Measurement of variation of Radon-thoron and their progeny concentrations in dwellings using pin hole based dosimeters

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Abstract

In the present investigation, newly designed pin hole based radon-thoron dosimeter with LR-115 track detectors has been used for the integrated determination of radon, thoron and their progeny levels in the indoor air of the dwellings of the Union Territory (U.T.) Chandigarh for checking the indoor air quality. The soil and the building materials are the major source of the indoor radon and the contribution of these towards indoor radon levels depends upon the radium content and exhalation rates and so can be used as a primary index for radon levels in the dwellings. Due to this the radon exhalation rate of some soil samples of the study area has been measured using active technique. The exhalation rate of the sand samples, utilized for the construction purpose, available from the study area has also been measured.

The concentration of indoor radon was varying from 24.2 ± 1.1 Bq m^{-3} to 62.1 ± 3.1 Bq m^{-3}. The thoron concentration was found to be varying from 3.0 ± 0.1 Bq m^{-3} to 99.2 ± 4.9 Bq m^{-3}. The annual inhalation dose received by the inhabitants of these dwellings is in the safe limits. A good positive correlation was found between indoor radon concentration and radon mass exhalation rate of the soil samples of the study area.

Keywords: Indoor Radon; indoor thoron; annual effective dose; exhalation rate

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INTRODUCTION

Radon is a noble but a natural radioactive gas which evolves from the radioactive decay of radium. The radium content of the soil is considered to be constant due to its long half-life. Atmospheric radon originates exclusively from the earth's surface (Chambers *et al.*, 2016a). Like radon, thoron is also a radioactive gas that originates from the radioactive decay of thorium present throughout the earth's crust and in many building materials. But radon is more dangerous than thoron because it has long half-life of 3.8 days (Chambers *et al.*, 2016b) in comparison to thoron half-life of 55.6 sec. The decay of radon, ^{222}Rn and thoron, ^{220}Rn in the environment acts as a source of low vapor pressure decay products that attach with other nuclei or aerosol particles. Its decay products, ^{218}Po (3.0 min), ^{214}Pb (26.8 min) and ^{212}Pb (10.64 h) (Papastefanou, 2009) may attach with the aerosol particles and can be inhaled inside which are known to cause lung cancer (Brookins, 1998). Many other studies have also supported the similar results (Cohen, 1987; BEIR IV, 1988; Nazaroff and Nero, 1988; Momcilovic and Lykken, 2007). Besides radon, thoron and its progeny, PM2.5 is also one of the factors, interaction to which causes various diseases like bronchitis, allergies, lung cancer, heart disease etc. that becomes the cause of premature deaths (Chelani, 2017). PM2.5 may act destructively as it can be inhaled easily (due to its small length which is equal to 3.6% of the diameter of a human hair) deep inside the lungs and can penetrate the pulmonary alveolar cells, thus mobbing into the blood circulatory system (Xing et al. 2017). It's long been recognized that the air quality of indoor environments has a critical factor for determining the human health but a complete data of different areas about this is still missing (Saraga *et al.*, 2017). To determine the health effects of inhaled pollutants it is necessary to measure the dose deposited in the respiratory tract during exposure (Rissler et al., 2017). But the most prominent cause for lung cancer is radon, so the focus of study of this paper is the measurement of radon, thoron and its progeny concentration and the annual effective dose received by the general public due to these radionuclides.

Radon and thoron after generation migrate through soil into the dwellings but their concentration in dwellings depends on many factors like its rate of exhalation in the soil, ventilation conditions and construction material of the dwelling. Radon poses grave health hazards beyond certain levels indoor as declared by many worldwide agencies like USEPA (United States Environmental Protection Agency), UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation), ICRP (International Commission on Radiological Protection) and WHO (World Health Organization). In many developed countries, radon awareness, its measurement and mitigation programmes exist. Many studies were conducted worldwide to prepare a national geographic information system based on radon-thoron map (Stojanovska *et al.,* 2013, Stoulos *et al.*, 2003). People of the developed countries are concerned about this problem and get their homes survey done (weather existing older homes or newly built one). But in countries like India, Bangladesh and Pakistan etc. the awareness of this problem is low due to low literacy rates along with the non existence of specialized awareness programmes. So the people of these countries are more prone to exposure to radon and its health hazards. For these countries the best remedy is to measure radon levels indoor at as many places as possible and report if the levels measured are found to be more than the safe limit.

