



Dose assessment from the exposure to attached and unattached progeny of radon and thoron in indoor environment

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Abstract

The radiation dose from the exposure to radon (^{222}Rn) and thoron (^{220}Rn) is mainly contributed by their progeny, not by the gases themselves. This study aims to investigate the health risk associated with the internal exposure to attached and unattached progeny of ^{222}Rn and ^{220}Rn in the indoor environment of Garhwal Himalaya, India. For this purpose, the passive measurements of attached and unattached progeny levels of ^{222}Rn and ^{220}Rn were performed in Garhwal Himalaya, India using nuclear track detector based recently developed progeny sensors. The measured values of unattached and total progeny concentrations were used to estimate the unattached fractions and annual effective doses. The annual mean unattached fractions of ^{222}Rn and ^{220}Rn progeny were found to be 0.15 ± 0.04 and 0.17 ± 0.05 , respectively. The estimated values of the annual effective doses were found to be 3.4 ± 1.9 mSv/y and 0.7 ± 0.4 mSv/y due to the progeny of ^{222}Rn and ^{220}Rn , respectively. The methodology and results obtained are discussed in details.

Keywords EERC · EETC · Attached and unattached fractions · DTPS · DRPS

Introduction

The inhalation of ^{222}Rn , ^{220}Rn and their daughters imparts a significant portion of the total dose from all natural sources of radiation to people (Jonsson 1988; UNSCEAR 2006). The exposure to these radioactive species has been recognized by the World Health Organization as second most significant cause of lung cancer next to smoking (WHO 2009). The activity levels of ^{222}Rn , ^{220}Rn and their progeny should, therefore, be monitored in the indoor atmosphere with reliable and accurate methods. Furthermore, as the lung doses are mainly contributed by the daughters of ^{222}Rn and ^{220}Rn and not by ^{222}Rn and ^{220}Rn ,

it becomes mandatory to perform direct measurements of the daughters. The daughters of ^{222}Rn and of ^{220}Rn possess high diffusivities and tendency to form clusters and then to stick on surfaces. Owing to these characteristics, freshly formed decay products get attached to aerosol particles present in the indoor atmosphere. The resulting distribution of ^{222}Rn and ^{220}Rn bearing particles is, in general, categorized into two classes, viz., the fine or unattached fraction (~ 1 nm radius), i.e. progeny clusters and the coarse or attached fraction (~ 75 nm radius) (Mayya et al. 2010). The coarse progeny is expected to move through the upper respiratory tract and leave alveoli during exhalation. A significant fraction of fine progeny also moves through the upper respiratory tract but is deposited in the alveoli and is then associated with somatic transport processes. It has been experimentally verified that the absorption of radon daughters by blood depends on particle size and the fine progeny is absorbed by the blood more rapidly in comparison with the coarse fraction (Butterweck et al. 2002). In general, a major portion of the dose to target tissues in the bronchial epithelium is contributed by the fine fraction (Chamberlain and Dyson 1956). Thus, to assess exposure, it is important to know the proportion of unattached and attached progeny fractions. The unattached fraction,

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defined as ratio of unattached to total progeny concentration, depends on aerosol concentration in air and can, therefore, be variable. For indoor atmosphere, a generic value of 5% (UNSCEAR 2000) seems to be assumed for dose estimation, if the value is not available in a specific case. However, in the light of recent investigations (Guo et al. 2012), 5% seems too low, and consequently doses are underestimated. More recently, the proposed value has been increased to 10% (Harrison and Marsh 2012). Therefore, for accurate dose assessment, it is necessary to measure the both types of progeny. In Garhwal Himalayan region of India, several studies were performed in the past to measure radon and thoron concentrations using passive techniques. However, a limited data is available on radon/thoron progeny (Prasad et al. 2015, 2016a; Ramola et al. 2015, 2016). As the consequential inhalation dose is mainly contributed from the progeny of ^{222}Rn and ^{220}Rn , a detailed survey on progeny measurements is needed for exact dose calculation. In this study, the attached (coarse) and unattached (fine) progeny levels of ^{222}Rn and ^{220}Rn were measured in 56 dwellings of Tehri Garhwal and Uttarkashi regions of Garhwal Himalaya, India. The measured values of activity levels were then used to estimate the inhalation doses from the exposure to the daughters of ^{222}Rn and ^{220}Rn . The study of seasonal variations in progeny activities was performed to understand the effect of environmental parameters on activity concentrations and dose quantities. An attempt has also been made to correlate the observed results with geology of the study area.

Study area

The geographical map of the investigated region showing the sampling locations is shown in Fig. 1. The map was prepared with Golden software (Surfer version) using Lambert Conformal Conical (LCC) projections according to NNRMS (2005) and transform formulae (Snyder 1987). The study area is located in Garhwal Himalaya, India at an altitude of 2500 m above the sea level.

