^{222}Rn distribution pattern in dwellings of copper mineralized area of East Singhbhum region, Jharkhand, India

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Seasonal variation of ^{222}Rn levels was studied in the dwellings in U–Cu mineralized area of East Singhbhum, Jharkhand, India. Copper mining and processing industry is operational in this area for the last hundred years. Copper minerals of this region contain a significant fraction of uranium and the decay products. To measure the activity concentration of ^{222}Rn, LR-115, type-II solid-state nuclear plastic track detector was used in an indigenously developed radon dosimeter cup. A higher value of ^{222}Rn activity concentration was recorded in some of the dwellings in the mineralized zone. The results at different locations adjoining the facilities show that the ^{222}Rn activity concentration varies to a great extent following an approximate log-normal distribution. The observed range varied from 29.1 and 314.6 Bq m^{-3} with an overall geometric mean of 72.3 Bq m^{-3} and geometric standard deviation 1.67. Further, in poorly ventilated dwellings ^{222}Rn levels were higher compared to the properly ventilated houses. The peak activity concentration of ^{222}Rn was recorded during winter (December–February). Appreciably lower activity concentration of radon was observed during summer and rainy seasons. The results reflect that the levels are higher than the global average indoor activity concentration of 40 Bq m^{-3} (UNSCEAR-1993) for ^{222}Rn, but are comparable to the studies carried out in similar types of geological formations.

Keywords: Copper mining, dwelling ventilation, radon distribution, seasonal variations.

Radon (^{222}Rn; $t_{1/2}$ = 3.82 day) is a gaseous decay product of ^{226}Ra in naturally occurring uranium series which is ubiquitous. Since the parent ^{226}Ra is inherently present in the terrestrial environment, its decay will lead to dispersal of radon gas into the atmosphere. The most significant factor governing the release of ^{222}Rn into the environment, by and large, depends on the abundance of radium in the Earth's crust or the extraneous materials containing radium-bearing components. It emanates from all types of soil and rocks to a certain degree and diffuses into the atmosphere. Factors that influence the diffusion of ^{222}Rn from soil into the air are the existence of uranium and radium in soil and rock, emanation capacity of the ground, porosity of the soil and/or rock, pressure gradient between the interfaces, soil moisture and water saturation grade of the medium[1], and is the most variable from one geographical formation to the another.

Releases of ^{222}Rn from uranium mining activities are well documented[2–4] and large databases pertaining to the atmospheric distribution of ^{222}Rn are confined either to uranium mining activities or areas adjoining uranium mining sectors. ^{222}Rn release from spring wells and other mining sectors such as lead, tin and bismuth is also documented. However, elevated levels of ^{222}Rn are also anticipated around copper industries, if the copper mineral contains significant amount of uranium and its decay products. Quantitative distribution of ^{222}Rn into the atmosphere around copper industry depends on factors such as uranium/radium content in the Earth's crust, climatic conditions, mining, processing and tailings management technology of the copper handling industries. ^{222}Rn and its progeny are the largest contributors of the collective dose from ionizing radiation that the world population is exposed to[5–7]. Also, ^{222}Rn and its progeny contribute three-quarters of the annual effective dose received by human beings from natural terrestrial sources and are responsible for about half of the dose from all the sources[8,9]. The average global outdoor ^{222}Rn concentration is 10 Bq m^{-3}, while indoor concentration is 40 Bq m^{-3} (ref. 8). The estimated dose from inhalation of ^{222}Rn and its progeny varies to a great extent; 10 mSv year^{-1} is not uncommon, particularly in cold countries. Since copper deposits of Singhbhum are associated with elevated levels of uranium and its decay products and discharges of process tailings are also the source of ^{222}Rn, emanation elevated concentration profile is expected in the areas surrounding the copper deposits and copper mineral handling facilities. The present communication summarizes the monitoring results of indoor ^{222}Rn concentration in the dwellings of Singhbhum copper mining area Jharkhand, eastern India.

