Assessment of indoor radon, thoron concentrations, and their relationship with seasonal variation and geology of Udhampur district, Jammu & Kashmir, India

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ABSTRACT

Background: The inhalation doses resulting from the exposure to radon, thoron, and their progeny are important quantities in estimating the radiation risk for epidemiological studies as the average global annual effective dose due to radon and its progeny is 1.3 mSv as compared to that of 2.4 mSv due to all other natural sources of ionizing radiation.

Objectives: The annual inhalation dose has been assessed with an aim of investigating the health risk to the inhabitants of the studied region.

Methods: Time integrated deposition based $^{222}\text{Rn}/^{220}\text{Rn}$ sensors have been used to measure concentrations in 146 dwellings of Udhampur district, Jammu and Kashmir. An active smart RnDuo monitor has also been used for comparison purposes.

Results: The range of indoor radon/thoron concentrations is found to vary from 11 to 58 Bqm⁻³ with an average value of 29 ± 9 Bqm⁻³ and from 25 to 185 Bqm⁻³ with an average value of 83 ± 32 Bqm⁻³, respectively. About 10.7% dwellings have higher values than world average of 40 Bqm⁻³ prescribed by UNSCEAR. The relationship of indoor radon and thoron levels with different seasons, ventilation conditions, and different geological formations have been discussed.

Conclusions: The observed values of concentrations and average annual effective dose due to radon, thoron, and its progeny in the study area have been found to be below the recommended level of ICRP. The observed concentrations of ^{222}Rn and ^{220}Rn measured with active and passive techniques are found to be in good agreement.

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Introduction

An environmental radiation originates from various natural and man-made sources. Individuals are continuously exposed to these radiations due to which certain effects are produced. These effects are classified into two categories: stochastic effects and deterministic effects. Stochastic effects occur by chance and because of long exposure to low-level radiation. Deterministic effects occur due to higher level of radiation exposure and turn out to be more serious as the level of exposure increases [1]. Radon contributes a large portion (approximately half) to the total annual radiation dose from all non-occupational sources. Radon and its short lived decay products (^{218}Po and ^{214}Po) present everywhere in atmosphere, are inhaled by humans, thus reaching the respiratory system. The energy released after alpha decay of radon and its progeny results in damaging of the sensitive inner lining of the lung, which increases the risk of cancer [2]. The association between radon exposure in dwellings and lung cancer risk has already

been demonstrated and confirmed by several surveys and pooled analysis of epidemiological studies in many countries [3–5].

Radon is a naturally occurring radioactive gas produced by the decay of ^{238}U and ^{232}Th , which are widely distributed in the Earth's crust and are found in all types of rocks, soils, water sources. Since ^{222}Rn has a half-life of 3.82 days, it can be released from the earth crust where it has been generated and has reasonable activity level. In contrast, ^{220}Rn level is negligible due to its short half-life ($t_{1/2} = 55$ s). Therefore, thoron concentration is considered to be much less than that of radon and its contribution to doses has been generally ignored in past [6]. But now days, thoron is more significant natural radiation than others and it is necessary to have information about ^{220}Rn levels in ambient environment for its dose assessment [7]. Presence of radon, thoron, and their short-lived progenies in the atmosphere are the most important contributors to human exposure from natural sources [8].

^{222}Rn is used as a geophysical tracer for locating hidden faults/thrust, in metrology, water research, in medicine, and for predicting earthquakes [9]. Radon in outdoor environment is diluted with air and dust particles but when it enters in houses, it accumulates in indoor environment. The large variation in radon and thoron concentration is due to topography, types of dwellings, and environmental parameters such as temperature, pressure, humidity, wind speed, weather, and life style of the population [10–14]. The variation in radon and thoron is also strongly affected by different soil types and geological formations [15,16]. In the absence of qualitative interpretations based on theory, it is important to evolve a scientific explanation based on extensive measurements.

In earlier studies, many researchers have been working on measurement of radon/thoron concentration in indoor environment by old techniques (Bare mode and Twin cup dosimeter) which are no more reliable because twin cup dosimeters have dual entrance for the gas and have turbulence or air flow effect which creates an ambiguity in the measurement. To remove this ambiguity, single entry-based pin hole $^{222}\text{Rn}/^{220}\text{Rn}$ discriminating dosimeters were developed which are more reliable [17].

Several studies have been carried out in India and worldwide, but no such study has been carried out earlier in Udhampur district, Jammu and Kashmir Himalayas, India. Single entry-based pin hole $^{222}\text{Rn}/^{220}\text{Rn}$ discriminating dosimeters are used in this study for the radon/thoron measurement in indoor air and this study is also

helpful in compiling the data for generating the radon map of a country.

The main objective of this study is to measure indoor radon and thoron concentrations in a selected region having almost similar geographical and topographical parameters. The variation of indoor radon and thoron concentrations based upon building construction materials, seasons, and geology of the region have also been discussed. The aim of this study is to estimate the annual effective dose for the assessment of health risk to the people of the studied region. In the present study, origin and Microsoft excel software has been used for statistical analysis and graphical representations.

