ESTIMATION OF ATTACHED AND UNATTACHED FRACTION OF RADON AND THORON PROGENY CONCENTRATION AND EQUILIBRIUM FACTOR FOR INHALATION DOSE ASSESSMENT.

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***Abstract**:*

In the present study, Estimation of indoor radon (^{222}Rn), thoron(^{220}Rn) and their equilibrium equivalent concentration (EEC) were carried out in 40 dwellings of five taluks situated in Coastal Uttara Kannada District, Karnataka, India, by using LR-115 type II-based pin hole twin cup dosimeters and deposition-based progeny sensors(DRPS/DTPS). The annual average indoor ^{222}Rn and ^{220}Rn concentrations observed in these dwellings were 60.445 and 79.151 Bqm^{-3}, respectively, while the average EEC (attached +unattached) for ^{222}Rn and ^{220}Rn was 33.196 and 1.143Bqm^{-3}. The average values of fine fraction for ^{222}Rn (f_{Rn}) and ^{220}Rn (f_{Tn}), were 0.137 and 0.241, respectively. The equilibrium factors for radon (F_{Rn}) and thoron (F_{Tn}) varied from 0.244 to 1.648 with an average of 0.611 and 0.010 to 0.058 with an average of 0.016respectively. The annual inhalation dose due to mouth and nasal breathing was calculated using dose conversion factors and unattached fractions. The indoor annual effective doses for ^{222}Rn (AEDR) and ^{220}Rn (AEDT) were found to be 2.163 mSva^{-1} and 0.381 mSva^{-1} respectively. The values of ^{222}Rn/ ^{220}Rn concentrations and annual effective doses obtained in the present study are well within the safe limits as recommended by the International Commission on Radiological Protection (ICRP) for indoor dwelling exposure conditions.

Keywords**: **EEC, Unattached fraction, Equilibrium factor, DCF , Effective dose, Coastal Uttara Kannada

Introduction:

Greater than 50% of natural background dose to the general public is due to the inhalation of radon, thoron and their decay products (UNSCEAR2008).The occurrence of radon, thoron and their decay products in indoor environment is due to their parent radium and thorium present in the building materials, rocks and the soils. For assessing the radiation dose received from inhalation of radon, thoron and progenies, estimation of their equilibrium factor is very important. Indoor radon is considered the second most important cause of lung cancer in general public, after smoking (UNSCEAR2008).On the basis of results of epidemiological studies in several nations the WHO has recommended to reducing the indoor radon reference level from 200 Bqm^{-3} to 100 Bqm^{-3} (WHO2009).This recommendation create an interest in radon study and large scale radon mapping programme all over the globe to measure the extent of radon risk in general public. In the earlier studies thoron concentration has been neglected because of its short half life (Steinhausler et al. 1994).In high background radiation areas having thorium-rich soil in India, China, and Brazil, thoron has a special significance. From an epidemiological point of view, these areas are preferred for the measurement of low level chronic radiation exposures on human health (Nair et al.1999). Thus now, focus has been given for simultaneous measurement of radon, thoron and their progeny concentration in indoor air.

The dominating sources of radiation dose to general public are the short-lived decay products ^{218}Po, ^{214}Pb and ^{214}Bi of radon, and ^{212}Pb and ^{212}Bi of thoron. In terms of equilibrium equivalent concentrations (EEC), the decay product concentrations have been measured using the following relations (ICRP 1981, Parminder Singh et al.2016):

$$\text{EEC}\,(^{222}\text{Rn}) = 0.105\,(^{218}\text{Po}) + 0.516\,(^{214}\text{Pb}) + 0.379\,(^{214}\text{Bi})$$

