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Full Length Research Paper

The spatial and volumetric variations of radon in Bangalore Metropolitan, India

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Radon levels have been measured in houses at ten different locations of Bangalore City, India. The study was focused on the basis of quality of construction, age of building and room volume. Solid state nuclear track detectors were used for measuring the concentrations. The average spatial values of ^{222}Rn and ^{220}Rn concentrations were found to be 33.4 ± 6.1 and 21.6 ± 2.5 Bqm^{-3}, respectively. However, the volumetric concentrations were ranged between 4.0 and 93.0 Bqm^{-3}. The annual dose rate due to ^{222}Rn, ^{220}Rn and their progenies for the population in the studied location ranged from 0.5 to 3.5 mSvy^{-1}. It is alarming that the dwellers of lower volumes receive a relatively higher dose rate and the result shows significant radiological risk. The magnitude and its effects of doses are discussed in detail.

Key words: Radon, dwellings, volume, dose rates.

INTRODUCTION

Measurement of indoor radon is significant due to the exposure of radon and its daughters, which contributes more than 50% of the total dose from natural sources on human beings (UNSCEAR, 2000). The dose deriving from the existence of radon in the air is directly linked to the inhalation of its short-lived daughters, which are deposited in the respiratory organs, if deeply inhaled; emit alpha-particles that are in contact with bronchial and pulmonary epithelium. On account of these, the dose deriving from the exposure of radon in closed spaces has been placed in direct relation to the risk of lung cancer (UNSCEAR, 2000). Some factors that influence the diffusion of radon 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 (Schery and Gaeddert, 1984). Solid state nuclear track based dosimeters are employed for the long - term integrated measurements (Stranden, 1980). Measurements on volumetric variations of ^{222}Rn and ^{220}Rn in dwellings are limited and this work seems to be the first of its kind. The paper reports the relationship between ^{222}Rn, ^{220}Rn and volume of rooms. The measurement for ^{222}Rn and ^{220}Rn concentrations in different locations were also carried out by using plastic track detectors and the results obtained are discussed in detail. The data is continuously obtained for a period of three years (2007 to 2010), covering more than 150 dwellings.

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Abbreviations: SSNTD, Solid state nuclear track detector; **EFs,** equilibrium factors; **CFs,** calibration factors; **WL,** working level; **RFM,** root finding method; **A/V,** ratio of area to volume; **GSC,** Government Science College.

Study area

The location selected for the present study is Bangalore Metropolitan, India and is shown in Figure 1. The district lies between the latitudes 12˚39' and 13˚13' N and longitudes 77˚22' to77˚52' E. The climate has four distinct

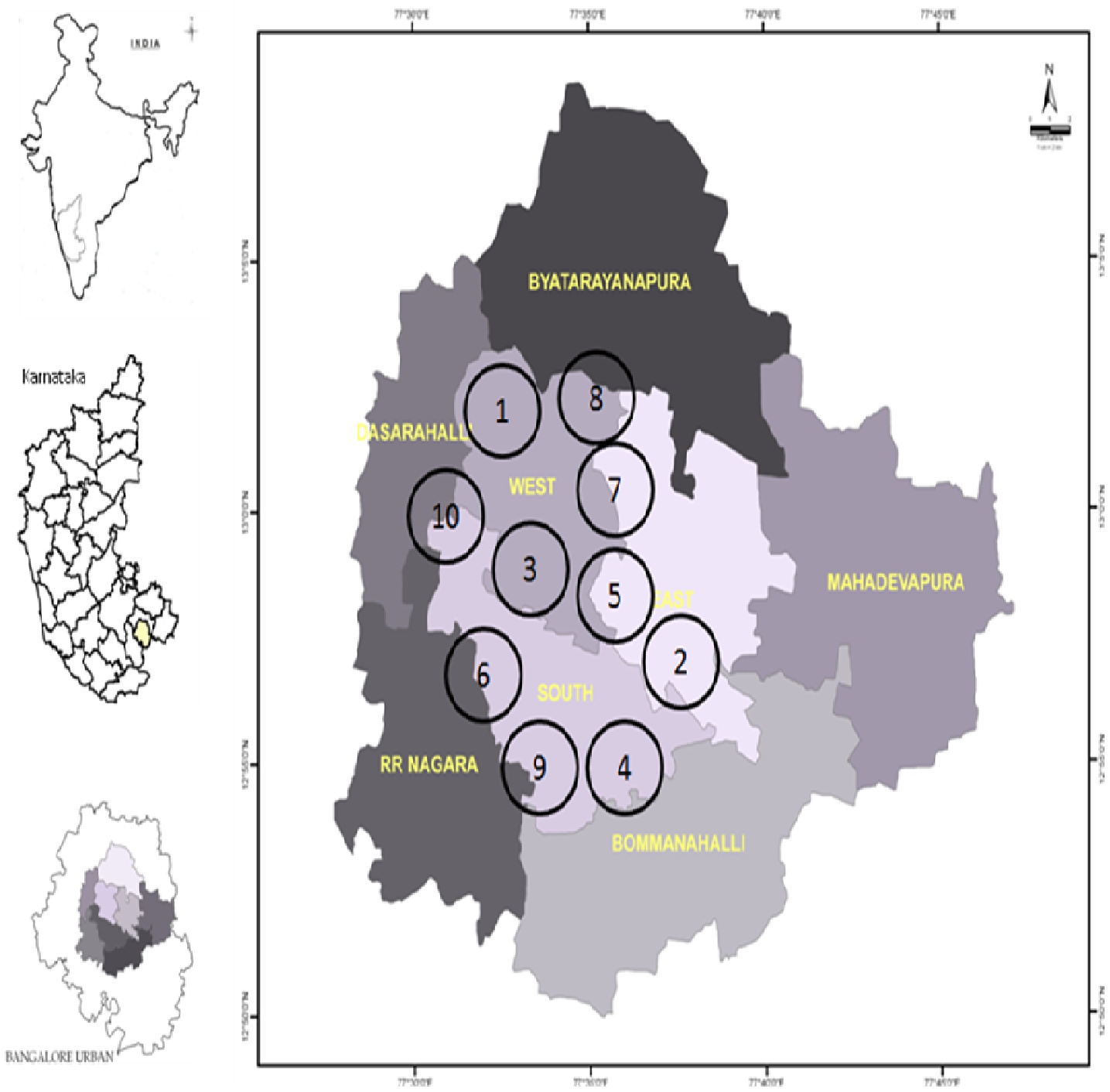

Figure 1. Map of Bangalore Metropolitan, India. 1: RAJ; 2: JNR; 3: SRPM; 4: PNR; 5: GNR; 6: SNR; 7: SPM; 8: MLM; 9: BSK; 10: VNR.

