Physical Review & Research International
2(2): 36-69, 2012

SCIENCEDOMAIN *international*
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Radon and Thoron levels in Dwellings of Bangalore City, India: A Review

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Review Article

Received 3rd March 2012
Accepted 17th April 2012
Online Ready 7th May 2012

ABSTRACT

Aims: ^{222}Rn, a radioactive inert gas is a large component of the natural radiation that humans are exposed to, can pose a threat to the public health when it accumulates in poorly ventilated residential and occupational settings. About half of the total radiation effective dose to the general public is due to the irradiation of the lungs by alpha particles following the inhalation of ^{222}Rn decay products. In this outlook, a comprehensive estimate of the natural inhalation dose requires both ^{222}Rn and ^{220}Rn levels in the indoor atmosphere.
Place and Duration of Study: Quite a large number of measurements have been carried out during the period 2007 to 2011. About 300 dwellings of different types of construction in ten different locations of Bangalore city, India were chosen on the basis of construction, age of the building, nature of walls, floorings, rooms and different volume of dwellings for the present study to see the effective dose rates due to indoor ^{222}Rn, ^{220}Rn and their progeny levels during different seasons of the year.
Methodology: The concentration of gamma active radio nuclides viz., ^{226}Ra, ^{232}Th and ^{40}K in soil samples were determined by gamma spectrometry method by employing an HPGe spectrometer. The activity of radon in water samples were determined using emanometry method. The emanometry setup is calibrated at BARC, Mumbai. Solid State Nuclear Track Detector based dosimeters were used for the measurement of ^{222}Rn and ^{220}Rn and this is a good technique to study the long-term measurements.
Results: The estimated concentration of ^{222}Rn and ^{220}Rn for the environment of Bangalore, India varied from 17.2 ± 1.2 to 85.8 ± 2.3 Bqm^{-3} and 8.3 ± 1.2 to 38.3 ± 5.4 Bqm^{-3} with a mean of 32.2 ± 1.6 and 21.4 ± 1.0 Bqm^{-3}, respectively. It is alarming that the dwellers of

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lower volume and granite floorings receive relatively a higher dose rate and the result shows significant radiological risk. Volumetric variations of indoor ^{222}Rn, ^{220}Rn and their progeny levels reveals higher concentrations in lower volume room compared to higher volume room at all the monitored locations.

Conclusion: The investigation shows no significant radiological risks for the inhabitants and is well within the limits prescribed by UNSCEAR. Further, it is recommended that the lower volume houses should have good ventilation and the dwellings should be granite free flooring, to reduce the effective dose rate. More detailed studies on the evaluation of public exposure from the natural radiation; particularly the exposure from ^{220}Rn and their progeny should be planned and performed in this region and in the country.

Keywords: Radon; thoron; SSNTD; HPGE; Emanometry; indoor; dose rate; dwellings.

1. INTRODUCTION

The significant contribution to ionizing radiation exposure is from natural sources. The levels of radioactivity in water, soil and air are important mainly because of two principal radiological effects. The first is the internal irradiation of lungs and other organs of the human body by alpha particles emitted by short-lived decay products of ^{222}Rn and ^{220}Rn and the second is the external irradiation of the body by gamma rays emitted from radio nuclides present in the area (UNSCEAR 2000). Elevated radon gas levels have been discovered in virtually every state. The United States Environmental Protection Agency (U.S. EPA) estimates that as many as eight million homes throughout the country have elevated levels of radon gas (Kumar et al*.,* 2011). In Europe, radon in the home accounts for about 9% of deaths from lung cancer and 2% of all deaths from cancer (Darby et al*.,* 2005). The ^{222}Rn, derived from the decay chain of ^{238}U and ^{220}Rn, derived from ^{232}Th. ^{222}Rn, a radioactive inert gas is a large component of the natural radiation that humans are exposed to, can pose a threat to the public health when it accumulates in poorly ventilated residential and occupational settings. About half of the total radiation effective dose to the general public is due to the irradiation of the lungs by alpha particles following the inhalation of ^{222}Rn decay products. The continuous exposure to higher levels of radon and its progeny may lead to malignant transformation which results in lung cancer. In view of these, a comprehensive estimate of the natural inhalation dose requires both ^{222}Rn and ^{220}Rn levels in the indoor atmosphere. In this stance, an extensive review on the radon levels is instigated and an attempt is made to investigate the ^{222}Rn and ^{220}Rn levels in dwellings of Bangalore Metropolitan, India. Five year results shows that the activity concentrations of ^{226}Ra, ^{232}Th, radon in ground water, the concentrations ^{222}Rn, ^{220}Rn and the dose rate are at alarming levels for the environment of Bangalore Metropolitan, India. The detailed experimental methodology, results and the control measures are discussed in detail.

2. STUDY AREA

The area of present study is Bangalore metropolitan, India and the locative map is shown in Figure 1. The district lies between the latitudes 12º39' to 13º13' N and longitudes 77º22' to 77º52' E. The climate is having four distinct seasons, viz., summer season (March to May), rainy season (June to September), autumn season (October and November) and winter season (December to February). April is usually the hottest month with the mean daily

maximum temperature of 30-35ºC and mean daily minimum at 20-24ºC. The geology of this part forms predominantly a granite terrain with numerous varieties of granites, granitic gneiss, pegmatite, 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 and black dolerite. These rocks form geological band of a width 15–25 km. The radioactivity reported for the building materials collected from this region is higher compared with soil radioactivity (Ramachandran et al*.,* 2003). However, major quantity of bricks used for the construction of the buildings are brought from places in the city out skirts called Nelamangala, Magadi etc. and a small portion from Hoskote, Ramanagara and Channapatna of radial distance 60 km. The average activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the soils of Nelamangala and Magadi are reported as 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 1073.0±15.6 Bqkg^{-1} respectively (Shiva Prasad et al*.,* 2008). The radon gas is occurring in the groundwater of the study area ranging from 55.9 BqL^{-1} to 1189.3 BqL^{-1} (Hunse et al*.,* 2010). The authors have also reported that the radon concentration is above the permissible limit of 11.8 BqL^{-1} and at places the concentration is as high as hundred times (Hunse et al*.,* 2010). In an earlier study carried out for the environment of Bangalore metropolitan Ningappa et al*.,* (2008) have reported that the value of radon concentration in the indoor air near granite quarries varies from 55 to 300 Bqm^{-3} with a median of 155 Bqm^{-3} and its progeny varies from 0.24 to 19.6 mWL with a median of 8.4 mWL. In Bangalore City, the concentration of radon varies from 18.4 to 110 Bqm^{-3} with a median of 45 Bqm^{-3} and its progeny varies from 1.62 to 11.24 mWL with a median of 4.15 mWL. Authors report the higher concentrations in granite quarries than in Bangalore city. Further, the main reason for the higher indoor radon and its progeny concentration was due to the mining activity and the types of the bedrock. The activity of radium varies in granitic regions of Bangalore rural district from 42.0 to 163.6 Bqkg^{-1} with a median of 112.8 Bqkg^{-1}. All the monitored houses were on the ground floor. About twenty-houses of different construction types were chosen each in all the monitored locations.