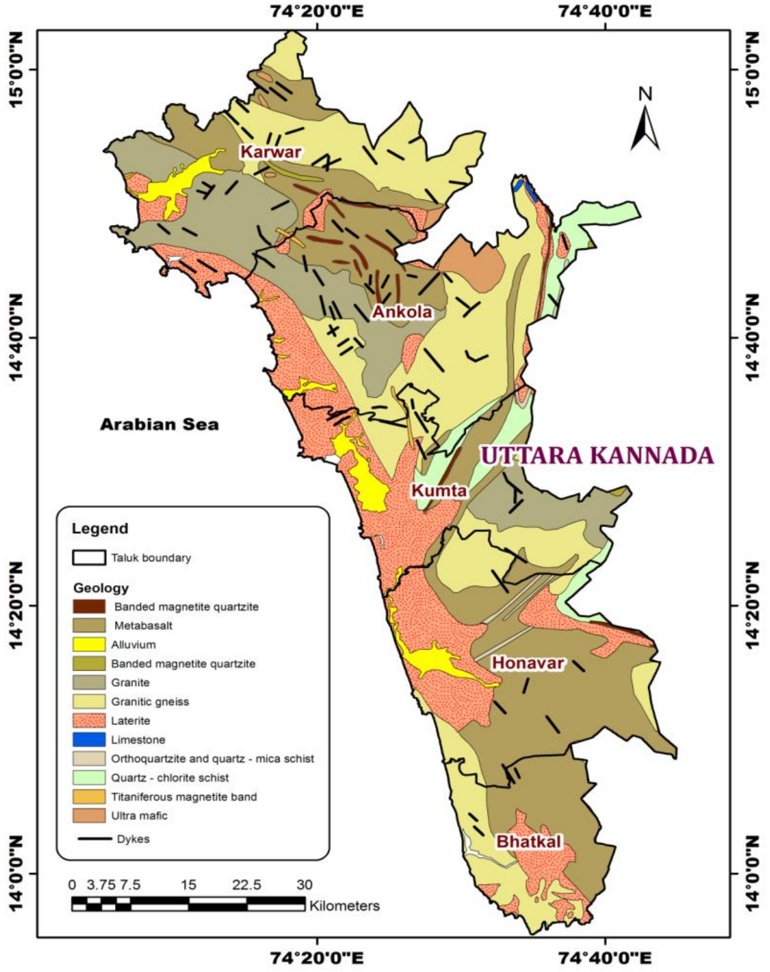
$$\text{EEC}\,(^{220}\text{Rn}) = 0.913\,(^{212}\text{Pb}) + 0.087\,(^{212}\text{Bi})$$

where ^{218}Po, ^{214}Pb, ^{214}Bi, ^{212}Pb and ^{212}Bi are individual activity concentrations in Bqm^{-3}. The radon and thoron gas concentration is conventionally used for the estimation of EEC of radon and thoron, by assuming equilibrium factor (F) values of 0.4 for radon and 0.02 for thoron (UNSCEAR 2008). Owing to the uncertainty involved in the equilibrium factors this is not advisable (Nikezicand Yu 2005). The short-lived decay products of radon (^{218}Po, ^{214}Pb and ^{214}Bi) and thoron (^{212}Pb and ^{212}Bi) are present in the environment in attached and unattached fractions (Mishra et al. 2010; Mayya et al. 2010). In order to assess the actual inhalation lung dose received by the general public, it is needed to measure directly the EEC in attached and unattached components, (Mishra et al. 2014).

Actually, the dose givers are electrically charged progeny produced by^{222}Rn and ^{220}Rn. These progenies tend to attach with surfaces and dust particles in the air and react with gases or vapour to form clusters, called as unattached particles (Parginn Babgotra et al.2015). The characteristic feature of unattached fractions is generally the particle size range from 0.5nm to 3nm. (Ramamurthi et al., 1989; Hopke et al.,1990). or the decay products having an activity median diameter (AMD) of less than10nm are referred as unattached progeny (Porstendo¨rfer1994), while those with an AMD in the range 10nm –1000nm are referred as attached progeny (Dankelmann et al. 2001). Using dose conversion factors (DCFs), the annual effective dose (AED) is estimated for radon, thoron and their decay product concentrations. Wide uncertainty is noticed in worldwide used DCFs since these factors depend not only on ventilation conditions but also on size of living room and aerosol concentration (Porstendorfer 2001). The most important factor influencing DCFs, compared to any other environmental factor, is the unattached fraction of decay products as unattached decay products have greater deposition efficiency in the lungs than the larger-sized attached decay products (Tokonami et al. 2003). In the earlier study we have estimated radon concentration in drinking water in five coastal taluks of Uttara Kannada district, Karnataka, India. In the present study along with radon, thoron concentration EEC in attached and unattached fractions have been estimated for the first time in this area.

Study area:

The study area coastal belt of Uttara Kannada district is located in Karnataka state of India between north latitudes13^{0} 55^{1} 02^{11}to 15^{0} 31^{1} 01^{11}and east longitudes 74^{0}0^{1}35^{11} to 75^{0}10^{1} 23^{11} The geology of coastal belt of Uttara Kannada consists of varieties of rocks as well as minerals. The geographical conditions are most favorable in the formation of different types of soils. Heavy rainfall and alternative seasons of heat and cold have lead to the formation of lateritic rocks. Such lateritic rocks are the parent material of rock types along the coastal belt of Uttara Kannada. The other common rock types along the study area are quartzite, granites, granitic gneisses, metabasalt and alluvium rocks. Minerals such as, Iron ore, Bauxite ore,magnetite, silicate etc. soil types include lateritic soil, alluvial soil, red loamy soil and sandy soil. Dwellings in this area are mostly made up of lateritic brick walls with cement plastering ,different types of granites, marbles ,vitrified tiles, kadapa and cement with red oxide are also used for walls and flooring.