seasons, which are, summer, rainy, autumn and winter. April is usually the hottest month with the mean daily maximum temperature of 30 to 35°C and mean daily minimum at 20 to 24°C. The geology of this part forms predominantly a granite terrain with numerous varieties of granites, granitic gneiss, pegmatite and charnockites and so on. The rocks around the study area are called Close pet granites (Ningappa et al., 2008). These rocks are

younger than the peninsular gneiss, made up of several types of potassium granites with variable color, texture and multiple intrusion relationship. The common rocks are pink, grey and porphyrite gneisses with large feldspars, black dolerite. These rocks form geological band of a width 15 to 25 km. Most of the studied houses in Bangalore City were constructed with cement and bricks that were made up of local soil and few were mud houses (Ningappa et al., 2008). The soil radioactivity reported in earlier studies is close to background levels from other regions of the country (Mishra and Sadasivan, 1974). The radioactivity reported for the building materials collected from this region is higher compared with soil radioactivity (Ramachandran et al., 2003). All the monitored houses were on the ground floor. About fifteen houses were chosen in all the monitored locations. Analysis is made on location wide, season wide and room volume.

MATERIALS AND METHODS

The present survey covered 10 locations in a span of three years. About 150 houses of different types of construction were surveyed for intervals of 90 days covering all the four seasons of a year. Solid State Nuclear Track Detector (SSNTD) based dosimeters (Nikolaeve and Ilic, 1999; Subba Ramu et al., 1994) were used for the survey. Since the sampling was passive and integrated for long duration, the diurnal variations in radon concentrations were taken into account (Ilic and Sutej, 1997).

The SSNTD based dosimeter system developed was a cylindrical plastic chamber divided into two equal compartments (Nambi et al., 1994), each having an inner volume of 135 cm^3 and height 4.5 cm. Dimensions of the dosimeter were chosen based on the ratio of the effective volume of the cup to its total volume to achieve maximum track registration for the cylindrical cup (Jha et al., 1982). The design of the dosimeter was well suited to discriminate ^{222}Rn and ^{220}Rn in mixed field situations, where both the gases are present. Cellulose nitrate films of LR-115 type II manufactured by the Kodak Pathe were used as detectors. The 12 µm thick film cut to 2.5 cm × 2.5 cm square was affixed at the bottom of each cup as well as on the outer surface of the dosimeter. The exposure of the detector inside the cup is termed as cup mode and the one exposed open is termed as the bare mode. One of the cups had its entry covered with a glass fiber filter paper that permits both ^{222}Rn and ^{220}Rn gases into the cup and is called the filter cup. The other cup was covered with a semi-permeable membrane (Ward et al., 1977) sandwiched between two-glass fiber filter papers and is called the membrane cup. This membrane had a permeability constant in the range of 10^{-8} to 10^{-7} cm^2s^{-1} (Wafaa, 2002) and allows more than 95% of the ^{222}Rn gas to diffuse through while it suppress the entry of ^{220}Rn gas almost completely. Thus, the SSNTD film inside the membrane cup registers tracks contributed by ^{222}Rn only, while that in the filter cup records tracks due to ^{222}Rn and ^{220}Rn. The third SSNTD film exposed in the bare mode registers alpha tracks contributed by the concentrations of both the gases and their alpha emitting progeny.

The dosimeters were kept at a height of 1.5 m from the ground and care was taken to keep the bare card at least 10 cm away from any surface. This ensured that errors due to tracks from deposited activity from nearby surfaces were avoided, since the ranges of alpha particles from $^{222}Rn/^{220}Rn$ are about 10 cm. After the exposure period of 90 days, the SSNTD films were retrieved and chemically etched in 2.5 N NaOH solutions at 60°C for 60 min with mild agitation (Miles, 1997). The tracks recorded in all the three SSNTD films were counted using a spark counter. A methodology was developed to derive the equilibrium factors (EFs) separately for ^{222}Rn and ^{220}Rn using the track densities based on the ventilation rates in the dwellings (Mayya et al., 1998). One may expect deposition of activity on the SSNTD film in the bare mode exposure, which may pose as an unknown parameter in the calibration factor. But it has been proven that the LR-115 (12 µm) film does not register tracks from deposited activity (Eappen and Mayya, 2004). This is because the E_{max} for LR-115 film is 4 MeV and all the progeny isotopes of ^{222}Rn /^{220}Rn emit alphas with energies greater than 5 MeV.

Calibration facility and standardization of dosimeter

Experiments were carried out at the Bhabha Atomic Research Centre, Mumbai, India to estimate the calibration factors (Ramachandran et al., 1995) separately for ^{222}Rn and ^{220}Rn, in a calibration chamber of stainless steel of 0.5 m^3 volume. The ^{222}Rn (or ^{220}Rn) gas was introduced into the chamber from standard sources obtained from Pylon, Canada. The calibration chamber had provisions for imputing aerosols from an aerosol generator, which was a Sinclair LaMer type condensation aerosol generator. It gave a laminar flow of mono-dispersed aerosols of di-2-ethylhexyl sebacate condensed on NaCl nuclei. The temperature settings of the boiler and re-heater were adjusted to obtain mono-dispersed aerosols of 0.25 µm diameter, which is close to the activity median aerodynamic diameter of 0.2 µm reported for indoor aerosols (Yihe et al., 1997). Aerosol concentrations of the order of 10^4 to 10^5 particles per cm^3 of air were generated to simulate the indoor environment conditions. Depletion of the aerosols inside the chamber was studied and accordingly input of the aerosols was regulated to maintain a near constant particle concentrations. The chamber had provisions for coupling an on-line Lucas cell system in conjunction with an Alpha Guard for continuous measurement of ^{222}Rn gas concentration. The Alpha Guard, kept inside the chamber, recorded hourly averaged ^{222}Rn concentrations. The on-line Lucas cell system used was coupled to an alpha counting setup and counts were taken synchronizing with the timing of the Alpha Guard.

The comparison of ^{222}Rn measured by the two systems for a wide range of concentrations showed very good correlation ($r = 0.97$) and had a slope not different from unity (Eappen et al., 2001). Calibration factors (concentration conversion factors) for ^{222}Rn and ^{220}Rn were required to convert the recorded tracks in the exposed SSNTD films into ^{222}Rn and ^{220}Rn concentrations. Calibration factors were estimated experimentally as well as theoretically for all the three modes of exposures. These are discussed in the following sections.

