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Seasonal variation of indoor radon/thoron and their progeny levels in lesser-Himalayas of Jammu & Kashmir, India

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Abstract

In this investigation, the passive estimation of radon (Rn^{222}), thoron (Rn^{220}) and their progenies have been measured in the dwellings of Reasi district of Jammu & Kashmir for a period of 1 year. These estimations have been done with the help of latest developed single entry Pin-hole based dosimeters and progeny sensors based on deposition. The annual Equilibrium factors for ^{222}Rn, ^{220}Rn, and their progenies have been calculated separately for each dwellings The average annual effective dose was found to be 0.9 ± 0.2 mSv/y for ^{222}Rn, which is less than prescribed limit of ICRP. The results obtained indicate no vital health hazards because of exposure of Rn^{222}, Rn^{220} and their progenies.

Keywords Deposition based sensors · Seasonal variation · Equilibrium factor · Prescribed level · House type

Introduction

Due to natural radiations, inhalation of ^{222}Rn, ^{220}Rn, and their decay-products contribute about 50% of worldwide effective dose to the general population [1]. Various case–control investigations of residential exposure to ^{222}Rn have been completed in different parts of the globe to enhance our understanding of the health risks of ionizing radiations. These controlled instigations provide the knowledge of an enchanting the risk of lung malignant with the expansion in exposure of ^{222}Rn [2]. ^{220}Rn, then again, has not been concentrated in detail because of reference to lung cancer risk. Recently, ^{220}Rn contribution is only recognized in the radiation dose [1, 3, 4].

The Inhalation dose due to ^{222}Rn and its short-lived progeny are the primary source and about 40% of the total radiation dose taken by the overall populace is the significant supporter to the issue in the respiratory tract, lung malady and sensitive tissue of the skin and cause skin disease [5, 6]. In Past decades, an equilibrium factor (fixed value = 0.4) (ratio of Equilibrium Equivalent Concentration of the short-lived to the Concentration of Radionuclide) can be utilized to measure the decay products of the radionuclide's [7], but in now a days, direct $^{222}Rn/^{220}Rn$ progeny sensors (DTPS/DRPS) have been utilized in this work for the progeny estimation. Unattached part, size distribution, and equilibrium factor are also the essential influent parameters related to the lung dose computation [8].

Radon (^{222}Rn) and thoron (^{220}Rn) decay into various short-lived radio-isotopes. After the decay of ^{222}Rn, the recently framed radio-active nuclides react with environmental gases and vapors and form a cluster of particles of size around 1 nm, which are Un-attached particles. These unattached radio-active nuclides may likewise combine with existed aerosols presented in the atmosphere within a time period of 1–100 s, framing the attached particles [9]. The buildup of activity of ^{222}Rn gas and its short-lived alpha emitters inside enclosed spaces may increase the radiation risk to the public. This applies especially to work environments like, underground mines, visitor surrenders, and water supply offices which deal with high radon ground water sources. By and large, health risk by radon (^{222}Rn) is considerably more far-reaching than by thoron (^{220}Rn). Since thoron (^{220}Rn) has a short span of life, it is less capable than the ^{222}Rn to move from the point where it is shaped [10]. As an outcome, materials used for building purposes are the most regular source of ^{220}Rn exposure. Conversely,

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radon (^{222}Rn), have the half-life of 3.8 days can diffuse in the soil in excess of meter from where it's shaped. As the result, the under-ground structures are normally the essential wellspring of indoor ^{222}Rn [11].

The northern part of India is well studied both in terms of radioactive nuclides and ^{220}Rn/^{220}Rn concentrations [1, 3, 4, 12–15]. However, such studies in Jammu and Kashmir region are scarce. No such type of study of natural radioactivity or indoor ^{222}Rn, ^{220}Rn and progeny concentration has been so far reported in Reasi district of Jammu & Kashmir. The most important geographical features of the study area are Reasi inlier and various fault lines. The fault is generally accompanied with specific changes in geographical qualities, such as an extensive increment in the porosity and porousness of deformed shakes along this zone. Hence this part of Himalayas is very significant for the study of ionizing radiations. Several studies have been conducted that elevated concentration of radon gas in soil and groundwater could be signs of an imminent earthquake. It is believed that the radon is released from cavity and cracks as the Earth crust is strained prior to the sudden slip of an earthquake [16]. The Present investigation includes the estimations of ^{222}Rn, ^{220}Rn, and their progeny concentration by utilizing deposition based time integrating passive technique. We aimed to see the effect of various factors like types of dwellings, the seasonal effect on observed values.

Geography of study area

Reasi district lies between 33°05″ North latitude and 74°50″ East longitudes. The district imparts its limits to Udhampur district in the South, Ramban in the east, Shopian in the north and Rajouri in the west. The study zone is watershed of the waterway Chenab and its tributaries (Ans, Rudd, Plassu, Banganga, Pai, and Anji). It falls in the area which can be termed as Outer Hill Region, comprising the slopes and hills of Siwalik, Lesser Himalaya. The areas within the jurisdiction of the present study are hilly, comprising several off-shoots of great mountains inter-woven closely. The hills are of moderate heights and are surmountable. Though the areas in the north are very high, rising to the heights of above 4256 m but present study areas have a normal height ranging between 400 and 900 m. This region is on the southern side of the Pir Panjal. Out of four rock zones defined in the district according to Census report of 2011, the present study falls in two rock zones namely

1. The Reasi Limestone Inlier and
2. The Siwalik belt

Another important geographic feature of the study area is Reasi inliers which are about 80 km long and 8–20 km wide. In the Reasi fault, the Sirban arrangement is compared against the Tertiary sedimentary progressions of the Subathu—and the Murree formations in the northern part and against the Siwalik formation in the south [17]. Main boundary thrust and Medicott–Wadia thrust passes through this region, raising the interest of geologist across the world to study this area in detail especially after the devastating earth quake of 2005. Map of the study area is shown in Fig. 1.

Materials and methods

Selection of locations

The study area is a cross segment of Medlicott–Wadia Thrust (MWT) near its interaction with Chenab river. MWT is the real dynamic (active) out-of-succession thrusts in Himalaya. In this region, MWT is generally referred to as Reasi Thrust. The determination of houses in the examination zone was taken to considering that cover the significant part of the study locale as logically feasible. The efforts were taken to select the dwellings with all impacting factors, such as building materials (cement, mud, marble, etc.) and ventilation conditions. The measurements were made in 87 houses of 28 villages for investigation of seasonal varieties in radon/thoron and their alpha emitter concentrations. Whole year was partitioned into three periods of 4-month time frame as set 1 (November–March); set 2 (March–July); and set 3 (July–November), respectively. The primary points are to cover diverse kind's types of houses, with the goal that the reported results can be utilized as representative estimations of ^{222}Rn and ^{220}Rn in the locale considered for the study.