Fig(1): Geological map of Costal taluks og Uttara Kannada District

Methodology:

Indoor ^{222}Rn and ^{220}Rn gas concentrations were estimated using LR-115 solid state nuclear track detectors (SSNTDs) .The BARC developed single entry pin hole based twin cup dosimeter was used. It consists of two compartments separated by a central pin hole disc which acts as thoron discriminator. To estimate EERC and EETC in attached and unattached fractions, deposition based direct radon/thoron progeny sensors (DRPS/DTPS) were used. The attached progeny concentrations were measured using wire mesh capped DRPS/DTPS.All the detectors were calibrated at the Radiological and Advisory division (RPAD), BARC, Mumbai. Dosimeter along with progeny sensors were hanged inside the houses at a distance of about 40 cm from walls, cellings and also from any doors, windows ,fans and other ventilations and at a height of 2.5 m from the floor.

Along with the estimation of radon/thoron concentrations, equilibrium equivalent concentrations in attached and unattached fractions were carried out in 40 dwellings of five coastal taluks of Uttara Kannada district for a period of 90 days (From July2017 to

September2017). After expose for a stipulated period of three months, the detectors were retrieved from the dosimeter and etched in 2.5N NaOH solution for $1\frac{1}{2}$ hour (90 minute) at 60^0C in constant temperature bath without stirring. After etching, the films were removed from the etching vessel and washed in running tap water to remove alkali from surface and then kept in distilled water for 1 hour and then they were dried up in laboratory conditions. The detectors have been peeled off from their cellulose acetate base and track counting was done with spark counter. The etched films have been pre sparked at 900V prior to these measurements. The spark counter was operated at operating voltage of 550V while measuring.

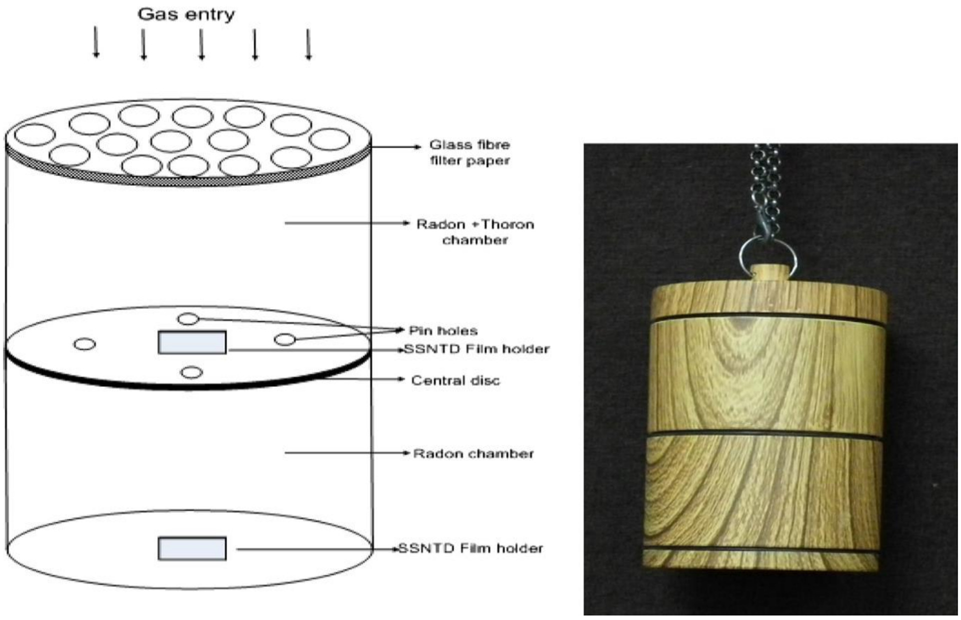
Estimation of radon (^{222}Rn) and thoron (^{220}Rn) gas concentrations

In the present study, by using single-entry pinhole-based twin cup dosimeters the radon (^{222}Rn) and thoron (^{220}Rn) gas concentrations were estimated. Details have been already discussed earlier (Sahoo et al. 2013). The dosimeter had a single entry through which gas enters the first chamber named the ‘radon + thoron’ chamber through a 0.56-µm glass fiber filter paper and subsequently diffused to ‘radon’ chamber through pin-holes preventing thoron to enter this chamber, due to its short half-life (55.6 s) as compared to radon (3.825 day). The radon (C_{Rn}) and thoron (C_{Th}) gas concentrations were estimated using Eqs. 1 and 2 (Sahoo et al. 2013):

$$C_{Rn}(\ Bqm^{-3}) = \frac{T_1 - B}{t\ x\ K_R} \qquad (1)$$

$$C_{Th}(\ Bqm^{-3}) = \frac{T_2 - T_1}{t\ x\ K_T} \qquad (2)$$

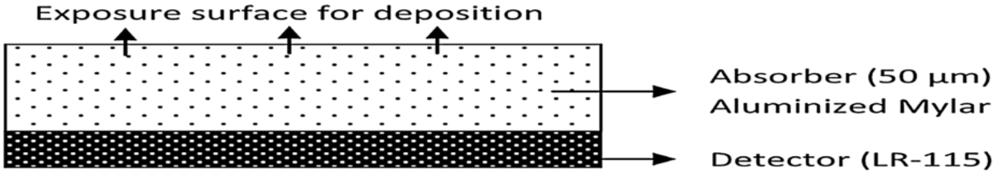
where T_1 and T_2 are the track densities (trackscm^{-2}) observed in ‘radon’ and ‘radon + thoron’ chamber, respectively, K_R and K_T are the calibration factors (0.017 trackcm^{-2}d^{-1} Bq^{-1}m^3) ,(0.010 trackcm^{-2}d^{-1} Bqm^{-3}) for ^{222}Rn in ‘radon’ chamber and ^{220}Rn in ‘radon + thoron’ chamber, respectively. t is time of exposure in days, B is the background counts (4 trackscm^{-2}),