Calibration factors (CFs) for ^{222}Rn and ^{220}Rn gases in the cup mode were determined through a series of experiments. The CFs for ^{222}Rn (k_R) and for ^{220}Rn (k_T) in terms of tr cm^{-2} per Bq d m^{-3} were obtained as:

$$k_R = \frac{24T}{C_R H} \quad and \quad k_T = \frac{24T}{C_T H}$$

where, T is the tracks per unit area (tr cm^{-2}), C_R is concentration of the ^{222}Rn gas (Bq m^{-3}), C_T is the level of ^{220}Rn gas (Bq m^{-3}) and H is the exposure time (hours) (Mayya et al., 1998). Experimentally

Table 1. Calibration factors for the cup mode and bare mode exposures (Eappen and Mayya, 2004).

Mode of exposure	Calibration factors (Tracks cm^{-2}/Bq d m^{-3})			
	^{222}Rn		^{220}Rn	
	Filter	Membrane	Filter	Membrane
Cup mode exposure				
Experimental	0.02 ± 0.004	0.019 ± 0.003	0.017 ± 0.003	0.0
Theoretical	0.021	-	0.016	-
Bare mode exposure				
Experimental	0.020 ± 0.002		0.019 ± 0.003	
Theoretical	0.019		0.019	

obtained CFs for ^{222}Rn and ^{220}Rn are given in Table 1 (Eappen and Mayya, 2004) for cup mode exposure. The CF for ^{222}Rn in the membrane compartment was found to be equal (0.019 tr cm^{-2} / Bq d m^{-3}) to that in filter paper compartment (0.02 tr cm^{-2}/Bq d m^{-3}). The CF for ^{220}Rn in the filter paper cup was 0.017 tr cm^{-2}/Bq d m^{-3}, and there were no tracks from ^{220}Rn in the membrane cup (Eappen and Mayya, 2004). The definition of the CF for the bare mode has certain ambiguities. In an earlier approach, the CF for the bare detector was defined as the track density rate obtained per unit working level (WL) (Barillion and Chambraude, 2000; Durrani and Ilic, 1997). In reality, track formation rate in the bare mode is not a unique function of WL, but would depend on the EF. If one defines the bare detector calibration factor as k_B (tr cm^{-2}/Bq d m^{-3}) of each species, it may be easy to show that this quantity is independent of the EF as well as the incident energy of the alpha particle. For a given track density rate T(tr cm^{-2} d^{-1}) and working level (W_R for ^{222}Rn and W_T for ^{220}Rn in mWL units) and the corresponding EFs, F_R and F_T, the calibration factors as defined above can be obtained for ^{222}Rn (k_{BR}) and ^{220}Rn (k_{BT}) respectively in terms of tr cm^{-2} / Bq d m^{-3} using the following equations.

$$k_{BR} = \left(\frac{T}{3.7W_R}\right)\left(\frac{F_R}{1+2F_R}\right)$$

$$k_{BT} = \left(\frac{T}{0.275W_r}\right)\left(\frac{F_T}{2+F_r}\right)$$

Based on this concept, CFs was derived for the species matrix for ^{222}Rn, ^{220}Rn and their progeny concentrations. They were found to be nearly constant for a wide range of EFs (0.1 - 0.72) supporting the basic assumption of the new approach. Table 1 shows the results of the CFs for the bare mode exposure for ^{222}Rn and ^{220}Rn. The CF for ^{222}Rn and ^{220}Rn are estimated as 0.02 tr cm^{-2}/Bq d $m^{-3}$and 0.019 tr cm^{-2}/Bq d m^{-3}, respectively and are nearly identical. This confirms the assumption that the bare card calibration factors are the same for the alpha emitters since they are functions of only the difference in the ranges and the lower and upper cut off energies of the detector. Hence for practical use, an average value of 0.02 tr cm^{-2}/Bq d m^{-3}may be used as the CF for ^{222}Rn and ^{220}Rn in the bare mode exposure.

A theoretical model was developed to derive the CFs for ^{222}Rn and ^{220}Rn for all the exposure modes (Eappen and Mayya, 2004). The theoretical model is based on certain parametric constants chosen after experimental verifications. These include the bulk-etching rate and the break down thickness for the spark counting technique. The present calculation used bulk etching rate as 4.0 µm/h and break down thickness as 3.0 µm. In the model, the upper and lower cut off energies for normal incident alphas are translated as residual ranges using the range energy relationship. The sphere of influence for the upper and lower cut off energies from normal incident angle to critical angle can be obtained from integrating for the total area covered under solid angle for residual length of alpha particles lying within those incident angles. With these considerations, the observable tracks per unit area on the film per unit exposure time can be computed using the following equation.

$$T_r = \frac{\eta c}{4\pi}\int_0^{2\pi} d\phi \int_{\theta=0}^{\theta_c} d\theta \int_{r=R_E-R_L(\theta)}^{R_F-R_U} \sin\theta\cos\theta dr$$

where η is the efficiency of track registration, C is the activity concentration of the species,ϕ is the solid angle suspending the area of influence, θ is the angle of incidence ranging from normal incidence (0°) to critical angle (θ_C), r is the radial distance from the point of emission, R_E is the range of the alpha particle corresponding to its max energy and R_L, R_U are the lower and upper cut off ranges for track registration for an incident angle θ The integration extends over a region of influence which is constructed by using detailed track development model. Eappen and Mayya (2004) have discussed the typical regions of influence for ^{222}Rn and ^{220}Rn and their progenies in bare mode exposure configuration. Eappen and Mayya (2004) showed that the region of influence is located farther from the detector for ^{220}Rn progeny as compared to ^{222}Rn and its progeny concentrations. For the cup mode exposure, integrations over the regions of influence would also include surface deposited activity contributions from the inner walls of the dosimeter.

A code was written in FORTRAN for calculating the CFs in different configurations using the theoretical model (Eappen et al., 2001). Several experimental studies were carried out in the calibration facility to determine the CFs under various EF and gas concentration conditions. Theoretical and the experimental CFs obtained for the cup mode and bare mode exposures showed close

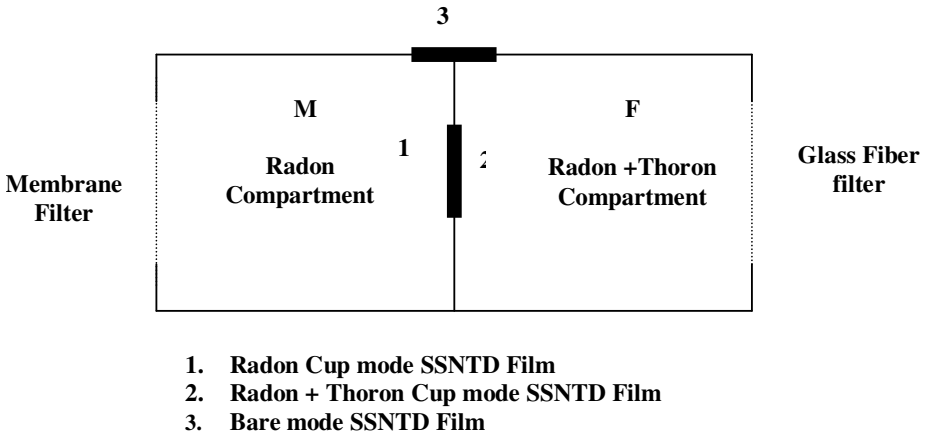

Figure 2. Schematic of twin cup radon-thoron dosimeter.

agreement.