Geology of study area

Figure 1 shows the studied area of Udhampur district, which is located in north India. It is situated in the south eastern part of Jammu and Kashmir State and is bounded from the west by Rajauri district, from the north by Anantnag district, from the north east by Doda district, from the south east by Kathua district, and from south west by Jammu district. It extends geographically from the latitudes $32^{\circ}34'$ – $33^{\circ}30'$ north and longitudes $74^{\circ}16'$ – $75^{\circ}38'$ east. The district Udhampur lies in the mighty Himalayan Range, therefore very small portion of the district (only 17% of total reporting area) is available for cultivation.

Physiographically, the district is occupied by three major units extending throughout the district. The unit

Figure 1. Surveyed study area. Source: Authors.

that extends in north eastern part is hilly tract of Siwalik formation, the unit extending in north southern part is Murree formation, and the one in north is Ramban and Sincha group. The Siwalik formations belong to the tertiary deposits of the outer Himalayas. They are mainly composed of sandstone and conglomerate rock formations, which are the solidified detritus of the great mountain range to their north. The remnant magnetization of siltstones and sandstones suggests a depositional age of 16–5.2 million years. These are the southernmost and geologically youngest east–west mountain chain of the Himalayas. These have many sub-ranges which extend from Kashmir to Arunachal Pradesh through Himachal Pradesh, Nepal, Uttarakhand, Bhutan, and West Bengal. Siwalik is not a continuous range instead it depicts discontinuity which is called “Doon” in the west and “Duar” in the east. The upper part of Siwalik is composed of conglomerates and boulders while the lower part is composed of clay and sandstones. These are bounded on the south by a fault system called the Main Frontal Thrust and on north by Main Boundary Thrust (MBT) with steeper slopes on that side. Below this, the coarse alluvial Ramban and Sincha zone makes the transition to the nearly level plains. In Ramban and Sincha formation, the Salkhala Group is exposed in North from Mantalai to Chenani area. It comprises a thick succession of carbonaceous slate, phyllites, schist, crystalline limestone, and basic intrusive of the Precambrian age [18].

The Murree formation generally consists of clay, siltstone, sandstone, and conglomerates. It was deposited as sand rich fluvial system. The provenance studies of the sandstone of the Murree formation suggest the supply of material from the orogenic belts to the north and characterized by mountain ranges trending NW–SE direction, deep narrow valley and terraces, valley filled deposits with gentle slopes. The district is also covered partly by Pir Panjal ranges and partly by Outer Himalayas. The hilly terrains with high hills exist in the northern and eastern part of the area and vary in elevation from 1100 to 2400 m. Structural hills belonging to Murree

and Siwalik groups are mostly longitudinal with altitude varying between 700 and 2200 m above mean sea level.

In Udhampur district, mainly alluvial soils are found, which are loamy with little clay content and contain small quantity of lime with high magnesium content. The color of the soil is brown and it is mixed with pebbles. This soil is generally found in the low lying areas in the west and also in hilly areas of the north. The district is drained by a number of perennial rivers and ephemeral streams. They form part of Indus major basin and Chenab sub-basin. These streams originate from northern mountainous regions and flows in southwestern direction.

Materials and methods

Sampling plan

The pin hole-based $^{222}\text{Rn}/^{220}\text{Rn}$ discriminating dosimeters and DRPS/DTPS have been deployed in 146 dwellings of Udhampur district, Jammu and Kashmir, India. The latitude and longitude of the study area were measured by ETREX-10 (Garmin make) GPS system. The latitude and longitude of the study area are important to prepare a radon–thoron GIS map for the country. The outdoor gamma dose rate has been measured in such locations using Dosimeter-Radiometer MKS-03D (SARAD) at about 1 m above the ground surface. The selected villages have been divided into three different zones depending upon obtained outdoor gamma dose rate. Five (10%), 26 (52%), and 19 (38%) villages have been selected in three gamma zones with outdoor gamma dose rate ranges from 0 to $0.10 \mu\text{Sv h}^{-1}$, $0.1–0.20 \mu\text{Sv h}^{-1}$, and $> 0.20 \mu\text{Sv h}^{-1}$.

The indoor radon/thoron and progeny concentrations were measured by single entry-based Pin hole dosimeter cup and DRPS/DTPS from November 2015–November 2016. The measurements were performed in three seasons: winter (November–March), summer (March–July), and spring (July–November). In general, four types of categories (on the basis of building materials) of houses have been selected in each zone for the deployment of dosimeters. These are Type A as marble – concrete, Type B as mud – mud, Type C as cemented – concrete, and Type D as tiles – concrete. The distribution of different type of dwellings in three gamma zones to estimate the number of detectors to be deployed in each type of dwellings is given by multivariate regression analysis as given in Table 1 [19].

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

Zone	Gamma level ($\mu\text{Sv h}^{-1}$)	Type A	Type B	Type C	Type D
Observed no. of houses in respective category of each zone					
1	0–0.1	330	560	950	320
2	0.1–0.2	2023	780	2565	930
3	>0.2	1235	979	2213	650
No. of dosimeters to be deployed in respective category of each zone					
1	0–0.1	9	11	15	9
2	0.1–0.2	17	11	20	11
3	>0.2	11	10	14	8

Notes: Type A = marble + cemented, Type B = mud + mud, Type C = cemented + cemented, Type D = tiles + cemented.