Measurement of ^{222}Rn/^{220}Rn concentrations

Measurements of ^{222}Rn and ^{220}Rn have been done by pinhole based ^{222}Rn/^{220}Rn discriminating cup by utilizing LR-115 Type II detector. The discriminating cup has the one passageway through which the gas goes to the primary chamber to be specific as "radon + thoron" chamber through a filter paper of 0.56 µm and then diffuses to 2nd part called "radon" chamber. LR–115 of size 3×3 cm^2 is lodged in both the chambers, such that LR-115 in primary chamber detects the tracks because of both ^{222}Rn and ^{220}Rn, while that in the 2nd part detects the tracks only because of ^{222}Rn gas. The reason is that only the radon gas enters the second chamber through 4 pin-holes of 2 mm in length and 1 mm in diameter made on a round circular disc owing to the very short half-life of ^{220}Rn (55 s). The alpha emanations from ^{222}Rn and ^{220}Rn creates the tracks on LR-115 detector lodged at the end of the primary chamber while tracks are enlisted on LR-115 which is at the top of the 2nd chamber due to the alpha's of ^{222}Rn only. The schematic graph of the pin-hole based ^{222}Rn/^{220}Rn discriminating cup is shown in Fig. 2.

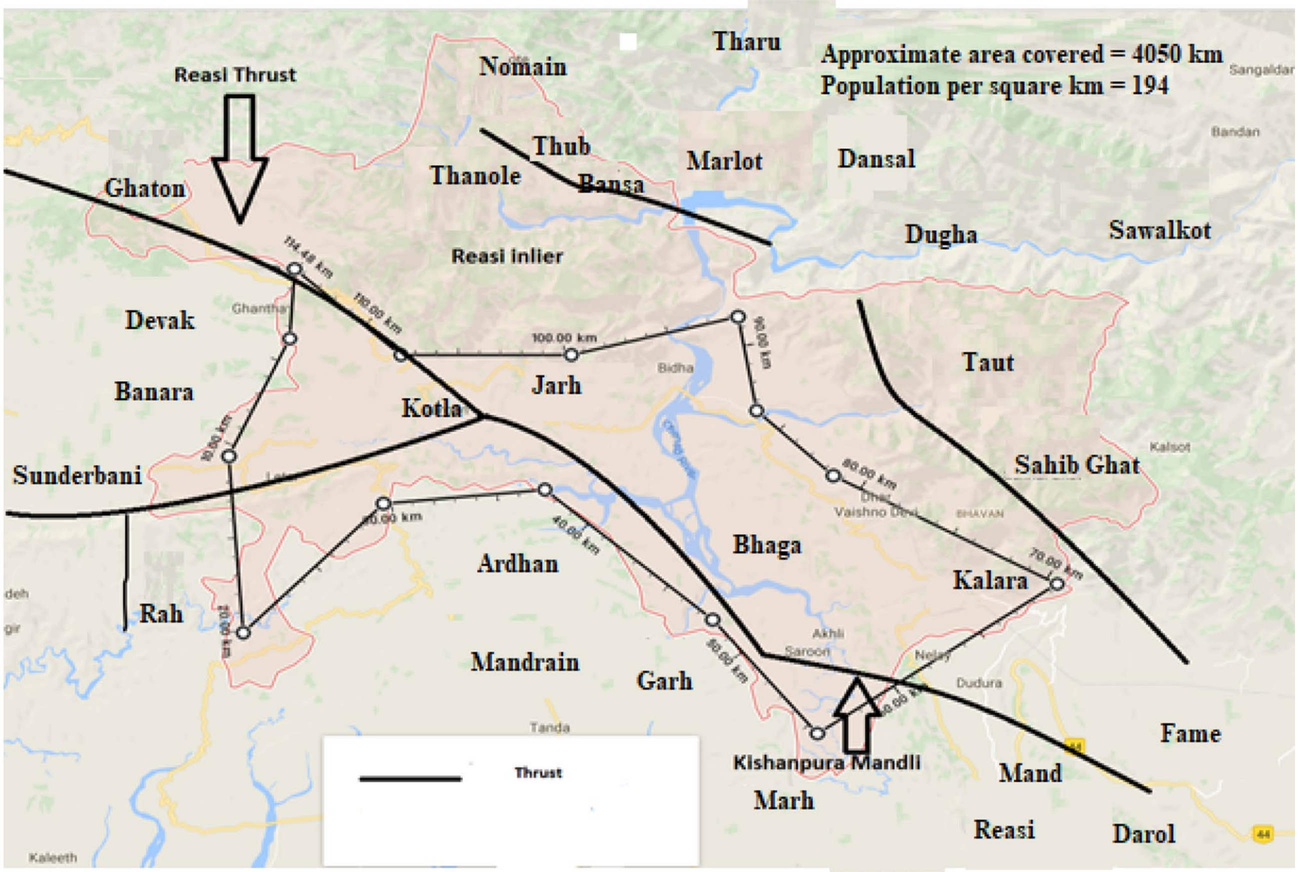


Fig. 1 Map showing the total area covered for the present study

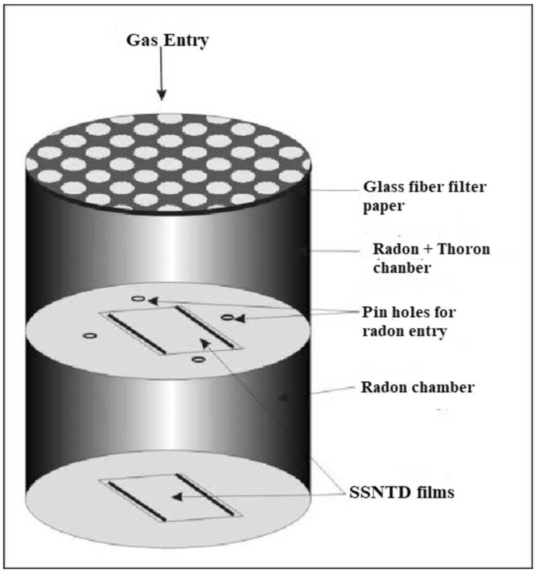


Fig. 2 Schematic diagram of pin-hole based dosimeter

The ^{222}Rn and ^{220}Rn concentrations in an indoor environment were figured as given by Sahoo [18]

$$^{222}\text{Rn}\ \left(\text{Bq/m}^3\right) = \frac{T_1 - B_1}{d - K_\text{R}} \tag{1}$$

$$^{220}\text{Rn}\ \left(\text{Bq/m}^3\right) = \frac{\left(T_2 - B_2\right) - \left(d \times 222_{\text{Rn}} \times K'_\text{R}\right)}{\left(d \times K_\text{T}\right)} \tag{2}$$

where T_1 and T_2 = tracks seen in ^{222}Rn and ^{222}Rn + ^{220}Rn chambers. B_1 and B_2 = back-ground track obtained for ^{222}Rn and ^{220}Rn. d = presentation time frame.