^{222}Rn gas and its short-lived decay progenies such as polonium, bismuth and lead are present in the atmosphere and therefore have radiological importance for study and analysis. ^{222}Rn gas and its progeny diffuse into the atmosphere and can accumulate in the closed living environment. ^{222}Rn gas is exhaled during breathing, but its short-lived progenies are material particles and therefore may not get exhaled and are deposited in the lungs[10]. Poor ventilation rate in dwellings may result in enhanced

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concentration of ^{222}Rn and its daughters in the closed atmosphere of a particular dwelling. High levels of ^{222}Rn daughters in such a dwelling may contribute to the possibility of lung cancer among its residents. Such types of dwellings have been studied in a number of countries, including the United States, Sweden and the United Kingdom[6].

United Nations Scientific Committee on the Effect of Atomic Radiation (UNSCEAR) estimated that out of total 2.4 mSv year^{-1} background dose, indoor inhalation dose due to ^{222}Rn, ^{220}Rn and their progeny is about 1.2 mSv year^{-1} (ref. 8). In the areas containing high ^{222}Rn concentration, the doses can be many times higher than the global yearly average dose of 1.3 mSv (IAEA). In India, inhalation of ^{222}Rn and its progeny causes about 52% out of 98% exposure dose from natural radioactive sources. These high indoor ^{222}Rn levels may exceed those of the international health advisory[11]. Extensive studies on indoor levels of ^{222}Rn daughters in some areas which may contain higher background have been done[12]. The SSNTD technique was used for the studies and the reported values of ^{222}Rn (GM) concentration varied between 35.3 and 86.0 Bq m^{-3} with a geometric mean of 9.4 mWL of potential alpha energy exposure level from ^{222}Rn daughters with annual effective dose equivalent value of 3.1 mSv.

An environment can possess ionizing radiation which may be either natural or produced artificially by human activity. Geographical changes which may be a result of mineralization, exploration and processing of minerals can increase the existing ^{222}Rn levels appreciably in the atmosphere surrounding such mineral handling facilities. A large quantity of radioactive waste is generated by mining and minerals processing operations, which may contain naturally occurring radioactive material (NORM)[13]. The concentration of radioactive material in this waste may be low, but since this waste is generated in large quantities, it becomes significant for the radiological environment of the location.

The study was conducted in Singhbhum region (Figure 1), Jharkhand. The area is known for widespread deposits of economically viable minerals such as copper and uranium[14–16]. Copper industry is operational in this area for more than a century and the area has witnessed extensive man-made geographical changes. The Singhbhum Copper Belt (SCB) comprises of a Proterozoic volcano-sedimentary rock that creates a shear zone known as Singhbhum shear zone[17]. Copper mineralization in SCB is localized along this shear zone. Prominent copper deposits of the belt are Chapri, Rakha, Surda, Kendadih, Pathargora, Badia and Dhobani. The processing plants are situated at Musabani and Ghatshila. The copper deposit of this region is associated with uranium deposits and accordingly the tailings/process wastes of copper industry contain significant amount of uranium and the decay series radionuclides[18]. Close to the copper deposits are economically viable uranium deposits at Jaduguda, Bhatin and Bagjata. The environment around copper and uranium industries is in close proximity with several common attributes. Major populations are residing in villages around these industries with three major townships at Rakha, Musabani and Jaduguda. Copper concentrator plant Ghatshila is closely linked with the nearby Ghatshila town with old historical patronage of copper refining. Figure 2 shows a schematic map of the copper mining and processing sites, township and villages. The copper tailings have previously been used for extraction of uranium by setting up recovery units at Rakha and Musabani.

The study is based on the periodic ^{222}Rn monitoring in dwellings using the dimensionally optimized passive ^{222}Rn dosimeter[19]. For the estimation of indoor ^{222}Rn activity concentration, single-chamber ^{222}Rn dosimeters were used with solid-state nuclear track detector. The type-II, Kodak LR-115, peelable, detector film was used in this integrated type of dosimeter. The dosimeter is a 60 ml volume cylindrical cup, one end of which is covered with a permeable membrane. The membrane acts as a barrier for ^{219}Rn and ^{220}Rn and permeates only ^{222}Rn to enter into the chamber[20]. The membrane end of this chamber is covered with perforated aluminium lid to prevent any wear and tear to the assembly. The other end of the cup is covered with a gasketted and threaded aluminium cap. These dosimeters were deployed in different types of dwellings such as houses with cemented roof and floors, cemented house with mud floor, mud houses with mud ceilings, and mud houses with thatched ceilings of the copper mining area of this region. The dosimeter is preferably placed at a height of breathing zone of the bedroom or location with maximum indoor occupancy. After an exposure period of three months, these detectors were retrieved. This three-month exposure was repeated during

Figure 1. Location of the study area.