This study is aimed to measure the concentration of indoor radon and thoron in the dwellings of different places of the study area having different air exchange conditions (depending upon number of doors and windows) in U.T. Chandigarh for which very little data is available in the literature. The previous studies of the different area nearby to the study area were being conducted by bare mode or twin cup dosimeter techniques, which were having their own limitations reported elsewhere (Sahoo *et al.,* 2013). The newly developed pin hole based radon-thoron dosimeters were used for the study of this area (Sahoo *et al.,* 2013). The calibration of the dosimeters and the systematic errors has been dealt elsewhere (Sahoo *et al.,* 2013). Another important task of this study was to study the correlation of soil exhalation rates with the measured concentration levels of the radon and thoron. The radon mass exhalation rates were measured by the active technique by measuring growth of radon in a closed sealed accumulator (Sahoo *et al.,* 2007). Scintillation Radon Monitor (SRM) was used to measure the radon growth in the accumulator.

METHODS

Geology of the area

Union Territory of Chandigarh is in the foothills of Shivalik hills, which is a part of the fragile Himalayan ecosystem. The city is the joint capital of both the states of Haryana and Punjab. It has approximately 114 km² of area and is surrounded by Haryana, Himachal Pradesh, Punjab and Uttaranchal. As per census 2011, total population of the city was 1,054,686 persons having a population density of 9252 persons/sq.km (Gupta, 2007). The altitude of the city ranges from 304 to 365 meters above mean sea level. It is located between 30° 40' N and 30° 46' N latitude and between 76° 42' E and 76° 51' E longitude (Gupta, 2007).

Chandigarh observes four seasons viz. summer, autumn, winter and rainy season. Summer starts in mid-March and lasts upto mid-June, Rainy season starts in late June and lasts up to mid-September, autumn starts in mid-September and lasts up to mid-November, winter starts in mid-November and lasts up to mid-March. The two hottest months are May and June in which the temperature varies from 40 °C & 25 °C, respectively (Gupta, 2007). It is being surrounded by Mohali and Ropar districts from Punjab and Panchkula and Ambala districts from Haryana.

Fig. 1 shows the areas in the different locations of the Chandigarh where the study of measurement of indoor radon and radon exhalation were conducted. The dosimeters were installed in different dwellings at different places of Chandigarh keeping uniformity in mind. The data of annual inhalation dose received by the dwellers was analyzed according to the guidelines given by International Commission on Radiological Protection (ICRP, 2009). The soil samples for the measurement of radon exhalation rates from Chandigarh were taken from the dwellings itself or an area falling close to the dwellings. However some of the soil samples were collected from the different parts of the Chandigarh as shown in Fig. 1 (shown by different symbols in the figure). Few sand samples of the local source (Khuda Lahora) and from other sources available from hardware stores of the Chandigarh were taken.

Indoor radon-thoron, their progeny concentration and annual effective dose study

In this study, we report the concentration of radon-thoron measured in single-family dwellings. The study of indoor radon concentration which may be representative of population exposure is carried out in a random sample of dwellings for feasibility reasons. (SSNTDs) Solid State Nuclear Track Detectors are used in single entry pin hole based radon thoron dosimeters (PRTM) for the measurement of indoor radon levels. The advantages of this dosimeter over the twin cup dosimeters were discussed by Sahoo et al. 2013.

This dosimeter consists of two chambers that are cylindrical in shape and has a length of 4.1 cm and radius of 3.1 cm. An internal coating of the chambers with the metallic powders has been done to have zero electric field inside so as to have a uniform deposition of the progenies formed from the gases throughout the volume (Sahoo et al. 2013). The schematics of the pin hole dosimeter is shown in Figure 2.

The two chambers are separated centrally by a pin-holes disc having four pin holes. The pin holes are 2 mm of length and 1 mm of diameter. The disk acts as a thoron discriminator. There is a common entry for both the gases in the dosimeter cups. The first chamber called "radon + thoron" chamber contains a glass fiber filter paper (pore size 0.7 μm) through which the gas enters into this and then only radon gas diffuses to second chamber called "radon" chamber through pin-holes that cuts the entry of thoron into this chamber. The solid state nuclear track detector strippable films of size 2 cm x 2 cm of LR-115 (Type-II) were fixed at the opposite ends of the entry face in the each chamber. The detector of first chamber measures the alpha particle tracks due to both the radon and thoron, while the detector of the second chamber measures the alpha tracks due to radon only.