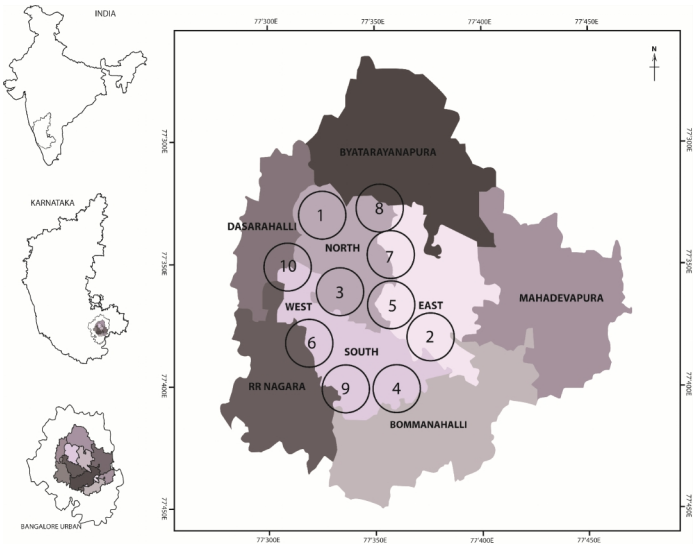

Fig. 1. Locative map of Bangalore metropolitan, India

1: RAJ, 2: JNR, 3: SRPM, 4: PNR, 5: GNR, 6: SNR, 7: SPM, 8: MLM, 9: BSK, 10: VNR

3. EXPERIMENTAL PROCEDURE

3.1 Activity Concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Soil

The concentration of gamma active radio nuclides viz., ^{226}Ra, ^{232}Th and ^{40}K in soil samples were determined by gamma spectrometry method by employing an HPGe spectrometer (Baeza et al., 1996). The places, which were free from surface runoff during heavy rain, were carefully selected near the dwellings. An area of ~0.5 m^2 was cleared of vegetation and roots. The marked spot was dug up to a depth of 15 cm and ~2 kg of soil was collected at each spot. Finally, the samples were mixed thoroughly and extraneous materials like plants, debris, big pieces of stones and pebbles were removed. Composite samples of ~2 kg was taken and sealed in a polythene bag. The samples were transferred to a porcelain dish and oven-dried overnight at 110ºC. The samples were powdered and sieved through 150 µm sieves, weighted and sealed in a 300-ml plastic container and kept for a month before counting by gamma spectrometry, in order to ensure that radioactive equilibrium was reached between ^{226}Ra, ^{222}Rn and its progeny. The spectrometer consisted of n-type HPGe coaxial detector (EG & G ORTEC USA) of 17% efficiency having a resolution of 1.75 keV at 1.33 MeV and 641 eV at 5.9 keV and coupled to a 4096 channel MCA. The detector was surrounded with lead shielding to reduce the entering of background radiation. The gamma spectrometric procedure was followed to estimate the activity of radium (Volchok et al., 1983; IAEA, 1989). The gamma peak of energy 609.51 keV (which is emitted by ^{214}Bi, a decay product of radium) with intensity of 46.1% was used as proxy for the quantitative determination of radium by gamma spectrometry. The activity of radionuclides (Bqkg^{-1}) was calculated using the formula (IAEA, 1989).

$$Activity\left(Bqkg^{-1}\right) = \frac{\left(S \pm \pm\right) \times 100 \times 100 \times 1000}{E \times W \times A}$$

Where S is the net counts per second under the photo peak of intensity, ± is the standard deviation of S, E is the counting efficiency (%), W is the mass of the sample (kg) and A is the gamma abundance (%) of the radionuclides.

3.2 Concentration of ^{222}Rn in Ground Water

The activity of the samples was determined by Emanometry method (Hightower and Watson, 1995). The emanometry setup is calibrated at BARC, Mumbai and the average efficiency of scintillation cells used was found to be 74%. The schematic of Radon bubbler is shown in Figure. 2.

The samples were collected from the selected locations around Bangalore City from manually operated bore wells. About 100ml of water sample was collected in airtight plastic bottles with minimum disturbance, the bottles were gently and completely filled so that zero headspace was present, care was taken so that no air bubble and aeration which may lead to out gassing (Raghavayya et al., 1980). The samples were brought to the laboratory within a short time and analyzed immediately. Activity concentration of ^{222}Rn in water was estimated by the emanometry (Strain and Watson, 1979). About 40-60 ml of water is transferred into the radon bubbler using vacuum transfer technique, a pre-evacuated, background counted scintillation cell is connected to the top end of the bubbler and the upper tap is slowly opened, effervescence is seen in the bubbler indicating the partial

disruption of dissolved air. The tap at the bottom of the bubbler is opened slowly and carefully so that vigorous effervescence results. Since both the taps of the bubbler are open, room air with only background radon enters the bubbler through the side of the capillary and breaks up into tiny bubbles due to sintered disc and carries with it the radon dissolved in water into the scintillation cell. Scintillation cell was stored for 180 minutes to allow radon to attain equilibrium with its daughters, and then it is coupled to a photomultiplier and alpha counting assembly. The efficiency of the scintillation cells used is found to be 74% and the MDL of the system was 0.041 BqL^{-1}.

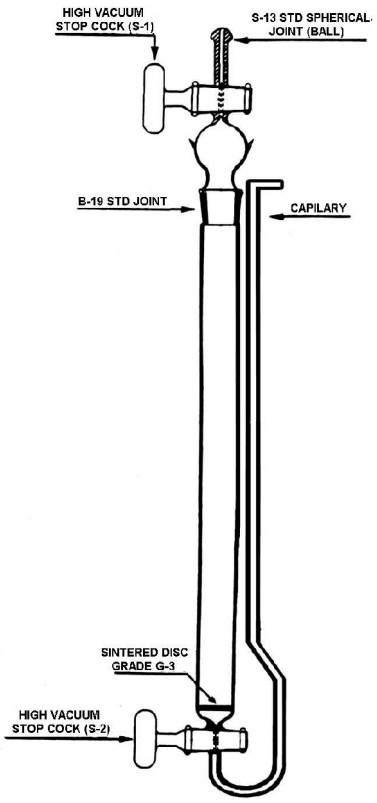

Fig. 2. Schematic of Radon Bubbler

The concentration is calculated using the relation given by Raghavayya et al., (1980)

$$Activity\,(BqL^{-1}) = \frac{6.97 \times 10^{-2} \times D}{V \times E \times e^{-a-} \times \left(1 - e^{-a-}\right)}$$

Where, *D* is the gross alpha counts above the background; *V* is the volume of water in radon bubbler (ml); *E* is the % efficiency of the scintillation cell; ^{a} is the decay constant of radon (2.098×10^{-6} s); T is the counting delay in seconds; *t* is the counting duration (1000 s) and $^{-}$ is the delay between water sampling and de emanation of radon from water sample to scintillation cell in seconds.

3.3 Solid State Nuclear Track Detectors

Solid State Nuclear Track Detector (SSNTD) based dosimeters were used for the measurement of ^{222}Rn and ^{220}Rn and this is a good technique for the long-term measurements (Fleischer 1988). The mode of sampling is passive and integrated for long duration taking into account the diurnal, monthly and seasonal variations of ^{222}Rn and ^{220}Rn concentrations. Spark Counter technique is applicable to plastic track detectors, which provides a convenient, economical and fast method for track counting. This technique was developed by Cross and Tommasino (1970) and is discussed in detail by Garkani (1989).

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. The schematic of double chamber dosimeter cup used is shown in Fig.3.

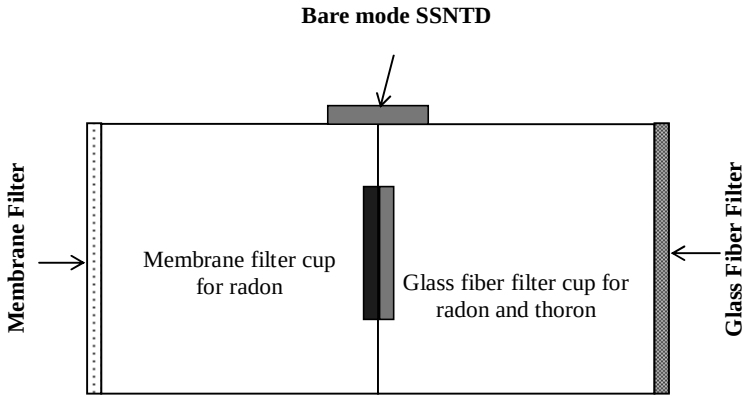

Fig. 3. Schematic of double chamber ^{222}Rn/^{220}Rn dosimeter cup used for the survey

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 into 2.5cm × 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} -10^{-7} cm^{2}s^{-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 60ºC for 60 minutes 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.

3.3.1 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 La Mer 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 $I0^5$ 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 obtained CFs for ^{222}Rn and ^{220}Rn are given in Table 5 (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 Equilibrium Factor (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 5 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,ω is the solid angle suspending the area of influence, θ is the angle of incidence ranging from normal incidence (0^o) 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 ¯ 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 agreement.

3.3.2 Dosimetric methodology

Inter-laboratory standardization experiments for the etching characteristics conducted using standard alpha sources also showed good agreements. A theoretical methodology was developed for evaluating the progeny concentrations using the twin cup ^{222}Rn - ^{220}Rn dosimeter system (Mayya et al., 1998)**.** 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 calibration factors (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 is 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 (Doe 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).

