

Assessment of attached and unattached progeny concentrations of $^{222}\text{Rn}/^{220}\text{Rn}$ and their contribution to dose using deposition-based progeny sensors

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Abstract The exposure of radiation from natural sources to population has become an important issue in terms of radiological protection. Mostly natural radiation comes from radon (^{222}Rn), thoron (^{220}Rn) and their solid short-lived daughter products that are the main threat to public health risk. The results presented in this paper are from a survey carried out in 40 villages of Jammu district, Sub-Mountainous region of Jammu and Kashmir, India, to quantify progeny concentration of radon and thoron using a passive time integrating, deposition-based technique. For estimating the total (attached + unattached) progeny concentration of radon/thoron, direct radon/thoron progeny sensors (DRPS/DTPS) have been used and only attached progeny concentration of radon/thoron has been measured by using wire-mesh capped direct radon/thoron progeny sensors (WM-DRPS/WM-DTPS). The study has been conducted for a period of 1 year during winter, rainy and summer seasons in all 112 dwellings. The exposure time of the sensors was 4 months. In this survey, the variability of progeny concentration of radon and thoron based upon variation in building construction materials and seasons-wise has also been discussed and efforts have been made to provide the reason for these variations. The highest level of progeny concentration of radon/thoron was found in the mud-type dwellings compared with dwellings made of

concrete, cement and marble. Indoor and outdoor gamma dose rate (μSvh^{-1}) has also been measured and correlated indoor gamma annual effective dose (μSvy^{-1}) with progeny annual effective dose (μSvy^{-1}).

Keywords Attached and unattached progeny · Building materials · LR-115 type-II · Progeny sensors · Unattached fraction

Introduction

Inhalation of short-lived decay products of radon and thoron, especially ^{214}Po and ^{212}Po , contributes greatest hazard to respiratory tract and lung cancer and also lead to significant doses to sensitive cells in the skin (Kendall and Smith 2002; Wang et al. 2011). The decay products of radon and thoron are isotopes of solid element, and a large fraction of the freshly generated ^{218}Po and ^{216}Po (80–82%) are positively charged (Porstendörfer and Mercer 1979). These generated positively charged atoms that become neutral by recombination with negative air ions and charge transfer processes in connection with trace gases (HNO_3 , NO_2 and SO_2) or vapors (H_2O) and other air impurities (Pagelkopf and Porstendörfer 2003) in less than 1 s to form clusters of size 0.5–5 nm (Reineking et al. 1985; Ramamurthi and Hopke 1989) called radioactive unattached particle. After this process, the clusters attach to the sub-micron sized aerosol particles in the air within 1–100 s, forming the radioactive aerosol or attached particles of size (100–500 nm). The relative ratio of fine (unattached) and coarse fraction (attached with aerosols) varies with different environmental conditions (Koli et al. 2016).

The attached particle is likely to pass the upper respiratory tract and leave alveoli during exhalation. A major

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part of unattached particle also passes the upper respiratory tract, but, due to small size and high diffusion coefficient, deposited on the inner layers of the bronchi (BB), bronchioles (bb) and in the alveolar interstitial region (AI) (Kendall and Smith 2002) and then is subjected to somatic transport processes (Kudo et al. 2015). As these particles decay in turn, they release small bursts of radiation. This radiation can damage lung tissue, which can lead to development of lung cancer (Sevc et al. 1976; Edling et al. 1986). The unattached fractions are predominantly responsible for dose received by the targets cells in the bronchial epithelium and initiate the process of carcinogenesis (Ashok et al. 2012). Radon and its progeny deliver substantially more dose to the lung than to systemic organs, and the gastrointestinal tract regions and small doses may also be received by the red bone marrow (Kendall and Smith 2002). The correlation between indoor radon and cancer has been reported by some researchers (Celik et al. 2008; Bernard et al. 2016).

The majority of radon, thoron and their decay products found in dwellings come from building materials, groundwater, soil underneath the dwellings and natural energy sources like cooking gas, coal (Porstendorfer 1994; Stojanovska et al. 2011). The air pressure inside the dwellings is usually lower than the air pressure in the soil beneath the dwellings because of the effects of wind and temperature. The radon gas arises from soil and rocks seeps through the foundations, basements and piping of buildings which can accumulate in the air dwellings that are poorly ventilated (Szabo et al. 2014). The origination of radon from building materials depends upon moisture, porosity and meteorological conditions. The indoor radon and thoron concentrations are found to be time dependent, and their concentrations are also dependent on temperature, weather or seasons and environmental parameters, which affect its entry and removal. Therefore, season-wise and building materials-wise measurement of progeny concentration of radon and thoron in the dwellings of the studied area is very important from the health physics point of view.

Due to the harmful effects of progeny concentration of radon and thoron, many researchers have reported the value of progeny concentration (Porstendorfer and Mercer 1979; Reineking et al. 1985; Edling et al. 1986; Kendall and Smith 2002) from different parts of the world and a little work has been reported in different regions of India (Bajwa et al. 2015; Bangotra et al. 2015; Ramola et al. 2016; Singh et al. 2016). The present study includes the measurement of attached and unattached progeny concentration of radon and thoron by using direct radon/thoron progeny sensors (DRPS/DTPS) and wire-mesh capped direct radon/thoron progeny sensors (WM-DRPS/WM-DTPS) for the first time in the Jammu district of Jammu and Kashmir, India.

Moreover, correlation between indoor gamma annual effective dose rates with progeny annual effective dose rate has also been measured. We aimed to see the effects of various distributions such as zone-wise, dwellings-wise and seasonal distributions on radon and thoron progeny concentrations.

Study region

Jammu district is located in north India and is the southernmost district of Jammu and Kashmir State. It extends geographically from the latitudes $32^{\circ}34'18''$ to $32^{\circ}54'4''$ north and longitudes $74^{\circ}27'60''$ to $75^{\circ}05'42''$ east. This district is bounded by Pakistan and Rajouri district in the west, Reasi and Udhampur districts in the north and northeast, Kathua district in the southeast and Punjab state in the south.

Physiographically, the district is occupied by two major units extending throughout the district. The unit that extends in the northern part is the hilly tract of Siwalik formations, and the unit extending in the southern part is a plain tract, the outer plain. The Siwalik range rises gradually in the northern part of the district, and outer plain merges with the Indo-Gangetic plain in the south. The Siwalik group is located between the main boundary thrust (MBT) in the north and the Himalayan frontal thrust (HFT) in the south.

The climate of the district is classified as sub-humid to subtropical type of climate. The sub-humid to subtropical district receives normal annual rainfall of 1246 mm. The summer season starting from April and lasting till June is followed by southwest Monsoon that has maximum rainfall of the year spread over the months of July, August and September.