The pin hole dosimeters were hanged in the rooms about 1 meter below the ceiling of the room and at a height more than 2 m above the ground level. This is done to avoid any direct exposure of LR-115 films to the alpha particles emitted from the construction material of the ceiling. The dwellers were instructed regarding the detectors and to clean and ventilate their homes as they usually would in the absence of detectors. Information regarding dimension of dwellings, building and roof materials as well as ventilation was gathered during deployment of dosimeter from the dwellings. The detectors were placed for a period of three months and after that the detectors were removed from the dwellings. During the whole span of study proper procedures were followed to minimize any extra exposures of films before and after their exposures in the dwellings. Each dosimeter was prepared shortly before deployment in the dwelling. After retrieval from dwelling, the detector films were stored in highly ventilated rooms and sealed in radon-proof steel almirah before being processed. The etching and counting of tracks from exposed detectors were carried out by the method described elsewhere (Mehta *et al.* 2015a, b). The counted tracks density is converted into radon and thoron concentration according to following relations.

$$C_T = \frac{T_2 - d.C_R.K_R^{'}}{d.K_T} \quad (1)$$

$$C_R = \frac{T_1}{d.K_R} \quad (2)$$

Where C_R and C_T are radon and thoron concentration, T_1 is the track density observed in 'radon' chamber. K_R is the calibration factor of radon in 'radon' chamber for radon (0.0170 ± 0.002 tr. cm^{-2} per Bq.d.m^{-3}) d is the number of days of exposure. T_2 is the track density observed in the 'radon + thoron' chamber K_R' (0.0172 ± 0.002 tr. cm^{-2} per Bq.d.m^{-3}) and K_T (0.010 ± 0.001 tr. cm^{-2} per Bq.d.m^{-3}) are the calibration factors of radon and thoron in 'radon + thoron' chamber (Sahoo et.al, 2013). The inhalation dose was calculated using conversion coefficient of 9 and 40 nSv/h/(Bq m^{-3}) with equilibrium factor of F_R= 0.4 and F_T = 0.1 for radon and thoron respectively

(UNSCEAR, 2006). The dose coefficient for radon and thoron were calculated using conversion coefficient of 0.17 nSv for radon and 0.11 nSv for thoron. The annual inhalation dose (mSv yr^{-1}) may be provided using the formula (UNSCEAR, 1993).

$$D\,(mSv) = \{(0.17+9F_R)\,C_R + (0.11+40F_T)\,C_T\} \times 7000\times10^{-6} \qquad (3)$$

Radon exhalation rate study (soil samples)

Active measurement of radon growth in a closed sealed accumulator was done to measure radon exhalation rate from the soil samples (Sahoo et al. 2007; Petropoulos et al. 2001). The soil samples were taken from the dwellings (if available) or from the area close to the dwelling. Some more soil samples were taken from the different parts of the city for the uniformity of the results. Soils were dried before sealing in the leak proof exhalation chamber. The chamber was connected to Scintillation Radon Monitor (SRM) to determine the growth of the radon in accumulator. The measurement was carried out till the radon growth reaches a saturated concentration. The growth data was then fitted to Eq. (4) (Kumar *et al.,* 2014) for estimating radon mass exhalation rate (J_m).

$$C = \frac{J_m\,M}{V\,\lambda_e}(1 - e^{-\lambda_e t}) + C_0 e^{-\lambda_e t} \qquad (4)$$

Where J_m represents the radon mass exhalation rates in (Bq/kg/h), M and V represent the mass of soil sample and effective volume of the chamber including the volume of the scintillation cell respectively. λ_e represents the effective decay constant which is sum of radon decay constant, radon back diffusion constant and chamber leakage rates if any, C_0 is initial radon concentration in chamber.

Radon exhalation rate study (sand samples)

The closed canister technique was used to find radon exhalation rates of the sand samples (Abu-Jarad *et al.,* 1980; Mehta *et al.* 2015b). The sand samples collected from the hardware store of the area under study were dried in an oven and 100 g of it was placed in the plastic cans similar to those used in the calibration experiment of Singh *et al.* (1997) and were sealed. The sensitive side of the SSNTD film was fixed at the lid of the canister to freely expose it to radon. After the exposure period 100 days, the detectors were removed, processed and tracks were counted as per the procedure given elsewhere (Mehta et al. 2015a). The track density was converted into radon activity using the calibration factor of 0.056 tr. cm^{-2} d^{-1}/Bqm^{-3} obtained from an earlier calibration experiment (Singh *et al.*, 1997). The radon mass and surface exhalation rates from the soil sample can be calculated by following relation

$$E_A = \frac{CV\lambda}{A(T + \frac{1}{\lambda}(e^{-\lambda T} - 1)} \quad (5)$$

$$E_M = \frac{CV\lambda}{M(T + \frac{1}{\lambda}(e^{-\lambda T} - 1)} \quad (6)$$

Where C is equilibrium radon activity inside the canister, V and A are volume and area of cross-section of the canister, M is the mass of the sample and λ is the radon decay constant, T is the time of exposure.