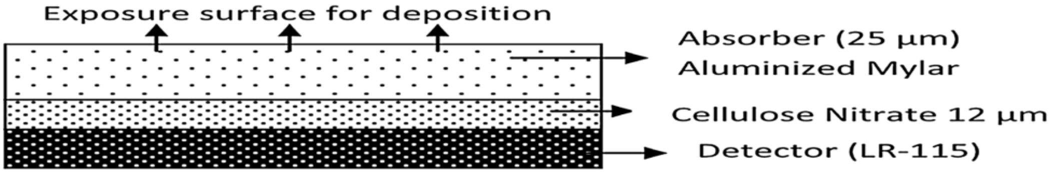
Fig(2) Schematic diagram of pin hole dosimeter.

Estimation of equilibrium equivalent radon/thoron concentrations (EERC/EETC)

In the indoor environment, the decay product concentrations have been estimated by deposition based direct radon (^{222}Rn) and thoron (^{220}Rn) progeny sensors (DRPS/DTPS) as shown in Fig.3. To detect 8.78 MeV α –particles emitted by ^{212}Po DTPS was made of passive nuclear track detectors (LR-115) covered with an absorber of 50 µm aluminized Mylar. Similarly, for the detection of 7.67 MeV α -particles from ^{214}Po, produced by the radioactive decay of ^{218}Po, ^{214}Pb and ^{214}Bi atoms ,DRPS has been prepared with an absorber made of a combination of aluminized Mylar(25 µm and cellulose nitrate film (12µm) with an effective thickness of 37 µm. The equilibrium equivalent thoron progeny concentrations (EETC) in the attached + unattached fractions were calculated using Eq. 3 (Mishra and Mayya 2008).



(a) DTPS



(b) DRPS

Fig. 3 Sketch of direct radon/thoron progeny sensors (DRPS/DTPS)

$$\text{EETC (Bqm}^{-3}\text{)} = \frac{T_T - B}{t\ x\ S_T} \qquad (3)$$

where T_T is the track density in DTPS, B is the background counts, t is time of exposure in days and S_T is the sensitivity factor for thoron progeny (0.94 trackcm^{-2}d^{-1} /EERC (Bqm^{-3})). In case of EERC the α-energy of ^{212}Po (thoron progeny) is higher than that of ^{214}Po (radon progeny) and will thus contribute to the track density obtained from the DRPS. Hence, for calculation of EERC, the tracks obtained from DTPS were eliminated from DRPS, to obtain the exact track density from radon progeny in DRPS (Eq. 4) (Mishra et al. 2009a):

$$T_{Rn} = T_{DRPS} - \frac{\eta_{RT}}{\eta_{TT}} T_{DTPS} \qquad (4)$$

where T_{Rn} are tracks only due to radon progeny, T_{DRPS} are total tracks in DRPS, T_{DTPS} are total tracks in DTPS, η_{RT} is the track registration efficiency (0.01) for thoron progeny in DRPS and η_{TT} is the track registration efficiency (0.083) for thoron progeny in DTPS. The equilibrium equivalent radon progeny concentrations (EERC) in attached + unattached fractions are then calculated by Eq. 5 (Mishra and Mayya 2008):

$$\text{EERC (Bqm}^{-3}\text{)} = \frac{T_{Rn} - B}{t\ x\ S_R} \qquad (5)$$

Where S_R is the sensitivity factor for radon progeny (0.09 ± 0.0036 track cm^{-2}d^{-1} /EERC (Bqm^{-3})). The sensitivity factors used for DTPS and DRPS were estimated (Mishra et al. 2010).

Estimation of unattached and attached ^{222}Rn/ ^{220}Rn progeny concentrations:

To estimate the attached progeny fractions for ^{222}Rn and ^{220}Rn, wire mesh capped DRPS/DTPS (Fig. 4) were used (Mayya et al. 2010). These sensors predominantly act as a coarse fraction deposition detector, as they remove considerable part of the activity associated with the fine fraction from the deposition environment of the detector and allow grater than the 95 % of activity associated with the coarse fraction to be deposited on them. Attached progeny concentrations of radon and thoron progeny were calculated by using the same formula as mentioned earlier for DRPS/DTPS, but with different sensitivity factors.