Dosimetric methodology

Inter-laboratory standardization experiments for the etching characteristics conducted by all the participants using standard alpha sources also showed good agreements. A theoretical methodology was developed for evaluating the progeny concentrations using the twin cup ^{222}Rn to ^{220}Rn dosimeter system (Mayya et al., 1998) (Figure 2). The mathematical basis used is similar to that developed by Planinic and Faj (1990, 1991) for radon dosimetry in which an auxiliary parameter, ventilation rate, was extracted from the equations relating the bare detector track densities to the gas and progeny levels. This approach is considered as most logical for ^{222}Rn - ^{220}Rn dosimetry with the bare and cup detector system. The data currently available in the literature were used for the parameters such as wall loss rates, unattached fractions and indoor turbulence levels (Porstendorfer, 1994). In this method, it was assumed that SSNTD kept in the bare mode responded only to the airborne alpha emitters and not to the alpha activity deposited on it. It was also assumed that the bare card CFs were same for alpha emitters since it is a function of only the difference in the ranges, lower and upper cut off energy of the detector. Let T_1, T_2 and T_3 be the track densities recorded in the membrane mode, filter mode and bare mode, respectively. Let k_R be the CFs for ^{222}Rn gas in membrane compartment and filter compartment, respectively and k_T be the calibration factor for ^{220}Rn in the filter compartment. If d is the duration of exposure (days), the gas concentrations of ^{222}Rn (Bq m^{-3}) and ^{220}Rn (Bq m^{-3}) the vicinity of the dosimeter can be determined from the observed track densities T_1 and T_2 using the following equations:

$$C_R = \frac{T_1}{dk_R} \quad and \quad C_T = \frac{T_2 - dC_R k_R}{dk_T}$$

Since the ^{222}Rn decay constant is far smaller than the usually encountered air change rates (ventilation rates), ^{220}Rn may be assumed to be spatially uniform. The activity fractions of the progeny are governed by their wall loss rates for the fine and the coarse fractions and the ventilation rates. The bare track densities are also dependent on the ventilation rates, which represent the progeny fractions for both gases. However unlike ^{222}Rn, ^{220}Rn is not uniformly distributed in the room due to its short half-life, but is expected to set up profiles (Doi and Kobayashi, 1994). The concentration C_T would be considerably lower than that present near the ground and the walls, which are the ^{220}Rn emitting surfaces. On the other hand, the thoron decay products, ^{212}Pb and ^{212}Bi, being longer lived would mix more or less uniformly in the room and their activities will be fractions of a representative average ^{220}Rn concentration. A turbulent-diffusive transport model developed by Mayya et al. (1998) was used to obtain the bare track densities in terms of this concentration and the indoor ventilation rates. This method, which is known as the root finding method (RFM), is theoretically the most satisfactory approach for determining ^{222}Rn, ^{220}Rn concentrations and their progeny working levels using the tracks recorded on the three SSNTD films. The progeny working levels were evaluated using the following relations:

$$WL_R = \frac{C_R F_R}{3700} = \frac{C_R(0.104F_{RA} + 0.518F_{RB} + 0.37F_{RC})}{3700}$$

$$WL_T = \frac{C_T F_T}{275} = \frac{C_T(0.908F_{TB} + 0.092F_{TC})}{275}$$

where F_R and F_T are the EFs for ^{222}Rn and ^{220}Rn progeny, respectively, which are related to the ventilation rate. However, in practice, it was found that small uncertainties in the recorded tracks propagate non-linearly leading occasionally to unacceptable solutions for the EFs. Considerable experience in measurements is required to eliminate these uncertainties, which is expected to be realized in the coming few years. Until then, it was decided to estimate the progeny concentrations using the cup based gas concentrations and the universally accepted EFs published elsewhere (UNSCEAR, 2000). Information obtained from the bare SSNTD is being used in conjunction with the RFM for building a database on the EFs. At present, the effective dose rate due to inhalation was estimated from the ^{222}Rn, ^{220}Rn and progeny concentrations using the UNSCEAR (2000) EFs as given in Table 2.

Table 2. Average concentration of ^{222}Rn, ^{220}Rn and their progeny in air and corresponding annual effective doses (UNSCEAR, 2000).

Radionuclide	Location	Concentration (Bq m^{-3})		Effective dose equivalent (mSv/ Bq h m^{-3})		Annual effective dose (μ Sv)	
		Gas	EEC^{+}	Gas	EEC	Gas	EEC
Radon	Outdoor	10	6	0.17	9	3	95
	Indoor	40	16	0.17	9	48	1009
Total							1155
Thoron	Outdoor	10	0.1	0.11	40	2.0	7
	Indoor	10	0.3	0.11	40	8.0	84
Total							101
Total annual effective dose equivalent due to ^{222}Rn and ^{220}Rn (μ Sv)							1256

$^{+}$ This is the equilibrium equivalent concentration (EEC) of radon/thoron and is the product of the concentration of radon/thoron and the equilibrium factor between radon/thoron and its decay products. The equilibrium factor has been taken as 0.6 for outdoor and 0.4 for indoor in the case of radon. In the case of thoron EF is taken as 0.01 for outdoor and 0.03 for indoor. These values are weighted for an occupancy factor of 0.2 for outdoor and 0.8 for indoor.