Geological background of study area

The information about the rock type, distribution of lithological units and other geological features of a region are of great importance in predicting radon emanation in the soil matrix and its transportation to the soil surface. Geologically, the Himalaya is divided into four litho-tectonic subdivisions: Outer Himalaya, Lesser Himalaya, Higher Himalaya and Tethys Himalaya (Heim and Gansser 1939). Tehri Garhwal region is characterized by the rocks of Lesser Himalaya and Central Himalaya. The Central Himalaya lies to the north of Main Central Thrust (MCT)

and Lesser Himalaya lies to south of it. A group of regional metamorphic rocks is exposed in Central Himalaya which is known as Central Crystallines. The main rock types of Central Crystallines are migmatites, quartzite, marble, etc. In general, the rocks of the Lesser Himalaya represent signs of multiple phases of deformation and metamorphism (Valdiya 1980). Uttarkashi district is characterized by higher Himalayan Crystallines and Lesser Himalayan sediments. The higher Himalayan Crystallines are thrust over the Berinag Formation of the Lesser Himalaya along the Main Central Thrust. Berinag Formation is triggered by the Damta Group of rocks (Valdiya 1980). The area is sandwiched between the Main Central Thrust to the north and the Srinagar Thrust to the south and lies in a highly seismotectonically active zone (Agarwal and Kumar 1973). Budhakedar region of Tehri Garhwal and Sainj (Bhatwari) region of Uttarkashi are exposed along the Main Central Thrust (MCT) (Heim and Gansser 1939). The MCT exposed along the Kumulti stream (Uttarkashi) divides the Gamri quartzite (massive quartzite and quartz sericite schist) of Garhwal Group from Central Crystallines (Gupta 1977).

Materials and methods

The measurements of total (i.e. sum of attached and unattached) progeny concentrations of ^{222}Rn and ^{220}Rn were carried out using direct progeny sensors in bare mode. For the measurements of attached progeny concentrations of ^{222}Rn and ^{220}Rn , wire-mesh capped direct progeny sensors were used. A brief description of these sensors employed for progeny measurements is given below:

Direct progeny sensors in bare mode

Direct progeny sensors work on the principle of registration of alpha tracks emitted from the progeny atoms deposited on LR-115 nuclear track detectors. The detector system is made up of aluminized Mylars (which act as absorbers) of suitable thicknesses fixed on LR-115 nuclear track detectors (Fig. 2). The direct thoron progeny sensor (DTPS) used for the measurement of ^{220}Rn progeny consists of a 50 μm aluminized Mylar mounted on LR-115 detector which detects alpha particles emitted from ^{212}Po only (alpha energy 8.78 MeV) and absorbs the higher energy particles. Similarly, the direct radon progeny sensor (DRPS) comprises of an absorber combination of aluminized Mylar (25 μm) and cellulose nitrate (12 μm) with a total thickness of 37 μm which records the tracks produced by alpha particles emitted from ^{214}Po (alpha energy 7.69 MeV) and attenuates the entry of higher energy particles to detector. The detail methodology of these sensors

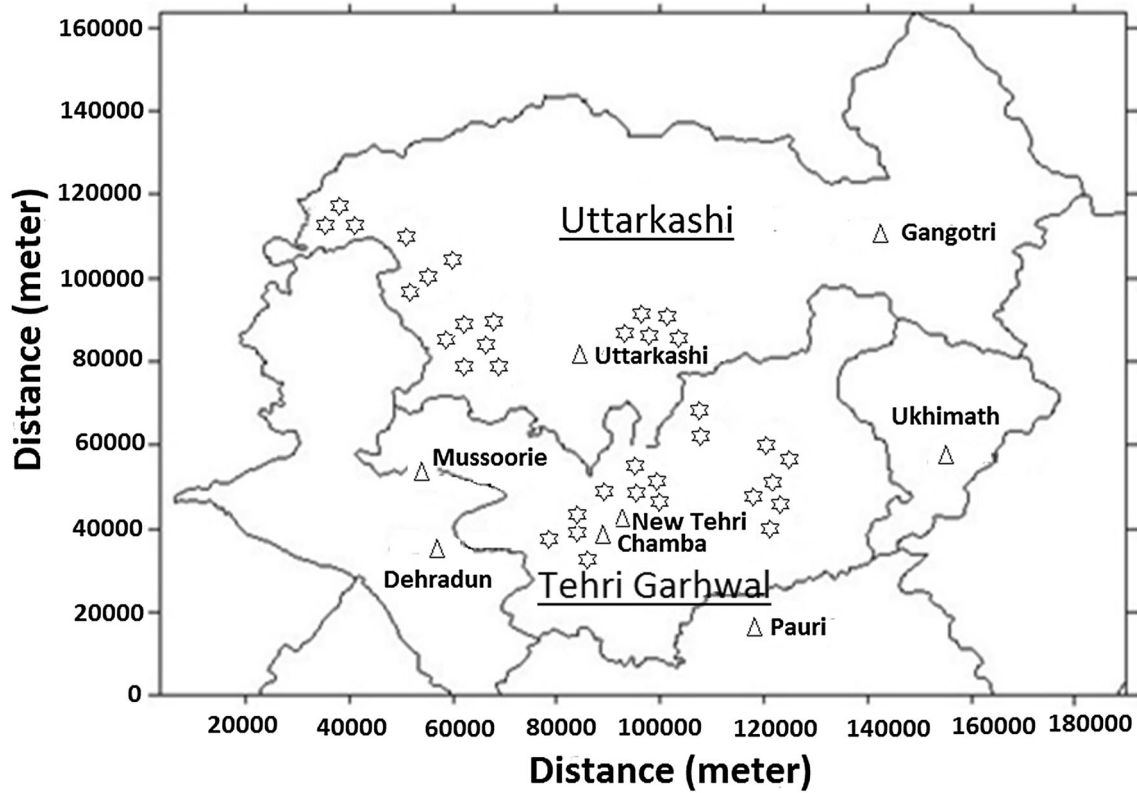
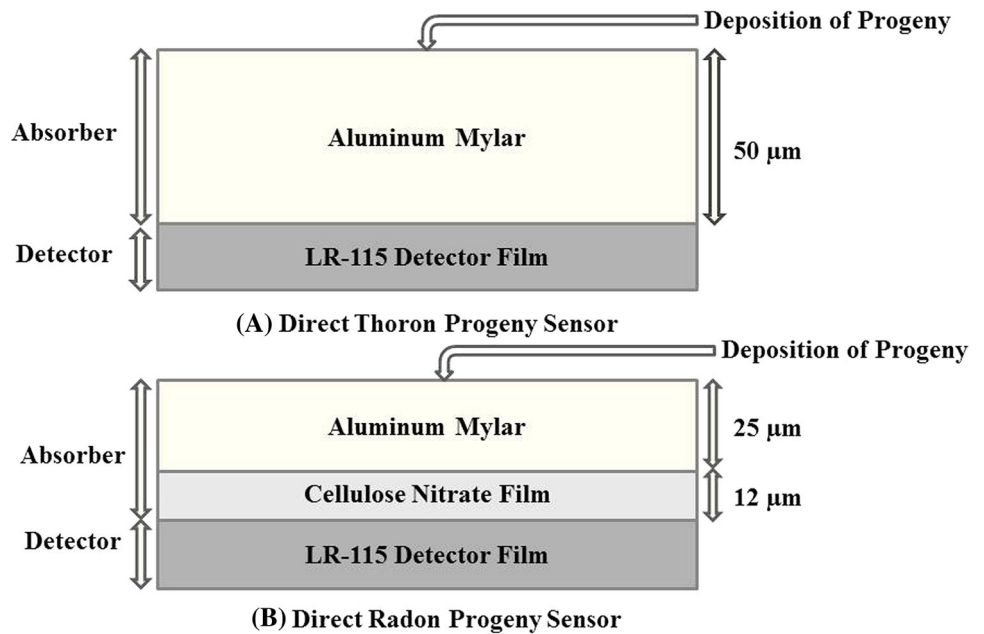