3.3.3 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, 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 below:

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

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

4. RESULTS AND DISCUSSION

Quite a large number of measurements have been carried out during the period 2007 to 2011. About 300 dwellings of different types of construction in ten different locations of Bangalore city, India were chosen on the basis of construction, age of the building, nature of walls, floorings, rooms and different volume of dwellings for the present study to see the effective dose rates due to indoor ^{222}Rn, ^{220}Rn and their progeny levels during different

seasons of the year. Further, dwellings 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 (0-window), partial (1-windows) moderate (2-windows), good (3-windows), very good (4-windows) and excellent (5-windows) ventilated houses.

4.1 Area Wise Variations

Levels of ^{222}Rn, ^{220}Rn and their short lived progeny concentrations were observed simultaneously for a period of three years by covering large area of Bangalore city. Fig. 2 summarizes the ^{222}Rn and ^{220}Rn found in the different locations.

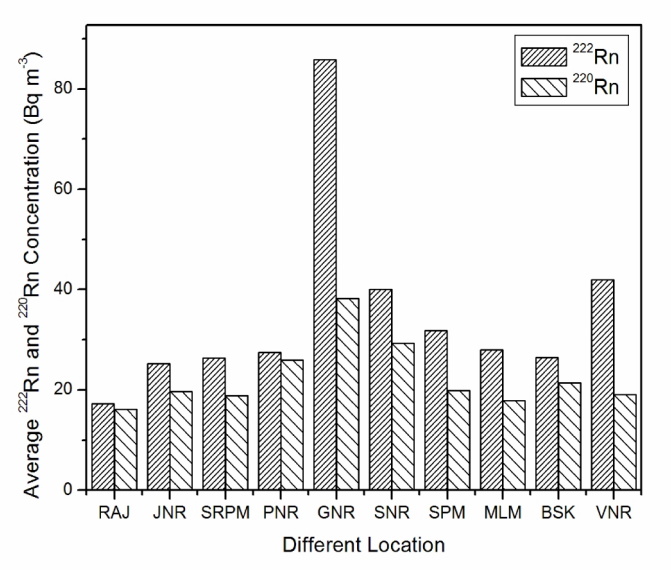

Fig. 2. Mean values of ^{222}Rn and ^{220}Rn

The lower ^{222}Rn concentrations were observed in Rajajinagar and higher in Government Science College of Gandhinagara and the lower and higher concentrations of ^{220}Rn were seen in Vijayanagar and Government Science College of Gandhinagara respectively, this is may be due to the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in soil around the respective areas (Shiva Prasad et al., 2008).

Estimated ^{222}Rn concentration levels at different locations of India varied from 6.4 to 95.4 Bqm^{-3} with a GM of 25.5 Bqm^{-3} (GSD 2.1), whereas for ^{220}Rn they were ranged between 3.5 and 42.8 Bqm^{-3} with a GM of 12.2 Bqm^{-3} (GSD 3.22) (Ramachandran et al., 2003). The AM values of ^{222}Rn and ^{220}Rn with different ventilation condition are given in Table 1. Results shows the concentration levels are higher in poor ventilated houses than in excellent ventilated houses. Comparisons of indoor ^{222}Rn concentration for different seasons were also made. The winter to summer ratio was observed maximum while the winter to autumn ratio was found minimum.

Higher values in winter are mainly because of ventilation factor. Indoor radon is influenced mainly by the ventilation condition of the dwellings. Winter to summer ratio in different locations were found to vary between 1.9 and 3.7 and this ratio is high compared to the ratio of winter to rainy and winter to autumn. This again depends on ventilation condition of the

dwellings. Concentrations of ^{222}Rn and its progeny also follow the same trend as it was recorded maximum in summer and minimum during winter (Ramachandran and Subba Ramu, 1989).

Table 1. Arithmetic mean values of ^{222}Rn and ^{220}Rn with different ventilation condition

Number of windows	Nature of Ventilation	AM ± SE	
		^{222}Rn (Bqm^{-3})	^{220}Rn(Bqm^{-3})
5	Excellent	7.3 ± 0.8	9.4 ± 0.9
4	Very Good	16.6 ± 0.9	10.6 ± 1.7
3	Good	31.3 ± 1.4	19.7 ± 2.0
2	Moderate	42.7 ± 1.1	29.5 ± 6.4
1	Partial	54.0 ± 1.5	33.9 ± 7.5
0	Poor	81.0 ± 3.5	38.6 ± 6.1

To get a clear idea of the spatial variations, the observed values were compared with the surveys made in different areas; the range (minimum to maximum) values of ^{222}Rn and ^{220}Rn are plotted in Fig. 3.

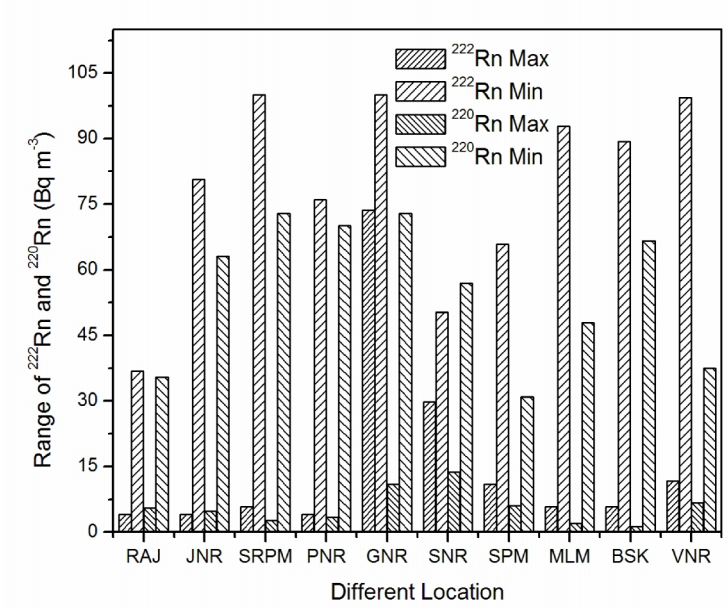

Fig. 3. Area wise range of ^{222}Rn and ^{220}Rn

Elevated levels are seen in poor ventilated houses of all locations, where most of the houses were built by local soil and sedimentary gravel. Some buildings with higher levels were found on gravel but all the lower values were observed in Rajajinagar area. This is may be due to the lower activity concentrations (Shiva Prasad et al., 2008) of ^{226}Ra and lower radon concentration in the ground water in the surrounding area (Hunse et al., 2010).Whereas the higher concentration is may be due to the higher activity concentrations of ^{226}Ra and higher

concentrations of radon in water in the monitored locations. The authors (Shiva Prasad et al., 2008; Hunse et al., 2010) have reported that, the activity concentrations of ^{226}Ra in the surrounding area of Rajajinagar (Mallathalli) and Gandhinagara (Lalbagh) were 23.7 ± 0.7 and 111.6±1.2 Bqkg^{-1} respectively, whereas the activity concentrations of ^{232}Th in the surrounding areas of Vijayanagar (Mallasandra) and Gandhinagara (Lalbagh) were 29.5 ± 0.9 and 95.4±1.5 Bqkg^{-1}. The concentrations of ^{222}Rn in water samples of Nagarbhavai (Vijayanagar), Rajajinagar and Lalbagh area were 97.2 ± 5.7, 166.6 ± 8.1 and 887.7 ± 34.1 BqL^{-1} respectively.

Frequency distribution of ^{222}Rn and ^{220}Rn are depicted in Fig. 4. About 60% of indoor ^{222}Rn levels were found to vary between 20 and 39 Bqm^{-3}. Higher concentrations of values more than 80 Bqm^{-3} were observed in 6% of the studied houses. Nearly 23% of buildings showed concentrations between 50–80 Bqm^{-3} and they were of 40-year old dwellings, poorly constructed, with several cracks in foundation, walls and basic slabs, thorough which radon can easily enter the rooms.