Experimental technique

Pin-hole-based $^{222}\text{Rn}/^{220}\text{Rn}$ discriminating dosimeter

The new design of the dosimeter system has a single entry through which gas enters the first chamber (“radon + thoron” chamber). It goes through a glass fiber filter paper ($0.56 \mu\text{m}$) which filters out the decay

products and subsequently diffuses to the second chamber ("radon" chamber) through four pin holes each having 2-mm length and 1-mm diameter, which removes the passage of ^{220}Rn gas in this chamber. These pinholes act as diffusion barrier which essentially cut off the entrance of thoron in second chamber due to its short half-life (55 s) as compared to that of radon (3.82 days). Since transmission factor for ^{222}Rn is about 0.98 while for ^{220}Rn , it is about 0.01. It indicates that present device successfully cuts off ^{220}Rn to about 99%, while keeping ^{222}Rn transmission at about 98% into the pinhole chamber (i.e. "radon" chamber). The schematic diagram of the dosimeter cup is shown in Figure 2. Both chambers are cylindrical and hollow each having a length of 4.1 cm and radius 3.1 cm. Chambers are covered from inside with metallic powders to have zero electric field inside the chamber volume, so that the decay products of the gasses will be uniform all through the volume [17].

Direct radon/thoron progeny sensors

The direct radon/thoron progeny sensors (DRPS/DTPS) are based upon a time-integrated deposition-based technique used for the measurement of total equilibrium equivalent concentration of radon and thoron. These are made of solid state nuclear track detector (LR-115) with absorbers of appropriate thickness. For ^{220}Rn progeny, the absorber is 50 μm aluminized mylar which selectively detects only 8.78 MeV α -particles emitted from ^{212}Po [20], while for ^{222}Rn progeny, the absorber is a combination of aluminized mylar and cellulose nitrate of effective thickness 37 μm to detect mainly 7.67 MeV α -particles emitted from ^{214}Po [21].

Detectors were initially installed for a period of 4 months. They were collected and reinstalled every 4 months, to cover the whole year. The solid state nuclear track detector (LR-115 Type – II) of size 3×3 cm was used for registration of alpha particles (track density).

After environmental exposure, detectors were retrieved and etched with 2.5 N sodium hydroxide solution in constant etching bath unit at a temperature of 60 °C for 90 min for developing the registered tracks at Research laboratory, D. A. V. College, Amritsar, India. The detectors were washed, dried, and the cellulose nitrate layers of the detector were peeled off from the polyester base. The track densities produced by the alpha particles were counted using spark counting technique. The detectors were first pre-sparked at 900 V to ensure that the developed track get completely punched off and then tracks were counted at 500 V twice or thrice. The track density from the detector was corrected by subtracting background track density due to detector storage and transport, etc.

Calculation of indoor ^{222}Rn and ^{220}Rn concentrations

The average track density is converted into radon and thoron concentrations according to following relations [17].

$$C_R = \frac{T_1}{d \times K_R}$$

and

$$C_T = \frac{T_2 - T_1}{d \times K_T}$$

where C_R and C_T are radon and thoron concentrations, T_1 is the track density observed in "radon" compartment, K_R is the calibration factor of radon in "radon" compartment for radon ($0.0170 \pm 0.002 \text{ tr.cm}^{-2} \text{ per Bq.d}^{-1} \cdot \text{m}^{-3}$), d is the number of days of exposure, T_2 is the track density observed in the "radon- thoron" compartment, and K_T ($0.010 \pm 0.001 \text{ tr. cm}^{-2} \text{ per Bq.d}^{-1} \cdot \text{m}^{-3}$) is the calibration factors of radon and thoron in "radon – thoron" compartment.

Figure 2. Schematic diagram of single entry-based pin hole dosimeter cup.

Calculations of EECR and EECT

The total equilibrium equivalent progeny concentrations of radon (EECR) and thoron (EECT) in air have been calculated as per following expressions [20].

$$EECR = \frac{T_R - B}{t \times S} - EECT$$

$$EECT = \frac{T_T - B}{t \times S}$$

where EECR and EECT are the equilibrium equivalents of ^{222}Rn and ^{220}Rn progeny concentration (Bq m^{-3}), T_R and T_T are the track densities (tracks cm^{-2}) observed in DRPS and DTPS, and B , t , and S are the background counts, exposure time, and sensitivity factors, respectively.

Estimation of annual effective dose

The total annual effective dose to radon and thoron progeny has been calculated by following equations given by UNSCEAR [22].

$$\text{AEDR (nSv}^{-1}) = \text{EECR}(\text{Bq m}^{-3}) \times 8760\text{hy}^{-1} \times 0.8 \times 9 \times 10^{-6}$$

$$\text{AEDT (nSv}^{-1}) = \text{EECT}(\text{Bq m}^{-3}) \times 8760\text{hy}^{-1} \times 0.8 \times 40 \times 10^{-6}$$

where EECR and EECT are equivalent equilibrium concentration of radon and thoron, respectively, 0.8 is the indoor occupancy factor, 9 and 40 are the dose conversion factors for radon and thoron progeny (mSv) [22,23] and 10^{-6} is the multiplication factor used to convert the nSv to mSv.