Fig. 1 Geographical map of the study area showing sampling locations

Fig. 2 Schematic diagram of direct progeny sensor in bare mode



is explained elsewhere (Mishra et al. 2009). For estimating ^{222}Rn progeny, the contribution of ^{220}Rn progeny (which emits higher energy alpha particles) to total tracks recorded on DRPS is eliminated from total tracks recorded on DRPS, using the equation (Mishra et al. 2009):

$$\text{Tracks}_{\text{DRPS}}^{\text{OnlyRnP}} = \text{Tracks}_{\text{DRPS}}^{\text{Total}} - \frac{\eta_{\text{RT}}}{\eta_{\text{TT}}} \text{Tracks}_{\text{DTPS}}^{\text{Total}}$$

where, η_{RT} and η_{TT} represent track registration efficiencies of ^{220}Rn progeny in DRPS and that in DTPS, respectively, $\text{Tracks}_{\text{DRPS}}^{\text{OnlyRnP}}$ represents the track density recorded on

DRPS due to radon progeny only and $\text{Tracks}_{\text{DRPS}}^{\text{Total}}$ and $\text{Tracks}_{\text{DTPS}}^{\text{Total}}$ are the acronyms used for total track density recorded on DRPS and DTPS, respectively.

The equilibrium equivalent thoron concentration (EETC) and equilibrium equivalent radon concentrations (EERC) are calculated using following relations (Mishra and Mayya 2008; Mishra et al. 2009):

$$\text{EETC} \left(\frac{\text{Bq}}{\text{m}^3} \right) = \frac{\text{Tracks}_{\text{DTPS}}^{\text{Total}}}{k_T \times t(\text{days})},$$

and

$$\text{EERC} \left(\frac{\text{Bq}}{\text{m}^3} \right) = \frac{\text{Tracks}_{\text{DRPS}}^{\text{OnlyRnP}}}{k_R \times t(\text{days})}$$

where, k_T and k_R represents sensitivity factors for DTPS and DRPS, respectively, and t is exposure time in days. The numerical values of k_T and k_R in natural environment given by Mayya et al. (2010) are $0.94 \text{ tracks cm}^{-2} \text{ d}^{-1}/\text{EETC} (\text{Bq m}^{-3})$ and $0.09 \text{ tracks cm}^{-2} \text{ d}^{-1}/\text{EERC} (\text{Bq m}^{-3})$, respectively.