Methodology

Sampling strategy

The measurement of radon-thoron progeny concentrations has been taken in 40 villages of Jammu district, India, from November 2014 to November 2015. A preliminary survey has been carried out in Jammu district in the month of October 2014 to select the villages in such a way so that whole district has been covered. To study the seasonal variation, whole year has been divided into three seasons of 4-month period as winter (November 2014–March, 2015); summer (March–July, 2015); and rainy (July–November 2015), respectively. The total number of 112 dwellings has been selected in 40 villages of Jammu district with average of two to three dwellings in each village. The choice of

dwelling was based on our convenience, willingness of the dwellers and types of building materials that had been used. The selected dwellings were divided into five types of categories in each zone on the basis of building materials: Type A as marble-reinforced cement concrete (R.C.C.), Type B as cemented-R.C.C, Type C as mud-R.C.C, Type D as proper mud and Type E as tiles-R.C.C, respectively.

Experimental technique

Dosimeter–radiometer

In the selected villages of Jammu district, ambient outdoor gamma dose rate has been measured by using dosimeter–radiometer MKS-03D gamma detector-meter at about 1 m above the ground surface. It is GM tube-based survey-meter with digital display. It can detect the gamma radiation ranged between 0.05 and 3.0 mE and can detect the ambient gamma radiations dose equivalent rate ranged between 0.1 μSv h⁻¹ and 0.1 Sv h⁻¹. Measurements were taken in indoor and outdoor during installation and retrieval of the detectors at all locations. According to the ambient maximum outdoor gamma dose rate (μSv h⁻¹), selected 40 villages have been divided into three zones having a range from 0 to 0.10, 0.10–0.20 and ≥0.20 μSv h⁻¹, respectively. The distribution of different type of dwellings in three gamma zones is a statistical representation to estimate the number of detectors to be deployed in each type of dwellings in the respective zone by using multivariate regression analysis (Sahoo and Sapra 2015) as summarized in Table 1. The data obtained for the internal exposure rate in μSv h⁻¹ were converted into internal absorbed dose rate (ADR_{in}) nGy h⁻¹ using conversion factor of 870 nGy h⁻¹ (Nagaraju et al. 2013).

Deposition-based progeny sensors

For the measurement of total (attached + unattached) progeny concentration of radon and thoron, direct radon/thoron progeny sensors have been deployed (Fig. 1a) and

the measurement of only attached radon-thoron progeny concentration has been taken with wire-mesh capped deposition-based progeny sensors (Fig. 1b). Both are made of passive nuclear track detectors (LR-115) mounted with absorbers of appropriate thickness with only the difference that former is in a bare mode which cannot separate the deposition of attached and unattached radon-thoron progeny on sensors and latter consists of DTPS/DRPS capped with a 200-mesh-type wire-screen (79 mesh cm⁻¹, wire diameter: 0.005 cm), which is used as unattached fraction separator due to Brownian diffusion (Mishra et al. 2009). DTPSs are absorber (aluminized mylar of 50 μm thickness) mounted with LR-115-type nuclear track detectors (2.5 cm × 2.5 cm) which selectively detect only the alpha particles emitted from ²¹²Po (8.78 MeV) atoms formed from the radioactive decay of ²¹²Pb and ²¹²Bi atoms deposited on the absorber surface (Mishra et al. 2009). Similarly, DRPS has an absorber thickness of 37 μm to detect mainly the alpha particles emitted from ²¹⁴Po (7.69 MeV) formed from the eventual decay of ²¹⁸Po, ²¹⁴Pb and ²¹⁴Bi atoms deposited on it (Mishra et al. 2009). DTPS and DRPS have lower detection limit of 0.1 and 1 Bqm⁻³, respectively.

Theoretical formalism

The health-related risk associated with the inhalation of short-lived decay progenies of radon and thoron, mainly reported as equilibrium equivalent concentration (EEC). The equilibrium equivalent concentration for radon EERC and for thoron EETC are the quantities directly related to the potential alpha energy concentration in air and hence to the inhalation dose.

Calculation of total (attached + unattached) and attached equilibrium equivalent concentrations

The total (attached + unattached) and attached equilibrium equivalent concentrations (EEC_{A+U}) of radon and thoron in the units of Bqm⁻³ were calculated by using the formula in Eqs. (1) and (2) (Mishra and Mayya 2008):

Table 1 Estimated number of detectors to be deployed in each type of dwellings in the respective zone from the observed number of dwellings in each type of dwellings in the corresponding gamma zone using the multivariate regression analysis

Zones	Gamma level (μSv h ⁻¹)	Type A	Type B	Type C	Type D	Type E
Observed number of dwellings in respective category of each zone						
1	0.0–0.10	5321	2354	1908	2300	1267
2	0.10–0.20	9765	3212	2565	2356	1200
3	>0.20	4321	1211	1432	1094	500
No. of detectors to be deployed in respective category of each zone out of 112 detectors						
1	0.0–0.10	16	7	6	7	6
2	0.10–0.20	20	6	6	6	5
3	>0.20	6	6	5	5	5

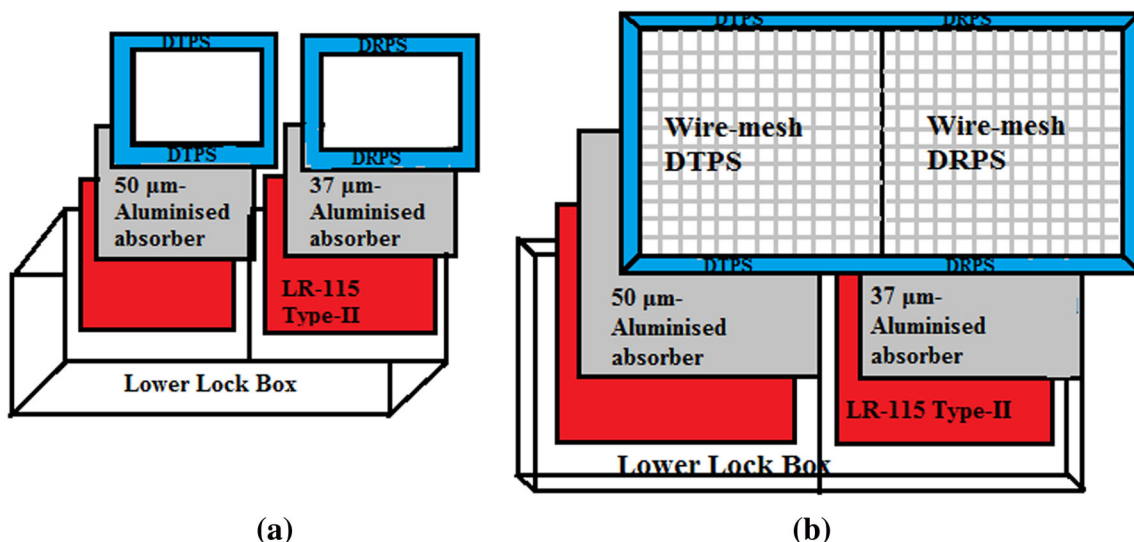


Fig. 1 Diagram of deposition-based progeny sensors. a DTPS/DRPS, b WM-DTPS/DRPS

$$EERC_{(i,j)} (\text{Bqm}^{-3}) = \frac{T_{r_{i,j}} - T_B}{(D \times S_{r_{i,j}})} \tag{1}$$

$$EETC_{(i,j)} (\text{Bqm}^{-3}) = \frac{T_{t_{i,j}} - T_B}{(D \times S_{t_{i,j}})} \tag{2}$$