Equilibrium factor

Equilibrium factor for radon, thoron, and their progeny was calculated using following expressions [24]:

$$F_{Rn} = \frac{EECR}{C_R}$$

$$F_{Tn} = \frac{EECT}{C_T}$$

Results and discussion

Indoor ^{222}Rn , ^{220}Rn , and progeny concentration

The annual statistical variation of indoor radon (^{222}Rn) and thoron (^{220}Rn) concentrations in 146 dwellings of Udhampur district is given in Table 2. The indoor radon concentration varies from 11 to 58 Bqm^{-3} with an arithmetic mean of $29 \pm 9 \text{ Bqm}^{-3}$ and geometric mean of 27 Bqm^{-3} . It is much less than the lower recommended reference level of ICRP ($100\text{--}300 \text{ Bqm}^{-3}$) [25]. Only 10.7% dwellings have higher values than world average of 40 Bqm^{-3} prescribed by United Nations Scientific Committee on Effects of Atomic radiations [22]. The present results of indoor radon concentration are also lower than the action level of 100 Bqm^{-3} recommended by World Health Organization [26]. Similarly, annual thoron concentration varies from 25 to 185 Bqm^{-3} with an average value of $83 \pm 32 \text{ Bqm}^{-3}$ and geometric mean of 77 Bqm^{-3} . The thoron concentration in indoor air is much higher than the global average value of 10 Bqm^{-3} [22]. The indoor thoron concentration is slightly higher than indoor radon level.

The 25th and 75th percentiles of radon concentrations are 21 and 35 Bqm^{-3} , respectively. This means that radon concentration in 25% of the dwellings is below 21 Bqm^{-3} while in 75% of the dwellings it is below 35 Bqm^{-3} . Similarly, the 25th and 75th thoron concentration percentile are 62 and 100 Bqm^{-3} , respectively. About 25% dwellings were containing thoron concentration below 62 Bqm^{-3} and 75% of the dwellings have below 100 Bqm^{-3} (Table 2). The frequency distributions of radon and thoron concentration of 146 dwellings in indoor air are given in Figure 3. It is clear from the Figure 3(a) that maximum of about 69.17% of radon concentration are found to vary from 20 to 40 Bqm^{-3} . All dwellings have concentrations within the recommended range of ICRP [25] and WHO [26]. From Figure 3(b),

Table 2. Statistical variations of ^{222}Rn , ^{220}Rn , and its progeny, equilibrium factor, and annual effective dose in 146 dwellings of Udhampur district, Jammu and Kashmir, Himalayas.

	^{222}Rn conc. (Bqm^{-3})	^{220}Rn conc. (Bqm^{-3})	Equilibrium equivalent concentration (Bqm^{-3})		Equilibrium factor		Annual absorbed dose (mSv^{-1})	
			EECR	EECT	F_{Rn}	F_{Tn}	AEDR	AEDT
Min	11	25	3.04	0.23	0.10	0.004	0.19	0.07
Max	58	185	38.37	5.49	0.98	0.09	2.42	1.54
Average	29	83	16.66	1.59	0.58	0.02	1.05	0.44
SD	9	32	6.09	0.74	0.17	0.01	0.38	0.21
GM	27	77	15.56	1.45	0.55	0.02	0.98	0.41
GSD	1.38	1.47	1.46	1.53	1.41	1.58	1.46	1.53
Median	27	78	15.91	1.41	0.57	0.02	1.00	0.39
Kurtosis	0.03	0.72	3.36	5.42	0.84	15.26	1.59	5.96
Skewness	0.69	0.82	0.99	1.92	0.22	2.88	0.98	1.95
25th Percentile	21	62	12.86	1.12	0.46	0.01	0.81	0.31
75th Percentile	35	100	19.68	1.84	0.71	0.03	1.59	0.51

Notes: ^{222}Rn and ^{220}Rn concentration is measured by Pin hole-based $^{222}\text{Rn}/^{220}\text{Rn}$ discriminating dosimeters. EECR and EECT are measured by direct radon thoron progeny sensors.

Figure 3. (a) Frequency distribution of ^{222}Rn concentration in 146 dwellings of Udhampur district. (b) Frequency distribution of ^{220}Rn concentration in 146 dwellings of Udhampur districts.

about 80.82% of thoron concentration is found to vary from 40 to 120 Bq m $^{-3}$.

The equilibrium equivalent concentration of radon (EECR) has been found to vary from 3.01 to 38.37 Bq m $^{-3}$ with an average value of 16.66 ± 6.09 Bq m $^{-3}$ and geometric mean of 15.56 Bq m $^{-3}$. Similarly, the equilibrium equivalent concentration of thoron (EECT) has been found to vary from 0.23 to 5.49 Bq m $^{-3}$ with an average value of 1.59 ± 0.74 Bq m $^{-3}$ and geometric mean of 1.45 Bq m $^{-3}$ (Table 2). ICRP prescribed an estimated expected concentration in buildings to be 2–50 Bq m $^{-3}$ and 0.04–2 Bq m $^{-3}$ for ^{222}Rn and ^{220}Rn progeny concentrations (EECR and EECT) [27]. All measured results of EECR are well within the ICRP range. However, 31 (21.23%) have higher values of EECT than the maximum

limit of ICRP [27] and the average value of EECT is well within the range.

The frequency distribution of equilibrium equivalent concentration of radon and thoron is given in Figure 4. It is clear from Figure 4(a), about 79% of EECR are found to vary from 1 to 20 Bq m $^{-3}$. From Figure 4(b), about 78% of EECT is found to vary from 0.3 to 2 Bq m $^{-3}$. Nearly 22% of the dwellings have equilibrium equivalent concentration of thoron more than the ICRP range [27].