Wire-mesh capped direct progeny sensors

This detector system consists of a bare mode direct progeny sensor covered by a 200 mesh type wire screen in such a way that the entire system eliminates the fine fraction and detects the coarse fraction (Fig. 3). The fine portion of the progeny atoms is stuck on the wire screen, and only the coarse progeny atoms enters the sensor. Thus, α -particles recorded by this sensor are the measure of coarse progeny concentration. The detailed description of measurement technique is given elsewhere (Mayya et al. 2010). The activity concentrations of attached progeny of ^{222}Rn and ^{220}Rn are estimated in the similar manner as in case of bare mode sensors. The sensitivity factors used in the calculation of coarse progeny using wire-mesh capped DTPS and DRPS are $0.33 (\text{Tracks.cm}^{-2} \text{ d}^{-1})/(\text{Bq m}^{-3})$ and $0.04 (\text{Tracks.cm}^{-2} \text{ d}^{-1})/(\text{Bq m}^{-3})$, respectively.

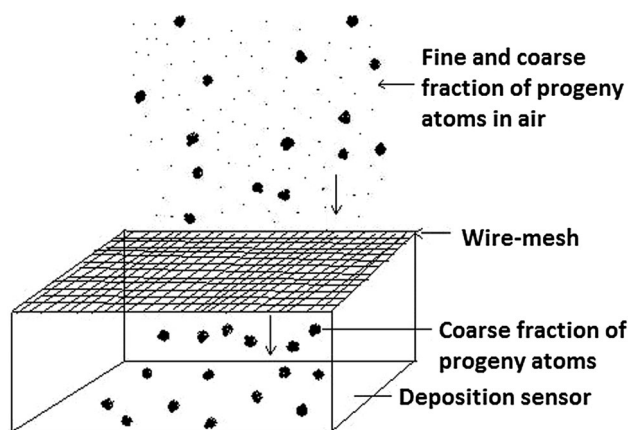


Fig. 3 Schematic diagram of wire-mesh capped direct progeny sensor

Uncertainties

In nuclear track detector based radon/thoron progeny measurement techniques, the results are mainly influenced by two types of uncertainties. First kind of uncertainty arises from random counting of track densities and second kind of uncertainty of calibration/sensitivity factors. In this paper, results are presented as $(AM \pm SD)$. Here, AM and SD stand for arithmetic mean and standard deviation of activity concentrations over number of houses (or locations), respectively. SDs denote sample standard deviations calculated from individual values, but standard deviations of the mean (standard error).

Detector installation, retrieval, chemical processing and counting of tracks

The bare mode DTPS/DRPS along with wire-mesh capped DTPS/DRPS were deployed for 3 months on the ceiling at a minimum height of 1.5 m and at least 10 cm away from the adjacent wall surfaces to avoid the registration of tracks due to progeny atoms deposited on wall surfaces. The arrangement was done in such a way that deposition surface (absorber surface) faces the indoor environment horizontally (i.e. the detector is suspended vertically). To study seasonal variation of progeny concentrations, after 3 months exposure, detectors were retrieved and a fresh set of detectors were installed in the same way in the same dwelling. The exposed detectors were sealed in doubly aluminized bags along with a few control detectors (for background correction) until further analysis. The latent tracks recorded on exposed detectors were made optically visible by chemically processing (etching) them with 2.5 N NaOH solution at 60°C for 1.5 h. The chemically processed detectors were counted for track density measurements using spark counter. The background subtracted mean track densities were finally used to obtain attached progeny concentrations of ^{222}Rn and ^{220}Rn using appropriate sensitivity factors.

Results and discussion

Descriptive statistics of total, attached and unattached fractions of radon/thoron progeny

The descriptive statistics of activity levels and unattached fractions of $^{222}\text{Rn}/^{220}\text{Rn}$ daughters for different seasons of a year are presented in Table 1. The annual mean values of total, attached and unattached radon progeny levels were found to be 53 ± 30 , 46 ± 24.3 and $7 \pm 9 \text{ Bq/m}^3$,

Table 1 Descriptive statistics of activity concentrations and unattached fractions of indoor radon and thoron progeny in Garhwal Himalaya

	AM \pm SD in different seasons				Annual mean			
	Rainy	Autumn	Winter	Summer	Min	Max	AM \pm SD	GM
EERC (attached + unattached) in Bq/m ³	56.6 \pm 34	62.4 \pm 68.4	65.9 \pm 45.4	28.4 \pm 30.1	9	160	53.3 \pm 30	46.2
EERC (attached) in Bq/m ³	50.8 \pm 30.6	52.5 \pm 51.4	57.4 \pm 41.7	24.3 \pm 28.1	7.4	109	46.2 \pm 24.3	40.3
EERC (unattached) in Bq/m ³	5.8 \pm 5.3	9.9 \pm 23.5	8.6 \pm 11.7	4.1 \pm 3	1.5	68.4	7.1 \pm 9	5.4
Unattached fraction (Rn Progeny)	0.11 \pm 0.06	0.14 \pm 0.08	0.15 \pm 0.11	0.19 \pm 0.09	0.07	0.34	0.15 \pm 0.04	0.14
EETC (attached + unattached) in Bq/m ³	2.7 \pm 2.2	3.6 \pm 3.8	2.6 \pm 1.9	1.3 \pm 1.2	0.7	8.4	2.5 \pm 1.6	2.1
EETC (attached) in Bq/m ³	2.3 \pm 2.1	3.2 \pm 3.3	2.2 \pm 1.7	1.1 \pm 1.2	0.5	7.1	2.2 \pm 1.4	1.8
EETC (unattached) in Bq/m ³	0.4 \pm 0.3	0.4 \pm 0.6	0.4 \pm 0.3	0.2 \pm 0.2	0.1	1.3	0.3 \pm 0.2	0.3
Unattached fraction (Tn progeny)	0.19 \pm 0.1	0.15 \pm 0.13	0.16 \pm 0.10	0.18 \pm 0.11	0.07	0.36	0.17 \pm 0.05	0.16