Measurement of attached/un-attached ^{222}Rn/^{220}Rn progeny

For the estimation of ^{222}Rn/^{220}Rn alpha emitters (progeny), LR-115 (12 μm cellulose nitrate covered on a 100 μm thick poly-ester base) SSNDTs based direct ^{222}Rn/^{220}Rn progeny sensor techniques were utilized for present examination. Samplers are made up of latent atomic track identifier (SSNDTs-LR) mounted with an absorber of suitable thickness for ^{220}Rn progeny, an absorber which is aluminium coated sheet of 50 µm thickness. It specifically recognizes just 8.78 MeV α-particles radiated from ^{212}Po. For radon descendants, absorber comprises with the suitable match of an aluminized coated sheet of 25 µm and cellulose nitrate of 12 µm of effective thickness 37 µm, which mostly recognizes α's produced from ^{214}Po (α energy = 7.69 MeV). For estimation of the only Attached ^{222}Rn and ^{220}Rn progeny to wire-mesh sensor were utilized as a part of the detached mode. Wire-mesh sensors comprise of direct sensors with a two hundred mesh wire-screen. The Un-attached part of the progenies is trapped on these wires and just attached part of the descendants get deposit on these sensors. The emitted alphas are deposited on wise caped progeny sensors is an estimation of the attached part of progeny concentration. Progeny concentration is ascertained by suspending DRPS/DTPS in the indoor environment far from entryway and windows [19].

Deployment details and analysis

The dosimeters both pinhole, as well as DTPS/DRPS along with WM-DTPS/WM-DRPS, were deployed in indoor environments of 28 villages in Reasi district, such that they were at least 1.5 m above the from any level and no less than 10 cm far from any of the surfaces for the time of 4 months. After the environmental exposure, the exposed detectors were retrieved and etched in 2.5 N NaOH solutions at 60 °C for 90 min without stirring [1, 4, 20]. The indicators were then cleaned in running water, dried, peeled and the track tallying was done using a spark counter with a voltage of 500 V. The tracks obtained from exposed films are converted into activity concentration using appropriate calibration factors.

Radon/thoron progeny

The total (attached + un-attached) and attached equilibrium equivalent concentration EEC$_{(A+U)}$ were computed using the relations given below [18, 21]:

$$\mathrm{EERC}(i,j)(\mathrm{Bqm}^{-}3) = \frac{T_{\mathrm{R}i,j} - T_{\mathrm{B}}}{D \times S_{\mathrm{R}i,j}} \tag{3}$$

$$\mathrm{EETC}(i,j)(\mathrm{Bqm}^{-}3) = \frac{T_{\mathrm{T}i,j} - T_{\mathrm{B}}}{D \times S_{\mathrm{T}i,j}} \tag{4}$$

where EERC(i,j) and EETC(i,j) = total equilibrium equivalent concentration of ^{222}Rn and ^{220}Rn progeny, i.e., i, and j stands for attached part. $T_{\mathrm{R}i,j}$ and $T_{\mathrm{T}i,j}$ = tracks (Tr cm^{-2}) produced on total and attached ^{222}Rn and ^{220}Rn progeny received in bare and wire-mesh sensors. T_{B} = back-ground received because of sensor timeframe of realistic usability and amid travel, D = the introduction of detector in given time frame (120 days). $S_{\mathrm{R}i,j}$ and $S_{\mathrm{T}i,j}$ are sensitivity coefficients for ^{220}Rn and ^{220}Rn progeny [22].

Since α energy of ^{212}Po (^{220}Rn progeny) is greater than the ^{214}Po (^{222}Rn progeny), the α's radiates from both ^{222}Rn and from ^{220}Rn progeny go through the absorber (37 µm) used in the DRPS. To compute exact ^{222}Rn progeny α's from DRPS, tracks of ^{220}Rn progeny must be subtracted using the following figures:

$$\mathrm{Tracks}\,\frac{\text{only Rn } P}{\mathrm{DRPS}} = \mathrm{Tracks}\,\frac{\mathrm{Total}}{\mathrm{DRPS}} - \frac{\eta_{\mathrm{RT}}}{\eta_{\mathrm{TT}}}\,\mathrm{Tracks}\,\frac{\mathrm{Total}}{\mathrm{DTPS}} \tag{5}$$

where η_{RT} and η_{TT} = track enrolment efficiencies for ^{220}Rn progeny in DRPS (0.01 ± 0.0004 for each α radiates from ^{220}Rn progeny) and that in DTPS (0.083 ± 0.0004 per each α's radiates from ^{220}Rn progeny [23], respectively

Calibration factors

The calibration factors used for the pinholes dosimeters are:

- For ^{222}Rn + ^{220}Rn section (K_{T}) (0.010 Tr cm^{-2} d^{-1}/Bq m^{-3}) and that for only ^{222}Rn section (K$_{\mathrm{R}}$) was 0.017 Tr cm^{-2} d^{-1}/Bq m^{-3} [18].
- For direct DTPS (direct thoron progeny sensors) and DRPS (direct radon progeny sensors), (0.94 Tr cm^{-2} d^{-1}/Bq m^{-3} and 0.09 Tr cm^{-2} d^{-1}/Bq m^{-3}) respectively [19].
- For wire–mesh capped DTPS and DRPS, the calibration factors were 0.33 Tr cm^{-2} d^{-1}/Bq m^{-3} and 0.04 Tr cm^{-2} d^{-1}/Bq m^{-3} respectively [20].

Un-attached equilibrium equivalent concentration and its un-attached part

The un-attached ^{222}Rn and ^{220}Rn progeny concentrations EC$_{(U)}$ have been figured out by just subtracting the attached EEC$_{(A)}$ from the total (attached + un-attached) concentration EEC$_{(A+U)}$ utilizing an expressions 6 and 7:

$$\mathrm{EERC}_{(U)} = \mathrm{EERC}_{(A+U)} - \mathrm{EERC}_{(A)} \tag{6}$$

$$\mathrm{EETC}_{(U)} = \mathrm{EETC}_{(A+U)} - \mathrm{EETC}_{(A)} \tag{7}$$

The unattached portion of potential alpha energy concentration (PAEC) of ^{222}Rn and ^{220}Rn progeny has been estimated utilizing the Eqs. (8) and (9) [1, 24]:

$$f_{\mathrm{p}}^{\mathrm{Rn}} = \frac{\mathrm{EERC}_{(U)}}{\mathrm{EERC}_{(A+U)}} \tag{8}$$

$$f_p^{Tn} = \frac{\mathrm{EETC}_{(U)}}{\mathrm{EETC}_{(A+U)}} \quad (9)$$

where f_p^{Rn} and f_p^{Tn} = unattached portions of ^{222}Rn and ^{220}Rn progeny, respectively

Equilibrium factor (EF)