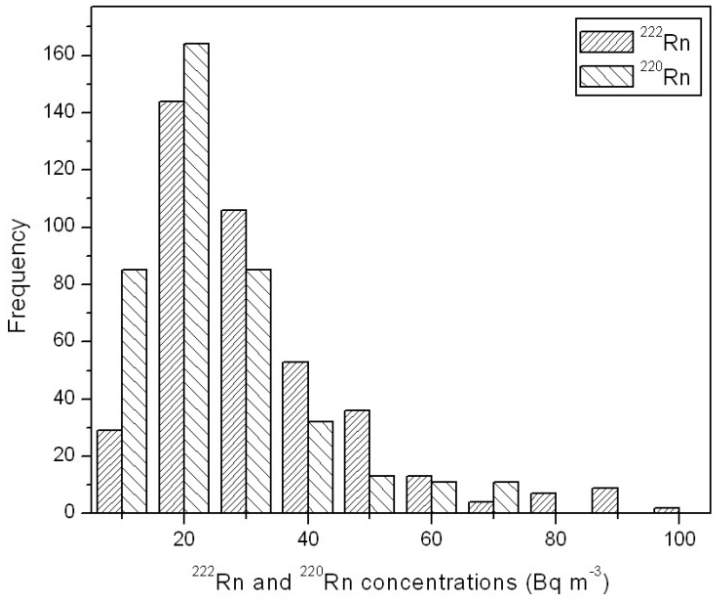

Fig. 4. Frequency distributions of ^{222}Rn and ^{220}Rn

About 85% of the dwellings have shown the ^{220}Rn concentrations below 30 Bqm^{-3} and 15% of them had the concentrations above 50 Bqm^{-3}. The estimated ^{222}Rn concentration levels at different locations of India varied from 6.4 to 95.4 Bqm^{-3} with a GM of 25.5 Bqm^{-3} (GSD 2.1), whereas for ^{220}Rn they were ranged between 3.5 and 42.8 Bqm^{-3} with a GM of 12.2 Bqm^{-3} (GSD 3.22) with the effective annual dose of 0.94 mSvy^{-1}. In general the radon concentration was found higher in mud houses than in cemented houses (Ramola et al., 1995). Such houses on the ground floor were directly constructed on the top of soil with a coating of mud. Being this case, the ground floor allows more radon to diffuse inside the houses because of higher porosity of materials used (Sathish et al., 2006). Further, the primary reason of high levels of radon is underlying geology (Harrell and Kumar, 1989). The Table 2 summarizes the annual average values of ^{222}Rn, ^{220}Rn and their dose rates in the

different locations of Bangalore city and also the number of houses monitored in each area during 2007 to 2011.

The arithmetic mean of ^{222}Rn concentration in dwellings of monitored area varied 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 they were 8.3 ± 1.2 to 38.3 ± 5.4 Bqm^{-3} with a mean of 21.5 ± 2.5 Bqm^{-3}. 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 Thuringia of Germany, with a weighted arithmetic mean for all the cities considered as 40 Bqm^{-3} (UNSCEAR, 2000). The observations made for Bangalore region also having the same range reported elsewhere.

Table 2. Annual Average concentrations of ^{222}Rn, ^{220}Rn and their 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

Annual average concentrations of ^{222}Rn and ^{220}Rn for the different seasons and temperature of Bangalore city are tabulated in Table 3.

Table 3. Typical seasonal variation of ^{222}Rn and ^{220}Rn concentration and temperature

Season	Period	Mean Temperature (ºC)	^{222}Rn	^{220}Rn
			Bqm^{-3}	
Winter	December - February	20	42.6	26.3
Autumn	September - November	24	24.9	19.2
Rainy	June - August	30	23.4	18.8
Summer	March - May	35	16.1	14.0

Obtained concentration showed a clear seasonal variation for ^{222}Rn and ^{220}Rn. The temperature profile shows the variations and is affecting the ventilation rate, showing maximum concentrations of ^{222}Rn and ^{220}Rn during winter and lower in summer. This is may be due to the increased in radon exhalation and reduced ventilation as observed elsewhere (George and Breslin, 1980; Toohey et al., 1985; 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 were well ventilated in summer season, indoor radon concentrations might be expected to be lower for summer than in winter season (Wilkening and Wicke, 1986).

To get a clear idea of the spatial variations, the observed values were 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 4. Elevated radon levels were 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. The reason being the existence of the subsurface 5 to 15 m deep clay layer is good barrier against radon emanation from ground water, especially when it is wet or frozen (Vaupotic et al., 1999). In the studies it is reported that the measured indoor air quality in 40 homes in East Tennessee have revealed the difference in the radon concentration in these homes according to their location. Also a home located in a valley tended to have a lower concentration than a home on a ridge. This was attributed to the presence of a deeper overburden of low activity soil on the valley floor.

Table 4. 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
	Bqm^{-3}		mWL	
Rajajinagar	4.0 – 36.8	5.5 – 35.4	0.01 – 0.9	0.01 – 0.5
Srinivasanagar	29.8 – 50.0	13.7 – 56.9	0.11 – 1.9	0.04 – 0.7
Sheshadripuram	5.8 – 100.0	2.7 – 72.9	0.02 – 1.6	0.01 – 0.8
Srirampuram	10.9 – 65.9	6.1 – 30.9	0.06 – 1.1	0.01 – 1.8
Padhmanabhanagar	4.0 – 76.0	3.4 – 70.1	0.01 – 1.5	0.01 – 3.4
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 – 1.2
Malleshwaram	5.8 – 92.9	2.0 – 47.9	0.02 – 2.2	0.01 – 4.8
Vijayanagar	11.7 – 99.4	6.7 – 37.5	0.04 – 1.4	0.02 – 0.9
Gandhinagara	73.6 –100.0	10.9 – 72.9	0.26 – 4.4	0.03 – 1.0

The ridges are of dolomite with relatively shallow soil cover which was thought to offer relatively lower resistance to diffusion of radon from the underlying uranium bearing shale (Hawthorne et al., 1986; Harrell et al., 1991; 1993). About 60% of indoor ^{222}Rn levels were found to vary between 20 and 39 Bqm^{-3}. The higher concentrations were observed in 6% of the studied houses, this is 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). About 23% of buildings showed ^{222}Rn concentrations vary between 50 and 80 Bqm^{-3}, were 40 year old and poorly constructed with several cracks in foundation, walls, basic slabs thorough which radon could easily enter the rooms (Vaupotic et al., 1999). The observed values of ^{222}Rn concentrations were found comparable with the variation observed in the country and ranges from 6.4 to 95.4 Bqm^{-3} with a geometrical mean of 25.5 Bqm^{-3} (George and Breslin, 1980). In general the radon concentration was found higher in mud houses than in cement houses (Ramola et al., 1995; Sathish et al., 2001). The ground floor of such houses is directly constructed on the top of soil with a coating of mud. The ground floor allows more radon to diffuse inside the houses because of higher porosity of materials used, which also justify

previous findings (Sathish et al., 2006). A comparison of indoor ^{222}Rn and ^{220}Rn concentration for different seasons of all the studied locations are shown in Table 5.

Table 5. 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}	
Vijayanagar	61.9	21.3	26.2	16.6	35.6	17.8	43.8	20.4
Malleshwaram	50.3	26.9	14.3	12.4	19.7	13.9	27.4	18.2
Srirampuram	43.9	25.9	18.3	15.5	28.3	18.1	36.6	19.9
Padhmanabhanagar	41.9	35.2	15.6	14.3	22.6	24.8	29.6	26.3
Banashankari	41.8	31.5	13.7	14.4	22.2	18.2	27.9	21.3
Sheshadripuram	38.8	21.8	17.3	12.2	24.5	20.5	28.5	20.7
Jayanagar	37.4	22.4	12.9	14.6	23.2	20.1	27.3	21.5
Rajajinagar	24.9	18.6	16.9	14.2	16.8	15.3	18.2	16.2

Due to poor ventilation, the radon is accumulated inside the houses and thus results higher concentration. The ^{222}Rn and ^{220}Rn concentrations were found higher in winter and low in summer. The higher values in winter are mainly because of ventilation factor (Ramola et al., 1997). The relative indoor ^{222}Rn concentrations are depicted in Table 6.