AM arithmetic mean, SD standard deviation, GM geometric mean

respectively. Similarly, the annual mean values total, attached and unattached thoron progeny concentrations were found to be 2.5 ± 1.6 , 2.2 ± 1.4 and 0.3 ± 0.2 Bq/m³, respectively. The annual mean values of ²²²Rn and ²²⁰Rn levels in the study area were previously reported to be 122 and 69 Bq/m³, respectively (Prasad et al. 2016b). The annual mean ²²²Rn concentration is above the reference level of 100 Bq/m³ suggested by World Health Organization as safe limit (WHO 2009). On the other hand, WHO recommends a reference level not exceeding 300 Bq/m³ in case of existing houses based on the epidemiological data obtained from China, Europe and North America (WHO 2009; ICRP 2011). These values of radon and thoron concentrations are higher than annual mean values at national (40 Bq/m³ for radon; 10 Bq/m³ for thoron) and international level (42 Bq/m³ for radon; 12.5 Bq/m³ for thoron) (Mishra et al. 2009; UNSCEAR 2000). Further, it was noticed that the attached (coarse) and unattached (fine) fractions of ²²²Rn progeny contribute 87 and 13% to total radon progeny, respectively. In case of ²²⁰Rn progeny, the attached (coarse) and unattached (fine) fractions were found to contribute 86 and 14%, respectively.

Dependence of ²²²Rn/²²⁰Rn progeny levels on seasons

The measurements were conducted in different seasons of a year to see the effect of environmental parameters (e.g. temperature, humidity, ventilation conditions, etc.) on activity levels of ²²²Rn and ²²⁰Rn progeny. The mean concentration of total (i.e. sum of attached and unattached) ²²²Rn progeny was found to be 57 ± 34 , 62 ± 68 , 66 ± 45 and 28 ± 30 Bq/m³ in rainy, autumn, winter and summer seasons, respectively. The mean activity levels of attached radon progeny was found to be 51 ± 31 , 53 ± 51 ,

57 ± 42 and 24 ± 28 Bq/m³ in rainy, autumn, winter and summer seasons, respectively. The mean values of unattached radon progeny levels were observed to be 6 ± 5 , 10 ± 24 , 9 ± 12 and 4 ± 3 Bq/m³ in rainy, autumn, winter and summer seasons, respectively. The concentrations are altogether low, which explains the high standard deviations, which result from measurement uncertainty, which is high for low concentrations, and geographical variability between locations. The activity concentrations can be assumed to be influenced by environmental factors such as temperature and ventilation conditions. In summer, total progeny activity concentrations appear lower than in the other seasons. This may be attributed to better ventilation conditions of the houses during winter and autumn seasons (colder months) of the year as compared to summer and rainy seasons. In case of thoron progeny also, higher activity concentrations were found in winter and autumn seasons compared to summer and rainy seasons.

Unattached fractions of ²²²Rn/²²⁰Rn progeny

The unattached fraction was calculated as the ratio of the unattached progeny concentration to the total progeny concentration. The annual mean unattached progeny fractions of ²²²Rn and ²²⁰Rn ranged from 0.07 to 0.34 with a mean of 0.15 ± 0.04 and from 0.07 to 0.36 with a mean of 0.17 ± 0.05 , respectively. A wide variation has recently been observed among unattached fractions in different parts of the northern India. Mehra et al. (2015) have reported the values of the unattached fractions in the range of 0.02–0.12 for radon progeny and 0.04–0.17 for thoron progeny in Mansa, Muktsar, Bathinda and Faridkot areas of Punjab, India (Mehra et al. 2015). In Muktsar and Mansa areas of Punjab, India; the unattached progeny fractions of ²²²Rn and ²²⁰Rn were reported to be 0.08 ± 0.04 and 0.08 ± 0.02 , respectively (Bangotra et al. 2015). The mean

values of unattached progeny fractions of ^{222}Rn and ^{220}Rn are reported to be 0.11 and 0.09, respectively, in Hamirpur region of Himachal Pradesh, India (Singh et al. 2016). In South West, West and North East regions of Punjab, India; the mean unattached progeny fractions of ^{222}Rn and ^{220}Rn are reported to be 0.099 and 0.071, respectively (Saini et al. 2017). A literature overview on fp (unatt. fraction) values for ^{222}Rn progeny is given in Guo et al. (2012). Essentially, a similar range of values is reported. The unattached fractions found here seem to be a bit higher than those found by the cited authors. Whether this has reasons related to geographical factors or is caused by methodological differences or mere statistical effects, cannot be decided at this stage. Guo et al. (2012) suggested that in rural environments the unattached fraction is somewhat higher because of lower aerosol load. This may also help interpreting the findings presented here. A similar finding is presented by Jílek et al. (2010), all quite close to the value 0.1 suggested by Harrison and Marsh (2012) for indoor workplaces. It seems that very little literature is available for unattached fractions of ^{220}Rn progeny; therefore, for the time being, we set it equal to the one of ^{222}Rn progeny in dose calculations.