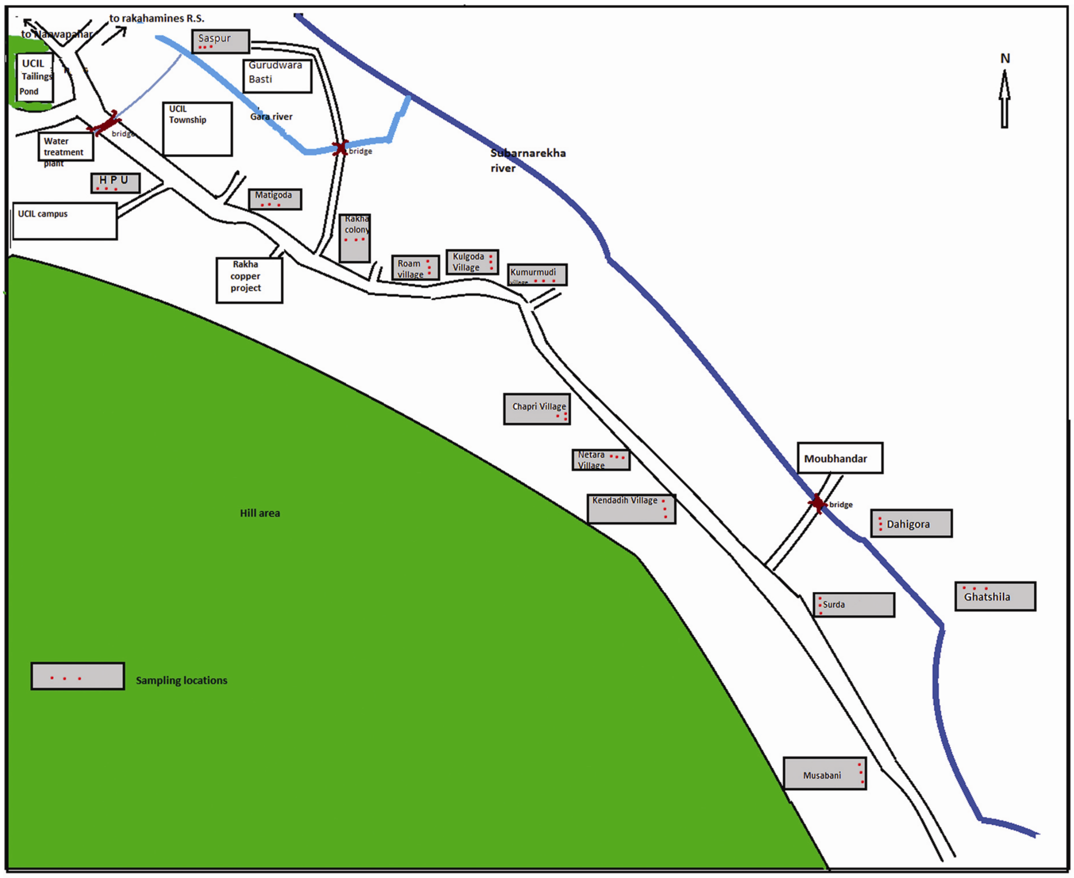

Figure 2. Map of the study area.

all four seasons of a calendar year to evaluate the annual indoor ^{222}Rn levels. The track formed as a result of interaction of α-particle from ^{222}Rn and its short-lived progeny is chemically etched in 10% NaOH solution at 60°C for optimum time and counted either manually in an image analyser or using a spark counter. The recorded track densities are converted to the actual ^{222}Rn activity concentration using a calibration curve generated in the laboratory by carrying out control experiments[21] and progeny concentration using approximate calibration factor[22]. The observed track density was then converted into ^{222}Rn exposure using the expressions derived empirically from the calibration curve[19].

The empirical relationship between exposure by ^{222}Rn and net track density is established as[19]

$$E = 0.554T,$$

where E is the exposure (Bq h l^{-1}), T the net track density (track cm^{-2}) and 0.554 is the conversion factor.