Table 6. Relative indoor ^{222}Rn concentrations

Name of the Location	Number of Houses		W/S*	W/R*	W/A*
Srirampuram	20		2.10	1.89	1.36
Rajajinagar	15		2.99	1.40	1.40
Vijayanagar	15		3.03	1.45	1.41
Sheshadripuram	15		3.69	1.94	1.76
Malleshwaram	13		2.76	1.31	1.21
Jayanagar	15		3.38	1.99	1.83
Banashankari	12		2.03	1.21	1.08
Padhmanabhanagar	15		2.83	1.30	1.24
Srinivasanagar	15		2.39	1.58	1.54
Gandhinagara	15		1.92	1.58	1.52
		Max	3.69	1.99	1.83
		Min	1.92	1.21	1.08
		AM	2.71	1.56	1.43
		GM	2.65	1.54	1.43

**W/S-Winter/Summer, *W/R-Winter/Rainy, *W/A-Winter/Autumn*

The winter/summer ratio was observed maximum while the winter/autumn ratio was found minimum. The winter/summer ratios in different locations were found to vary between 1.92 and 3.69 and this ratio is high compared to the ratios of winter/rainy and winter/autumn. This again depends on ventilation condition of the houses. The concentrations of ^{222}Rn and its progeny also follow the same trend as it was recorded maximum in summer and minimum during winter (Wilkening, 1986; Virk and Sharma, 2000). 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 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 (Ramola et al., 1997).

4.2 Activity Concentrations of ^{226}Ra, ^{232}Th and ^{40}K

The average activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in soil samples at different sites of Bangalore Metropolitan were measured using HPGe detector, the obtained results are presented in Table 7. The average concentrations of ^{226}Ra, ^{232}Th and ^{40}K obtained from 15 samples collected at 5 zones of Bangalore city were found as 56.8 ± 33.8, 80.7 ± 19.9 and 683.1 ± 47.8 Bqkg^{-1} respectively. Whereas the observed range of activity concentrations were 23.7 to 111.6 Bqkg^{-1}, 50.6 to 98.7 Bqkg^{-1} and 302.1 to 1262.1 Bqkg^{-1} respectively. The concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the soil samples were less at city outskirts namely Nelamangala and Magadi, which were reported as 31.3 ± 0.6, 52.6 ± 0.9, 303.1 ± 6.1 Bqkg^{-1} and 16.9 ± 0.6, 57.5 ± 1.1 and 1073.0 ± 15.6 Bqkg^{-1} respectively. The concentrations of ^{226}Ra, ^{232}Th and ^{40}K observed in the present study are higher than the worldwide average of 32.0, 40.0 and 420.0 Bqkg^{-1} respectively (UNSCEAR, 2000).

Table 7. ^{226}Ra, ^{232}Th and ^{40}K concentration in different zones

Zone	Location	^{226}Ra	^{232}Th	^{40}K
		BqKg^{-1}		
1. Hebbal	Rajajinagar Vijayanagar Malleshwaram	45.9±0.9	50.6±1.1	350.8±7.4
2. Katriguppe	Banashankari Padhmanabhanagar Srinivasa Nagar	64.2±1.3	98.7±1.9	1139.1±19.6
3. Lalbagh	Majestic Jayanagar Sheshadripuram	111.6±1.2	95.4±1.5	1262.1±18.7
4. Kengeri	R R Nagar K S Town RV College	38.9±0.6	87.7±1.1	302.1±5.9
5. Mallathalli	Mallathalli	23.7±0.7	71.2±1.2	361.8±7.7

4.3 Concentration of ^{222}Rn in Ground Water

The average value of ^{222}Rn levels in the ground water of different locations are depicted in Table 8. The range and the mean value were found as 14.3 – 480.2 BqL^{-1} and 166.2 BqL^{-1} respectively. All the study locations have shown the higher concentration, than the permissible limit of 11.1 BqL^{-1} for drinking water. The EPA suggests that necessary action to be initiated to reduce the ^{222}Rn levels. The mean value of radon concentrations in the ground water is above the EPA's maximum contaminant level, but it is well below the mean value of 207 BqL^{-1} reported in the wells of southern part of Poland (Kusyk and Ciesla, 2002). It is interesting to note that the overall mean value obtained from this study is about two fold greater than the mean value of 87 BqL^{-1} reported from a study conducted in Bangalore rural and urban district. The average value of the radon concentration in ground waters of Bangalore city with a population density of 2978.6 persons per sq km is much higher than the concentration in Bangalore rural district with a population density of 322.9 persons per sq

km. The correlation between $^{226}Ra/^{222}Rn$ and $^{232}Th/^{220}Rn$ in the study locations were found to be 0.97 and 0.68 respectively, where as the correlation between ^{222}Rn in water and in air were found as 0.83.

Table 8. ^{222}Rn concentrations in ground waters of Bangalore city

Zone	Location	^{222}Rn (BqL^{-1})	^{222}Rn (BqL^{-1})
1. Hebbal	Rajajinagar	25.3 ± 0.04	
	Vijayanagar	58.2 ± 0.06	57.5 ± 0.06
	Malleshwaram	89.4 ± 0.08	
2. Katriguppe	Banashankari	54.1 ± 0.08	
	Padhmanabhanagar	247.6 ± 1.20	2227.3 ± 0.9
	Srinivasanagar	380.3 ± 1.20	
3. Lalbagh	Majestic	480.2 ± 0.06	
	Jayanagar	350.5 ± 1.40	430.5 ± 0.75
	Sheshadripuram	460.8 ± 0.80	
4. Kengeri	R R Nagar	90.5 ± 0.08	
	K S Town	14.3 ± 0.03	95.2 ± 0.30
	RV College	180.9 ± 0.80	
5. Mallathalli	Mallathalli	20.8 ± 0.04	
	Nagarbhavai	15.8 ± 0.03	20.2 ±0.04
	Jnanabharathi	23.9 ± 0.04	

4.4 Radiation Dose

The absorbed dose rates in air were calculated from the concentrations of ^{226}Ra, ^{232}Th and ^{40}K at different zones of Bangalore city using the following relation (UNSCEAR, 1998):

$$D = [(0.427 \times A_{Ra}) + (0.666 \times A_{Th}) + (0.043 \times A_K)] \text{ nGy h}^{-1}$$

The absorbed dose and effective doses to the general public are presented in the Table 9. The absorbed dose rates were found to vary in the range of 68.38 - 165.46 nGyh^{-1} with a mean value of 107.42 ± 43.7 nGyh^{-1}. The mean value is about two times higher than the global average value of 55 nGyh^{-1} (UNSCEAR, 1988). The effective dose to the general public is found to vary in the range of 83.90 – 203.02 µSvy^{-1} with a mean value of 131.80 ± 53.66 µSvy^{-1}. The people residing in the areas of Majestic, Jayanagar and Sheshadripuram belonging to zone – 3 receive higher doses compared to other residents of Bangalore city. Many studies have revealed that the granites, pegmatites and other acidic rocks are generally rich in ^{238}U compared to other rocks (Mishra and Sadasivan, 1971). The ^{226}Ra being the daughter of ^{238}U was therefore rich in the areas having granitic geology (Dillon, 1991; Otwama, 1998). Lalbagh is having a granitic bed and hence, the areas around Lalbagh have higher concentrations of ^{238}U and ^{226}Ra. The dose rates due to ^{222}Rn, ^{220}Rn and their progeny were found to vary from 0.76 to 1.26 mSvy^{-1} however the average dose rates for the environment of Bangalore due to ^{222}Rn, ^{220}Rn and their progeny were 1.2 ± 0.06 mSvy^{-1}.