The sensitivity factor for EETC attached form is 0.33 trackcm^{-2}d^{-1} /EETC (Bqm^{-3}), while that for radon, EERC attached form is 0.034 trackcm^{-2}d^{-1} /EERC (Bqm^{-3}). The DRPS and DTPS without mesh were used to measure the total EEC (attached + unattached). The EEC (unattached) was then obtained by subtracting the EEC(attached) measured with the wire-mesh-capped DRPS/DTPS from the total EEC (attached +unattached) for ^{222}Rn and ^{220}Rn separately.

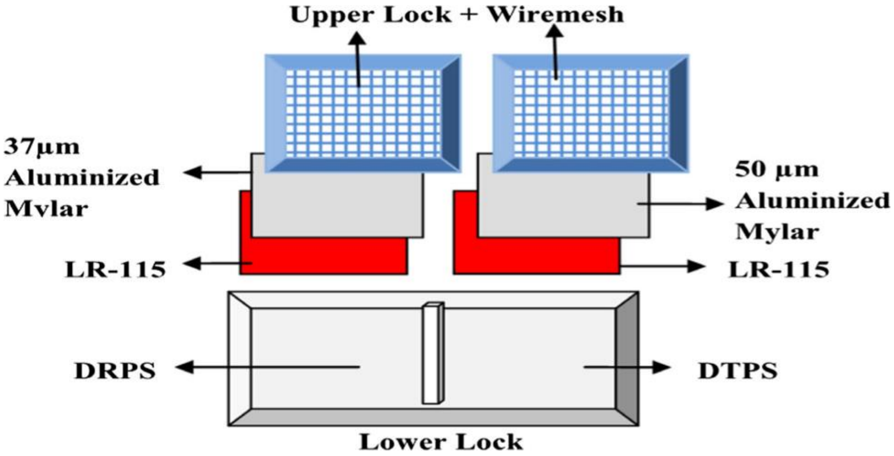


Fig. 4 Sketch of wire-mesh-capped direct radon/thoron progeny sensors (DRPS/DTPS)

The time-integrated fine fraction for radon (f_{Rn}) and thoron (f_{Tn}) was then calculated according to (Knutson 1988):

$$f_{Rn} = \frac{EERC_U}{EERC_{U+A}} \qquad (7)$$

$$f_{Tn} = \frac{EETC_U}{EETC_{U+A}} \qquad (8)$$

where $EERC_{U+A}$ and $EETC_{U+A}$ are total (attached +unattached) EEC of ^{222}Rn and ^{220}Rn progeny, respectively.$EERC_A$ and $EERC_U$ are the equilibrium equivalent concentrations of attached and unattached ^{222}Rn progeny, $EETC_A$ and $EETC_U$ are the equilibrium equivalent concentration of attached and unattached ^{220}Rn progeny, respectively.

Equilibrium factors for ^{222}Rn and ^{220}Rn

The equilibrium factors for radon (F_{Rn}) and thoron (F_{Tn}) were calculated by using Eqs. 9 and 10:

$$F_{Rn} = \frac{EERC_{U+A}}{C_{Rn}} \qquad (9)$$

$$F_{Tn} = \frac{EETC_{U+A}}{C_{Th}} \qquad (10)$$

where C_{Rn} and C_{Th} are the ^{222}Rn and ^{220}Rn activity concentrations respectively,

Dose conversion factor and dose calculations

The DCF$_s$ for mouth and nasal breathing were calculated by using Eqs. 11 and 12 given by (Porstendo¨rfer 1996):

$$DCF_M = 101 \times f_{Rn} + 6.7 \times (1- f_{Rn}) \qquad (11)$$

$$DCF_N = 23 \times f_{Rn} + 6.2 \times (1- f_{Rn}) \qquad (12)$$

where DCF_M is dose conversion factor for mouth breathing, DCF_N is that for nasal breathing, both calculated in mSv WLM^{-1} (WLM—working level month), and f_{Rn} is the fine fraction for radon. The inhalation dose due to mouth (ID_M) and nasal (ID_N) breathing and the effective lung dose (ELD) which is the absorbed dose averaged over the lung based on human respiratory tract model (HRTM) of ICRP, was estimated by Eq. 13 (ICRP 1993; Nero 1988):

$$\text{ELD or ID (mSv a}^{-1}\text{)} = C_R \text{ x } \frac{F_{Rn}}{3700} \text{x} \frac{7000\ ha^{-1}}{170} \text{ x DCF} \qquad (13)$$

where C_{Rn} is the gas concentration, F_{Rn} is the equilibrium factor and DCF is the dose conversion factor for radon.