Average ^{222}Rn activity concentration in a dwelling is calculated as

$$^{222}\text{Rn (Bq m}^{-3}) = \frac{0.554 * T * 1000}{t},$$

where T is the average track density (number of tracks cm^{-2}) and t, the indoor occupancy period (5840 h year^{-1}).

Annual indoor inhalation dose of the population residing in these dwellings was evaluated using the relation[23,24]

$$\text{Average annual inhalation dose (mSv)} = \frac{^{222}\text{Rn (Bq m}^{-3}) * F * t * 4}{170 * 3700},$$

where $F = 0.4$ equlibrium factor[23].

DCF (dose conversion factor) = 4 mSv per working level month (WLM^{-1}) for members of the public.

The track etch detection technique is considered to be a reliable tool for integrated and prolonged measurements of indoor ^{222}Rn activity concentration[18,19,25–28]. The mode of sampling is passive and integrated for long duration taking into account the monthly and seasonal variations of ^{222}Rn activity concentration. Representative dwellings from the copper mining area were selected based on their mode of construction, ventilation status and proximity from the copper mining, processing and tailings disposal sites. The actual indoor occupancy has been previously worked out to be 16 h day^{-1} for the climatic conditions existing in Singhbhum with prolonged summer and

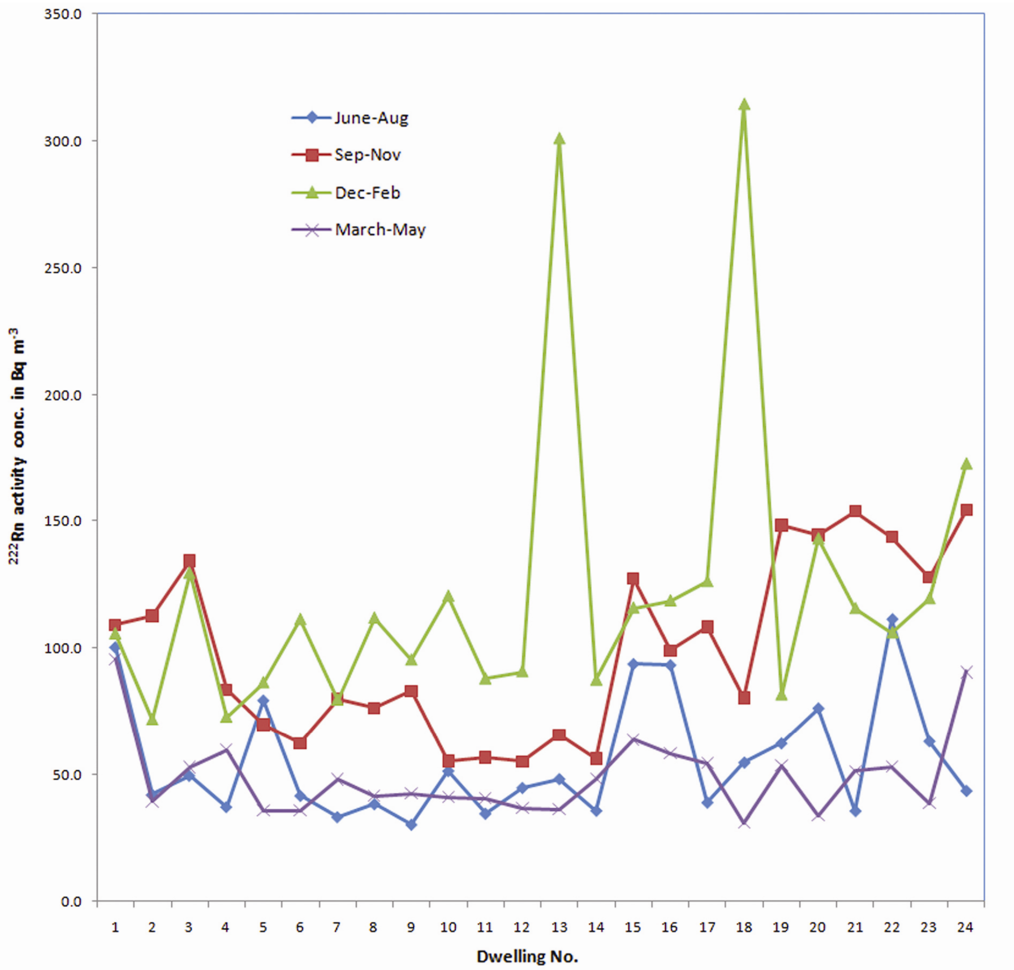

Figure 3. Seasonal variation in ^{222}Rn activity concentration in the dwellings.