RESULTS AND DISCUSSION

Concentration of indoor radon, thoron and annual dose

The pin hole based radon-thoron dosimeters were used in the autumn season of the year to measure the indoor radon and thoron levels in some dwellings of Chandigarh and the results obtained were listed in table 1. The necessary information regarding the latitude and longitude of the dwellings chosen was given in this table. The levels of indoor radon, indoor thoron and their progeny concentration were also given along with the amount of annual dose received by the dwellers. It also has the number of the effective doors and windows (small + large) which remained open for at least 8 hrs in a day during the study period (The dwellings were actually having more number of windows than reported, but few remained closed for most of the time due to inaccessibility or due to habit of the occupants). The indoor radon levels in Chandigarh found to be varying from 24.2 ± 1.1 Bq m^{-3} to 62.1 ± 3.1 Bq m^{-3}. The indoor thoron levels varied from 3.0 ± 0.1 Bq m^{-3} to 99.2 ± 4.9 Bq m^{-3}. The average value of indoor radon and thoron were found to be 39.9 Bq m^{-3} and 31.1 Bq m^{-3} respectively. The progeny levels of radon and thoron were found to be 2.61 to 6.7 mWL and 0.08 to 2.7 mWL respectively. The average of progeny levels for radon and thoron were 4.3 mWL and 0.8 mWL respectively. The annual inhalation dose for the dwellers was found to be 0.83-3.89 mSv with an average value of 1.9 mSv.

Fig. 3 shows the variation of average indoor radon-thoron levels with the effective number of outlets available in the dwellings for the air circulation. This shows the decrease of indoor radon-thoron levels with the increase of number of outlets. Similar trends were shown in table 2, which provides the value of average annual inhalation dose received by the dwellers according to the air circulation conditions which depends upon the effective number of outlets/vents (doors and windows) operating in the specific room where the dosimeter has been placed. It indicates that the value of annual dose received by the dwellers of those dwellings was on lower side where more number of doors and rooms were open for more than 8 hrs a day. This result indicates one of the methods of mitigation of radon problem, which depends upon the evacuation of the internal air to lower the radon levels indoor.

Soil and sand samples radon exhalation rates

The results of radon exhalation study of different soils collected from the Chandigarh are listed in table 3. The minimum radon mass exhalation rate measured was 1.96 mBq/kg/h and the maximum was 12.52 mBq/kg/h. The average value was found to be 5.26 ± 1.18 mBq/kg/h. The result of this study in this area shows lower values than that of the world wide average.

The results of the study of both mass and surface exhalation rate of the sand samples from different sources available from hardware stores of Chandigarh were shown in table 4. The values of mass exhalation rates and surface exhalation rates vary from 0.9 to 1.9 mBqkg^{-1}h^{-1} and 20.1 to 42.7 mBqm^{-2} h^{-1} respectively. The average values of mass and surface exhalation rates were found to be 1.4 ± 0.2 mBqkg^{-1}h^{-1} and 31.0 ± 4.9 mBqm^{-2} h^{-1} respectively. The table also contains the value of equilibrium radon concentration which varies from 24.6 to 52.4 Bqm^{-3} with an average of 38.0 ± 5.7 Bqm^{-3}.

A very good positive correlation (R^2=0.97) was found between indoor radon concentration and radon mass exhalation rate of the area of Chandigarh as shown in Fig. 4. This correlation is an indication of the direct relationship between the radium content of the soil and the construction materials with the values of radon levels to be present in the dwellings.

CONCLUSIONS

The indoor radon and indoor thoron levels was found to be 24.2 ± 1.1 Bq m^{-3} to 62.1 ± 3.1 Bq m^{-3} and 3.0 ± 0.1 Bq m^{-3} to 99.2 ± 4.9 Bq m^{-3} respectively. The average value of indoor radon and indoor thoron was 39.9 Bq m^{-3} and 31.1 Bq m^{-3} respectively. Since the variation in the values of indoor radon activity for all the dwellings of the area under study are well below the recommended level of 300 Bqm^{-3} so that radon poses no harmful effects for the peoples of this area. The average annual inhalation dose received by the dwellers was found to be 0.83 to 3.89

mSv having an average value of 1.9 mSv. However, the amount of annual dose received has some dependence on the effective number of vents operating in the dwellings. The measured values of radon mass exhalation rates of the soils of Chandigarh were varying from 1.96 to 12.52 mBq/kg/h with an average of 5.26 ± 1.18 mBq/kg/h. The values of mass exhalation rates and surface exhalation rates of sands of the study area varied from 0.9 to 1.9 $mBqkg^{-1}h^{-1}$ and 20.1 to 42.7 $mBqm^{-2}\,h^{-1}$ respectively. The average values of mass and surface exhalation rates of sand samples were found to be 1.4 ± 0.2 $mBqkg^{-1}h^{-1}$ and 31.0 ± 4.9 $mBqm^{-2}\,h^{-1}$ respectively. The exhalation rate was found to be lower in comparison to the average value of worldwide studies. A strong positive correlation (R^2=0.97) was found between indoor radon and mass exhalation rate of soil of Chandigarh. The exhalation study of the soils and sands of this place shows values within the safe limits which indicate the safe levels of the indoor radon. This indication was confirmed by the results of indoor radon study. The observed radon values in the present study are comparable with other studies reported for the dwellings of the nearby areas as shown in table 5.