The activity concentration of the short-lived radon progeny in air is always less than that of the radon gas. Equilibrium factor is the ratio of radon and its short lived radioactive decay products, which is a measure of the degree of disequilibrium between the radon gas and its progeny [11]. If the activity concentration of the short-lived radon progeny is equal to the activity concentration of the radon gas (i.e., secular equilibrium has been reached), then *F* would be 1. But practically, it is always less than 1 [12]. The variation of EF mainly depends on environmental conditions like humidity, sort of houses, and ventilation rate, etc. [25]. Therefore, EF for ^{222}Rn and ^{220}Rn have calculated as:

$$\mathrm{EF}_{Rn} = \frac{\mathrm{EERC}_{A+U}}{222_{Rn}}$$

$$\mathrm{EF}_{Tn} = \frac{\mathrm{EETC}_{A+U}}{220_{Rn}}$$

Annual effective dose

^{222}Rn and ^{220}Rn doses depend basically on ^{222}Rn progeny and the duration of exposure, the breathing rate and airborne molecules including the activity size dissemination of ^{222}Rn descendant's aerosol and the un-attached part [26]. The dose transformation factor given by UNSCEAR [7] has been utilized to evaluate the Annual Inhalation dosage. The annual effective dosage (Sv y^{-1}) for ^{222}Rn (AE_{Rn}) and that of ^{220}Rn (AE_{Tn}) were assessed utilizing the equations [7]:

$$\mathrm{AE}_{Rn} = \mathrm{EERC}_{(A+U)} \times \mathrm{DCF}_{Rn} \times \mathrm{OF} \times T_{Rn(exp)}$$

$$\mathrm{AE}_{Tn} = \mathrm{EETC}_{(A+U)} \times \mathrm{DCF}_{Tn} \times \mathrm{OF} \times T_{Tn(exp)}$$

where DCF_{Rn} (9 nSv y^{-1} Bq^{-1} m^{-3}) and DCF_{Th} (40 $nSvh^{-1}$ Bq^{-1} m^{-3}) = radon and thoron dose conversion factor, OF = indoor occupancy factor, and $T_{Rn(exp)}$ and $T_{Rn(exp)}$ = exposure span per year (7000 h y^{-1}) respectively

Annual inhalation dosage

The total Annual Inhalation dosage because of introduction of indoor ^{222}Rn, ^{220}Rn and their progenies has been determined by utilizing the following expression [7]

$$D(\mathrm{mSv/y}) = \left\{\left(0.17 + 9 \times \mathrm{EF}_{Rn}\right) \times C_{Rn} + \left(0.11 + 40 \times \mathrm{EF}_{Tn}\right) \times C_{Tn}\right\} \times 8760 \times 0.8 \times 10^{-6}$$

where EF_{Rn} = equilibrium factor for ^{222}Rn and EF_{Tn} = equilibrium factor for ^{220}Rn. C_{Rn} = radon concentration and C_{Tn} is ^{220}Rn concentration. 0.17 and 0.11 (nSv/Bq/m^3/h) = the dose transformation co-efficient for ^{222}Rn and ^{220}Rn, 9 and 40 (nSv/Bq/m^3/h) = the dose transformation factors for ^{222}Rn and ^{220}Rn progenies, 8760 h/y = indoor inhabitancy time, 0.8 = the Indoor occupancy factor.

Results and discussion

^{222}Rn/^{220}Rn in an indoor environment

The overall results of ^{222}Rn and ^{220}Rn in indoor environment of 28 villages (approximate two to three dwellings in each village) of Reasi district (lesser Himalayan region) of Jammu & Kashmir, India are presented in Table 1. The range of indoor radon concentration in studied dwellings have been from 18 ± 3 to 59 ± 13 Bq m^{-3} with arithmetic mean (AM) of 29 ± 9, and geometric mean (GM) of 28 Bq m^{-3}, respectively. The obtained results of indoor ^{222}Rn are much less than the suggested reference range (100–300 Bq m^{-3}) prescribed by ICRP [27]. In three villages, the indoor ^{222}Rn concentration is greater than the world average value given by UNSCEAR, but the average value of indoor ^{222}Rn in studied area is less than the global average [28].

The calculated results of indoor ^{222}Rn are compared with neighboring states of the studied region. The obtained results of indoor radon in the study region (18–59 Bq m^{-3}) are comparable to that of Jammu district (16–50 Bq m^{-3}) [29] and Udhampur district (11–58 Bq m^{-3}) [4] of Jammu & Kashmir and Jalandhar (6–47 Bq m^{-3}) [3] and Kapurthala district (19–63 Bq m^{-3}) [30] of Punjab. But observed concentration is less than that of Tosham region (37–80 Bq m^{-3}) [31] of Haryana, Hamirpur region (25–208 Bq m^{-3}) of Himachal Pradesh [32] and Garhwal Himalayas (13–291 Bq m^{-3}) [1]. A high value of ^{222}Rn concentration in Tosham Haryana is due to the presence of granite rocks while in Garhwal Himalayas, it is due to active boundary thrust.

Similarly, indoor thoron concentrations in same dwellings have been found to vary from 30 ± 1 to 204 ± 19 Bq m^{-3} with an AM of 85 ± 42 Bq m^{-3} and GM of 76 Bq m^{-3}. The obtained results of ^{220}Rn concentration are much greater than the global value given by UNSCEAR [33]. The ^{220}Rn concentration is comparatively much greater than the ^{222}Rn concentration in each dwelling due to diffusive transportation of radon, suggesting high thoron emanation rate in soil and material used for building purposes in the examined region. Therefore,

Table 1 ^{222}Rn, ^{220}Rn, EEC, and annual effective dose in 28 villages of Reasi District, Jammu & Kashmir