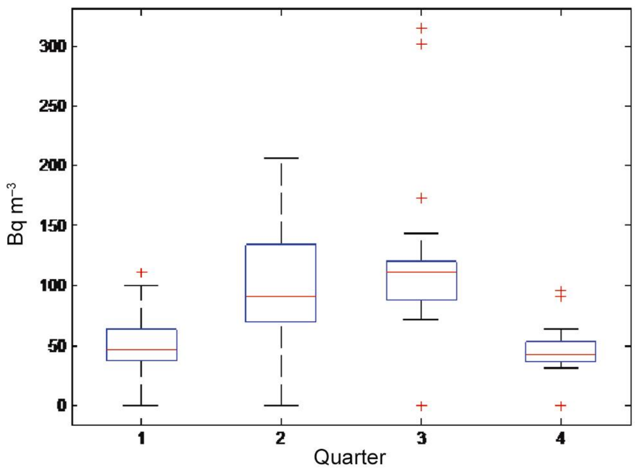

Figure 4. Boxplot showing seasonal variation of ^{222}Rn activity concentration in the dwellings.

comparatively short winter. The coldest season is January, with lowest temperature around 5°C whereas during summer (May and June) the temperature may be as high as 45°C. By and large, the summer season begins in March and continues till June. This is followed by rainy season starting from July and lasting till mid-October. These two seasons reflect more outdoor occupancy with low activity concentration of radon. In 12 villages 30 dwellings were selected for the deployment of the dosimeters. After the three months exposure period, the detectors were recovered and processed in the laboratory. The population distribution in rural areas is scarce and scattered in small villages. The study villages are situated in the foothills of Singhbhum shear zone. The construction type of dwellings does not follow a definite pattern due to the wide variation in socio-economic status. Well-ventilated, cemented roof and floor were found in more than one-third of the dwellings, whereas in others a mixed-type construction was found with cemented wall and mud floor or vice-versa. Least ventilated dwellings of mud wall and floor with or without small window and local tile or thatch roof were also found.

The seasonal variation in ^{222}Rn activity concentration is shown in Figure 3. Maximum activity concentration was found during the third quarter (December–February)