where $EERC_{(i,j)}$ and $EETC_{(i,j)}$ are the equilibrium equivalent concentration (Bqm^{-3}) of radon and thoron for total progeny, i.e., i , and for attached progeny, i.e., j , $T_{r_{i,j}}$ and $T_{t_{i,j}}$ are the track density (Tr cm^{-2}) of total and attached radon and thoron progenies recorded in DRPS/DTPS and WM-DRPS/WM-DTPS, T_B is the background tracks contributed due to detector shelf-life and during transit, D is the exposure period for detectors, i.e., 120 days, $S_{r_{i,j}}$ is the sensitivity factor for total [$0.09 (\text{Tr cm}^{-2} \text{d}^{-1}/\text{EERC} (\text{Bqm}^{-3}))$] and attached [$0.04 (\text{Tr cm}^{-2} \text{d}^{-1}/\text{EERC} (\text{Bqm}^{-3}))$] radon progenies, and S_{r_j} is the sensitivity factor for total [$0.94 (\text{Tr cm}^{-2} \text{d}^{-1}/\text{EETC} (\text{Bqm}^{-3}))$] and attached [$0.33 (\text{Tr cm}^{-2} \text{d}^{-1}/\text{EETC} (\text{Bqm}^{-3}))$] thoron progenies, respectively (Mishra et al. 2014).

Some alpha particles from thoron progeny with energy 8.78 meV have impact on radon sensor with absorber energy 7.69 meV. So, to calculate accurate radon progeny alpha particles from DRPS, tracks of thoron progeny have to be subtracted from it using the following equation (Mishra et al. 2014):

$$\text{Tracks} \frac{\text{only RnP}}{\text{DRPS}} = \text{Tracks} \frac{\text{Total}}{\text{DRPS}} - \frac{\eta_{RT}}{\eta_{TT}} \text{Tracks} \frac{\text{Total}}{\text{DTPS}} \tag{3}$$

where η_{RT} and η_{TT} are the track registration efficiencies for thoron progeny in DRPS (0.01 ± 0.0004 per alpha particle emitted from thoron progeny) and that in DTPS (0.083 ± 0.004 per alpha particle emitted from thoron progeny) (Mishra et al. 2009), respectively. Therefore, the DRPS

should be always deployed along with DTPS to achieve this radon progeny and thoron progeny discrimination.

Calculation of unattached equilibrium equivalent concentration and unattached fraction

The unattached equilibrium equivalent concentration (EEC_U) has been calculated by simply subtracting the attached equilibrium equivalent concentration (EEC_A) from the total (attached + unattached) equilibrium equivalent concentration (EEC_{A+U}) using expression (4) and (5):

$$EERC_{(U)} = EERC_{(A+U)} - EERC_{(A)} \tag{4}$$

$$EETC_{(U)} = EETC_{(A+U)} - EETC_{(A)} \tag{5}$$

The unattached fraction (f_p) of potential alpha energy concentration of ^{222}Rn and ^{220}Rn progeny has been calculated by using the formula in Eqs. (6) and (7) (Knutson 1988; Ramola et al. 2016):

$$f_p^{\text{Rn}} = \frac{EERC_U}{EERC_{A+U}} \tag{6}$$

$$f_p^{\text{Tn}} = \frac{EETC_U}{EETC_{A+U}} \tag{7}$$

where f_p^{Rn} and f_p^{Tn} are unattached fractions of radon and thoron progeny, respectively.

Calculation of annual effective doses

Radon and thoron doses Doses depend mainly on the concentration of radon progeny, the duration of exposure, the breathing rate and the aerosol properties, including the activity size distribution of the radon progeny aerosol and the unattached fraction (Porstendörfer and Mercer 1979).

The dose conversion factor reported by UNSCEAR (2008) has been used to estimate the annual indoor inhalation dose. Annual effective dose (μSvy^{-1}) for radon AED_{Rn} and that for thoron AED_{Tn} were calculated using the formula (UNSCEAR 2008):

$$\text{AED}_{\text{Rn}} = \text{EERC}_{\text{A+U}} \times \text{DCF}_{\text{Rn}} \times \text{OF} \times \text{T}_{\text{Rn}(\text{exp})} \quad (8)$$

$$\text{AED}_{\text{Tn}} = \text{EETC}_{\text{A+U}} \times \text{DCF}_{\text{Tn}} \times \text{OF} \times \text{T}_{\text{Tn}(\text{exp})} \quad (9)$$

where DCF_{Rn} ($9 \text{ nSvh}^{-1} \text{ Bq}^{-1} \text{ m}^3$) and DCF_{Tn} ($40 \text{ nSvh}^{-1} \text{ Bq}^{-1} \text{ m}^3$) are the radon and thoron dose conversion factors, OF (0.8) is the indoor occupancy factor, and $\text{T}_{\text{Rn}(\text{exp})}$ and $\text{T}_{\text{Tn}(\text{exp})}$ are the exposure duration per year (7000 hy^{-1}), respectively.

Indoor gamma doses The annual dose resulting from absorbed dose attributed to gamma-ray emission from the radionuclides (^{226}Ra , ^{232}Th and ^{40}K) is obtained using the formula:

$$\text{AEDE}_{\text{In}} = \text{ADR}_{\text{In}} \times \text{DCF}_{\text{In}} \times \text{OF}_{\text{In}} \times \text{T}_{\text{In}(\text{exp})} \quad (10)$$

where AEDE_{In} is the indoor gamma annual effective dose equivalent (μSvy^{-1}), DCF_{In} is the indoor dose conversion factor of 0.7 SvGy^{-1} (UNSCEAR 1988), OF_{In} is the indoor occupancy factor (0.8), and $\text{T}_{\text{In}(\text{exp})}$ is the indoor exposure duration per year (7000 hy^{-1}), respectively.

Results and discussion

Indoor and outdoor gamma dose rates

The overall value of indoor and outdoor gamma dose rate of Jammu district is listed in Table 2. The range of indoor gamma dose rate has been varied from 0.05 to $0.22 \mu\text{Svh}^{-1}$ with an average value of $0.14 \pm 0.03 \mu\text{Svh}^{-1}$, while outdoor gamma dose rate has been varied from 0.09 to $0.25 \mu\text{Svh}^{-1}$ with an average value of $0.15 \pm 0.04 \mu\text{Svh}^{-1}$, respectively. The range of indoor absorbed dose rate has been varied from 44 to 191 nGyh^{-1} with an average value of $115 \pm 31 \text{ nGyh}^{-1}$. ICRP (2010) has suggested a limit of $1000 \mu\text{Svy}^{-1}$ for gamma annual effective dose rate. The value of indoor annual effective dose equivalent has been varied from 171 to $750 \mu\text{Svy}^{-1}$ with an average value of

$452 \pm 120 \mu\text{Svy}^{-1}$ and found well within the safe limit suggested by ICRP (2010). According to outdoor gamma dose rate, the selected 40 villages have been characterized into three different zones that are summarized in Table 3 (part A). In the first zone, eight villages were selected with a range varied from 0.09 to $0.10 \mu\text{Svh}^{-1}$ with an average value of $0.09 \pm 0.004 \mu\text{Svh}^{-1}$; in the second zone, twenty-five villages were selected with a range varied from 0.12 to $0.20 \mu\text{Svh}^{-1}$ with an average value of $0.15 \pm 0.03 \mu\text{Svh}^{-1}$; and in the third zone, seven villages were selected with a range varied from 0.21 to $0.25 \mu\text{Svh}^{-1}$ with an average value of $0.22 \pm 0.02 \mu\text{Svh}^{-1}$, respectively. The distribution of Jammu district according to zone-wise is presented in Fig. 2. Zone 1 covered 8%, zone 2 covered 25%, and zone 3 covered 7% of the Jammu region. About 60% of the Jammu district has not been covered because the north part of area is a mountainous area not a residential and it is at very height and south part of the area comes under the other province, respectively.