Sr. no.	Villages	^{222}Rn conc. (Bq m^{-3})	EERC$_{(A+U)}$ (Bq m^{-3})	EERC$_{(A)}$ (Bq m^{-3})	EERC$_{(U)}$ (Bq m^{-3})	EF$_{Rn}$	AED$_{Rn}$ (mSv y^{-1})	f_p^{Rn}	^{220}Rn conc. (Bq m^{-3})	EETC$_{(A+U)}$ (Bq m^{-3})	EETC$_{(A)}$ (Bq m^{-3})	EETC$_{(U)}$ (Bq m^{-3})	EF$_{Tn}$	AED$_{Tn}$ (mSv y^{-1})	f_p^{Tn}	D (mSv y^{-1})
1	Darol	37 ± 6	17 ± 5	15 ± 0.1	2	0.5	0.9	0.1	55 ± 0.4	1.8 ± 0.4	1.4 ± 0.1	0.4	0.03	0.4	0.2	1.71
2	Nomain	21 ± 3	17 ± 3	13 ± 1	4	0.8	0.9	0.2	79 ± 14	2.1 ± 0.1	1.2 ± 0.2	0.9	0.03	0.5	0.5	1.81
3	Sarna	31 ± 1	22 ± 5	16 ± 11	6	0.7	1.2	0.3	199 ± 33	2.0 ± 0.9	3.1 ± 0.2	BDL	0.01	0.6	–	2.12
4	Silla	30 ± 0.1	17 ± 10	15 ± 9	2	0.6	0.9	0.1	154 ± 96	1.4 ± 0.1	0.9 ± 0.3	0.5	0.01	0.4	0.3	1.72
5	Mari	20 ± 3	15 ± 3	11 ± 3	4	0.7	0.8	0.3	30 ± 1	1.1 ± 0.1	0.6 ± 0.1	0.5	0.04	0.3	0.5	1.27
6	Bidda	32 ± 4	30 ± 10	25 ± 7	5	0.9	1.5	0.1	90 ± 18	2.9 ± 0.5	2.9 ± 0.1	BDL	0.03	0.7	–	2.68
7	Gujar koti	40 ± 15	22 ± 0.2	18 ± 1	4	0.5	1.1	0.2	103 ± 29	2.7 ± 0.4	1.7 ± 0.9	1.0	0.03	0.7	0.4	2.25
8	Talwara	26 ± 8	22 ± 2	17 ± 2	5	0.9	1.2	0.2	106 ± 36	1.6 ± 0.1	1.5 ± 0.2	0.1	0.02	0.4	0.05	2.18
9	Khans	37 ± 1	19 ± 4	14 ± 2	5	0.5	1.0	0.3	64 ± 1	1.1 ± 0.2	1.0 ± 0.5	0.1	0.02	0.3	0.1	1.62
10	Dhirti	28 ± 12	19 ± 2	13 ± 3	6	0.7	1.0	0.3	85 ± 13	2.1 ± 0.1	1.5 ± 0.7	0.6	0.02	0.5	0.3	1.81
11	Kotla	29 ± 4	16 ± 4	13 ± 1	3	0.5	0.8	0.1	88 ± 17	1.7 ± 0.3	1.3 ± 0.2	0.4	0.02	0.4	0.2	1.51
12	Panthal	19 ± 2	14 ± 2	7 ± 1	7	0.7	0.7	0.5	56 ± 1	0.9 ± 0.1	0.7 ± 0.1	0.2	0.02	0.2	0.2	1.22
13	Chamba	27 ± 4	21 ± 1	18 ± 6	3	0.8	1.1	0.1	103 ± 26	2.9 ± 0.3	2.1 ± 0.7	0.8	0.03	0.7	0.3	2.34
14	Parthal	31 ± 8	19 ± 0.3	16 ± 7	3	0.6	1.0	0.2	48 ± 38	1.7 ± 0.1	1.4 ± 0.1	0.3	0.03	0.4	0.2	1.65
15	Garn	29 ± 2	22 ± 0.3	16 ± 2	6	0.8	1.1	0.3	75 ± 17	1.3 ± 0.1	1.0 ± 0.6	0.3	0.02	0.3	0.2	1.97
16	Karua	47 ± 3	29 ± 0.7	24 ± 2	5	0.6	1.5	0.1	209 ± 19	2.1 ± 0.6	2.0 ± 1.2	0.1	0.01	0.6	0.1	2.58
17	Dab khalsa	59 ± 13	15 ± 3	14 ± 4	1	0.2	0.8	0.1	31 ± 22	1.1 ± 0.3	0.6 ± 0.1	0.5	0.04	0.3	0.5	1.19
18	Bharakh	29 ± 1	13 ± 1	11 ± 2	2	0.5	0.7	0.2	76 ± 5	1.2 ± 0.3	0.9 ± 0.1	0.3	0.02	0.3	0.2	1.43
19	Bhambla	19 ± 2	10 ± 3	7 ± 2	3	0.5	0.5	0.3	49 ± 0.3	1.5 ± 0.3	0.9 ± 0.7	0.6	0.03	0.4	0.4	1.07
20	Kantha	24 ± 4	14 ± 1	11 ± 1	3	0.6	0.7	0.2	93 ± 32	2.2 ± 0.2	1.3 ± 0.0	0.9	0.02	0.6	0.4	1.53
21	Jadli	18 ± 0.1	15 ± 6	15 ± 4	BDL	0.8	0.8	–	73 ± 36	2.0 ± 0.6	1.7 ± 1.4	0.3	0.03	0.5	0.2	1.59
22	Sula	27 ± 0.4	14 ± 3	12 ± 3	2	0.5	0.8	0.2	49 ± 16	1.2 ± 0.8	0.7 ± 0.1	0.5	0.03	0.3	0.5	1.33
23	Malat	26 ± 1	17 ± 0.5	14 ± 0.6	3	0.6	0.9	0.2	74 ± 6	1.4 ± 0.3	1.1 ± 0.3	0.3	0.02	0.7	0.2	1.49
24	Pouni	21 ± 1	12 ± 0.3	12 ± 0.4	BDL	0.6	0.6	–	67 ± 8	1.3 ± 0.1	1.0 ± 0.5	0.3	0.02	0.3	0.3	1.25
25	Garn jagir	25 ± 8	18 ± 3	12 ± 4	6	0.7	0.9	0.3	53 ± 20	1.6 ± 0.1	1.5 ± 1.1	0.1	0.03	0.4	0.9	1.62
26	Ransoo	28 ± 15	16 ± 4	12 ± 2	4	0.6	0.9	0.3	99 ± 22	3.3 ± 0.7	3.1 ± 2.4	0.2	0.03	0.8	0.1	2.00
27	Kheralair	19 ± 3	18 ± 2	12 ± 1	6	0.9	0.9	0.3	65 ± 4	1.4 ± 0.1	1.4 ± 0.3	BDL	0.02	0.3	–	1.51
28	Simbal	27 ± 4	21 ± 0.2	17 ± 10	4	0.8	1.1	0.2	94 ± 21	1.0 ± 0.1	2.3 ± 0.1	BDL	0.01	0.3	–	1.73
Min.		18	10	7	1	0.3	0.5	0.1	30	0.9	0.6	0.1	0.01	0.2	0.05	1.07
Max.		59	30	25	6	0.9	1.5	0.5	204	3.3	3.1	1.0	0.04	0.8	0.5	2.68
Mean		29	18	14	4	0.7	0.9	0.2	85	1.8	1.4	0.4	0.02	0.4	0.3	1.72
S. D.		9	4	4	2	0.2	0.2	0.1	42	0.6	0.6	0.3	0.01	0.2	0.1	0.42
G. M.		28	18	14	3	0.6	0.9	0.2	76	1.6	1.2	0.3	0.02	0.4	0.2	1.68

S.D. standard deviation, *G.M.* geometric mean high thoron content might be due to thorium-rich soil [12]. Figure 3 represents the variation of indoor ^{222}Rn and ^{220}Rn concentration in studied locations of Reasi district, Jammu & Kashmir.

The radon level in study area can be reduced by taking some short term steps. These general steps are to seal cracks and holes found in walls, floors, drains and pipes. Renovate existing basement floors, particularly earth floors. Increase ventilation in the subfloors beneath the basement. Install a device that sucks the radon from the lowest space in the basement (radon sump system). Avoid using exhaust fans for a continuous amount of time. When you are not using the fireplace, shut the chimney damper. By using these steps, we can help to minimize radon in our daily life.