Inhalation dose

Absorbed dose rates to the critical cells of the respiratory tract due to ^{222}Rn, ^{220}Rn and their progeny can be estimated on the basis of aerosol characteristics, its size distribution, unattached fraction, breathing fraction, and fractional deposition in the airways, mucous clearance rate and location of the target cells in the airways. Several models have been developed to assess the inhalation dose rates to the population due to ^{222}Rn, ^{220}Rn and their progeny (Jacobi, 1993; Subba Ramu et al., 1988). Lung dose distribution assessment carried out by different agencies from 1956 to 2000 showed a large variation in dose conversion factors (UNSCEAR, 1993, 2000). The estimated dose conversion factors varied drastically based on the breathing rate as well as the target tissue mass. In the present study, the dose conversion factors reported by UNSCEAR (2000) were used to estimate the indoor inhalation dose rates D (μSvh^{-1}) due to ^{222}Rn, ^{220}Rn and their progeny as shown:

$$D = 10^{-3}[(0.17 + 9F_R)C_R + (0.11 + 40F_T)C_T]$$

Numerical values given in the aforementioned relations are the dose conversion factors for gas and progeny concentrations.

RESULTS AND DISCUSSION

The natural radioactivity contents of soil samples of Bangalore region reported by earlier studies are 15.2, 16.90 and 486.7 Bqkg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively (Mishra and Sadasivan, 1971) and the concentrations of ^{238}U, ^{232}Th and ^{40}K in the building rocks of Karnataka region are 33, 30.5 and 412.3 Bqkg^{-1}, respectively (Ramachandran et al., 2003). However, major quantity of bricks used for the construction of the buildings in Bangalore City are brought from places in the city out skirts called Nelamangala, Magadi and a small quantity from Hoskote, Ramanagara and Channapattana. The average activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the soils of Nelamangala and Magadi are 31.3 ± 0.6, 52.6 ± 0.9 and 303.1 ± 6.1 Bqkg^{-1} and 16.9 ± 0.6, 57.5 ± 1.1 and 1073 ± 15.6 Bqkg^{-1}, respectively (Shiva Prasad et al., 2008).

Volumetric variations of indoor ^{222}Rn and ^{220}Rn

Rooms were broadly classified into '6-groups' on the basis of volume ranged from 30 to 310 m^3 such as 30–40, 45-60, 65-75, 80-100, 110-120 and 200-310 m^3. About 7 rooms were selected in each dimension at ten different locations. Hence, the total number of rooms covered in each volume is 42 rooms. However, the total number of rooms monitored is 42×10 locations = 420 rooms. These 420 rooms have been analyzed for four seasons and lead to 1680 measurements. The total number of films (LR-115 detectors) exposed during this period of measurement is more than 5000. The frequency distribution of ^{222}Rn and ^{220}Rn levels in dwellings is presented in Figures 3 and 4. Geometric means of indoor ^{222}Rn and ^{220}Rn levels in the study area are 23.0 and 20.0 Bqm^{-3} with GSDs 2.1 and 2.0, respectively. Cumulative frequencies against the ^{222}Rn/^{220}Rn values showed linear regression with correlation coefficient equals 1 for both the cases. A linear correlation with correlation coefficient nearing one indicates a common factor predominant in the various categories of rooms governing the gas concentrations in these houses. Inhalation dose is computed using UNSCEAR (2000) dose conversion factors. Inhalation dose calculated from the total results varied from 0.3 to 4.5 mSvy^{-1} with a geometric mean of 1.3 mSvy^{-1} (GSD 2.1). Table 3 show

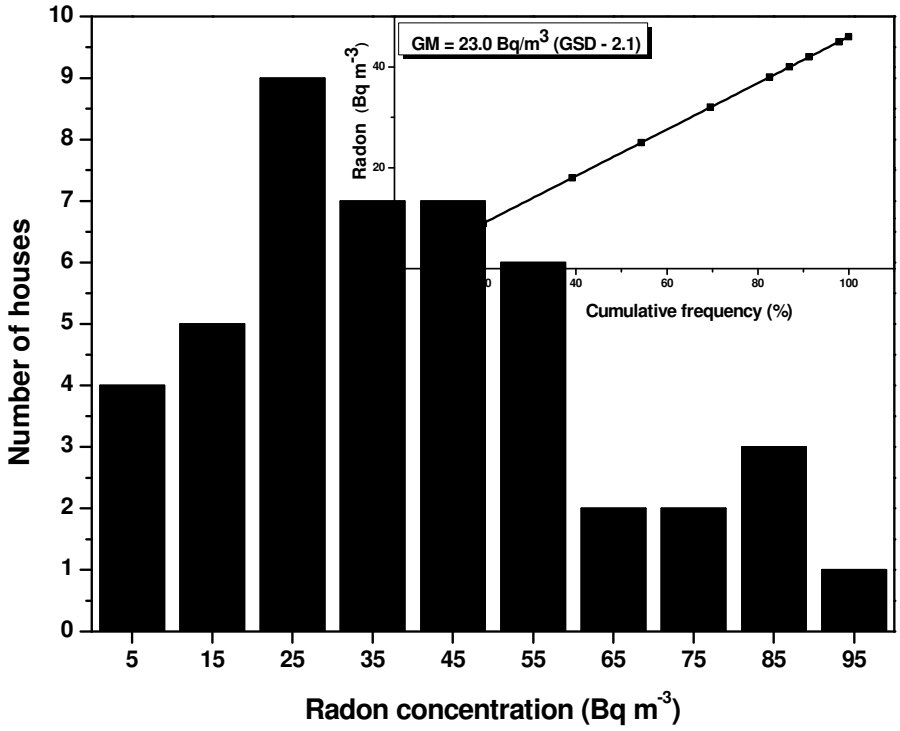

Figure 3. ^{222}Rn levels in dwellings.

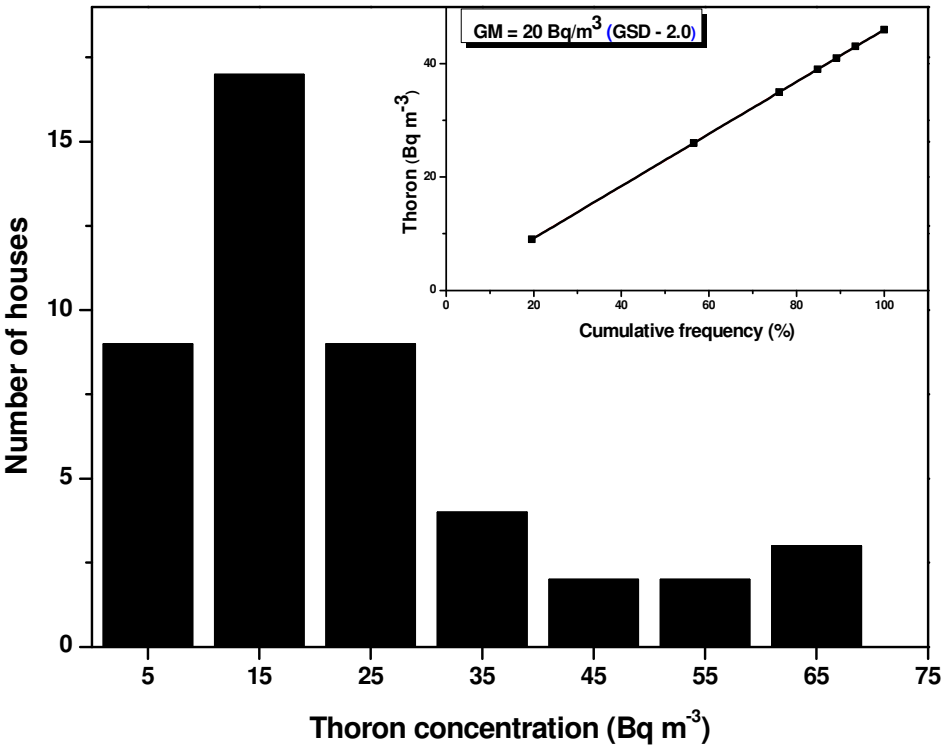

Figure 4. ^{220}Rn levels in dwellings.