Radon and thoron progeny concentrations

Table 4 provides the whole information of the study area regarding the total (attached + unattached), attached and unattached equilibrium equivalent radon and thoron concentrations. The total equilibrium equivalent ^{222}Rn concentration ($\text{EERC}_{\text{A+U}}$) and ^{220}Rn concentration ($\text{EETC}_{\text{A+U}}$) were found to vary from 8 to 26 Bqm^{-3} with an average value of $18 \pm 5 \text{ Bqm}^{-3}$ and from 0.6 to 2.6 Bqm^{-3} with an average value of $1.4 \pm 0.5 \text{ Bqm}^{-3}$, respectively. The frequency distribution of total (attached + unattached) equilibrium equivalent thoron concentration and radon concentration is presented in Figs. 3 and 4. A log-normal distribution is one of the well-known characteristics of radon and its progeny (Bossew 2010), and in the present study, the distribution of radon and thoron progeny concentration follows log-normal distribution. To find the geometrical spread of data, arithmetic mean, geometric mean and geometric standard deviation were calculated. Figure 3 shows that mode distribution frequency observed at three intervals, i.e., 0–0.5, 2.6–3.0 and 3.1–3.5 Bqm^{-3} , respectively. The frequency distribution was highest at 38 and 29% and lowest at high thoron

Table 2 Indoor and outdoor gamma dose rate (μSvh^{-1}), indoor absorbed dose rate (nGyh^{-1}) and indoor gamma annual effective dose rate (μSvy^{-1}) in villages of Jammu district, Jammu and Kashmir

Statistical parameters	Gamma dose rate (μSvh^{-1})		ADR_{In} (nGyh^{-1})	AEDE_{In} (μSvy^{-1})
	Outdoor	Indoor		
Min.	0.09	0.05	44	171
Max.	0.25	0.22	191	750
Average	0.15	0.14	115	452
S.D.	0.04	0.03	31	120

Table 3 Variation of total (attached + unattached), attached and unattached progeny concentration of radon and thoron with different zones, dwellings and seasons

Part	Different studies	Outdoor gamma dose rate ($\mu\text{Sv h}^{-1}$)	No. of villages	EETC _(A+U) (Bqm^{-3})	EETC _(A) (Bqm^{-3})	EETC _(U) (Bqm^{-3})	EERC _(A+U) (Bqm^{-3})	EERC _(A) (Bqm^{-3})	EERC _(U) (Bqm^{-3})
A	Zone-wise distribution	Zone-1 (0.09–0.10)	8	1.2 ± 0.4	1.3 ± 0.1	0.1	16 ± 4	15 ± 4	1.7
		Zone-2 (0.12–0.20)	25	1.4 ± 0.5	1.3 ± 0.4	0.2	18 ± 4	17 ± 4	1.9
		Zone-3 (0.21–0.25)	7	1.4 ± 0.4	1.3 ± 0.3	0.1	18 ± 4	16 ± 3	1.8
	Building materials		No. of dwellings	EETC _(A+U) (Bqm^{-3})(M*)	EETC _(A) (Bqm^{-3})(M*)	EETC _(U) (Bqm^{-3})	EERC _(A+U) (Bqm^{-3})(M*)	EERC _(A) (Bqm^{-3})(M*)	EERC _(U) (Bqm^{-3})
B	Dwellings-wise distribution	Marble + R.C.C.*	43	1.2 ± 0.5 (1)	1.0 ± 0.4 (1)	0.2	16 ± 6 (15)	14 ± 5 (14)	2
		Cement +R.C.C.	39	1.5 ± 0.7 (1.2)	1.3 ± 0.5 (1.4)	0.3	19 ± 6 (17)	16 ± 6 (16)	3
		Mud + R.C.C.	17	1.8 ± 0.9 (1.4)	1.6 ± 0.8 (1.7)	0.2	21 ± 9 (17)	19 ± 7 (19)	2
		Mud + Mud	6	2.0 ± 0.9 (1.7)	1.7 ± 0.7 (1.5)	0.3	20 ± 6 (15)	18 ± 6 (16)	2
		Tiles + R.C.C	7	1.2 ± 0.4 (1)	1.0 ± 0.4 (1.5)	0.2	15 ± 4 (15)	13 ± 5 (13)	2
	Seasons								
C	Seasonal-distribution	Summer	112	1.5 ± 1.3 (1)	0.9 ± 0.6 (0.7)	0.6	17 ± 13 (13)	13 ± 9 (10)	4
		Winter	112	1.9 ± 1.2 (1.7)	1.3 ± 0.8 (1)	0.6	25 ± 15 (22)	18 ± 11 (15)	8
		Rainy	112	1.5 ± 0.6 (1.4)	1.1 ± 0.5 (1.1)	0.4	15 ± 7 (14)	11 ± 5 (11)	5