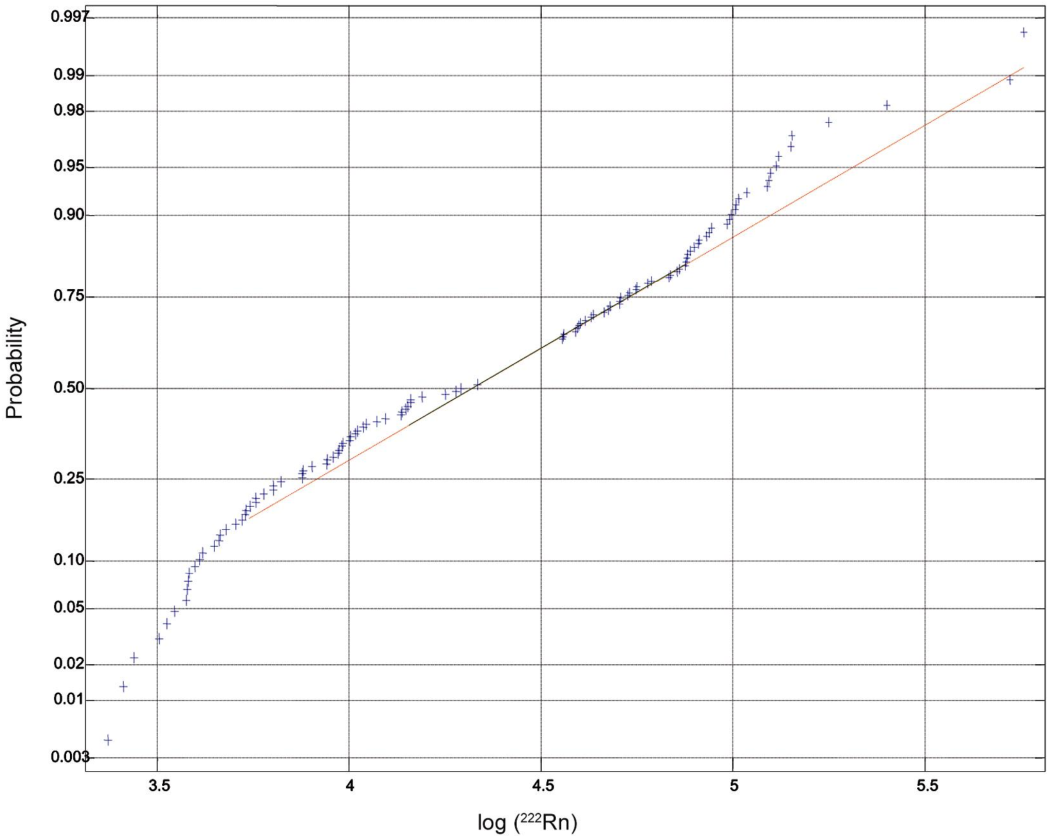

Figure 5. Log-normal probability plot of ^{222}Rn distribution in the dwellings.

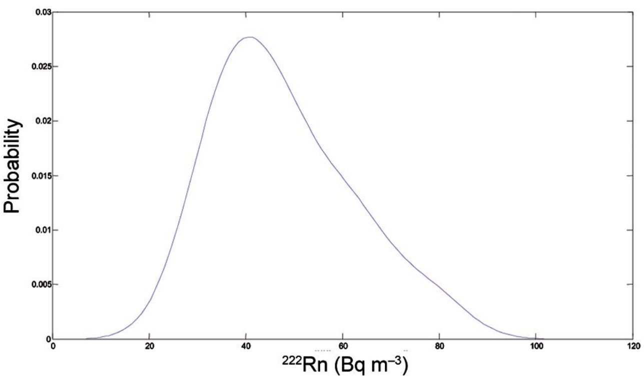

Figure 6. Ksdensity plot of ^{222}Rn distribution in the first quarter (June–August).

with two values exceeding 300 Bq m^{-3}. These elevated values in two dwellings in only one season with comparable levels in the remaining part of the year reflect poor ventilation during winter. In the last quarter (March–May) reflecting the summer season, most of the dwellings had ^{222}Rn activity concentration less than 50 Bq m^{-3}; the highest activity concentration was close to 100 Bq m^{-3}. In general, the increase in activity concentration profile of ^{222}Rn starts during the second quarter (September–November). Further, seasonal variation was not observed in one house and the activity concentration was close to 100 Bq m^{-3}. This house is only intermittently used for residential purpose and the construction type is cemented wall, roof and floor. Median, first and third quartile, rest of the data and outliers are presented in Figure 4. As evident from the figure, wide variation is found during the second quarter and least variation is found in the fourth quarter with two outliers. In one house, except in the first quarter the range itself varies from 90 to 172 Bq m^{-3}. Whereas the other outlier reveals intermittent residential occupancy as explained earlier. The median activity concentration during the first and fourth quarter and second and third quarter seems to converge. In the first and fourth quarter the activity concentration of ^{222}Rn was 47 and 43 Bq m^{-3}, whereas, in the second and third quarter it was 92 and 112 Bq m^{-3} respectively. The median ^{222}Rn activity concentration profile can be classified into two broader seasons with March–August and September–February, having similar type of pattern. When the entire set of data was incorporated covering all the four seasons and tested for statistical distribution, lognormal distribution can be approximated. Though some censored values and some outliers were found deviating from perfect log-normal assumption (Figure 5). The Jarque–Bera test and

Table 1. Location-wise seasonal variation of ^{222}Rn concentration (Bq m^{-3}) in dwellings of copper mining belt of East Singhbhum, Jharkhand