The total annual effective dose received by individuals in indoor environment is the sum of the annual effective dose from radon (AEDR) and that from thoron (AEDT), due to the combined effect of gas and progeny concentrations (Eqs. 14 and 15) (UNSCEAR 2008):

$$\text{AEDR (mSv a}^{-1}\text{)} = [(C_R \text{ x } 0.17) + (\text{EERC x } 9)] \text{ x } 8760 \text{ h x } 0.8 \text{ x} 10^{-6} \qquad (14)$$

$$\text{AEDT (mSv a}^{-1}\text{)} = [(C_T \text{ x } 0.11) + (\text{EETC x } 40)] \text{ x } 8760 \text{ h x } 0.8 \text{ x} 10^{-6} \qquad (15)$$

where the dose conversion factor values are 0.17 and 9 nSv $Bq^{-1}h^{-1}m^{3}$ for radon gas concentration (C_{Rn}) and radon equilibrium equivalent concentration (EERC),respectively, whereas those for thoron gas concentration(C_{Th}) and thoron equilibrium equivalent concentration (EETC) are 0.11 and 40 nSv $Bq^{-1}h^{-1}m^{3}$, respectively.

Results and Discussion:

Radon (C_{Rn}) and thoron (C_{Tn}) gas concentrations

The concentration levels of radon, thoron in various dwellings at different locations of five coastal talus of Uttara Kannada distriuct are summarized in the Table 1. These estimations were carried out in rainy season. (from July2017 to September2017). The measured values of activity concentrations of radon C_{Rn} vary from 20.752 to 100.163 Bqm^{-3} with mean values 60.445 Bqm^{-3} and that of Thron (C_{Tn}) vary from 15.000 to 132.222 Bqm^{-3} ^{3}with mean value of 79.151 Bqm^{-3}, respectively. This variation in C_{Rn} and C_{Th} may be because of different geographic location of each village with differences in geology, different ventilation conditions, uranium and radium content present in rocks and building materials used for the construction of the investigated dwellings. The estimated values of C_{Rn} and C_{Th} are well within the reference level of 300 $Bqm^{-3.}$, recommended by ICRP (2011). The mean value of radon concentration is 1.63 times the world's average value of 37 Bqm^{-3} (UNSCEAR 2000). In this study it is observed that compared to ^{222}Rn gas concentration, the ^{220}Rn gas concentration is little bit higher. This might be due to the fact that thorium-rich construction materials were used for the investigated dwellings, and are or due to the presence of thorium-rich soil in this region.

Equilibrium equivalent radon/ thoron concentrations (EERC/EETC)

The equilibrium equivalent concentrations of radon and thoron (EERC and EETC) observed in the present study are also given in Table 1. The observed values of EERC vary from20.436 to 49.713 Bqm^{-3} with mean value of 33.196 and EETC vary from 0.783 to 1.670 Bqm^{-3} with an average of 1.143 Bqm^{-3}. It was observed that a wide variation in precursors as well as progenies concentration. This might be due to different environmental conditions such as temperature and humidity in different indoor environments investigated. The ratio between EETC and EERC in the present study varies from 0.020 to 0.073 with an average value of 0.036. The average value is slightly higher than the lower range of 0.01 but much less than the upper limit of 0.5. (UNSCEAR 2000).

The observed $EERC_A$ and $EERC_U$ vary from 12.932 to 46.337 $Bqm^{-3}$and 0.706 to 9.363 Bqm^{-3} with an average of 28.838 $Bqm^{-3}$and 4.319 Bqm^{-3} respectively, whereas $EETC_A$and $EETC_U$ range from 0.446 to1.323 $Bqm^{-3}$and from 0.033 to 0.844 Bqm^{-3}, with an average of 0.848 $Bqm^{-3}$and 0.295 Bqm^{-3} respectively. The unattached EERC is about 15 % and EETC is about 35.23 % of their corresponding attached EERC and EETC, respectively. The values of unattached fraction for radon(f_{Rn}) and thoron (f_{Tn}) were found to be in the range from 0.022

to 0.367 and from 0.028 to 0.560 with amean value of 0.137 and 0.241, respectively. For lung dose assessments f_{Tn} values are considered compared to f_{Rn} all along the globe and which are 0.02 and 0.1, respectively (UNSCEAR 2006), the values obtained in the present study for f_{Rn} are in close agreement, while those for f_{Tn} are somewhat higher.

Equilibrium factors for ^{222}Rn and ^{220}Rn (F_{Rn} and F_{Tn})

The observed values of F_{Rn} and F_{Tn} obtained in the present study vary from 0.244 to 1.648 with an average of 0.611 and 0.010 to 0.058 with an average of 0.016, respectively, as given in Table 1. The average value of F_{Tn} is smaller than the globally used value of 0.02 while F_{Rn} little bit higher than globally used values of 0.4 (UNSCEAR 2008). It is noted that equilibrium factor values cannot be larger than one because the concentration of progenies cannot be larger than that of its progenitor. The frequency distributions of F_{Rn} and F_{Tn} are shown in Figs. 5 and 6, respectively. Figure 5 shows that about 12.5 % of the dwellings have F_{Rn} values less than 0.4, while about 82.5 % of the dwellings have values in the range from 0.41 to 0.80 and 5% of the dwellings have values greater than 0.8 From Fig. 6, it is clear that for about 85 % of the dwellings the F_{Tn} values were less than the proposed value of 0.02, and for 15 % of the dwellings the values were in the range from 0.02 to 0.058 From this study it is concluded that the equilibrium factor values obtained in the present study are in good agreement with those proposed by UNSCEAR.