* M Median

* R.C.C. Reinforced Cement Concrete

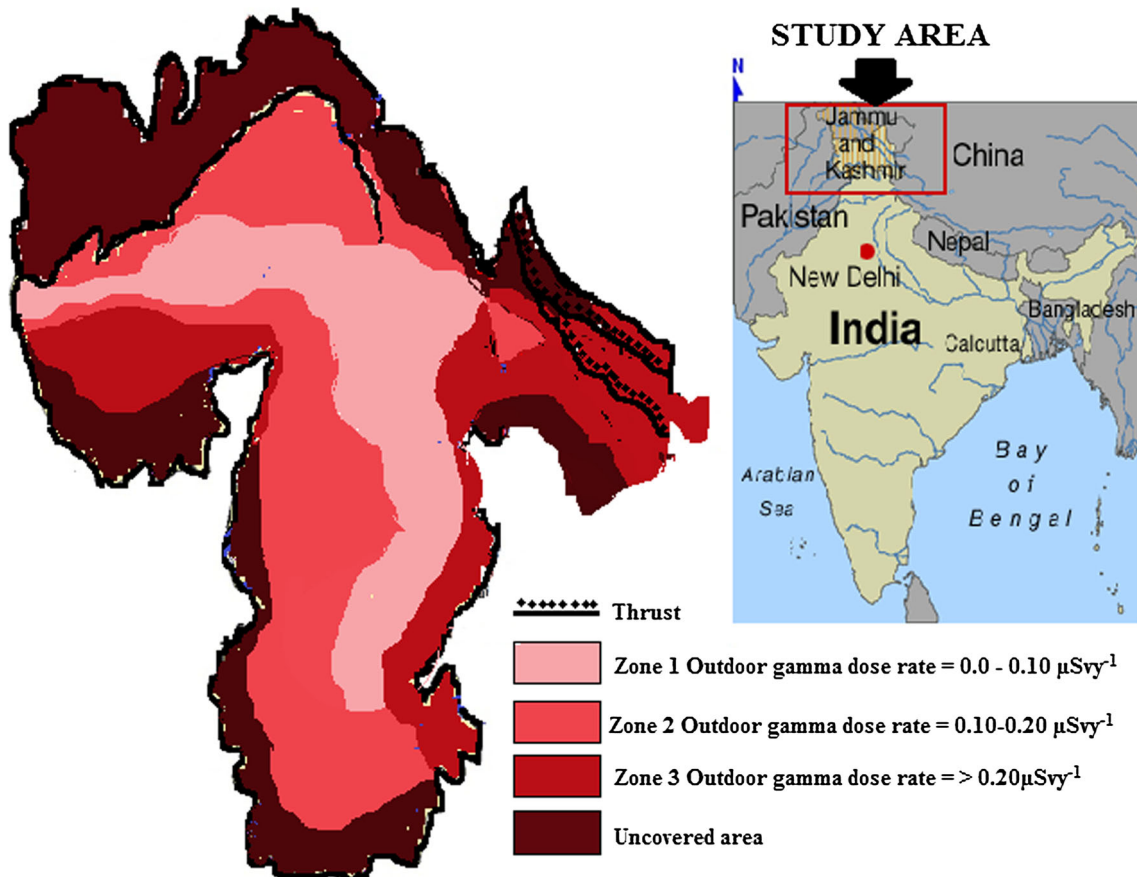


Fig. 2 Distribution of map according to outdoor gamma dose rate

Table 4 Variation of EEC, unattached fraction of radon and thoron and their annual effective dose rate

Sr. no.	Villages (no. of dwellings)	EETC _(A+U) (Bqm ⁻³)	EETC _(A) (Bqm ⁻³)	EETC _(U) (Bqm ⁻³)	AED _{Tn} (μSvy ⁻¹)	f _p ^{Tn}	EERC _(A+U) (Bqm ⁻³)	EERC _(A) (Bqm ⁻³)	EERC _(U) (Bqm ⁻³)	AED _{Rn} (μSvy ⁻¹)	f _p ^{Rn}	$\frac{EETC_{A+U}}{EERC_{A+U}}$
Min.		0.6	0.6	0.1	134	0.06	8	8	1	403	0.04	0.03
Max.		2.6	2.2	0.8	582	0.43	26	23	7	1310	0.4	0.12
Mean		1.4	1.2	0.3	303	0.18	18	16	2	885	0.15	0.08
S.D.		0.5	0.4	0.2	103	0.10	5	4	1.8	227	0.09	0.02
G.M.		1.3	1.2	0.2	287	0.15	17	15	2.5	858	0.12	0.08

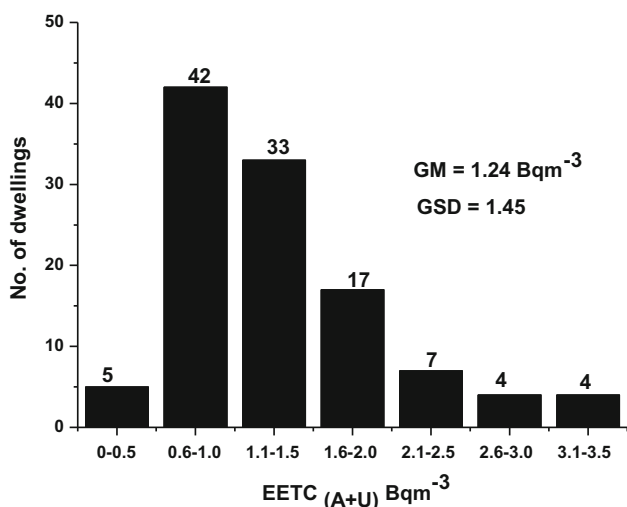


Fig. 3 Frequency distribution of total thoron progeny concentration in 112 numbers of dwellings

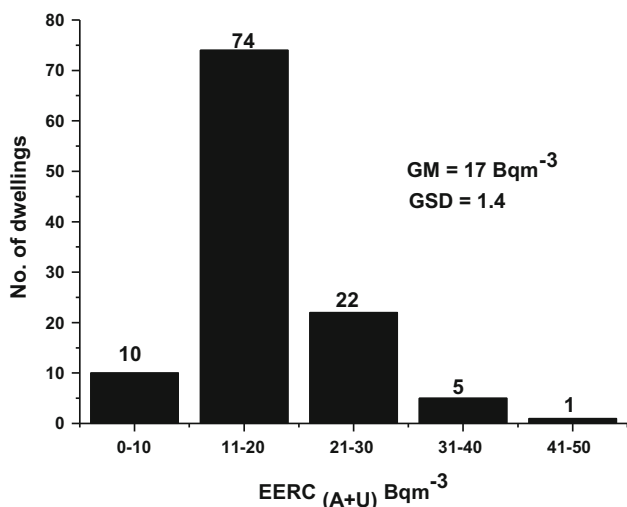


Fig. 4 Frequency distribution of total (attached + unattached) radon progeny concentration in 112 dwellings of Jammu district

progeny concentration. Figure 4 shows that 9% dwellings have radon progeny concentration between 0 and 10 Bqm⁻³. The Majority of the dwellings surveyed (66%) have radon progeny concentration between 11 and 20 Bqm⁻³, while 20% of the dwellings have radon progeny concentration between 21 and 30 Bqm⁻³. Only 4% dwellings have radon progeny concentration between 31 and 40 Bqm⁻³. The variation found in the radon and thoron progeny concentration in the dwellings may be explained due to nature and type of building materials used in the dwellings, different ventilation and the variation in the radioactive levels in the soil beneath the dwellings.

The statistical distribution of thoron and radon progeny concentration is presented in Figs. 5 and 6. The highest radon and thoron progeny concentration was in total (attached + unattached) progeny concentration. Longer whisker in positive direction and larger mean than median indicate that radon and thoron progeny concentration was positively skewed. The EERC_A and EERC_U in the

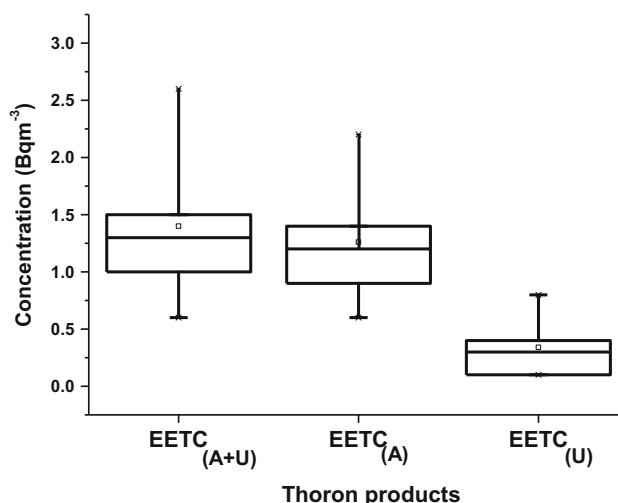


Fig. 5 Distribution of total (attached + unattached), attached and unattached thoron progeny concentrations (Bqm⁻³)