Dwellings no.	Location	House type	^{222}Rn concentration (Bq m^{-3}) June–August	September–November	December–February	March–May	Annual average
1	Kendadih village	Cemented house	100.3	109.2	105.8	95.8	102.8
2	Kendadih near temple	Cemented house	42.2	112.9	72.1	39.6	66.7
3	Kendadih near temple	Tiled roof, cemented floor	49.6	134.4	129.7	53.1	91.7
4	Netara village	Thatched roof, mud and clay house	37.3	83.9	73.1	60.0	63.6
5	Netara village	Tiled roof, cemented floor, mud walls	29.1	76.3	0.0	52.3	39.4
6	Chapri village	Thatched roof, mud and clay house	79.4	70.1	86.7	36.0	68.1
7	Chapri village	Thatched roof, mud and clay house	41.7	62.7	111.5	35.9	62.9
8	Roam village	Tiled, roof, mud and clay walls and floor	63.6	76.5	111.6	0.0	62.9
9	Roam village	Cemented house	33.3	80.2	79.8	48.3	60.4
10	Kulgora village	Tiled roof floor and walls cemented	38.4	76.7	112.1	41.8	67.3
11	Kulgora village	Tiled roof, mud and clay floor and walls	30.3	83.3	95.6	42.8	63.0
12	Ghatshila	Cemented house	51.5	55.8	120.7	41.4	67.3
13	Ghatshila	Cemented house	34.7	57.1	88.2	40.6	55.2
14	Ghatshila	Cemented house	44.8	55.5	91.1	37.0	57.1
15	Dahigora	Cemented house	48.3	65.9	301.2	36.6	113.0
16	Dahigora	Cemented house	35.8	56.6	87.7	48.4	57.1
17	Musabani	Tiled roof, mud and clay floor and walls	44.8	0.0	0.0	45.7	22.6
18	Musabani, near bakery	Tiled roof, mud and clay floor and walls	93.7	127.5	116.0	64.1	100.3
19	Qr. no. type-3/1	Cemented house	93.3	99.2	118.9	58.7	92.5
20	Surda main road	Cemented house	0.0	130.0	131.1	42.8	75.9
21	Surda main road	Cemented house	39.0	108.5	126.4	54.6	82.1
22	Kumurmudi village	Cemented house	64.1	206.8	114.3	0.0	96.3
23	Kumurmudi village	Tiled roof, cemented floor, walls with cement plaster on mud and clay	54.8	80.6	314.6	31.2	120.3
24	Rakha copper project	Cemented house	62.4	148.3	81.9	53.7	86.6
25	Matigoda	Cemented house	53.6	147.3	91.3	0.0	73.0
26	Saspur	Cemented house	76.3	144.4	143.1	33.9	99.4
27	Saspur	Cemented house	35.7	153.8	115.8	51.6	89.2
28	Saspur	Tiled roof, mud and clay floor and walls	111.3	143.7	106.2	53.2	103.6
29	Saspur	Tiled roof, mud and clay floor and walls	63.3	127.9	119.7	38.9	87.5
30	Saspur	Cemented house	43.6	154.2	172.9	90.8	115.4

All values have been rounded-off up to one decimal place.

Lilliefors test were confirmed for assuming null hypothesis ($h = 0$) for log-normal distribution. The significance level P was 0.17 for Jarque–Bera test and 0.11 for Lilliefors test, with $h = 0$. The log-normal assumption with geometric mean of 72.3 and geometric standard deviation of 1.67 can be further approximated based on the near identical values of median and geometric mean (73 and 72.3 Bq m^{-3}). However, dataset for individual season reflects different distribution patterns. The first quarter results reveal normal distribution barring the outlier data. The Jarque–Bera test ($h = 0$, $P = 0.17$) and Lilliefors test ($h = 0$, $P = 0.11$) both reveal normal distribution with mean 48 Bq m^{-3} and standard deviation 13.8. The ksdensity plot of the first quarter is presented in Figure 6. In the second quarter the data distribution was neither normal nor log-normal. The maximum likelihood estimate (MLE) reveals two probable concentrations in the second quarter at 104 and 38.6 Bq m^{-3}. Similarly, in the third quarter also, MLE approach can be approximated as both normal and log-normal assumptions do not hold. The MLE reveals two probable activity concentrations in the third quarter at 122 and 56 Bq m^{-3}. Similarly except the outlier values the fourth quarter distribution can be approximated as normal with mean 46 Bq m^{-3} and standard deviation 9. Variation between the minimum and maximum values of ^{222}Rn activity concentration can be attributed to different ventilation conditions during summer and to the difference in the dwelling heights. The indoor average annual inhalation dose based on the geometric mean concentration of radon can be worked to be 1.07 mSv $year^{-1}$, presuming an occupancy period of 5840 h $year^{-1}$, equilibrium ratio of 0.4 and dose conversion factor of 4 mSv WLM^{-1} (ref. 29).