The indoor ^{222}Rn concentration of the studied area of Udhampur district was compared with some neighboring regions of Punjab, Haryana, Himachal Pradesh, Garhwal Himalaya of India and Islamabad, Lahore, Poonch (Azad Kashmir), Muzaffarabad, and Punjab region of Pakistan as depicted in Table 3. The observed values of ^{222}Rn concentration in indoor air were found

Figure 4. (a) Frequency distribution of EECR in dwellings of Udhampur district. (b) Frequency of EECT in dwellings of study region.

to be lesser than Western Haryana [28] and Tosham ring of southeast Haryana [29], Hamirpur of Himachal Pradesh [30], Tehri [24], Kuman [31] and Dehradun [32] of Uttarakand Himalaya, Lahore [33], Poonch (Azad Kashmir) [34], and Muzaffarabad of Pakistan [1]. The higher value of radon concentration in Western and Tosham Haryana is due to regional geology of the area [28] and the presence of radioactive rich granite rocks [29], in Hamirpur district of Himachal Pradesh is due to thorium rich soil [30] and in Dehradun is due to presence of MBT which is tectonically active area [32] and due to granite rocks in Kauman Himalaya [31], in Lahore and Poonch (Azad Kashmir) is due to crevice and cracks produced due to earthquake and high concentration of radium content in the building materials [33,34].

But radon concentration in indoor environment of the study area is comparable to Jalandhar and Kapurthala district of Punjab [35,36], Islamabad and Punjab region of Pakistan [37,38]. The comparable indoor radon concentration in Jalandhar and Kapurthala district is because these regions lie in foothills of the Siwalik Himalayas whereas in Islamabad and Punjab of Kashmir is due to granite rocks, uranium rich soil and these regions are in the vicinity of Murree region of Pakistan having same geology as explained above.

Equilibrium factor (F)

The statistical variation of equilibrium factor of radon and its progeny and thoron and its progeny has been calculated and listed in Table 2. The equilibrium factor of radon and its progeny (F_{Rn}) is 0.10–0.98 with an average value of 0.58 ± 0.17 and GM of 0.55 which is higher than the globally accepted value (0.4) recommended by UNSCEAR [22]. The equilibrium factor for thoron and its progeny varies from 0.004 to 0.09 with an average of 0.02 which is comparable with value of 0.02 given by UNSCEAR [22].

Table 3. Comparison of results of present study with other studies.

S. no.	Location	Radon concentration (Bq m ⁻³)	References
1	Jalandhar, Punjab	6–47	[38]
2	Kapurthala, Punjab	19–63	[39]
3	Tosham, Haryana	37–80	[32]
4	Western Haryana	126–172	[31]
5	Hamirpur, HP	25.5–208.5	[33]
6	Garwal Himalaya	27–148	[35]
7	Tehri, Himalaya	13–291	[27]
8	Kauman, Himalaya	40–208	[34]
9	Islamabad, Pakistan	20–83	[40]
10	Lahore, Pakistan	20–90	[36]
11	Poonch, Azad Kashmir, Pakistan	86 ± 3	[37]
12	Punjab, Pakistan	55 ± 13	[40]
13	Muzaffarabad city, Pakistan	14–155	[1]
14	Udhanpur, J&K	11–58	Present study

The frequency distribution of equilibrium factor of radon and its progeny and thoron and its progeny is given in Figure 5. It is clear from Figure 5(a), about 60% of F_{Rn} are found to vary from 0.2 to 0.6. From Figure 5(b), about 78% of F_{Tn} are found to vary from 0.01 to 0.03.

Annual effective dose

The annual effective doses (AEDs) for inhalation of radon, thoron, and its progeny are presented in Table 2. The range, arithmetic mean $\pm$ standard deviation, and geometric mean (geometric standard deviation) of effective dose due to radon and its progeny (AEDR) is 0.19 to 2.42 mSv⁻¹, 1.05 ± 0.38 mSv⁻¹, and 0.98 (1.46) mSv⁻¹, respectively. Similarly, the range, arithmetic mean $\pm$ standard deviation, and geometric mean (and geometric standard deviation) of effective dose due to thoron and its progeny (AEDT) is 0.07 to 1.53 mSv⁻¹, 0.44 ± 0.21 mSv⁻¹, and 0.41 (1.53) mSv⁻¹, respectively. The total average annual inhalation dose due to radon, thoron, and its progeny is estimated to be 1.49 ± 0.52 mSv⁻¹ (range 0.48 to 3.25 mSv⁻¹) which is comparable to the annual inhalation dose of 1.15 mSv⁻¹ [22] and less than the 3–10 mSv⁻¹ [39]. Therefore, radon has higher value than thoron, so it is considered as the major contributor to the total dose received by residents in the study region but calculated values are within the safe range of ICRP. The frequency distribution of total annual inhalation dose of the studied dwellings is given in Figure 6. The frequency distribution is highest at 1.0 to 1.4 mSv⁻¹ and lowest at more than 1.8 mSv⁻¹. About 51.37% dwellings have value of total inhalation dose well within the dose of 1.15 mSv⁻¹ recommended by UNSCEAR [22].