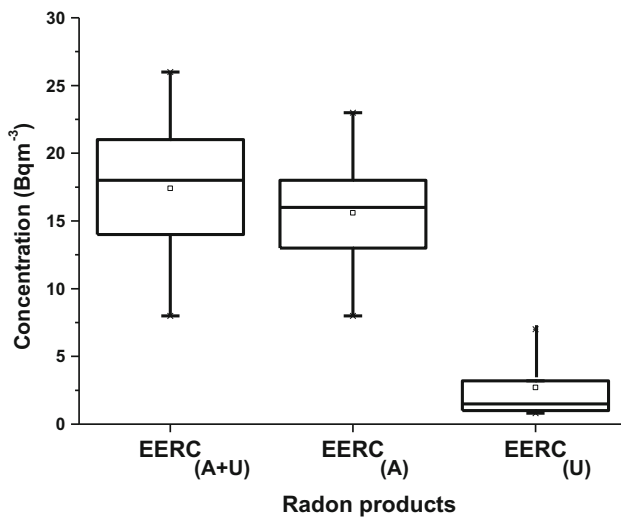


Fig. 6 Distribution of total (attached + unattached), attached and unattached radon progeny concentrations (Bqm^{-3})

dwellings varied from 8 to 23 Bqm^{-3} with a median value of 16 Bqm^{-3} and from 1 to 7 Bqm^{-3} with a median value of 1.5 Bqm^{-3} , respectively. Similarly, The EETC_A and EETC_U in the dwellings ranged from 0.6 to 2.2 with a median value of 1.2 Bqm^{-3} and from 0.1 to 0.8 Bqm^{-3} with a median value of 0.3 Bqm^{-3} , respectively. The ICRP (1993) estimated expected concentrations in buildings, which in terms of EERC is 2–50 Bqm^{-3} and EETC is 0.04–2 Bqm^{-3} . The results obtained were within the range of ICRP estimated (ICRP 1993). This corresponds to thoron/radon EEC ratio of 0.08 which is in the range of worldwide specified value 0.01–0.5 (UNSCEAR 2000) (Table 3). About 14 dwellings (35%) have shown thoron unattached progeny concentration as below detectable level (BDL), and about 10 dwellings (25%) have shown radon unattached progeny concentration as BDL. As the main threat to mankind is from inhalation of unattached progeny concentration, these BDL values show that those dwellings are free from any kind of risk. The average value of unattached fraction for radon progeny f_p^{Rn} and unattached fraction for thoron progeny f_p^{Tn} was 0.15 ± 0.09 and 0.18 ± 0.10 , respectively. The f_p values in indoor environments are quite similar to the results of Guo's measurements of unattached fraction (f_p : 9–16%) in indoor environment (Guo et al. 2012) and Canoba's measurements in dwellings without additional aerosol sources in Argentina (f_p : 9–29%) (Canoba and Lopez 2000), respectively.

Figure 7 shows the comparison of total (attached + unattached) equilibrium equivalent radon and thoron concentration with outdoor gamma dose rate. The average values of total (attached + unattached) equilibrium equivalent concentration $\text{EEC}_{(A+U)}$ (Bqm^{-3}) were found 16, 18 and 18 Bqm^{-3} for radon and were found 1.2,

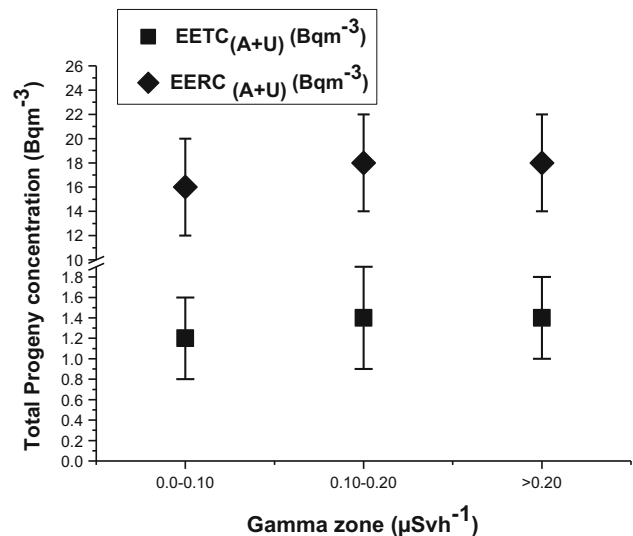


Fig. 7 Comparison of equilibrium equivalent concentration (Bqm^{-3}) of radon and thoron in three gamma zones ($\mu\text{Sv h}^{-1}$)

1.4 and 1.4 Bqm^{-3} for thoron in the first zone ($0-0.10 \mu\text{Sv h}^{-1}$), second zone ($0.10-0.20 \mu\text{Sv h}^{-1}$) and third zone ($\geq 0.20 \mu\text{Sv h}^{-1}$), respectively, as also shown in Table 3 (Part A). The value of total (attached + unattached) equilibrium equivalent concentration of radon and thoron was found maximum in the second and third zones as shown in Fig. 7. The higher concentration of radon and thoron progeny in the second zone might be due to mineralogical content present in soil of that area. The higher concentration of radon and thoron progeny in the third zone may be due to high natural radioactivity levels in soil and building materials existing in this region and the presence of main boundary thrust in this region (Ramola et al. 2006) as shown in Fig. 2. Also few locations of zone 3 are in the vicinity of thrust providing potential pathways for the higher emanation of radon gas from the deeper part of the crust (Choubey et al. 2003).

Annual effective doses from radon and thoron

The annual effective dose due to radon progeny (AED_{Rn}) received by the inhabitants in the dwellings under study varied from 403 to 1310 $\mu\text{Sv y}^{-1}$ with an average value of $885 \pm 227 \mu\text{Sv y}^{-1}$ and annual effective dose due to thoron progeny (AED_{Tn}) received by the inhabitants in the dwellings under study varied from 134 to 582 $\mu\text{Sv y}^{-1}$ with an average value of $303 \pm 103 \mu\text{Sv y}^{-1}$, respectively (Table 3). Figure 8 shows the box whisker plot of the annual effective dose rate for radon progeny AED_{Rn} ($\mu\text{Sv y}^{-1}$) and for thoron progeny AED_{Tn} ($\mu\text{Sv y}^{-1}$). The 50% of the annual effective dose for thoron and radon was greater than 291 and 907 $\mu\text{Sv y}^{-1}$. The geometric mean of AED_{Rn} and AED_{Tn} was 854 and 287 $\mu\text{Sv y}^{-1}$, respectively.