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Table 1: Radon, thoron and their progeny levels in some dwellings of Chandigarh in autumn season

Table 2: Dependence of average annual dose upon the air circulation conditions of the dwellings

Table 3: Radon exhalation rates from soil samples of Rupnagar using scintillation radon monitor

Table 4: Equilibrium radon concentration, mass exhalation and surface exhalation rate in the sand samples

Table 5: Comparison of indoor radon and annual average dose of the present study with other studies of the nearby areas measured by pin hole dosimeters

Table 1. Radon, thoron and their progeny levels in some dwellings of Chandigarh in autumn season

Location	Door (D) + Windows (W)	Latitude & Longitude	Radon Concentration C_R(Bq m^{-3}) AM + SE	Thoron Concentration C_T (Bq m^{-3}) AM + SE	Progeny levels of Radon C_R (mWL)	Progeny levels of Thoron C_T (mWL)	Annual Dose (mSV)
DW-1	1D + 1W	30° 44'29"N 76° 44'12"E	62.10 ± 3.10	9.87 ± 0.49	6.71	0.27	1.92
DW-2	1D + 2W	30° 45'22"N 76° 46'32"E	40.52 ± 2.03	10.30 ± 0.52	4.38	0.28	1.37
DW-3	1D	30° 44'22"N 76° 44'35"E	39.22 ± 1.96	99.22 ± 4.96	4.24	2.68	3.89
DW-4	1D	30° 44'17"N 76° 44'36"E	56.21 ± 2.81	36.65 ± 1.83	6.08	0.99	2.54
DW-5	1D + 1W	30° 44'17"N 76° 44'36"E	43.14 ± 2.16	71.35 ± 3.57	4.66	1.93	3.19
DW-6	1D + 1W	30° 45'20" N 76° 46'22" E	32.06 ± 1.6	19.36 ± 0.9	3.46	0.52	1.40
DW-7	2D + 2W	30° 42'31" N 76° 44'40" E	27.90 ± 1.1	3.0 ± 0.1	3.00	0.08	0.83
DW-8	1D + 2W	30° 41'42" N 76° 45'20" E	42.94 ± 2.20	19.35 ± 1.01	4.58	0.51	1.58
DW-9	2D + 1W	30° 44'06" N 76° 45'55" E	31.40 ± 1.52	6.12 ± 0.29	3.40	0.16	1.01
DW-10	1D + 2W	30° 42'22" N 76° 44'23" E	24.18 ± 1.3	36.18 ± 1.5	2.61	0.98	1.68

- AM = Arithmetic Mean, SE = Standard Error = σ/√ N, Where σ is SD (Standard Deviation) and N is the no. of observations, DW = Dwelling

Table 2. Dependence of average annual dose upon the air circulation conditions of the dwellings

S. No	Air Circulation (depends on number of doors and windows)	No. of dwellings	Average annual Dose (mSv)
1	Low (1D)	2	3.22
2	Moderate (1D + 1W)	3	2.17
3	High (1D + 2W)	3	1.54
4	Very high (2D + 1/2W)	2	0.92

- D = Door, W = Window

Table 3. Radon exhalation rates from soil samples of Rupnagar using scintillation radon monitor

Sr. No	Location	Radon mass exhalation rates (mBq/kg/h)
1	DW-2	4.21
2	DW-3	4.22
3	DW-4	5.78
4	DW-7	2.89
5	DW-10	1.96
6	S-1(Near PGI)	7.14
7	S-2(Mullanpur barrier)	12.52
8	S-3 (Khuda Lahoran	3.38
	AM ± SE	5.26 ± 1.18

- AM = Arithmetic Mean, SE = Standard Error = σ/√ N, Where σ is SD (Standard Deviation) and N is the no. of observations, S = Site, DW = Dwelling

Table 4. Equilibrium radon concentration, mass exhalation and surface exhalation rate in the sand samples