Correlation between attached and unattached progeny

The relationship between attached and unattached progeny fractions was obtained using linear regression method. Figures 4 and 5 illustrate the least square fit lines and their equations for progeny of ^{222}Rn and ^{220}Rn , respectively. The measured values of attached progeny was found to be positively correlated with that of unattached progeny with Pearson correlations $R^2 = 0.27$ and 0.59 , for ^{222}Rn and ^{220}Rn , respectively. Since the attached progeny is directly related to aerosol concentration in the indoor atmosphere, the observed positive correlation between attached and unattached progeny suggests that the aerosol concentration

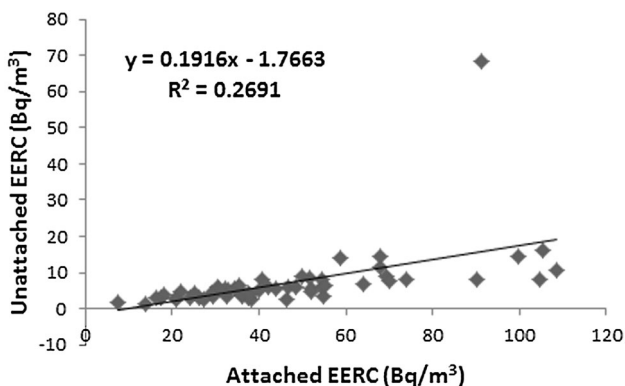


Fig. 4 Relationship between attached and unattached EERC

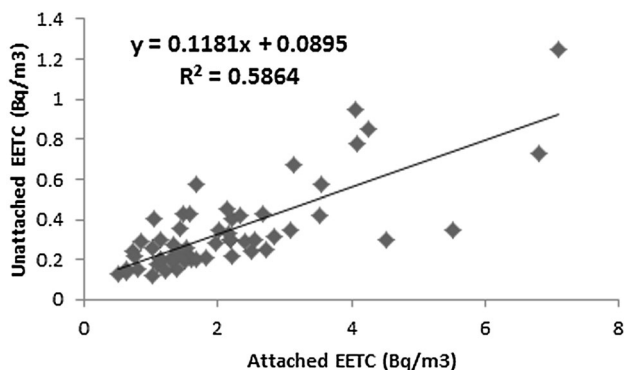


Fig. 5 Relationship between attached and unattached EETC

in the indoor environment of investigated Garhwal Himalaya is almost uniform. However, further attempts are needed to measure the aerosol concentrations in the area using specific measurement techniques.

Influence of geology

The information about the geology of a particular region may be helpful in explaining the variability of radon/thoron progeny in that region. In the present investigation, wide variation in radon/thoron progeny levels has been observed over the investigated regions located in Garhwal Himalayan region. The relatively higher activity levels of $^{222}\text{Rn}/^{220}\text{Rn}$ progeny were found in Budhakeadar area of Tehri Garhwal and Sainj(Bhatwari) area of Uttarakashi which may be due to the vicinity to the Main Central Thrust (MCT) in these regions. These regions are exposed along the MCT. Emanation rate of radon/thoron from soil is higher in such thrust areas as compared to other regions.

Estimation of annual effective doses

The calculation of dose was done using UNSCEAR relations as follows (UNSCEAR 2000):

$$D_{\text{RnP}} \left(\frac{\text{mSv}}{\text{y}} \right) = \text{EERC}_{\text{Total}} (\text{Bq m}^{-3}) \times 9 \text{nSv} (\text{Bq h m}^{-3})^{-1} \times 0.8 \times 8760 \text{ h} \times 10^{-6} \tag{1}$$

$$D_{\text{TnP}} \left(\frac{\text{mSv}}{\text{y}} \right) = \text{EETC}_{\text{Total}} (\text{Bq m}^{-3}) \times 40 \text{nSv} (\text{Bq h m}^{-3})^{-1} \times 0.8 \times 8760 \text{ h} \times 10^{-6} \tag{2}$$

where, $D_{\text{RnP}} \left(\frac{\text{mSv}}{\text{y}} \right)$ and $D_{\text{TnP}} \left(\frac{\text{mSv}}{\text{y}} \right)$ are annual effective doses from the internal exposure to progeny of ^{222}Rn and ^{220}Rn , respectively. $\text{EERC}_{\text{Total}}$ and $\text{EETC}_{\text{Total}}$ are annual mean total progeny concentrations of ^{222}Rn and ^{220}Rn in the study area, respectively. The number 0.8 is the fraction