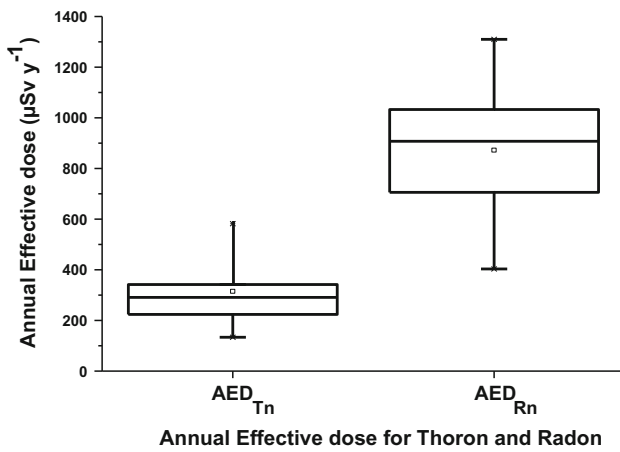


Fig. 8 Box whisker plot of annual effective doses

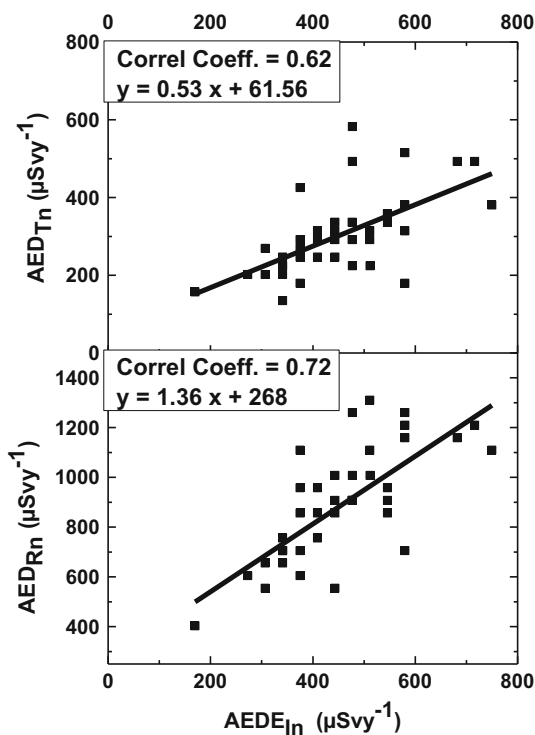


Fig. 9 A linear correlation coefficient of annual effective dose rate for radon progeny and thoron progeny with indoor gamma annual effective dose rate

The values of annual effective dose obtained for the study region are within the safe range from 3000 to 10,000 $\mu\text{Sv y}^{-1}$ recommended by ICRP (2011) and also below the recommended reference level of 10,000 $\mu\text{Sv y}^{-1}$ (WHO 2009).

Figure 9 illustrates the least square fit line and its equation for annual effective dose rate due to radon and thoron progeny with indoor gamma annual effective dose rate. A good positive correlation coefficient of 0.61 with

slope 0.53 has been observed between annual effective dose rate for thoron progeny (AED_{Tn}) $\mu\text{Sv y}^{-1}$ and indoor gamma annual effective dose rate (AEDE_{In}) $\mu\text{Sv y}^{-1}$. Similarly, a very good positive correlation of 0.72 with slope 1.36 has been observed between annual effective dose rate for radon progeny (AED_{Rn}) $\mu\text{Sv y}^{-1}$ and indoor gamma annual effective dose rate (AEDE_{In}) $> \mu\text{Sv y}^{-1}$.

Variation attributable to building materials

The building materials are a significant source of radon in dwellings. Higher radon exhalation rates from building materials and presence of the source of uranium in building materials results in higher indoor radon concentration. Table 3 (Part B) shows the variation of equilibrium equivalent concentration of radon and thoron along the different building materials. The distribution of total thoron and radon progeny concentration among different type of dwellings is presented in Figs. 10 and 11. The average total (attached + unattached) and attached equilibrium equivalent concentrations of radon and thoron were found to be maximum in mud + mud and mud + R.C.C. dwellings. The average value of thoron progeny for total (attached + unattached) and attached was 1.8 ± 0.9 and $1.6 \pm 0.8 \text{ Bqm}^{-3}$ in mud + R.C.C dwellings and was 2.0 ± 0.9 and $1.7 \pm 0.7 \text{ Bqm}^{-3}$ in mud + mud dwellings, respectively. Similarly, the average value of radon progeny for total (attached + unattached) and attached was 21 ± 9 and $19 \pm 7 \text{ Bqm}^{-3}$ in mud + R.C.C dwellings and was 20 ± 6 and $18 \pm 6 \text{ Bqm}^{-3}$ in mud + mud dwellings, respectively. The minimum value of radon and thoron progeny was observed in marble + R.C.C and tiles + R.C.C. The average value of $\text{EETC}_{(\text{A}+\text{U})}$ and $\text{EETC}_{(\text{A})}$ was 1.2 ± 0.5 and 1.0 ± 0.4 in marble + R.C.C and 1.2 ± 0.4 and 1.0 ± 0.4 in tiles + R.C.C. dwellings,

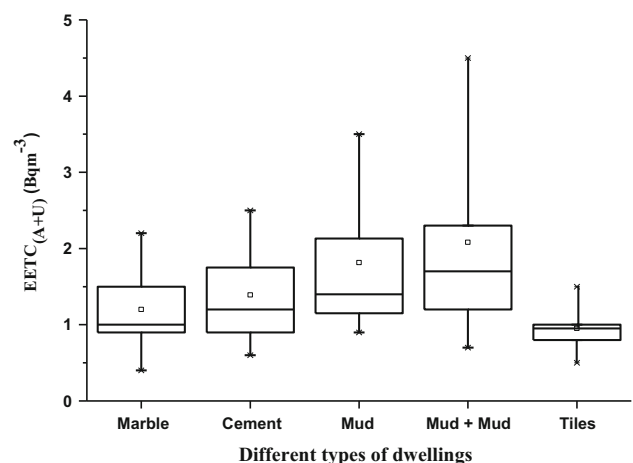


Fig. 10 Distribution of total (attached + unattached) thoron progeny concentration among different types of dwellings

respectively. Similarly, the average value of $EERC_{(A+U)}$ and $EERC_{(A)}$ was 16 ± 6 and 14 ± 5 in marble + R.C.C and 15 ± 4 and 13 ± 5 in tiles + R.C.C. dwellings, respectively. The values of radon and thoron progeny concentration in the different dwellings are found to be comparatively same, this may be due to their small half-lives. But among all the dwellings, mud type of dwellings has slightly high value of radon and thoron progeny concentration because sources of radon and thoron in the indoor air are ground and

building materials used in the construction (Avinash et al. 2014). The mud houses mainly consist of mud brick and soil floor, and indoor radon and thoron emanate mainly from the earth surface through the gap in soil to the atmosphere. The Kruskal–Wallis test (Kruskal and Wallis 1952) was applied under the null hypothesis that the median of $EETC_{(A+U)}$ and $EERC_{(A+U)}$ for different building materials is the same, but the test showed a statistically significant difference among the medians of the $EETC_{(A+U)}$ for different building materials with test static of 12.08 at 99% confidence level ($p = 0.01$). Also the median of the $EERC_{(A+U)}$ for the different building materials showed a statistically significant difference with test static of 7.60 at 90% confidence level ($p = 0.10$).