Regional variability of indoor radon–thoron level

The geographical formations, lithology, hydrology, and soil play an important role in the measurement of indoor radon and thoron levels [40]. On the basis of local geology, the study region is divided into three different geological formations: Shiwalik formation, Murree formation, and Ramban and Sincha form. The statistical comparison of indoor radon and thoron concentration with indoor and outdoor gamma dose rate in three different geological formations is given in Table 4. In Shiwalik formation, the variation of radon and thoron concentration was 11 to 58 Bqm⁻³ with an average of 30 ± 9 Bqm⁻³ and from 29 to 185 Bqm⁻³ with an average of 80 ± 31 Bqm⁻³, respectively. It ranged from 12 to 49 Bqm⁻³ with an average of 28 ± 9 Bqm⁻³ and from 46 to 183 Bqm⁻³ with an average of 99 ± 33 Bqm⁻³, respectively, in Murree region and from 14 to 45 Bqm⁻³ with an average of 25 ± 8 Bqm⁻³ and from 25 to 118 Bqm⁻³ with an average of 76 ± 24 Bqm⁻³, respectively, in Ramban and Sincha form. The average of indoor and outdoor

Figure 5. (a) Frequency distribution of equilibrium factor of radon and its progeny. (b) Frequency distribution of equilibrium factor of thoron and its progeny.

Figure 6. Frequency distribution of total annual effective dose in studied dwellings of Udhampur district.

gamma dose rate was $0.12 \pm 0.04 \mu\text{Sv h}^{-1}$ and $0.21 \pm 0.07 \mu\text{Sv h}^{-1}$ in Shiwalik, $0.12 \pm 0.04 \mu\text{Sv h}^{-1}$ and $0.18 \pm 0.09 \mu\text{Sv h}^{-1}$ in Murree, and $0.15 \pm 0.03 \mu\text{Sv h}^{-1}$ and $0.15 \pm 0.07 \mu\text{Sv h}^{-1}$, respectively, in Ramban and Sincha form. The average values of radon concentration in three regions gives almost similar results but the maximum average

radon concentration was found in Shiwalik region due to its geology (cobble, pebble and gravel, granite, red purple shales, clays), soil, and source term conditions [41]. The maximum thoron concentration was found in Murree region having Purple/Red colored sand and clay which are rich sources of thorium. A positive correlation has been observed between radon and thoron concentration in three different geological formations. Figure 7 shows the variation of radon and thoron concentration with Pearson coefficient of 0.3, 0.6, and 0.58 in Shiwalik, Murree, and Ramban and Sincha form.

Zone-wise distribution

On the basis of outdoor gamma dose rate, study region has been divided into three zones with Zone 1 having dose rate less than $0.1 \mu\text{Sv h}^{-1}$, zone 2 having $0.1\text{--}0.2 \mu\text{Sv h}^{-1}$, and greater than $0.2 \mu\text{Sv h}^{-1}$ in zone 3. The annual average concentrations were found to be $26 \pm 9 \text{ Bq m}^{-3}$, $29 \pm 9 \text{ Bq m}^{-3}$, and $30 \pm 7 \text{ Bq m}^{-3}$ for ^{222}Rn and was found $81 \pm 34 \text{ Bq m}^{-3}$, $83 \pm 32 \text{ Bq m}^{-3}$, and $89 \pm 31 \text{ Bq m}^{-3}$ for ^{220}Rn in first zone, second zone, and third zone, respectively (Table 4). The values of radon and thoron concentrations were found to be higher in third zone. Our

Table 4. Variation of ^{222}Rn , ^{220}Rn , indoor, and outdoor gamma dose rate in different geological formation.

	Shiwalik				Murree				Ramban and Sincha			
	^{222}Rn (Bq m^{-3})	^{220}Rn (Bq m^{-3})	Gamma dose rate ($\mu\text{Sv h}^{-1}$)		^{222}Rn (Bq m^{-3})	^{220}Rn (Bq m^{-3})	Gamma dose rate ($\mu\text{Sv h}^{-1}$)		^{222}Rn (Bq m^{-3})	^{220}Rn (Bq m^{-3})	Gamma dose rate ($\mu\text{Sv h}^{-1}$)	
			Indoor	Outdoor			Indoor	Outdoor			Indoor	Outdoor
Min	11	29	0.03	0.06	12	46	0.03	0.08	14	25	0.09	0.09
Max	58	185	0.22	0.36	49	183	0.21	0.4	45	118	0.2	0.3
Average	30	80	0.12	0.21	28	99	0.12	0.18	25	76	0.15	0.15
SD	9	31	0.04	0.07	9	33	0.04	0.09	8	24	0.03	0.07
GM	28	74	0.12	0.2	27	94	0.11	0.16	25	71	0.14	0.14
Median	28	75	0.12	0.19	27	87	0.12	0.17	25	78	0.14	0.13

Figure 7. Relation between radon and thoron concentration in different geological formations.

results of zone-wise distribution fairly agree with the results of Kumar et al. (2017) [35] for the dwellings of Jalandhar, Punjab. Figure 8 shows the comparison of average radon and thoron concentration with outdoor gamma dose rate. The vertical axis of the graph represents the average ^{222}Rn and ^{220}Rn concentration and error bar on each column represents the standard deviation (S.D) of the radon and thoron concentration in each zone.

Figure 8. Variation of ^{222}Rn and ^{220}Rn in different gamma zones.