Table 3. ^{222}Rn and ^{220}Rn levels in different volume of rooms.

Volume of room (m^3)	^{222}Rn (Bqm^3)			^{220}Rn (Bqm^3)		
	Range		Average ± SD	Range		Average ± SD
	Min.	Max.		Min.	Max.	
30 - 40	67.3	93.0	81.1 ± 9.3	42.3	69.4	57.5 ± 9.7
45 - 60	48.5	62.0	54.1 ± 4.4	27.5	36.8	31.0 ± 3.6
65 - 75	39.8	47.4	43.4 ± 2.9	18.8	27.1	22.6 ± 3.4
80 - 100	25.2	35.1	30.7 ± 3.8	13.2	17.4	15.7 ± 1.2
110 - 200	12.9	20.5	16.7 ± 2.7	09.6	12.5	11.0 ± 1.1
200 - 310	07.1	10.5	07.3 ± 2.2	06.6	09.0	06.9 ± 1.3

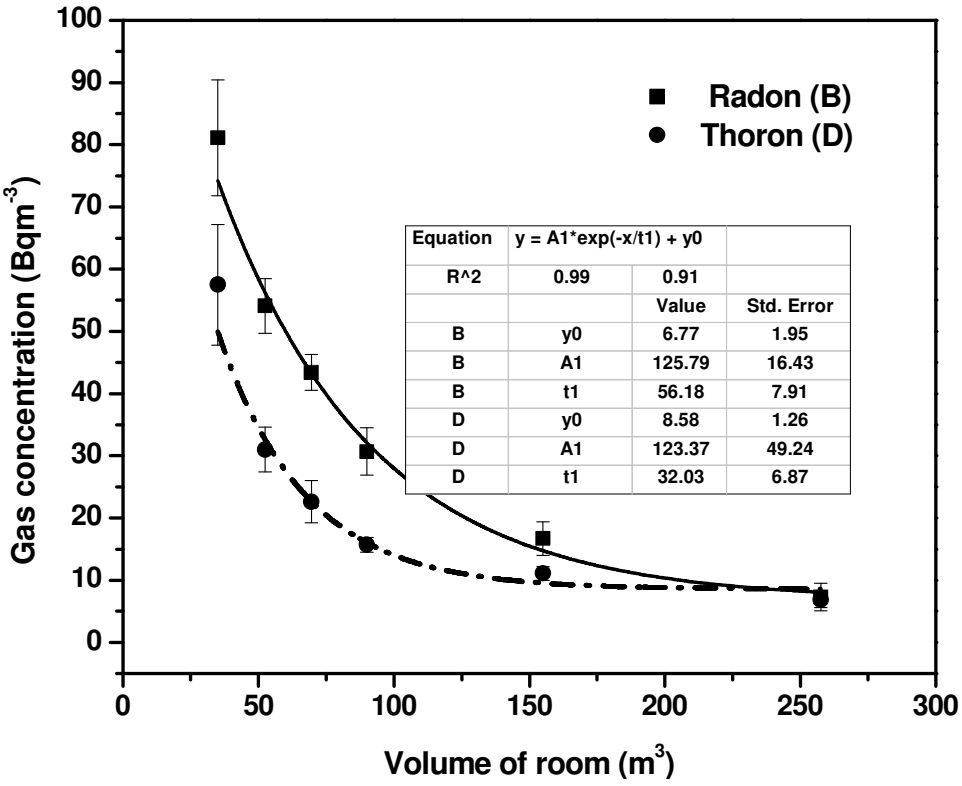

Figure 5. Gas concentrations with volume of dwellings

the range and average values of ^{222}Rn and ^{220}Rn levels in room volume ranging from 35 to 300 m^3. The higher concentrations were observed in a room of lower volume than in larger volume.

A plot of ^{222}Rn and ^{220}Rn concentrations is made against room volume shown in Figure 5. The concentrations decrease with increase in volume of the rooms. However, in the case of ^{220}Rn the effect is almost nullified beyond room volumes greater than 150 m^3. If we consider that the exhalation rate for ^{222}Rn and ^{220}Rn from the room surfaces is almost same, assuming that the materials used for construction in these houses are similar, it is expected that the gas concentrations will decrease with increase in volume of the room since the surface to volume ratio decreases with increase in room volume.

A plot of volume against ratio of area to volume (A/V) is shown in Figure 6. The A/V ratio also showed an

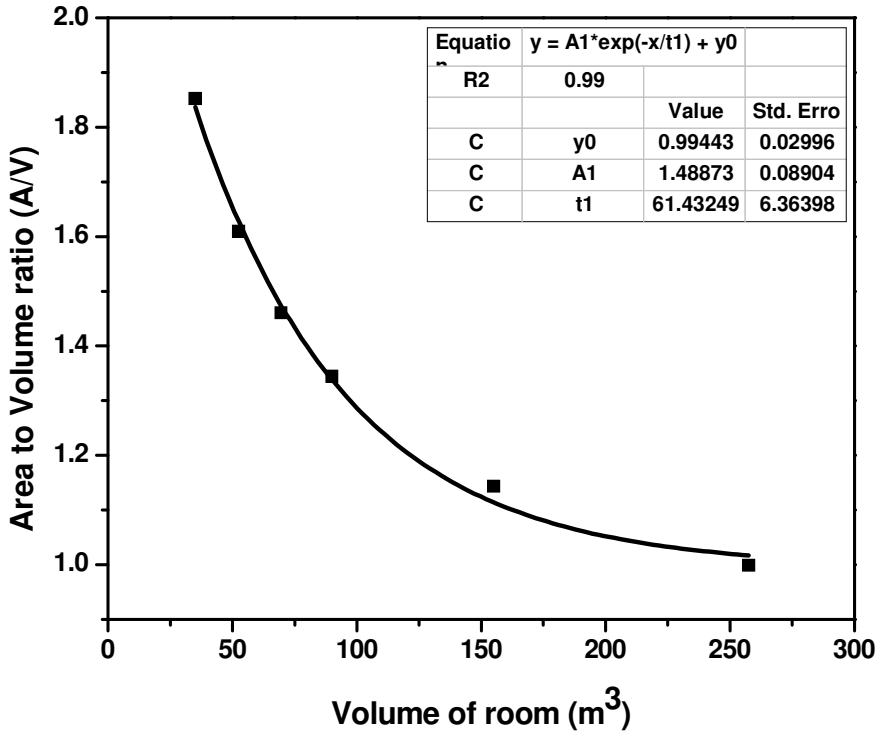

Figure 6. Correlation between A/V ratio and volume of dwellings.