Sr. No.	Location	Codes	Equilibrium Radon concentration (Bqm^{-3})	Mass exhalation rate ($mBqkg^{-1}h^{-1}$)	Surface exhalation rate ($mBqm^{-2}h^{-1}$)
1	Chandigarh (Khuda Lahora)	Sand-1	39.2	1.4	31.9
2		Sand-2	35.8	1.3	29.2
3	Other Sources (from hardware store)	Sand-3	24.6	0.9	20.1
4		Sand-4	52.4	1.9	42.7
	AM ± SE		38.0 ± 5.7	1.4 ± 0.2	31.0 ± 4.9

- AM = Arithmetic Mean, SE = Standard Error = $\sigma/\sqrt{N}$, Where σ is SD (Standard Deviation) and N is the no. of observations

Table 5. Comparison of indoor radon and annual average dose of the present study with other studies of the nearby areas measured by pin hole dosimeters

S. No.	Location	Radon Concentration (Bq m^{-3})	Annual Dose (mSV)	Reference
1	Jalandhar, Punjab	36.0	1.27	Mehra et al. 2016a
2	Ludhiana, Punjab	28.0	--	Mehra et al. 2016b
3	Kapurthala, Punjab	42.0	1.69	Mehra et al. 2016a
4	Mansa, Punjab	54.0	--	Bangotra et al. 2015
5	Mukatsar, Punjab	56.0	--	Bangotra et al. 2015
6	Rupnagar, Punjab	20.3	1.3	Mehta et al., 2015b
7	Hamirpur, Himachal Pradesh	85.0	2.13	Bajwa et al. 2016
8	Kurukshetra, Haryana	21.0	--	Chauhan et al. 2016
9	Panchkula, Haryana	24.0	--	Chauhan et al. 2016
10	Yamunanagar, Haryana	36.0	--	Chauhan et al. 2016
11	Karnal, Haryana	23.0	--	Chauhan et al. 2016
12	**Chandigarh**	39.9	1.9	**Present Study**

Figure Captions

Fig. 1. Location map of the study area

Fig. 2. (a) Schematic diagram (b) Actual single entry radon, thoron dosimeter cup

Fig. 3. Variation of indoor radon-thoron levels effective number of outlets for air circulation

Fig. 4. Correlation between indoor radon concentrations and radon mass exhalation rate