Effective dose calculations

The effective dose due to inhalation (ID) using the dose conversion factors (DCFs) calculated from Porstendorfer model (Porstendorfer J 1996) were estimated separately for mouth and nasal breathing (Table 2). The dose conversion factors for mouth (DCF_M) and nasal (DCF_N) breathing obtained in the present study vary from 8.820 to 40.942 mSv WLM^{-1} and 6.578 to 12.369 mSv WLM^{-1} with an average value of 19.608 and 8.500 mSv WLM^{-1}, respectively. The average value of inhalation dose due to nasal breathing (ID_N) (3.090 mSv a^{-1}) is 2.26 times smaller than that due to mouth breathing (ID_M) is 6.989 mSv y^{-1}. The frequency distributions of ID_M and ID_N are shown in Fig. 7. From this figure, it can be seen that about 45 % of the dwellings have ID_N values in the range from 2 to 3 mSv y^{-1} and about 40 % of the dwellings have ID_M values greater than 6 mSv y^{-1}. The effective lung dose values due to radon (ELD_{Rn}) and thoron (ELD_{Tn}) (calculated including the ICRP tissue weighting factor of 0.12 for the lung) with their unattached progeny concentrations are also given in Table 2. For this a DCF of 5.7 mSv WLM^{-1} for indoor radon and 1.9 mSv WLM^{-1} for indoor thoron and their corresponding unattached progeny concentrations were used, as well as the tissue weighting factor of 0.12 for the lungs proposed by ICRP (UNSCEAR 2008; ICRP 2007). The resulting values for ELD_{Rn} were found to be in the range from 0.145 to 6.795 mSv y^{-1} with an average of 1.869 mSv a^{-1}, while those for ELD_{Tn} were found to be in the range from 0.185 to 5.699 mSv a^{-1} with an average of 1.850 mSv a^{-1}. It is emphasized here that it is important to calculate ELD values because during inhalation the lungs receive the greatest dose from radon and their progeny and dose to lungs from radon progeny is 100 times greater than that from the radon gas alone (ICRP 2007). It is also necessary to quantify the unattached and attached components of progeny concentrations for the assessment of true inhalation lung doses (Mishra et al. 2014).

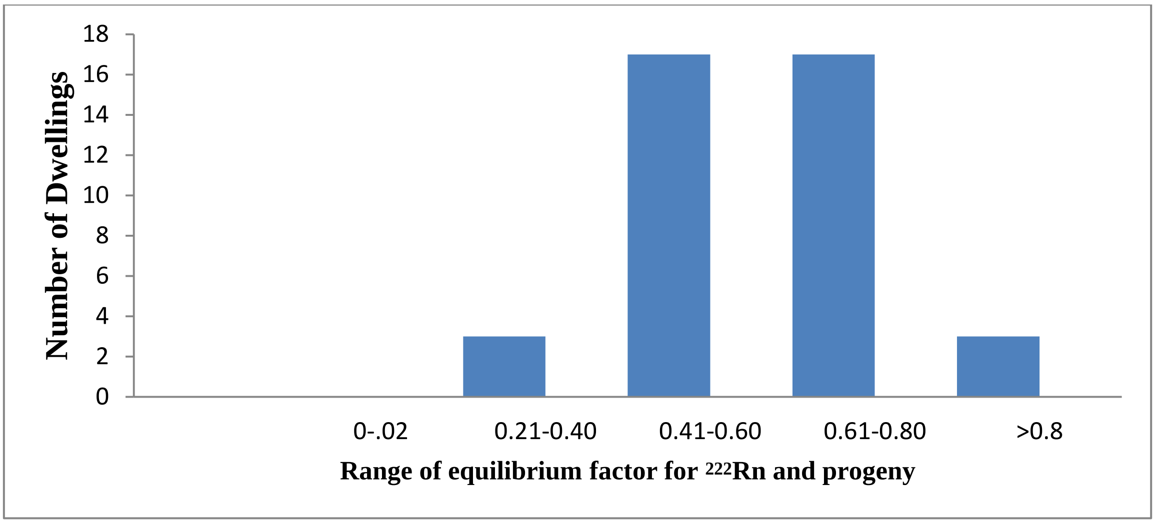


Fig.5. Frequency distribution of the equilibrium factor between radon concentration and its progeny