exponential fit in decreasing order with a correlation coefficient 0.99. It is interesting to note that the fitting parameter *t* in Figure 6 is 61.4 which closely match with effective decay value for radon (56.2) in Figure 5. This clearly indicates that the radon values inside dwellings covered under the study is predominantly depended on A/V ratio inside the houses. Effect of ventilation seems negligible when the measurement was carried out for long durations. However, the results of thoron were different compared to radon. The *t* value is almost half (32) to that of A/V ratio. One can speculate certain other phenomenon governing the thoron values. It is only logical to say that predominance of thoron profile inside the room exists to some extend and in rooms having larger volumes concentration of thoron is profound from surfaces closer to dosimeter placement.

Spatial variation of indoor ^{222}Rn and ^{220}Rn levels

The construction materials used for building the houses are predominantly of cement, concrete and bricks made up of local soil. About 150 dwellings in ten different locations of Bangalore city were selected on the basis of construction, ventilation and age of the building to see the effective dose rates due to indoor ^{222}Rn, ^{220}Rn and their progeny levels in dwellings. The houses were categorized on the basis of ventilation that depends on number of windows, doors and usage pattern (such as closed, open, partially open/close) to identify them as poor (no or 1-window), moderate (2-windows) and good (3 and above windows) ventilated houses. The annual average values of ^{222}Rn, ^{220}Rn and their dose rates in the different locations of study area are summarized in Table 4 including the number of houses monitored. The arithmetic mean of ^{222}Rn concentration varies from 17.2 ± 1.2 to 85.9 ± 2.3 Bqm^{-3} with a mean of 33.3 ± 6.1 Bqm^{-3}, whereas for ^{220}Rn it vary from 8.3 ± 1.2 to 38.3 ± 5.4 Bqm^{-3} with a mean of 21.5 ± 2.5 Bqm^{-3}. The lower values of ^{222}Rn concentrations were observed in Rajajinagar and higher in Government Science College (GSC) of Gandhinagara. The reason may be due to the fact that the activity concentrations (^{226}Ra) in the surrounding area (Mallathalli: 23.7±0.7) are lower compared to the Gandhinagara (Lalbagh: 111.6±1.2). The lower and higher concentrations of ^{220}Rn were seen in Vijayanagar (Mallasandra: 29.5±0.9) and GSC of Gandhinagara (Lalbagh: 95.4±1.5), respectively. This is again due to the activity concentrations of ^{232}Th in the respective area (Shiva Prasad et al., 2008).

Hunse et al. (2010) have reported that the radon in water in Rajajinagar (166.62±8.08 BqL^{-1}) is low and

Table 4. Annual average concentrations of ^{222}Rn, ^{220}Rn and their effective dose rates.

Name of the location	Number of dwellings monitored	AM ± SD		Dose rate ($mSvy^{-1}$)
		^{222}Rn	^{220}Rn	
		Bqm^{-3}		
Rajajinagar (RAJ)	15	17.2 ± 1.2	16.1 ± 1.4	0.7
Srinivasanagar (SRN)	15	40.0 ± 1.9	29.2 ± 4.3	1.5
Sheshadripuram (SHPM)	15	31.8 ± 3.1	19.8 ± 2.0	1.1
Srirampuram (SRPM)	20	26.3 ± 3.2	18.8 ± 1.6	0.9
Padhmanabhanagar (PNR)	15	27.5 ± 1.7	25.9 ± 2.0	1.1
Jayanagar (JNR)	15	25.3 ± 1.6	19.7 ± 1.2	0.9
Banashankari (BSK)	12	26.5 ± 2.0	21.4 ± 2.2	1.0
Malleshwaram (MLM)	13	27.9 ± 2.9	17.8 ± 1.5	0.9
Vijayanagar (VNR)	15	25.5 ± 3.8	8.3 ± 1.2	0.7
Gandhinagara (GNR)	15	85.9 ± 2.3	38.3 ± 5.4	2.7
AM ± SD		33.3 ± 6.1	21. 5 ± 2.5	1.2 ± 0.03

Table 5. Area wise range of ^{222}Rn, ^{220}Rn and their progeny levels.

Name of the location	Range			
	Concentration of ^{222}Rn	Concentration of ^{220}Rn	^{222}Rn progeny	^{220}Rn progeny
	$Bq\ m^{-3}$		m WL	
Rajajinagar	4.0 - 36.8	5.5 - 35.4	0.02 - 0.9	0.02 - 0.5
Srinivasanagar	29.8 - 50.3	13.7 - 56.9	0.12 - 1.9	0.04 - 0.7
Sheshadripuram	5.8 - 100.0	2.7 - 72.9	0.02 - 1.6	0.02 - 0.9
Srirampuram	10.9 - 65.9	6.1 - 30.9	0.06 - 1.1	0.02 - 1.9
Padhmanabhanagar	4.0 - 76.0	3.4 - 70.1	0.01 - 1.5	0.02 - 3.5
Jayanagar	4.0 - 80.7	4.8 - 63.1	0.02 - 2.2	0.01 - 1.7
Banashankari	5.8 - 89.4	1.3 - 66.6	0.02 - 4.4	0.01 - 1.3
Malleshwaram	5.8 - 92.9	2.0 - 47.9	0.02 - 2.2	0.02 - 4.8
Vijayanagar	11.7 - 99.4	6.7 - 37.5	0.03 - 1.4	0.02 - 0.9
Gandhinagara	73.6-100.0	10.9 - 72.9	0.23 - 4.4	0.03 - 1.0