Table 9. Radiation dose to the population of Bangalore city

Zones	Gamma dose		Dose from dissolved radon (μSvy^{-1})			Inhalation dose due to ^{222}Rn, ^{220}Rn and their progeny ($mSvy^{-1}$)
	Absorbed dose $nGy\ h^{-1}$	Effective dose μSvy^{-1}	Lung	Stomach	Effective dose	
Zone -1 Hebbal	68.38 ± 1.43	83.91 ± 1.76	161.0	302.02	463.31	0.90 ± 0.04
Zone-2 Katriguppe	142.13 ± 2.66	174.39 ± 3.27	635.73	1192.55	1829.40	1.20 ± 0.06
Zone-3 Lalbagh	165.46 ± 2.31	203.02 ± 2.84	1203.86	2258.27	3464.24	1.26 ± 0.06
Zone-4 Kengeri	88.00 ± 1.24	107.99 ± 1.52	266.34	499.61	766.42	1.00 ± 0.05
Zone -5 Mallathalli	73.09 ± 1.42	89.69 ± 1.75	56.54	106.06	162.70	0.76 ± 0.03

4.5 Flooring Wise Variations and Dose Rates

Wide ranges of concentrations were observed in dwellings of different floorings. The concentrations of ^{222}Rn and ^{220}Rn in mosaic floorings, stone floorings, red oxide floorings, concrete floorings and granite floorings were ranged from 4.50 to 30.99 and 12.28 to 37.84, 14.32 to 40.35 and 17.54 to 46.78, 13.88 to 50.29 and 19.30 to 57.89, 22.81 to 76.02 and 29.82 to 82.71, 36.84 to 87.33 and 39.18 to 100.00 Bqm^{-3} respectively. Whereas the geometric mean concentrations of ^{222}Rn and ^{220}Rn were 11.89 and 18.15, 20.83 and 25.27, 26.92 and 33.14, 40.42 and 49.47, 62.85 and 80.44 Bqm^{-3} respectively with the median values 10.76 and 16.66, 18.71 and 23.10, 26.30 and 31.39, 38.01 and 45.69, 62.86 and 85.01 Bqm^{-3} respectively. The mean concentrations of ^{222}Rn and ^{220}Rn levels in different type of floorings are depicted in Figure 5(a). Higher concentrations were observed in granite flooring houses and lower in mosaic flooring. Granite is rich of radium and it may be the reason for higher concentration of radon in granite flooring houses. The materials used for construction of buildings are sufficiently porous and allow radon to enter into the indoor atmosphere (Gaso et al*.,* 2005). Granite samples show higher radon exhalation rate than mosaic. There is a positive correlation between radium content of granite with radon exhalation and its concentration (Al-Jarallah, 2001).

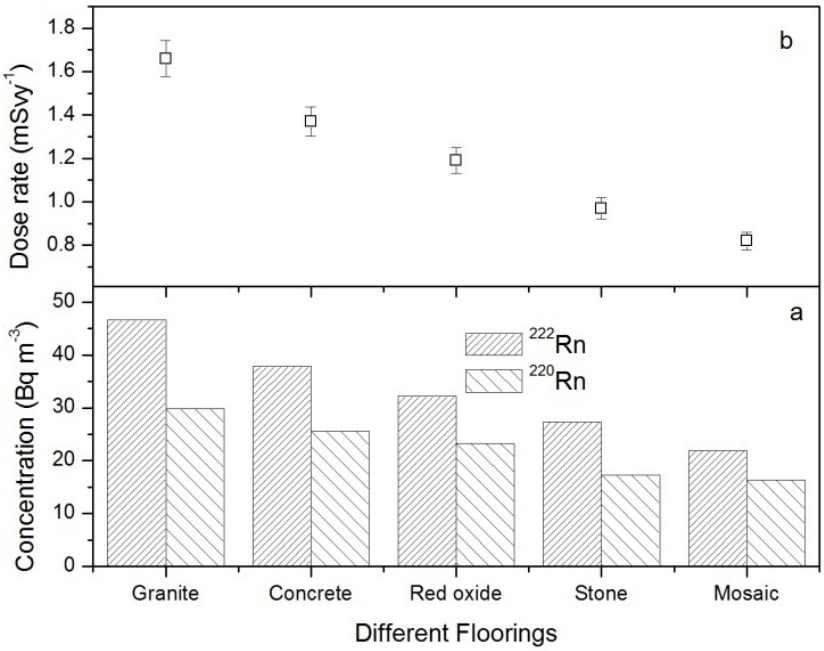

Fig. 5. Floor wise ^{222}Rn, ^{220}Rn and dose rates

The variations of dose rates in different floorings are shown in Fig. 5(b). The elevated dose levels were observed in the granite floorings and the lower levels in mosaic floorings. Correlation between ^{222}Rn, ^{220}Rn and their progeny levels were analyzed and a positive correlation of 0.98 between ^{222}Rn and its progeny and 0.81 between ^{220}Rn and its progeny were observed. The lower correlation might be due to the fact that many physical and meteorological factors affect the variation of the radon progeny in indoor as well as outdoor. Indoor and outdoor pressure difference, wind speed, wind direction and aerosol concentration in the air are main factors in this respect (Sahota et al., 2005).

4.6 Wall Wise Variations and Dose Rates

Broad variations of concentrations were observed in dwellings of different walls. The concentrations of ^{222}Rn and ^{220}Rn in concrete wall, cement wall, brick wall and mud wall were ranged from 12.87 to 22.56 and 14.46 to 33.92, 5.82 to 16.96 and 11.7 to 18.71 and 17.54 to 35.67 and 22.81 to 44.34 and 23.98 to 57.89 and 29.82 to 99.42 Bqm^{-3} respectively. Whereas the geometric mean concentrations of ^{222}Rn and ^{220}Rn were 16.35 and 21.76, 9.43 and 15.13, 23.08 and 29.97, 33.07 and 46.68 Bqm^{-3} respectively with the median values 16.10 and 19.32, 7.9 and 15.20, 20.47 and 24.56, 27.47 and 39.76 Bqm^{-3} respectively. The mean concentration of ^{222}Rn and ^{220}Rn levels in different walls are portrayed in Figure 6(a) and the respective dose rates in Figure 6(b). Higher concentrations and dose rates were observed in mud wall houses and lower in concrete walls. Concentrations were found to vary from type of wall. The variation is may be due to the random distribution of radioactive rock species used ignorantly in the construction of houses (Kumar et al*.,* 1994). A correlation of 0.98 and 0.93 is observed between ^{222}Rn, ^{220}Rn and their progenies, Sreenath Reddy et al*.,* (2006) have reported the similar observation for the environment of Hyderabad, India. Further, the author states that the dwellings with mud floor exhibits relatively higher dose, this establishes the facts that sub surface soil are the predominating source of indoor ^{222}Rn, ^{220}Rn. The dose in the dwellings with mud walls recorded higher dose than other type of walls. Since the mud walls are constructed using local soil and it may contain higher ^{226}Ra and ^{232}Th content. Ramachandran et al*.,* (1989) and Folkerts et al*.,* (1984) in their studies have observed the strong correlation between radon activity and mass exhalation rate (0.9), which may be due to the radium content and porosity in the samples.

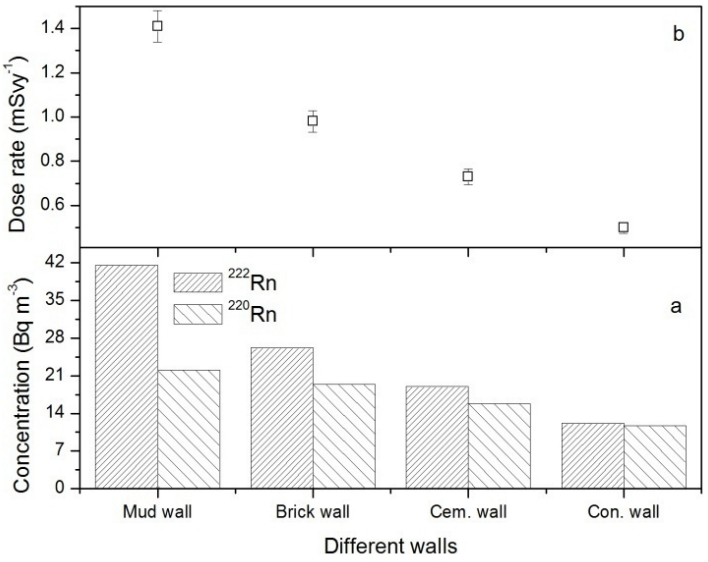

Fig. 6. Wall wise ^{222}Rn, ^{220}Rn and dose rates

4.7 Room Wise Variations and Dose Rates

Extensive variations in the concentrations were observed in different rooms of the dwellings. The concentrations of ^{222}Rn and ^{220}Rn in living room, kitchen, bed room and bath room were ranged from 5.85 to 17.54 and 13.3 to 27.49, 18.13 to 35.67 and 23.98 to 43.27, 24.98 to

52.05 and 29.86 to 58.48, 29.24 to 61.99 and 45.03 to 81.29 Bqm^{-3} respectively. Whereas the geometric mean concentrations of ^{222}Rn and ^{220}Rn were 11.42 and 21.45, 25.30 and 32.26, 34.10 and 42.63, 44.75 and 62.66 Bqm^{-3} respectively with the median values 10.23 and 21.63, 25.18 and 30.07, 30.65 and 40.06, 45.98 and 65.93 respectively. Annual average values of indoor ^{222}Rn and ^{220}Rn concentrations in different rooms of houses are depicted in Figure 7(a). Higher concentrations were observed in bath room, bed room and lower in living rooms. The figure trend reveals the soaring concentration in bathroom compared to the other rooms of the houses. Bed rooms might be expected to be least ventilated, on the average based upon limited use patterns and bath rooms may receive some additional ^{222}Rn due to ^{222}Rn dissolved in water (Sathish et al*.,* 2006). ^{222}Rn is shown to be released in spray from faucets or shower fixture (Gessel and Prichard, 1980). Air in living rooms on the other hand is most readily diluted due to outdoor air blow. Variations of dose rate in different rooms of the houses are shown in Fig. 7(b). Higher dose rates were observed in bed room and bath rooms. Correlations between ^{222}Rn, ^{220}Rn and their progenies have shown the linear variations with the regression coefficient 0.74 and 0.94 respectively.