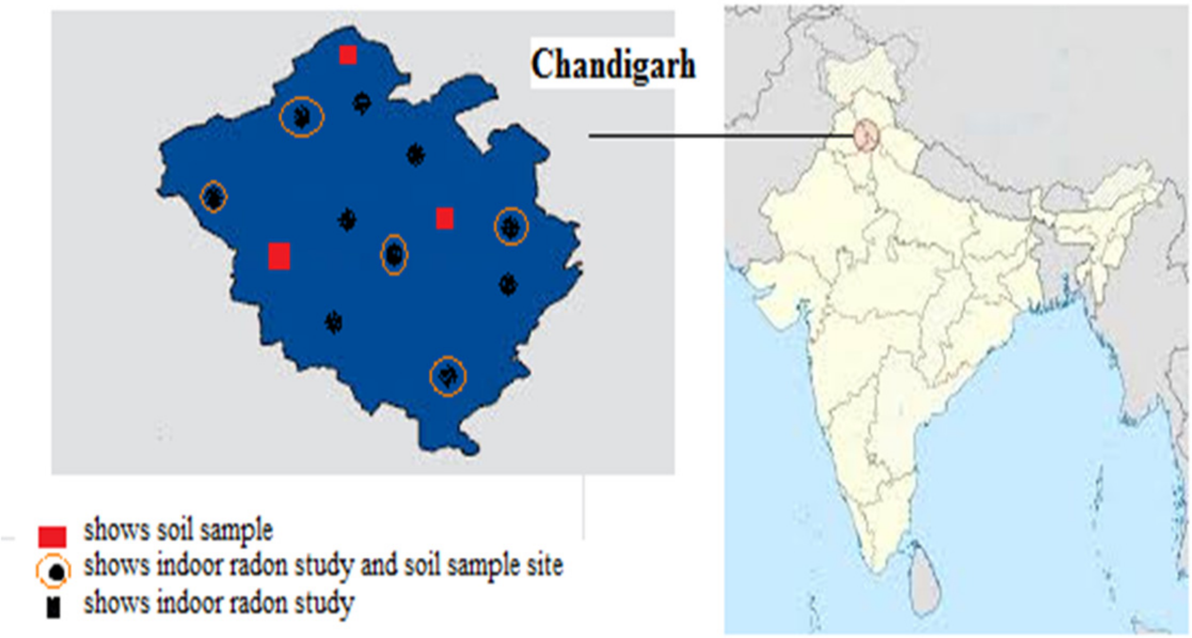

Fig.1: Location map of the study area

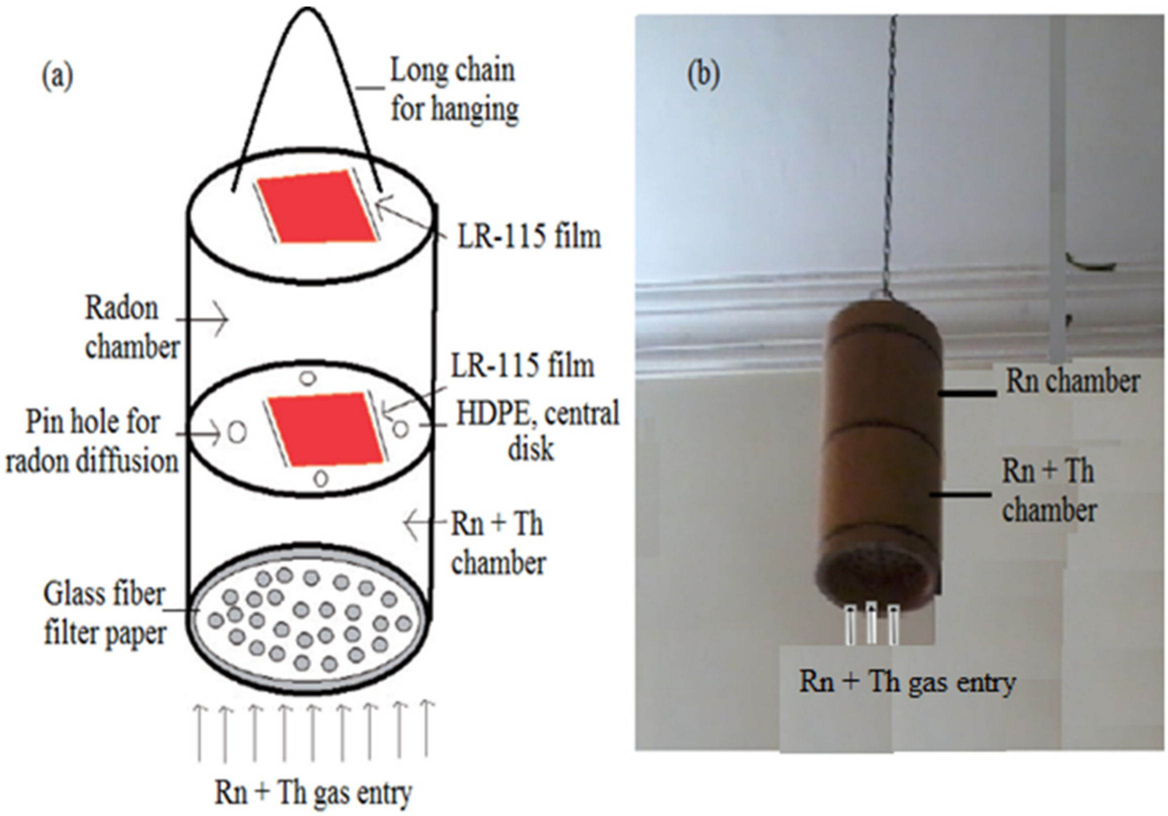

Fig. 2: (a) Schematic diagram (b) Actual single entry radon, thoron dosimeter cup