Higher concentrations are in Cubbon Park (GSC: 764.05±35.4 BqL^{-1}). The results show that there is a direct correlation between radon in water and indoor radon. The radon in water of other location is in between these two values with fair correlation between radon in water and indoor radon. The average indoor radon concentration reported for dwellings of different cities across the world varies between 8.7 Bqm^{-3} for Australia and 190 Bqm^{-3} for Saxony and Turingia of Germany, with a weighted arithmetic mean for all the cities considered of 40 Bqm^{-3} (UNSCEAR, 1993). The effective radiation dose due to ^{222}Rn and ^{220}Rn ranged between 0.5 to 3.5 $mSvy^{-1}$ with arithmetic mean of 1.2 $mSvy^{-1}$. The observations made for Bangalore region were also of the same order reported elsewhere. To get a clear idea of the spatial variations, the observed values are compared with the surveys made in different areas. The range of ^{222}Rn, ^{220}Rn and their progenies for each location are given in Table 5. The elevated radon levels are seen in poor ventilation houses of all the locations where most of the houses were built by local soil and sedimentary gravel. Some buildings with higher radon levels were found on gravel but all the lower values observed in Rajajinagar area. This may be due to the lower activity concentrations of ^{226}Ra (Shiva Prasad et al., 2008) and also low radon in water (Hunse et al., 2010) in the surrounding region. The

Table 6. Location wise seasonal variations of indoor ^{222}Rn and ^{220}Rn concentrations.

Name of the location	Winter		Summer		Rainy		Autumn	
	^{222}Rn	^{220}Rn	^{222}Rn	^{220}Rn	^{222}Rn	^{220}Rn	^{222}Rn	^{220}Rn
	Bqm^{-3}		Bqm^{-3}		Bqm^{-3}		Bqm^{-3}	
Rajajinagar	24.9	18.6	10.9	14.2	14.8	15.3	18.2	16.2
Srinivasanagar	36.6	19.9	18.2	16.2	24.9	15.3	29.6	21.3
Sheshadripuram	43.9	25.9	18.3	15.5	28.3	18.1	36.6	19.9
Srirampuram	38.8	21.8	17.3	12.2	20.5	20.5	28.5	20.7
Padhmanabhanagar	41.9	35.2	15.6	14.3	22.6	24.8	29.6	29.3
Jayanagar	37.4	22.4	12.9	14.6	23.2	20.1	27.3	21.5
Banashankari	41.8	31.5	13.7	14.4	22.2	18.2	27.9	21.3
Malleshwaram	50.3	26.9	14.3	12.4	19.7	13.9	27.4	18.2
Vijayanagar	61.9	21.3	26.2	16.6	35.6	17.8	43.8	20.4
Gandhinagara	73.6	49.7	24.5	20.1	40.3	24.5	51.4	25.8

observed concentration reveals that 81% of indoor ^{222}Rn levels are found to vary between 4 and 39 Bqm$^{-3.}$ The higher concentrations (40 to 80 Bqm^{-3}) were observed in 15% of the studied houses, this may be due to the buildings without the basic concrete slab or the slab that was not properly built or already damaged (Vaupotic et al., 1999). Nearly 4% of buildings show ^{222}Rn concentrations above 80 Bqm^{-3} with a maximum of 100 Bqm^{-3} and they were 40 year old. The poor construction of houses leads to the several cracks in foundation, walls, basic slabs thorough which radon can easily enter the rooms (Vaupotic et al., 1999). The observed values of ^{222}Rn concentration are found comparable with variation observed in the country and ranges from 6.4 to 95.4 Bqm^{-3} with a geometrical mean 25.5 Bqm^{-3} (Ramachandran et al., 2003). In general the ^{222}Rn concentration was found higher in mud houses than in cement houses. The ground floor of such houses is directly constructed on the top of soil with a coating of mud. The ground floor allows more ^{222}Rn to diffuse inside the houses because of higher porosity of materials used (Ramola et al., 1995). Whereas for ^{220}Rn, about 83% of the dwellings have shown the concentrations below 30 Bqm^{-3}, 11% ranged between 31- 49 Bqm^{-3} and 6% of the dwellings showed the concentrations above 50 Bqm^{-3} with a maximum of 72.9 Bqm^{-3}. The reported values of mean indoor ^{222}Rn and ^{220}Rn concentrations for India is 23.0 and 12.2 Bqm^{-3} respectively and the total inhalation dose rate is 0.9 mSvy^{-1} (Ramachandran et al., 2003). A comparison of indoor ^{222}Rn and ^{220}Rn concentration for different seasons of all the studied locations are shown in Table 6. The obtained concentration shows a clear seasonal variation. Higher concentrations were observed winter months and lower in summer months. This may be due to the enhanced radon exhalation and reduced ventilation as observed elsewhere (Virk and Sharma, 2000). Radon levels in closed environment are affected both by the degree of exchange with outdoor air as measured by the ventilation rate and by changes in the entry rate of radon rich air from the underlying soil and rocks. Since majority of the houses are well ventilated in summer season, indoor radon concentrations might be expected to be lower for summer than in winter season (Wilkening, 1986). The indoor ^{222}Rn and ^{220}Rn were influenced mainly by the ventilation condition of the house. In GSC high ^{222}Rn and ^{220}Rn concentrations in summer is observed than in winter. This anomaly observed in the college is may be due the fact that the class rooms will be closed for longer duration in summer holidays. The emanation of radon also contributes higher radon from rocks and local stones. In addition, the mud houses have small doors and a small window, which remain closed for most of the time to conserve the energy (Ramachandran et al., 2003). The observed winter/summer ratio was found maximum while the winter/autumn ratio was found minimum. The winter /summer ratio in different locations are found to vary between 1.9 and 3.7 and this ratio is high compared to the ratios of winter/rainy and winter/autumn. Again this is correlated with the ventilation condition of houses. The concentrations of ^{222}Rn and its progeny also follow the same trend as it was recorded maximum in winter and minimum in summer (Virk and Sharma, 2000; Vaupotic et al., 1999). However the ^{220}Rn and its progeny concentration was found maximum during winter and minimum during rainy. This behavior is may be due to low emanation rate of ^{220}Rn during rainy season and also it may be due to the possibility of brief half life, it cannot escape easily from the soil capillaries that are mostly occupied by water during the rainy season (Sathish et al.,

2001).

Conclusions

It is observed that the concentrations of indoor ^{222}Rn, ^{220}Rn and their progeny levels are higher in poor ventilated houses than in well ventilated houses. The higher ^{222}Rn and ^{220}Rn concentrations may be due to the presence of radioactive contents in the building. Radon levels in houses were found to be inversely related to room sizes. Thoron levels did not show much effect with increase in room volumes. Inhalation dose measured in the houses were comparable with natural background areas.

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