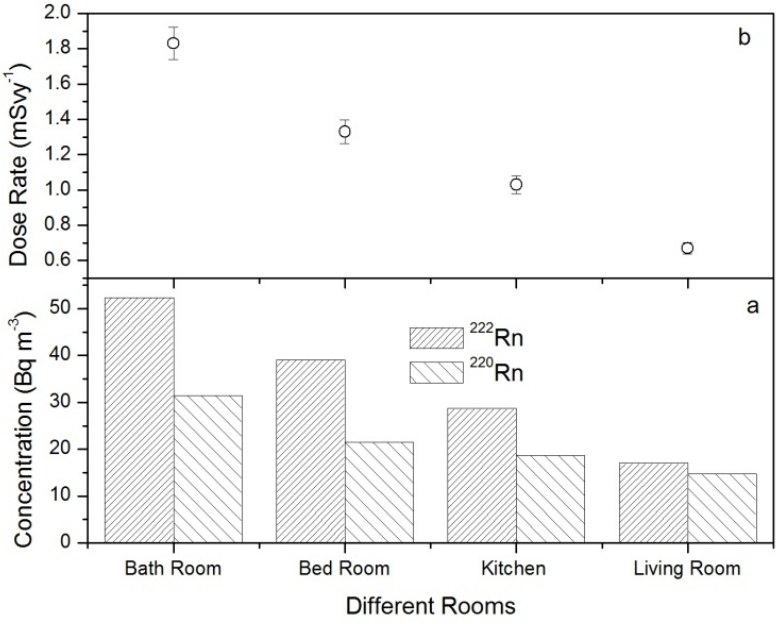

Fig. 7. Room wise ^{222}Rn, ^{220}Rn and dose rates

The frequency distribution revealed the higher concentrations in least ventilated rooms (bath rooms) and lower in well ventilated rooms (living rooms).

4.8 Season Wise Variations and Dose Rates

Wide-spread concentrations on different seasons of calendar year were observed. The concentrations of ^{222}Rn and ^{220}Rn during winter, summer, radon and autumn seasons were ranged from 36.84 to 100.00 and 12.28 to 23.39, 13.88 to 50.29 and 4.05 to 11.7, 19.30 to 76.02 and 7.02 to 14.04, 24.56 to 85.81 and 8.19 to 18.13 Bqm^{-3} respectively. Whereas the geometric mean concentrations of ^{222}Rn and ^{220}Rn during winter, summer, radon and autumn seasons were 76.97 and 18.02, 26.58 and 6.02, 40.49 and 10.40, 51.55 and 13.35 respectively with the median values 17.54 and 85.08, 5.85 and 23.68, 10.53 and 40.64,

13.37 and 50.58 Bqm^{-3} respectively. Mean values of the ^{222}Rn and ^{220}Rn concentrations of all the studied locations during different seasons are shown in Fig. 8(a) and the annual effective dose rates in Fig. 8(b).

Concentration shows apparent seasonal variations. Concentration is found to be maximum during the winter and minimum in summer months as observed elsewhere (Virk and Sharma, 2000). Radon levels in closed environment are also found to be affected both by the degree of exchange with outdoor air as measured by the ventilation rate, and also by the changes in entry of excess of radon from the soil and rocks underneath the ground. With possible temperature variations, majority of the houses are well ventilated in summer season, and the indoor radon concentrations might be expected to be lower for summer than in winter season (Ramachandran et al., 2001). Higher concentrations observed during winter season is may be due to the radioactive gases are trapped near to the surface because of temperature inversions. In summer, the higher rate of vertical mixing and dispersions lifts the aerosols to higher altitudes resulting in a decrease in the concentration near the ground level air (Sesana et al., 2003). Magalhaes et al., (2003) have observed a two order of magnitude of variability, with a maximum of 50 Bqm^{-3} in winter and a minimum of 0.5 Bqm^{-3} in summer months. In addition radon exhalation rate also decreases during monsoon as soil pores get filled by water and hence, resulting in lower concentration of ^{222}Rn and ^{220}Rn (Nagaraja et al., 2003a).

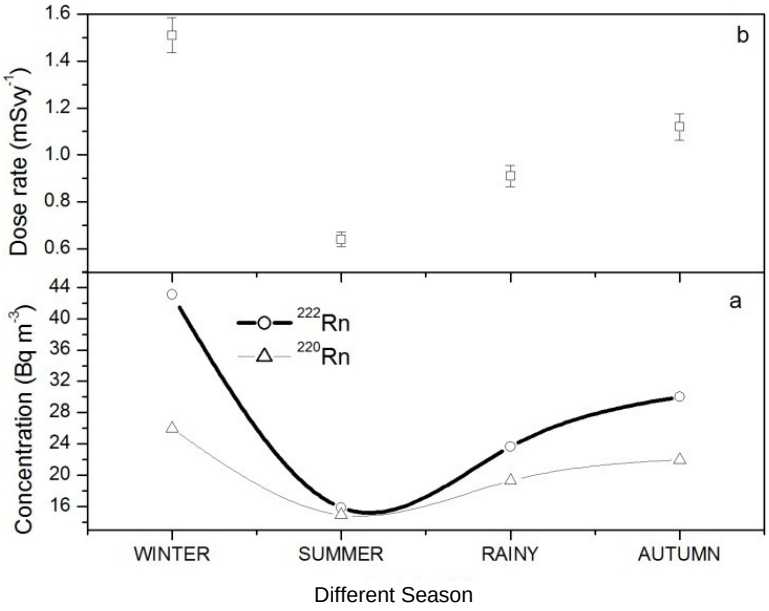

Fig. 8. Season wise ^{222}Rn, ^{220}Rn and dose rates

The correlations between ^{222}Rn, ^{220}Rn and their daughter products showed a good correlation of 0.97 and 0.77 between ^{222}Rn and its progeny and ^{220}Rn and its progeny respectively. Looking at the seasonal correlation coefficients, wind speed may play a significant role for radon variations in all seasons and horizontal advection is, in principle, as important as vertical mixing for the dilution of surface atmospheric radon (Piero et al., 2009).

Correlation between ^{222}Rn and ^{220}Rn concentrations including the errors as weighted average is depicted in Fig. 9.