The ^{222}Rn concentration profile is presented in Table 1. The mean values of the ^{222}Rn activity concentration of all the studied dwellings during different seasons are shown in Figure 3. The activity concentration shows clear trends of seasonal variations. It is observed that the indoor ^{222}Rn activity concentration levels are higher during winter and autumn compared to summer and the rainy season. The concentration was found to be maximum during winter and minimum in summer[30,31]. Since most of the dwellings are well ventilated in the summer season, the indoor ^{222}Rn activity concentration may be expected to be lower for summer than winter[32]. During winter season the windows are closed most of the time, which results in poor ventilation and consequently the ^{222}Rn concentration inside the dwellings builds-up. Moreover, houses made with mud walls have some cracks in the floor and ceiling from which ^{222}Rn emanation takes place and contributes to the build-up. As it depends on the building material and mode of construction of the mud houses, the floor of such houses allows more ^{222}Rn to diffuse inside the room because of higher porosity of the material used. The emanation of ^{222}Rn from building material (stone and soil) is also higher than the normal building material and may contribute additional ^{222}Rn inside the room. ^{222}Rn and ^{220}Rn in indoor environments mainly originate from emanation of the gases from the walls, floor and ceilings. Most of the terrestrial building materials available have 3–4 orders of magnitude higher concentration of ^{222}Rn gas in pore spaces than in the atmosphere, permanently maintained by the continuous decay of its parent nuclides. High concentration leads to a large ^{222}Rn/^{220}Rn gradient between the materials and open air. Levels of ^{222}Rn and ^{220}Rn in the open atmosphere are governed by the balance between the rate of exhalation and the dilution process in the atmosphere.

Since 1970, indoor ^{222}Rn levels have been measured and several large-scale surveys have been carried out by many agencies all over the world[8,33]. Typical worldwide indoor and outdoor levels of ^{222}Rn are about 45 and 7 Bq m^{-3} respectively[34]. Surveys performed in dwellings of India indicate that the indoor ^{222}Rn activity concentration varies between 2.2 and 56 Bq m^{-3} with a geometric mean of 15.1 Bq m^{-3} (ref. 35). This information has facilitated the understanding of many environmental processes which affect the distribution of ^{222}Rn levels both indoors and outdoors and the related radiation exposure to humans.

In conclusion, the seasonal variation of ^{222}Rn activity concentration in the studied dwellings suggests that the median ^{222}Rn activity concentration profile can be divided into two broader seasonal groups, such as March–August and September–February. The results show that ^{222}Rn activity concentrations at different locations vary between 29.1 and 314.6 Bq m^{-3} with an overall geometric mean of 72.3 Bq m^{-3} and geometric standard deviation 1.67. The indoor average annual inhalation dose is worked to be 1.07 mSv $year^{-1}$ presuming an occupancy period of 5840 h $year^{-1}$ and equilibrium ratio of 0.4 (ref. 23). The level of radon in the dwellings is high compared to the global average of 40 Bq m^{-3} (ref. 10), but comparable to the levels found in similar geological formations. Thus the activity concentration of ^{222}Rn in the studied dwellings depends on their ventilation condition and type of construction material used.

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The 25 April 2015 Nepal earthquake and its aftershocks

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The massive $M_w = 7.8$ earthquake which rocked the Nepal Himalaya on 25 April 2015 is the largest to have occurred in this region in the past 81 years. This event occurred by slip on a ~150 km long and 55 km wide, shallow dipping (~5°) segment of the Main Himalayan Thrust (MHT), causing the Himalaya to lurch southwestward by 4.8 ± 1.2 m over the Indian plate. The main shock ruptured the frictionally locked segment of the MHT, initiating near the locking line and rupturing all the way updip close to its surface expression

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