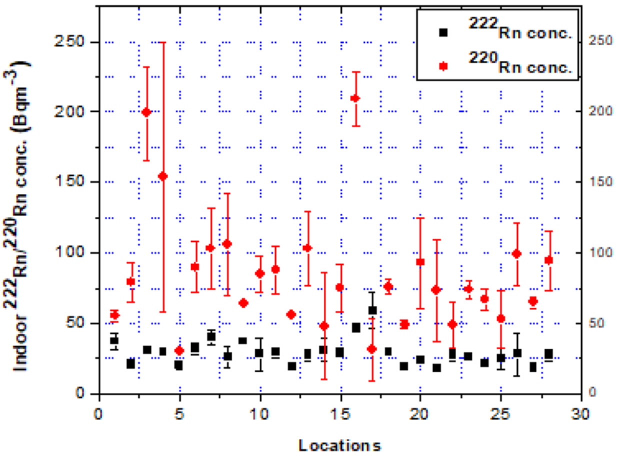
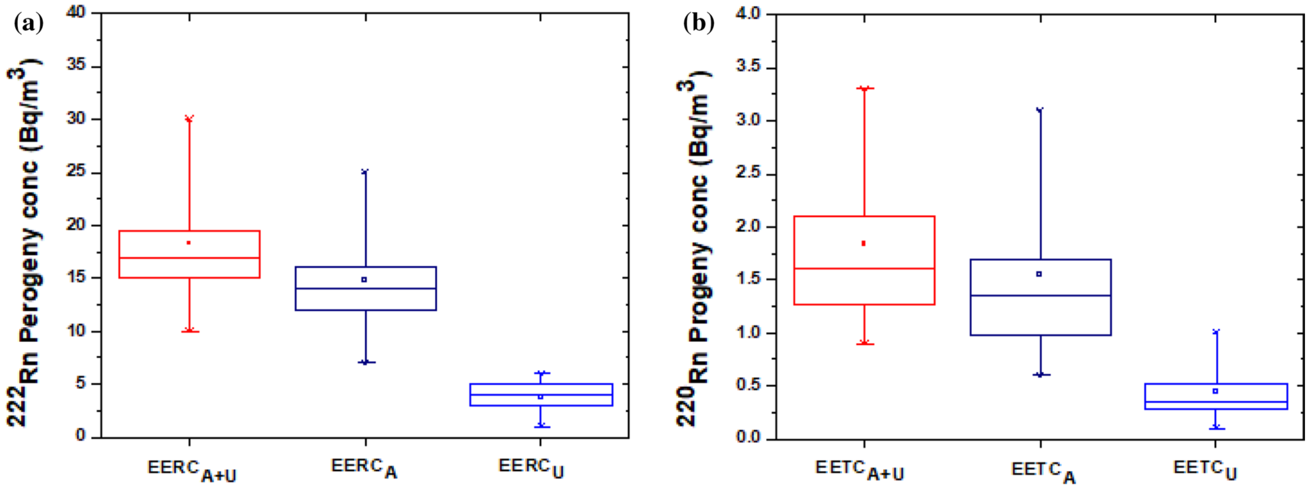


Fig. 3 Variation of indoor ^{222}Rn/^{220}Rn concentration in studied locations

^{222}Rn/^{220}Rn progeny concentration

Table 1 gives the knowledge about the calculated results of progeny concentrations of ^{222}Rn and ^{220}Rn in examined dwellings of the studied region. The total equilibrium equivalent (EERC$_{A+U}$) of ^{222}Rn and (EETC$_{A+U}$) ^{220}Rn concentration were found to vary from 10 to 30 Bq m^{-3}with a mean of 18 ± 4 Bq m^{-3} and from 0.9 to 3.3 Bq m^{-3} with a mean of 1.8 ± 0.6 Bq m^{-3}, respectively. Majority of EERC$_{A+U}$ lies in the range of 14–25 Bq m^{-3} and about 4% of total dwellings have radon progeny concentration above the 25 Bq m^{-3}, respectively. But the overall results of radon progeny concentration in buildings lie within the range (2–50 Bq m^{-3}) prescribed by ICRP [11]. Similarly, most of the thoron progeny concentration lies in the range of 1.1–2.1 Bq m^{-3} and about 7% dwellings have higher thoron progeny level than 2.1 Bq m^{-3}. However, 28% of the locations have higher thoron progeny than the range suggested by ICRP [11]. The variation seen in progeny of radon and thoron is might be the presence of radium content in bedrocks, different material used for construction as well as decorative purposes, ventilation rate, and type of houses. Figure 4 represents the variation of ^{222}Rn and ^{2202}Rn progeny in studied houses. Longer the whisker plot in a positive direction and mean is larger than median shows that ^{222}Rn and ^{220}Rn progeny was well positively skewed.

The attached progeny concentration (EERC$_A$) of ^{222}Rn and (EETC$_A$) of ^{220}Rn in examined locations has been varying from 7 to 25 Bq m^{-3} with an AM of 14 ± 4 Bq m^{-3} and from 0.6 to 3.1 Bq m^{-3} with an AM of 1.4 ± 0.3 Bq m^{-3}, respectively. Similarly, EERC$_U$ and EETC$_U$ in the dwellings ranged from 1 to 6 Bq m^{-3} with an AM of 4 ± 2 Bq m^{-3} and from 0.1 to 1.0 Bq m^{-3}, respectively.



(a) (b)

Fig. 4 **a** Box Whisker plot for radon progeny. **b** Box plot for thoron progeny

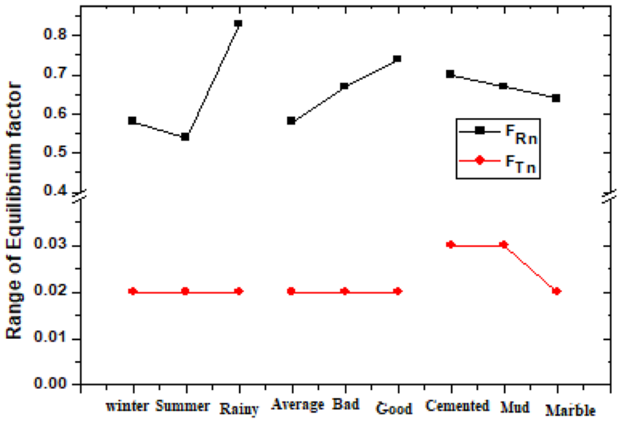


Fig. 5 Variation of equilibrium factor in different ventilation conditions, seasons, and type of houses

Equilibrium factors

The annual estimation of equilibrium factor (EF) for ^{222}Rn and its progeny and ^{220}Rn and its progeny have been ranged from 0.2 to 0.9 with a mean of 0.6 ± 0.2 and from 0.01 to 0.04 with an average of 0.02 ± 0.01 respectively as given in Table 1. The seasonal variations of EF for ^{222}Rn and ^{220}Rn are graphically presented in Fig. 5 and tabulated in Table 1. The annual average of equilibrium for ^{222}Rn and its progeny has been observed to be little higher than its global value (0.4) as detailed by UNSCEAR [34]. These values are calculated for the first time for this part of Himalayas. The annual average of EF for ^{220}Rn and its progeny have been observed to be lower than the all-around accepted value (0.02) as detailed in UNSCEAR [7]. Radon progeny and the EF depend to a great extent on the environmental conditions, which may result in the variation in dosage calculations. Due to the comparatively short half-life of ^{220}Rn as compared to its decedents results in the non-uniformity of ^{220}Rn EF even in the natural environment. The large variation in estimated results of EF suggests that while calculating the radiation dosage because of the exposure of ^{222}Rn, ^{220}Rn and their decedents, the EF ought to be determined separately for an individual houses.

Estimation of an unattached fraction

Unattached fractions have also been calculated using progeny concentrations of ^{222}Rn and ^{220}Rn. In normal conditions, the unattached fractions of Rn^{222} (f_p^{Rn}) and Rn^{220} (f_p^{Tn}) have been found varying from 0.1 to 0.5 with an AM of 0.2 and from 0.05 to 0.5 with an AM of 0.3, respectively. These obtained values are close to ^{222}Rn and ^{220}Rn progeny concentrations. The obtained average result of radon unattached fraction is comparable to the prescribed value (0.15) reported in the literature [35–37]

A weak positive correlation has been seen between f_p^{Rn} and EF$_{Rn}$ with Pearson's coefficient of 0.22 as shown in Fig. 6. This weak relationship is due to low particle concentration inside the homes. The reason for this low attachment rate is might be due to high particle concentration in selected dwellings. Among these lines, ^{222}Rn progeny are for the most part free and in this way plate out on surfaces prompting an imperative dis-equilibrium amongst ^{222}Rn and its progeny [38].