Ventilation conditions

The results of measurements of indoor radon and thoron concentrations in the different ventilation conditions of the various dwellings are presented in Table 5. The houses are distinguished on the basis of windows, doors, and usage pattern (such as closed, open, or partial) to identify them as good, average, or bad. The storage rooms mostly have one door in dwelling and were closed during most of the time due to low usage, therefore these are considered as badly ventilated. On the other hand, the bedroom, hall, drawing room, study room are expected to have a good ventilation rate than store room and thus identified as average (1 door and 1 window) or good (1 door and 2 and above windows). The value of indoor radon concentration varies from 14 to 44 Bqm^{-3} with an average of $25 \pm 8 \text{ Bqm}^{-3}$ in good ventilation conditions. It ranges from 11 to 49 Bqm^{-3} with an average of $28 \pm 8 \text{ Bqm}^{-3}$ in average ventilation conditions and from 15 to 56 Bqm^{-3} with an average of $31 \pm 10 \text{ Bqm}^{-3}$ in bad ventilation conditions, respectively. Similarly, the value of thoron concentration varies from 37 to 143 Bqm^{-3} with an average value of $77 \pm 21 \text{ Bqm}^{-3}$ in good ventilation. It ranges from 34 to 183 Bqm^{-3} with an average of $82 \pm 32 \text{ Bqm}^{-3}$ in average and from 25 to 185 Bqm^{-3} with an average of $91 \pm 34 \text{ Bqm}^{-3}$ in bad ventilation conditions, respectively. The annual average value of indoor ^{222}Rn and ^{220}Rn concentration has been found maximum in bad ventilations and minimum in good ventilation. The higher values of indoor radon and thoron concentration in bad ventilation conditions has been also reported by Sathish et al. [42] and Chauhan et al. [43]. This is due to the difference in ventilation rates and accumulation of gas in bad ventilated dwellings which enhance the radon and thoron concentration. Figure 9 shows the comparison of average radon and thoron concentration with different ventilation conditions and error bars on vertical column represents the S.D of the ^{222}Rn and ^{220}Rn concentration in different ventilation conditions. Out of 146 dwellings, maximum annual average radon and thoron concentration was found in 54 (36.98%) bad ventilated dwellings and minimum in 44 (30.14%) good ventilated dwellings.

Variation attributable to building characteristics

The results of measurement of indoor radon and thoron concentration in different types of dwellings are also listed in Table 5. The variation of indoor radon in different type of dwellings was from 11 to 42 Bqm^{-3} with an average of $27 \pm 8 \text{ Bqm}^{-3}$ in marble type houses. It ranges from 14 to 56 Bqm^{-3} with an average of $64 \pm 11 \text{ Bqm}^{-3}$ in mud type, from 14 to 51 Bqm^{-3} with an average of $26 \pm 8 \text{ Bqm}^{-3}$ in cemented, and from 23 to 37 Bqm^{-3} with an average of $28 \pm 5 \text{ Bqm}^{-3}$ in tile types of houses, respectively. Similarly, the variation of indoor thoron concentration in different dwellings was from

Table 5. Variation of ^{222}Rn and ^{220}Rn concentration with different zones, seasons, and house hold parameters.

		Zone-wise distribution			Ventilation conditions			Type of houses				Seasonal variation		
		Zone 1	Zone 2	Zone 3	Good	Average	Bad	Type A	Type B	Type C	Type D	Winter	Summer	Rainy
^{222}Rn	Min	14	11	14	14	11	15	11	14	14	23	9	7	7
	Max	47	56	58	44	49	56	42	56	51	37	99	72	67
	Average	26	29	30	25	28	31	27	34	26	28	33	27	29
	SD	9	9	7	7	8	10	8	11	8	5	16	15	11
^{220}Rn	Min	25	29	32	37	34	25	29	45	24	54	11	12	15
	Max	180	185	183	143	183	185	183	185	144	119	369	322	197
	Average	81	83	89	77	82	91	79	103	80	83	94	79	82
	SD	34	32	31	21	32	34	32+	40	27	18	42	31	37

Figure 9. Variation of ^{222}Rn and ^{220}Rn with ventilation conditions. **Figure 11.** Seasonal variation of annual average ^{222}Rn and ^{220}Rn concentration. **Figure 10.** Variation of ^{222}Rn and ^{220}Rn with different types of houses. **Figure 12.** Correlation of ^{222}Rn concentration with an active and passive technique.

29 to 183 Bqm⁻³ with an average of 79 ± 32 Bqm⁻³ in marble, from 45 to 185 Bqm⁻³ with an average of 103 ± 40 Bqm⁻³ in mud, from 24 to 144 Bqm⁻³ with an average of 80 ± 27 Bqm⁻³ in cemented, and from 54 to 119 Bqm⁻³ with an average value of 83 ± 18 Bqm⁻³ in

tile type of houses. The annual average concentration of radon and thoron concentration was found maximum in mud types of dwellings (floor – mud, walls – bricks and roof – mud) because of continuous and higher exhalation rate in soil [44] due to porosity, cracks, and defective joints in wall, roof, and floor. On the other

Figure 13. Correlation of ^{220}Rn concentration with an active and passive technique.

hand, cemented, marble, and tile floor houses consist of cemented wall and concrete roof which also exhale radon, but less than soil. The variation of radon and thoron concentration in different types of dwellings is mud > tiles > marble > cemented. Maximum annual average radon and thoron concentration was found in 24 (16.44%) mud type of dwellings and minimum in 69 (47.26%) in cemented types of dwellings. Figure 10 gives the comparison of indoor radon and thoron concentration in different types of dwellings.