of time an individual spends inside the house. The numbers 9 and 40 represent the dose conversion factors (DCFs) for ^{222}Rn and ^{220}Rn progeny in nSv units, respectively (UNSCEAR 2000). Since the DCFs used in the calculation are expressed in nSv units, the estimated dose (nSv) was multiplied by 10^{-6} to express the dose in mSv unit. $D_{\text{RnP}}\left(\frac{\text{mSv}}{\text{y}}\right)$ and $D_{\text{ThP}}\left(\frac{\text{mSv}}{\text{y}}\right)$ were observed to range from 0.6 mSv/h to 10.1 mSv/h with a mean value of 3.4 ± 1.9 mSv/h and from 0.2 mSv/h to 2.3 mSv/h with a mean value of 0.7 ± 0.4 mSv/h, respectively. $D_{\text{ThP}}\left(\frac{\text{mSv}}{\text{y}}\right)$ has been found to contribute about 17% to the total radiation dose due to both progeny species. In Yamuna, Tons valleys of Garhwal Himalaya, ^{220}Rn and progeny was observed to contribute about 30% of total annual inhalation dose (Prasad et al. 2016b; Ramola et al. 2016). The average value of total radiation dose from the exposure to both progeny species was found above the safe limits recommended by UNSCEAR (UNSCEAR 2000). The high dose values were found in few houses whereas in most of the dwellings the dose values have been found within the reference level. Figures 6 and 7 represent the histograms showing the frequency distributions of annual effective doses from the exposure to progeny of ^{222}Rn and ^{220}Rn ,

respectively. The high dose values were found in Budhakedar area of Tehri Garhwal and Sainj (Bhatwari) region of Uttarkashi which may be due to the vicinity to the Main Central Thrust (MCT) in these regions. From frequency distributions of ^{222}Rn and ^{220}Rn it is clear that the annual effective doses are higher than the reference level in few houses.

Conclusions

The estimated average values of total radiation dose from exposure to daughters of ^{222}Rn and ^{220}Rn were found to be slightly above the UNSCEAR reference level. It is worth noticing that activity levels of $^{222}\text{Rn}/^{220}\text{Rn}$ progeny and associated radiation doses were observed well below the reference level in majority of houses. Seasonal variability of activity levels of $^{222}\text{Rn}/^{220}\text{Rn}$ progeny suggests that they are affected by environmental factors. A significant contribution (17%) of thoron progeny to the total annual effective dose validates that thoron cannot be ignored in dose calculation as it was often considered in the past. A positive correlation has been found between the coarse and fine progeny. Results presented in this study are based on

Fig. 6 Frequency distribution of annual effective dose from the exposure to ^{222}Rn progeny

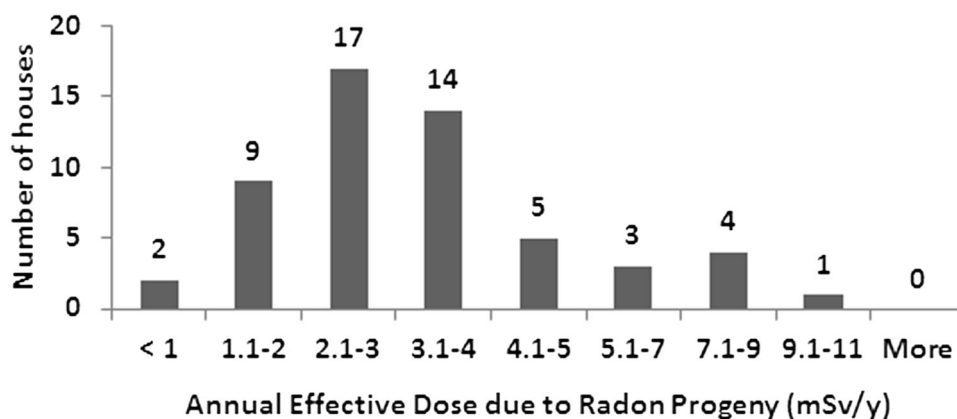
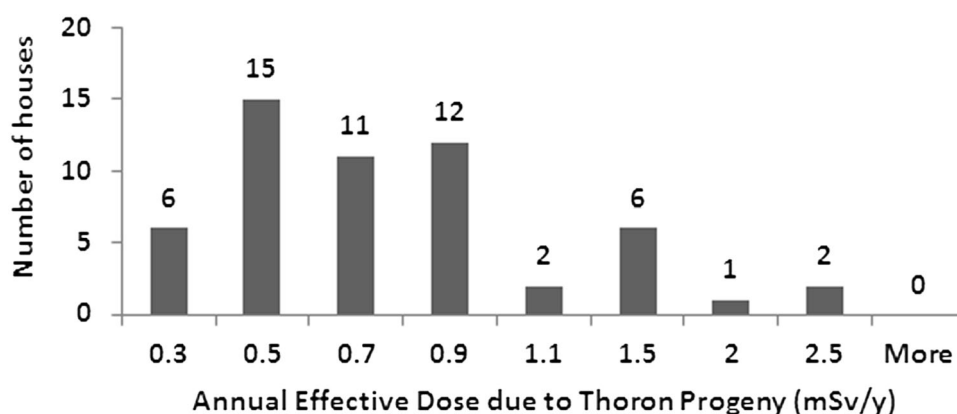


Fig. 7 Frequency distribution of annual effective dose from the exposure to ^{220}Rn progeny



the preliminary measurements carried out in the study area. In future, we intend to carry out a comprehensive study to set reference radiation level for Garhwal Himalayan region, taking into account the uncertainties in the assessment of various affecting factors.