Seasonal variation

The temperature of the studied area generally varies from minimum of 6 °C in winter nights to maximum of 39 °C during peak summers. The annual average concentrations of ^{222}Rn during winter, summer and rainy seasons have been found to be 38 ± 21, 26 ± 7 and 23 ± 7 Bq m^{-3}, whereas for ^{220}Rn they were found as 127 ± 73, 68 ± 38, and 81 ± 34 Bq m^{-3} as shown in Table 2. Graphical representation of a variation of indoor ^{222}Rn and ^{220}Rn and progeny concentration is given in Fig. 7. Results of seasonal variations of ^{222}Rn reveal maximum concentrations during the winter season. This might be due to temperature inversion which is generally expected in winter. Also, houses are kept closed during this season for most of the time which leads to poor ventilation [1]. The concentration gradually decreases during summers and rainy seasons, lowest being in the rainy season. ^{222}Rn concentration is found a bit more in summers than in rainy season in contrast to the usual trend of winter maximum and

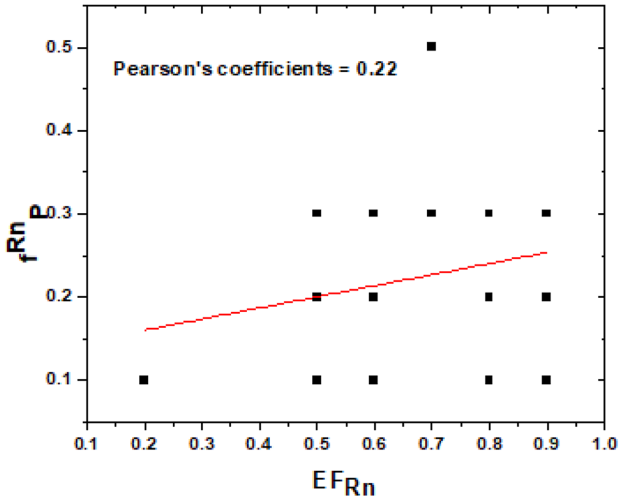


Fig. 6 Correlation between EF$_{Rn}$ and f_p^{Rn}

Table 2 Seasonal, ventilation and dwelling type variation of radon, thoron and its progeny (attached, unattached and total) concentration along with equilibrium factors

	Seasons			Ventilation			Dwelling type		
	Winter	Summer	Rainy	Average	Bad	Good	Cemented	Mud	Marble
^{222}Rn (Bq m^{-3})	38 ± 21	26 ± 7	23 ± 7	31 ± 7	33 ± 13	23 ± 6	27 ± 7	30 ± 9	28 ± 6
EERC$_{A+U}$ (Bq m^{-3})	22 ± 8	14 ± 4	19 ± 5	18 ± 5	22 ± 4	17 ± 6	19 ± 5	20 ± 6	18 ± 4
EERC$_A$ (Bq m^{-3})	16 ± 9	13 ± 4	14 ± 7	14 ± 5	17 ± 4	11 ± 5	16 ± 5	15 ± 4	14 ± 3
EERC$_U$ (Bq m^{-3})	6	4	4	3	4	4	3	4	4
EF$_{Rn}$	0.58	0.54	0.83	0.58	0.67	0.74	0.7	0.67	0.64
^{220}Rn (Bq m^{-3})	127 ± 15	38 ± 38	81 ± 34	80 ± 62	103 ± 43	69 ± 23	68 ± 29	76 ± 63	61 ± 46
EETC$_{A+U}$ (Bq m^{-3})	2.3 ± 1.5	1.3 ± 0.6	1.6 ± 0.6	1.7 ± 0.6	2.4 ± 0.6	1.4 ± 0.7	1.7 ± 0.6	2.1 ± 0.7	1.4 ± 0.5
EETC$_A$ (Bq m^{-3})	1.8 ± 1.4	1.2 ± 1	1.4 ± 0.5	1.3 ± 0.6	2.2 ± 0.5	1.1 ± 0.7	1.1 ± 0.6	1.7 ± 0.9	0.9 ± 0.4
EETC$_U$ (Bq m^{-3})	0.8	0.6	0.3	0.4	0.6	0.4	0.5	0.3	0.7
EF$_{Tn}$	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.02

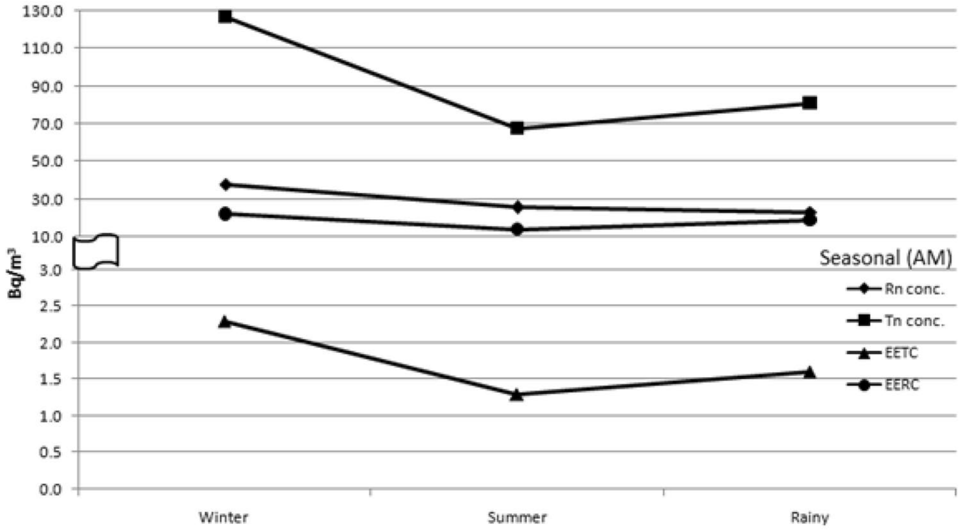


Fig. 7 Seasonal variation of indoor radon/thoron and its progeny

summer minimum as observed elsewhere. This might be due to the fact that temperature variation is almost the same during these two seasons in the studied area so ventilation rate is almost the same. But during rainy season soil becomes saturated with water and hence less concentration is exhaled.

Radon progeny concentration is also observed to be maximum in winters and minimum in rainy season. A similar trend is observed for ^{220}Rn and its progeny concentrations. As decay constant of ^{220}Rn is significantly larger than the ventilation rate, the difference in ventilation conditions does not influence ^{220}Rn concentrations. It is seen that the thoron concentration in all seasons is higher than the corresponding indoor radon concentration. This might be due to thorium-rich construction material used to build houses or thorium-rich soil in the region.