Seasonal variation

The statistical parameters of indoor radon and thoron concentration in term of minimum, maximum, arithmetic mean, and standard deviation in three different seasons (winter, summer, and rainy) covering a year are presented in Table 5. The indoor radon concentration varies from 9 to 99 Bqm^{-3} with an average of $33 \pm 16 \text{ Bqm}^{-3}$ in winter, from 7 to 72 Bqm^{-3} with an average of $27 \pm 15 \text{ Bqm}^{-3}$ in summer, and from 7 to 67 Bqm^{-3} with an average of $29 \pm 11 \text{ Bqm}^{-3}$ in rainy season, respectively. Similarly, the thoron concentration varies from 11 to 369 Bqm^{-3} in winter, 12 to 322 Bqm^{-3} in summer, and 15 to 197 Bqm^{-3} in rainy and the average values are found to be $94 \pm 42 \text{ Bqm}^{-3}$, $79 \pm 31 \text{ Bqm}^{-3}$, and $82 \pm 37 \text{ Bqm}^{-3}$, respectively. The indoor radon concentration was found to be higher in winter season while it is minimum in summer season. The study region is one of the partial cold climate areas and wide climate variation prevails from place to place. Hence, most occupants close their rooms during these times which results in accumulation of radon inside the room. On the other hand, in summer season (March to July) the occupant kept their doors and windows open for increasing the air exchange rates. Due to increased temperature and air-mixing, the radon gas concentration gets reduced. Seasonal variation of radon and thoron concentration is shown in Figure 11.

Table 6. Indoor ^{222}Rn and ^{220}Rn concentration in some locations by active and passive technique.

Village name	GPS	^{222}Rn conc (Bqm^{-3})		^{220}Rn conc (Bqm^{-3})	
		Smart RnDuo	Dosimeter	Smart RnDuo	Dosimeter
Bilaspur	N 32°41.158' E 75°15.426'	19.95 ± 4.57	26.76 ± 2.35	59.22 ± 14.01	83.47 ± 30.35
Chugwan	N 32°41.562' E 75°14.718'	29.17 ± 6.51	37.39 ± 12.32	85.23 ± 14.01	126.78 ± 80
Thial	N 32°41.625' E 75°13.088'	34.98 ± 7.92	43.67 ± 28.16	68.83 ± 28.83	97.15 ± 40.32
Baryalta	N 32°42.572' E 75°10.911'	27.84 ± 6.98	32.10 ± 12.45	78.56 ± 25.54	130.93 ± 45
Rount	N 32°56.303' E 75°07.977'	19.76 ± 4.12	39.52 ± 16.78	64.03 ± 9.62	183.00 ± 65.82
Banara	N 32°41.625' E 75°13.088'	22.46 ± 8.62	40.37 ± 12.02	131.24 ± 56.48	153.22 ± 36.62
Gangera	N 32°56.383' E 75°08.422'	34.03 ± 6.87	42.87 ± 19.93	240.36 ± 26.32	185.00 ± 90.12
Udhampur	N 32°55.562' E 75°07.901'	31.31 ± 12.34	37.38 ± 16.73	72.28 ± 12.74	119.14 ± 30.29
Jakhar	N 32°56.240' E 75°07.187'	23.60 ± 6.34	18.78 ± 5.88	56.38 ± 9.27	132.19 ± 74.21
Bali	N 32°58.593' E 75°10.423'	35.69 ± 16.34	51.51 ± 4.69	199.28 ± 59.27	162.99 ± 50.24

Comparison of active and passive technique

The activity concentrations of ^{222}Rn and ^{220}Rn in some dwellings of study area were also measured by Smart RnDuo monitor (active technique). The advanced SMART RnDuo (active technique) is manufactured by Bhabha Atomic Research Centre, Mumbai, India for the measurement of ^{222}Rn and ^{220}Rn concentration in air, water, and soil [45,46]. The observed concentrations of radon ^{222}Rn and ^{220}Rn by smart RnDuo monitor are found to be in fare agreement with passive dosimetry (pinhole dosimeter) as given in Table 6. The correlation coefficient of radon and thoron with active and passive technique is (Pearson coefficient 0.62 and 0.63) given in Figures 12 and 13. It is evident from Table 6, both the techniques led to the same conclusions as for as radon and thoron is concerned with various locations in the study area. On comparing, radon concentration in Bali location, it was found maximum with Smart RnDuo monitor as well as Pin hole cup dosimeters. Similar trend was also observed in case of thoron measurements.

Conclusions

Following conclusions are drawn from the study;

- ^{222}Rn and ^{220}Rn concentration in the studied area are lower than the recommended action level of ICRP.
- The observed average progeny concentration of ^{222}Rn and ^{220}Rn are less than the estimated range of ICRP.
- The indoor radon and thoron levels are found to be higher in mud types of dwellings while minimum values are found in concrete type dwellings.
- While comparing the results based on seasonal variation, the radon levels were found higher in winter season and lower in summer season which is usually expected.
- The results showed that about 10.7% of the dwellings have radon concentration greater than world average range [22]. Difference of building construction material and air flow patterns can be attributed to the observed variability.
- The maximum average radon level is found in Shiwalik region and thoron level in Murree region because of regional geology of the area.

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