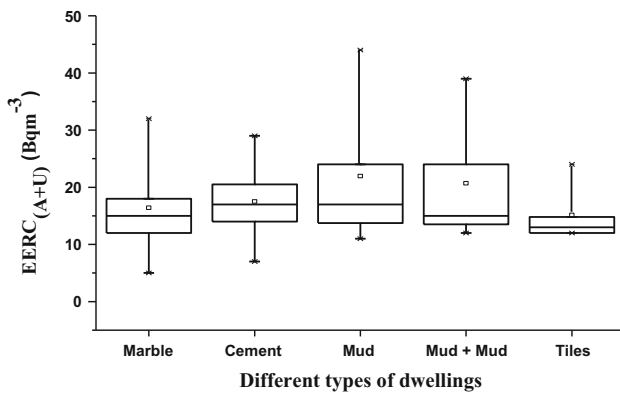
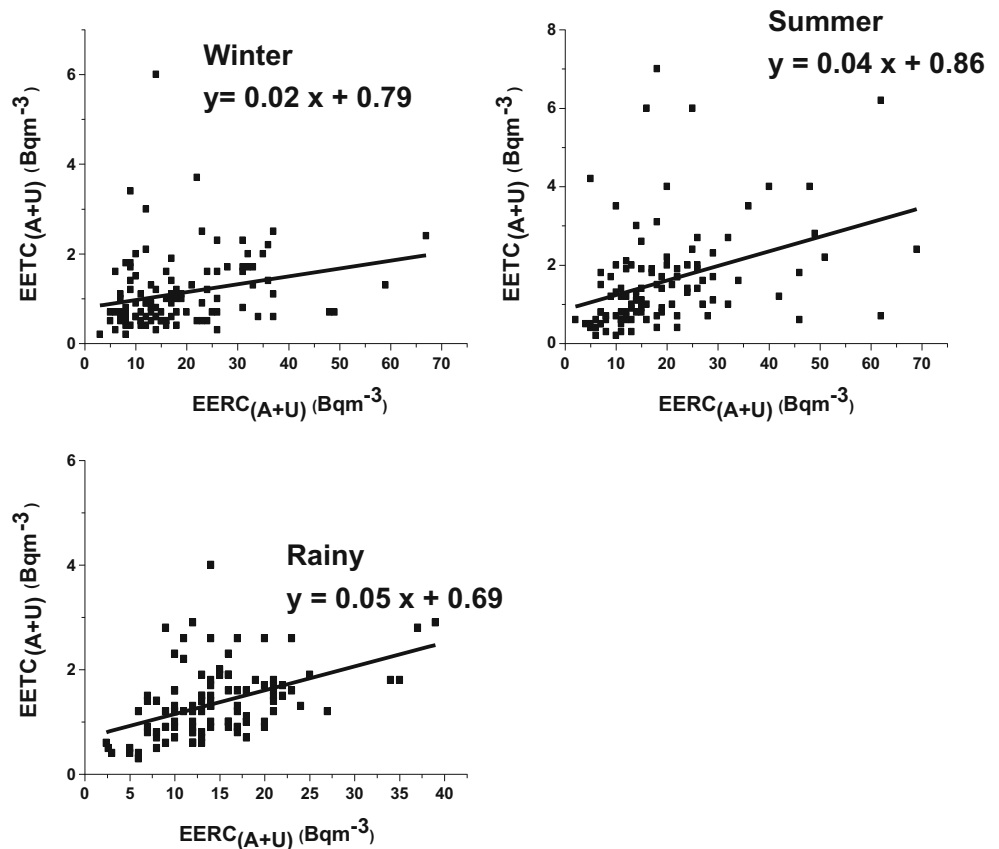


Fig. 11 Distribution of total (attached + unattached) radon progeny concentration among different types of dwellings

Seasonal variation

The range of progeny concentration for radon and thoron as a function of seasonal variation is given in Table 3 (Part C). The average radon progeny concentration was always found to be higher than that of thoron progeny concentration. In the seasonal variation of equilibrium equivalent concentration of radon and thoron, maximum concentration of radon and thoron progeny concentration has been found in winter season as compared to other

Fig. 12 Seasonal variation of equilibrium equivalent concentration of radon and thoron



seasons. The Kruskal–Wallis test (Kruskal and Wallis 1952) was applied under the null hypothesis that the median of $EETC_{(A+U)}$ and $EERC_{(A+U)}$ for different seasons is the same. The statistically significant evidence at $p = 0.15$ shows that there is a difference in the medians of different seasons for $EETC_{(A+U)}$. Similarly for $EERC_{(A+U)}$, the statistically significant evidence at $p = 0.005$ shows that there is a difference in the medians of different seasons. In order to derive a correlation between total (attached + unattached) equilibrium equivalent concentration of radon and thoron as a function of different seasons, the $EETC_{(A+U)}$ (Bqm^{-3}) was plotted against the $EERC_{(A+U)}$ (Bqm^{-3}) obtained in different seasons and a linear fitting of the data points was done (Fig. 12) (Mishra et al. 2004), from which the equation indicating the radon–thoron progeny correlation has been deduced (shown in the figure). From this equation, the thoron progeny concentration was derived to be about 5% that of radon progeny in the rainy season, 4% in summer and the minimum of 2% in winter. This also indicates a maximum exhalation of radon during the winter period.

Conclusions

- The average value of indoor and outdoor gamma dose rate was found to be 0.14 ± 0.03 and $0.15 \pm 0.04 \mu Sv h^{-1}$, respectively. The value of indoor annual effective dose equivalent has been varied from 171 to $750 \mu Sv y^{-1}$ with an average value of $452 \pm 120 \mu Sv y^{-1}$ and was found well within the safe limit suggested by ICRP (2010).
- The results obtained for total (attached + unattached), attached and unattached progeny concentrations of radon and thoron were within the ICRP estimated range (ICRP 1993).
- The value of total (attached + unattached) equilibrium equivalent concentration of radon and thoron was found maximum in the second and third zones which may be due to the presence of mineralogical content in the second zone and the presence of main boundary thrust in the third zone.
- The values of radon and thoron progeny concentration were found slightly maximum in mud type of dwellings as compared to other dwellings because mud houses mainly consist of mud brick and soil floor which enhances the emanation of radon and thoron.
- The values of annual effective dose rate obtained for the study region are within the safe range from 3000 to $10,000 \mu Sv y^{-1}$ recommended by ICRP (2011) and also below the recommended reference level of $10,000 \mu Sv y^{-1}$ (WHO 2009).

- A good positive correlation coefficient of 0.61 has been observed between annual effective dose rate for thoron progeny (AED_{Tn}) $\mu Sv y^{-1}$ and indoor gamma annual effective dose rate ($AEDE_{In}$) $\mu Sv y^{-1}$, and correlation coefficient of 0.72 has been observed between annual effective dose rate for radon progeny (AED_{Rn}) $\mu Sv y^{-1}$ and indoor gamma annual effective dose rate ($AEDE_{In}$) $\mu Sv y^{-1}$, respectively.

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