Variation according to types of houses

Observed values of ^{222}Rn, ^{220}Rn and progeny concentration levels in dwellings for different construction materials used covering all the three seasons are tabulated in Table 2. Graphical representation of observations is shown in Fig. 8. It is observed that the average ^{222}Rn and ^{220}Rn concentrations are greater in the Mud type (Mud floor + Mud wall) dwellings. Likewise, the average values of EERC and EETC are also found maximum in the Mud type abodes. This is in accordance with the trend reported elsewhere and this might be explained on the criteria of high porosity and permeability in these types of houses as radon easily enters these houses from the ground below due to high porosity [39]. On the other hand, modern housing techniques using types of cements blocks or marbles have shown low values of ^{222}Rn and ^{220}Rn concentration.

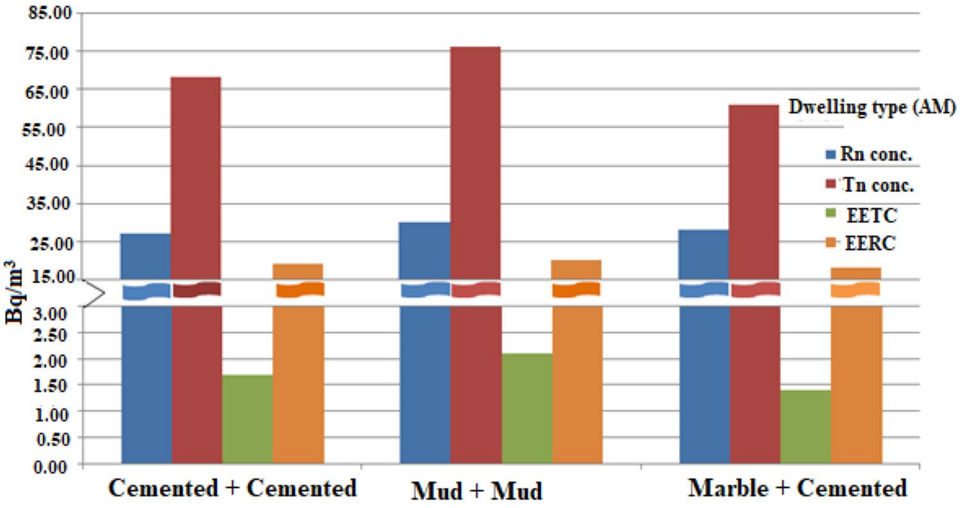


Fig. 8 Variation of radon/thoron and its progeny in different type of dwellings

This may be due to low porosity and low diffusion rate in cemented houses.

Houses in which floors are constructed using local construction material are found to have high thoron concentration than those constructed using marbles, which are mainly brought from outside. Due to its short half-life (55.6 s), ^{220}Rn in soil gas underneath a building, in most cases can't survive sufficiently enough to enter the building and contribute to the indoor ^{220}Rn level. In this way, indoor ^{220}Rn is ordinarily due to the exhalation from thorium, which might be available in materials utilized on the inside surfaces of the building. Also cemented floors are more porous than marble floors. Seeing it in combination with the fact that high thoron concentration is observed in comparison to radon concentration for all types of dwelling during all seasons, we might conclude that high indoor thoron concentration is due to thorium-rich bricks and local construction material like sand used in the construction of walls.

Dependent of radon, thoron, and its progeny on ventilation condition of houses

In mud houses, inhabitants used to keep a low number of doors and windows, which give poor ventilation conditions to a house. An attempt has been made to study variation in ^{222}Rn, ^{220}Rn, and their progeny concentration according to ventilation conditions. It is observed that values are high in the poorly ventilated room in comparison to average and good ventilated rooms. Average ^{222}Rn and ^{220}Rn concentration is found lowest in well ventilated rooms in accordance with the trends observed in other studies. Figure 9 shows variation in radon, thoron and its progeny concentration according to ventilation conditions of the rooms selected. Figure 9 shows the graphical representation of data observed.

Estimation of radiation doses

The annual effective dose due to indoor ^{222}Rn and its progenyare found to vary from 0.5 to 1.5 mSv y^{-1} with an arithmetic mean of 0.9 ± 0.2 mSv y^{-1} while the annual effective dose due to thoron and progeny are found to vary from 0.2 to 0.8 mSv y^{-1} with an arithmetic mean of 0.4 ± 0.2 mSv y^{-1}. The total annual inhalation dose (D) due to exposure of indoor ^{222}Rn, ^{220}Rn, and their progenies is found to vary from 1.07 to 2.68 mSv y^{-1} with an average value of 1.72 mSv y^{-1}. These values are less than the safe limit (3–10 mSv y^{-1}) [40] and pose no health risk to the population of the examined area. The contribution of indoor ^{220}Rn and its progeny to total dose is about 1/4th. Thus thoron can't be ignored while evaluating radiation measurements.

Conclusions

The annual average values of indoor radon concentration are found lower than the world-wide average of 40 Bq m^{-3}, whereas thoron concentration is found to be higher than the world-wide average of 10 Bq m^{-3} as well as the national average of 12.2 Bq/m^3. The ^{222}Rn, ^{220}Rn, and progeny concentrations have been found to be relying on type of season, ventilation conditions and type of building materials used to construct houses. Houses in which floors are constructed using local construction (mud and rocks) material are found to have high thoron concentration than those constructed using marbles, which are mainly brought from outside. Also, overall very high thoron concentration levels point to the fact that soil of the region is thorium-rich. The annual equilibrium factor for radon and its progeny and thoron and its progeny have been within the globally expected value prescribed by UNSCEAR. The large variation in the thoron

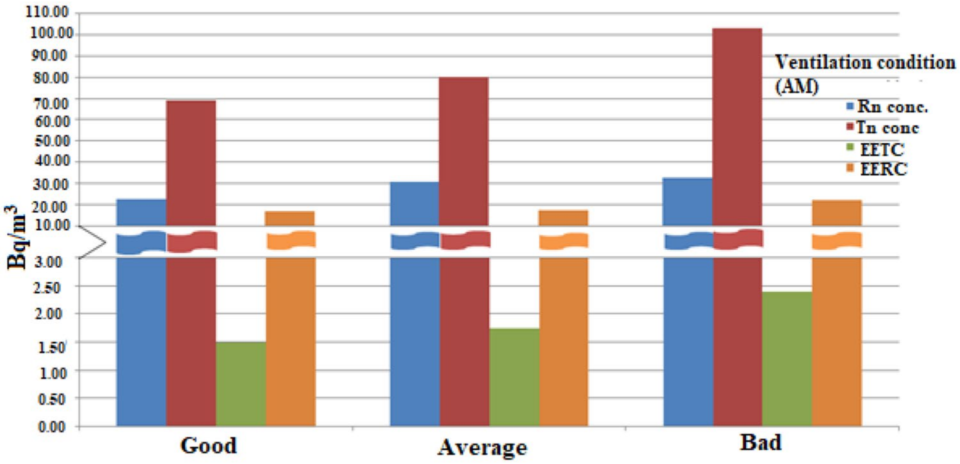


Fig. 9 Variation of gas and its progeny concentration in different type of dwellings

equilibrium factor even for the similar natural conditions is due to its short life.

Moreover, radiation dose is within safe limit and poses no health risk to the population of the study area. The contribution of indoor thoron and its progeny to total inhalation dose is about 1/4th. Thus thoron cannot be neglected while assessing radiation doses.

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