY. Springer, fifth ed.
Saat, A., Hamzah, Z., Bakar, Z.A., Munir, Z.A., Sumari, S.M., Hassan, M., 2010. Some remarks on diurnal radon concentration at various locations in peninsular Malaysia. Journal of Nuclear and Related Technology 7, 49–57.
Sulaiman, I., Omar, M., 2010. Environmental radon/thoron concentrations and radiation levels in Sarawak and Sabah. Journal of Nuclear and Related Technology 7, 1–13.
Sulaiman, I., Omar, M., Hassan, A., 1994. Radon Concentrations in the Air in Malaysia. Malaysian Institute for Nuclear Technology Research (MINT), pp. 503–516.
UNSCEAR, 2000. UNSCEAR Report 2000: Sources and Effects of Ionizing Radiation (46 (A/55/46).). U. N. PUBLICATION.
UNSCEAR, 2006. Effects of Ionizing Radiation-Volume II. Scientific Annexes C, D, and E.
Wu, Q.F., Pan, Z.Q., Liu, S.L., Wang, C.H., 2016. Outdoor radon concentration in China. Nukleonika 61, 373–378. https://doi.org/10.1515/nuka-2016-0062.
Zunic, Z.S., Janik, M., Tokonami, S., Veselinovic, N., Yarmoshenko, I.V., Zhukovsky, M., Ishikawa, T., Ramola, R.C., Ciotoli, G., Jovanovic, P., Kozak, K., Mazur, J., Celikovic, I., Ujic, P., Onischenko, A., Sahoo, S.K., Bochicchio, F., 2009. Field experience with soil gas mapping using Japanese passive radon/thoron discriminative detectors for comparing high and low radiation areas in Serbia (balkan region). J. Radiat. Res. 50, 355–361. https://doi.org/10.1269/jrr.08098.