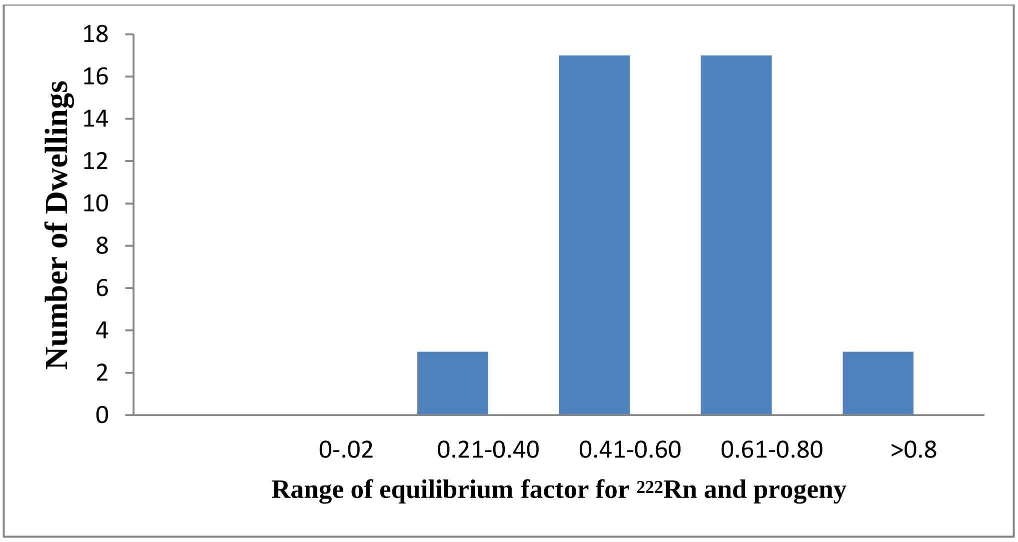


Fig. 6 Frequency distribution of the equilibrium factor between thoron concentration and its progeny

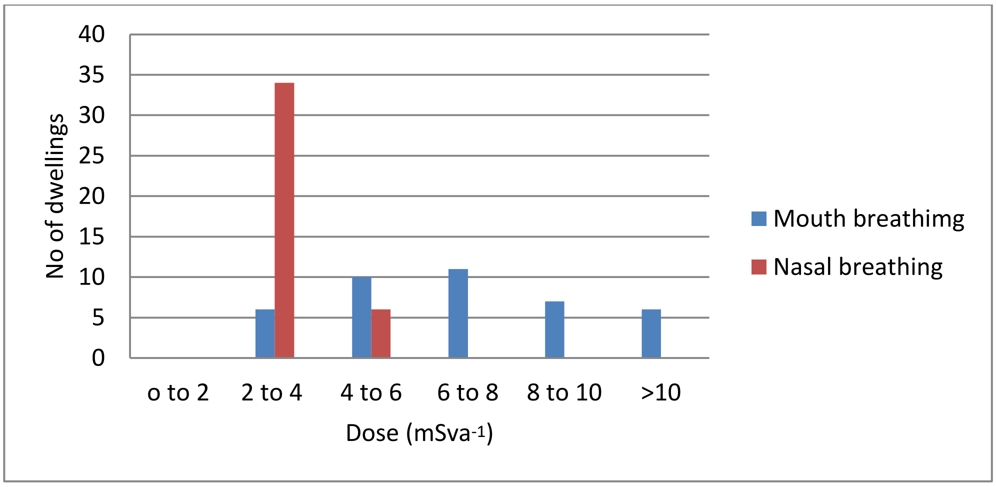


Fig7.Frequency distribution of inhalation dose calculated for mouth and nasal breathing

The values of annual effective dose obtained without separation of the attached and the unattached progeny fraction from radon (AEDR) and that from thoron (AEDT) were found to be in the range from 1.322 to 3.149 mSv a^{-1} and from 0.254 to 0.538 mSv a^{-1} with an average 2.163 mSv y^{-1} and 0.381 mSv a^{-1} respectively. The values of total annual effective dose obtained for the study region are within the safe range from 3 to 10 mSv a^{-1} recommended by ICRP (2011) and also below the recommended reference level of 10 mSv a^{-1} (WHO 2009). By comparing dose values with and without unattached fraction as given in Table 2, it can be observed that doses calculated using the unattached fraction show slightly lower values and also smaller uncertainties as compared to the dose values without unattached fraction, for both radon and thoron. Thus, the measurement of attached and unattached fraction plays a significant role for future dose assessment studies.

Conclusions

- The annual average values of ^{222}Rn, ^{220}Rn and their equilibrium equivalent activity concentrations obtained in this study for 40 different dwellings were within the reference levels as recommended by ICRP.
- In majority of investigated houses the ^{222}Rn gas concentrations were lesser than ^{220}Rn gas concentration.
- The attached fraction of progeny nuclides for both ^{222}Rn and ^{220}Rn showed greater values than the unattached fraction, and it was also found that the average value of the unattached fraction for radon progeny is approximately equal to the UNSCEAR preferred value of 0.1.
- The inhalation dose due to nasal breathing is 2.26 times smaller than the mouth breathing, when DCFs calculated from the Porstendorfer model were used.
- The total annual effective dose from indoor radon, thoron and their progeny concentrations in the study area are within the reference level of 3–10 mSv a^{-1} proposed by ICRP (2011).

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