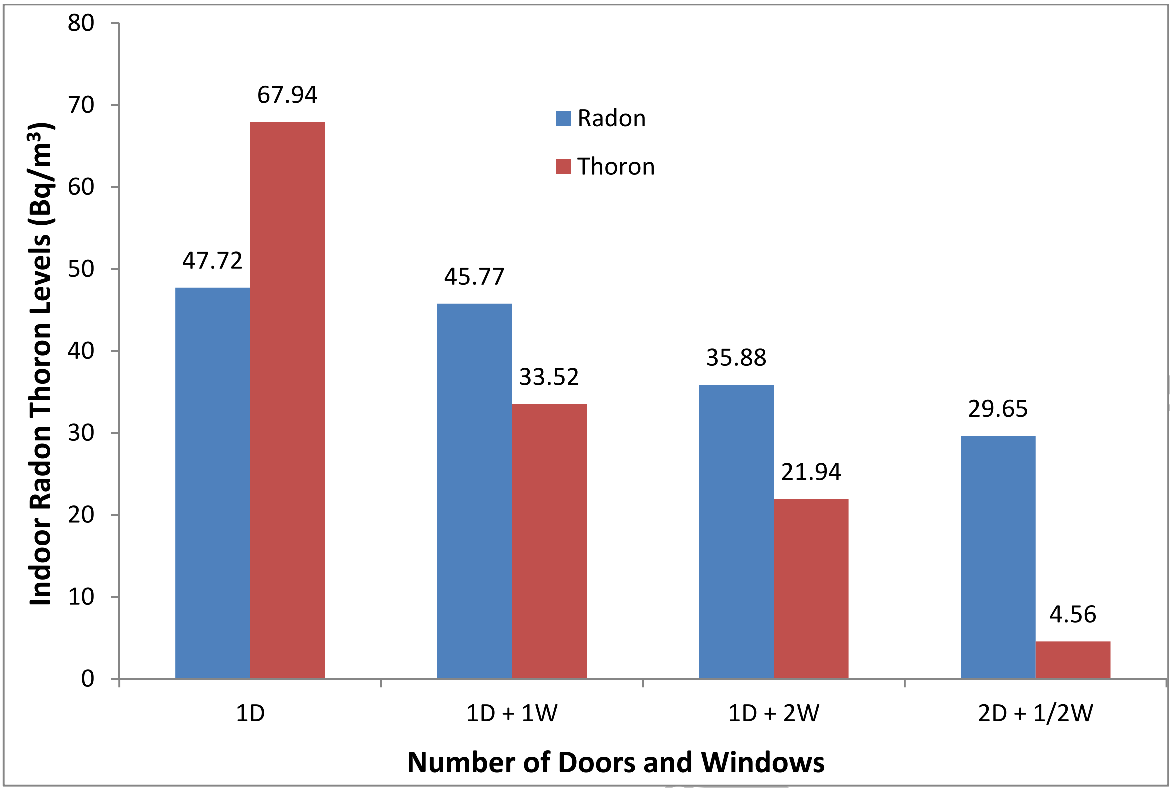

Fig. 3. Variation of indoor radon-thoron levels effective number of outlets for air circulation (D = Doors, W = Window)

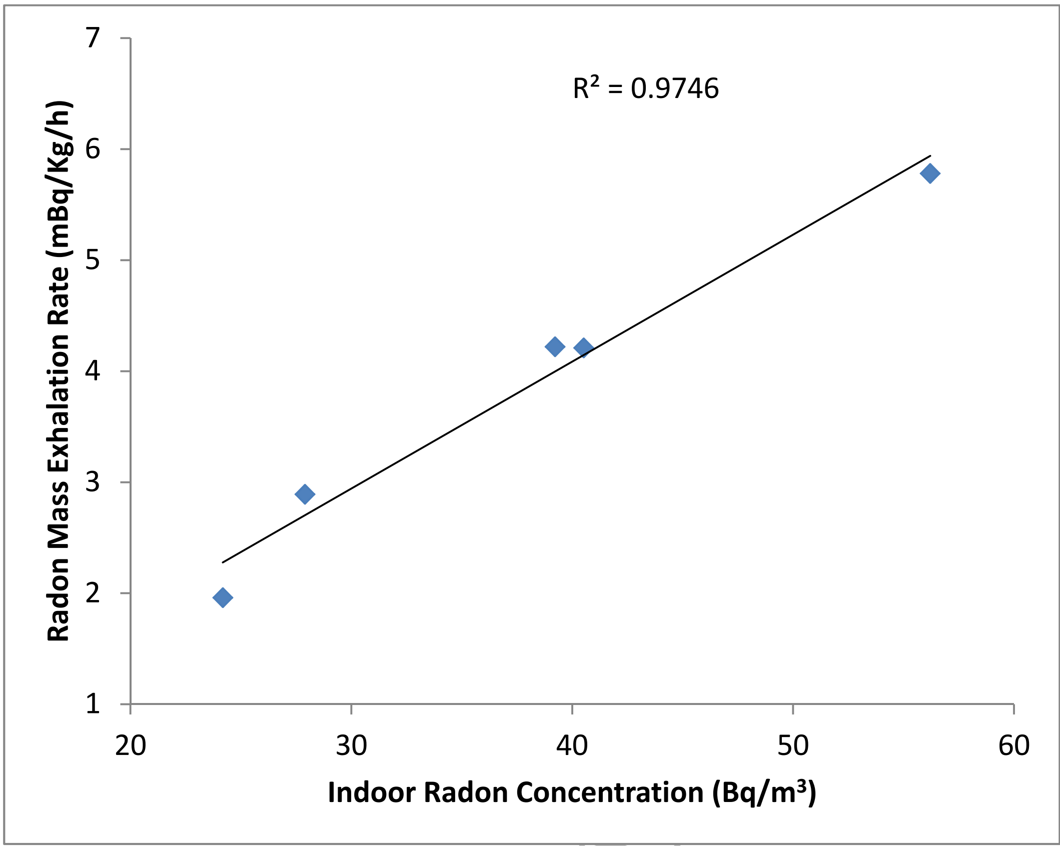

Fig. 4. Correlation between indoor radon concentrations and radon mass exhalation rate