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References

- Agarwal NC, Kumar G (1973) Geology of the upper Bhagirathi and Yamuna valleys, Uttarkashi district, Kumaun Himalaya. *Himal Geol* 3:2–23
- Bangotra P, Mehra R, Kaur K et al (2015) Estimation of EEC, unattached fraction and equilibrium factor for the assessment of radiological dose using pin-hole cup dosimeters and deposition based progeny sensors. *J Environ Radioact* 148:67–73
- Butterweck G, Schuler C, Vessù G et al (2002) Experimental determination of the absorption rate of unattached radon progeny from respiratory tract to blood. *Radiat Prot Dosimetry* 102:343–348
- Chamberlain AC, Dyson ED (1956) The dose to the trachea and bronchi from the decay products of radon and thoron. *Br J Radiol* 29:317–325
- Guo Q, Zhang L, Guo L (2012) Assessment of the unattached fraction of indoor radon progeny and its contribution to dose: a pilot study in China. *J Radiol Prot* 32:447
- Gupta SK (1977) Geology and petrology of part of Upper Bhagirathi Valley Central crystalline, M. Tech Dissertation Report, Dist. Uttarkashi, UP
- Harrison JD, Marsh JW (2012) Effective dose from inhaled radon and its progeny. *Ann ICRP* 41:378–388
- Heim A, Gansser A (1939) Central Himalaya: geological observations of the Swiss expedition 1936
- ICRP (2011) International commission on radiological protection. Radiological protection against radon exposure. Draft report for consultation
- Jílek K, Thomas J, Tomášek L (2010) First results of measurement of equilibrium factors F and unattached fractions fp of radon progeny in Czech dwellings. *Nukleonika* 55:439–444
- Jonsson G (1988) Indoor 222Rn measurements in Sweden with the solid-state nuclear track detector technique. *Health Phys* 54:271–281
- Mayya YS, Mishra R, Prajith R et al (2010) Wire-mesh capped deposition sensors: novel passive tool for coarse fraction flux estimation of radon thoron progeny in indoor environments. *Sci Total Environ* 409:378–383
- Mehra R, Bangotra P, Kaur K et al (2015) Estimation of attached and unattached progeny of 222Rn and 220Rn concentration using deposition based progeny sensors. *Radiat Prot Dosimetry* 167:92–96
- Mishra R, Mayya YS (2008) Study of a deposition-based direct thoron progeny sensor (DTPS) technique for estimating equilibrium equivalent thoron concentration (EETC) in indoor environment. *Radiat Meas* 43:1408–1416
- Mishra R, Mayya YS, Kushwaha HS (2009) Measurement of 220 Rn/222 Rn progeny deposition velocities on surfaces and their comparison with theoretical models. *J Aerosol Sci* 40:1–15
- NNRMS standards (2005) A national standard for EO images, thematic & cartographic maps, GIS databases and spatial outputs. Report ISRO: NNRMS: TR: 112: 2005/Committee Report; Ed. Government of India, Department of Space, Indian Space Research Organisation, July 2005. www.nnrms.gov.in/greennrms/download/NnrmsStandardsDoc.pdf. Accessed 22 June 2015
- Prasad M, Rawat M, Dangwal A et al (2015) Measurements of radon and thoron progeny concentrations in dwellings of Tehri Garhwal, India, using LR-115 deposition-based DTPS/DRPS technique. *Radiation protection dosimetry* 167(1–3):102–106
- Prasad M, Rawat M, Dangwal A et al (2016a) Variability of radon and thoron equilibrium factors in indoor environment of Garhwal Himalaya. *J Environ Radioact* 151:238–243. <https://doi.org/10.1016/j.jenvrad.2015.10.017>
- Prasad M, Rawat M, Dangwal A et al (2016b) Study of radiation exposure due to radon, thoron and progeny in the indoor environment of Yamuna and Tons Valleys of Garhwal Himalaya. *Radiat Prot Dosim* 171:187–191. <https://doi.org/10.1093/rpd/ncw055>
- Ramola RC, Prasad M, Rawat M et al (2015) Comparative study of various techniques for environmental radon, thoron and progeny measurements. *Radiat Protect Dosim* 167:22–28
- Ramola RC, Prasad M, Kandari T et al (2016) Dose estimation derived from the exposure to radon, thoron and their progeny in the indoor environment. *Sci Rep*. <https://doi.org/10.1038/srep31061>
- Saini K, Singh P, Singh P et al (2017) Seasonal variability of equilibrium factor and unattached fractions of radon and thoron in different regions of Punjab, India. *J Environ Radioact* 167:110–116
- Singh P, Saini K, Mishra R et al (2016) Attached, unattached fraction of progeny concentrations and equilibrium factor for dose assessments from 222. *Radiat Environ Biophys* 55:401–410
- Snyder JP (1987) Map projections—a working manual. US geological survey professional paper 1395 (1987). <http://pubs.er.usgs.gov/publication/pp1395>. Accessed 22 June 2015
- UNSCEAR (2000) United Nations scientific committee of the effect of atomic radiation. Source and effects of ionizing radiation. Annex-B: exposures from natural radiation sources. United Nation, New York
- UNSCEAR (2006) United Nations scientific committee on the effects of atomic radiation., report to the general assembly with scientific annexes, VOLUME II, scientific annexes C, D and E. United Nation, New York
- Valdiya KS (1980) Geology of kumaun lesser Himalaya. Wadia Institute of Himalayan Geology, Dehradun
- WHO (2009) WHO handbook on radon: a public health prospective. In: Hajo Zeeb, Ferid Shannoun (eds). WHO library cataloguing-in-publication data