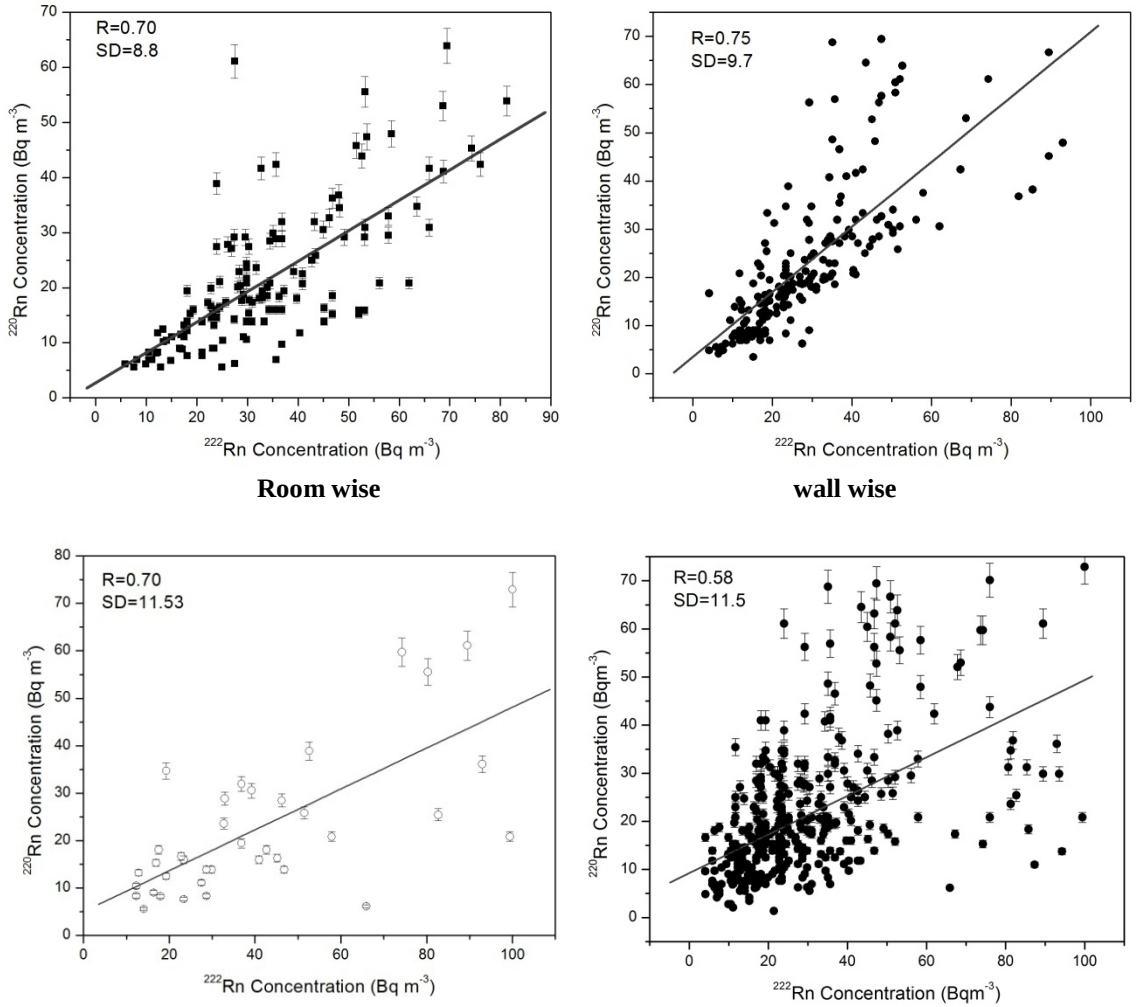

Fig. 9. Correlation between ^{222}Rn and ^{220}Rn

The correlation coefficient for ^{222}Rn and ^{220}Rn in room wise, wall wise, flooring wise and season wise were 0.70, 0.75, 0.70 and 0.58 respectively. Higher correlation is observed in wall wise variations and the lower in season wise variations. Weak correlation may reflect differences in the interior and surface structures of the grains and pore spaces (Hassan et al., 2011). In addition to parent nuclide concentrations and grain structure, the emanation coefficient may influence exhalation rates. Exhalation rates may be low even with high concentrations of the parent nuclides are present if the emanation coefficient of the material has a low value (Hassan et al., 2011).

4.9 Room Volume Wise Variations and Dose Rates

Rooms were classified broadly 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. At least 7 rooms were selected for each dimension and this is covered for ten different locations. Hence, the total number of rooms covered in each volume is 42 rooms of different dwellings. 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. Volumetric variations of ^{222}Rn, ^{220}Rn, their progeny and dose rates were measured in 42 houses for a period of three years and the obtained data are shown in Fig. 10(a). Higher concentrations were observed in lower volume room than in the higher volume room. The concentrations in a dwelling of volume 30-310m^3 ranged from 4 to 93 Bqm^{-3}.

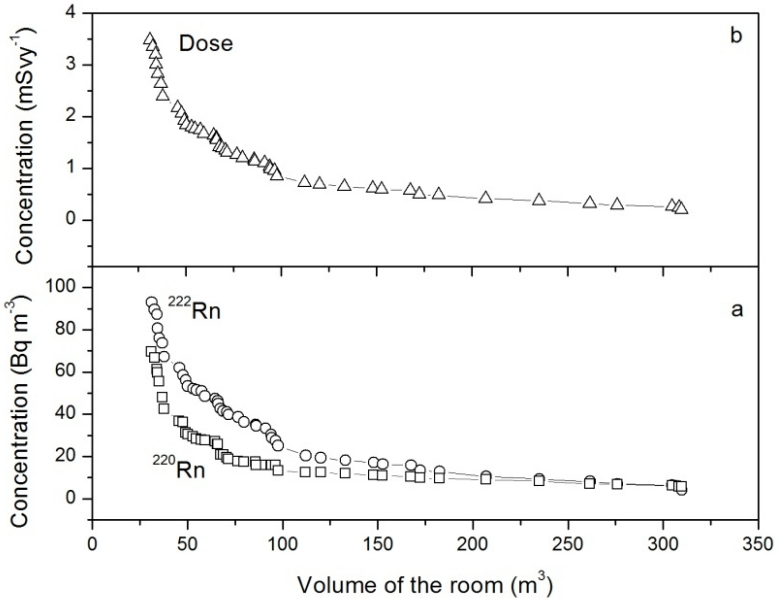

Fig. 10. Room volume wise ^{222}Rn, ^{220}Rn and dose rate

This result obviously indicates that though the observations have been made almost for similar type of constructions, ventilation and lifetime of the houses, but as the volume of the room increases the concentrations drops exponentially and it becomes almost constant above the house of volume 150 m^3. The regression coefficients for the exponential drop for ^{222}Rn and ^{220}Rn are 0.99 and 0.98 respectively. The variations of dose rates are shown in

Fig. 10(b). The present work reveals that the dwellers of lower volume houses will expose themselves to the higher dose rates and is 4.4 times of the dose received in higher volume houses. Correlations between ^{222}Rn, ^{220}Rn and their progenies have shown the positive correlation of 0.79 and 0.96 between ^{222}Rn, ^{220}Rn and their progenies respectively. Frequency distribution of ^{222}Rn and ^{220}Rn reflected the higher concentrations in lower volume rooms and lower concentration in higher volume rooms.

The natural radioactivity contents of soil samples of Bangalore region reported by earlier studies are 15.2, 16.9 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 33.0, 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, and 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). The frequency distribution of ^{222}Rn and ^{220}Rn levels in dwellings is presented in Figs. 11 and 12.

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. A correlation with dwellings volume and gas concentrations is attempted in this study which is explained below.

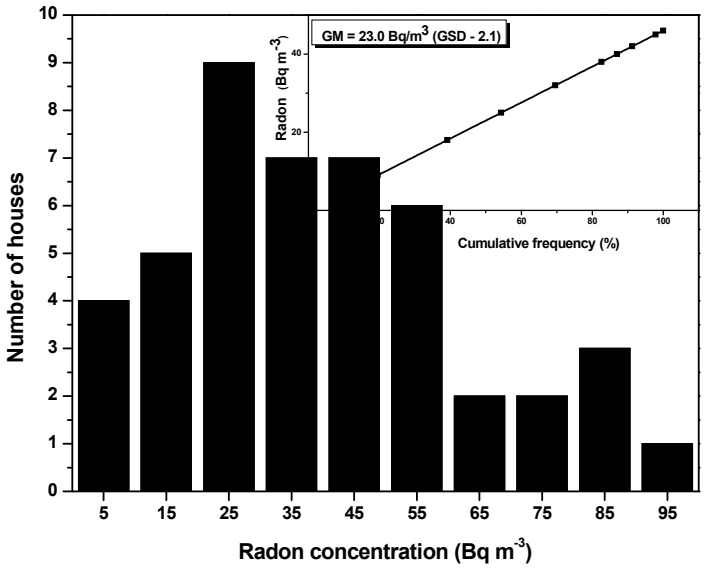

Fig. 11. ^{222}Rn levels in dwellings

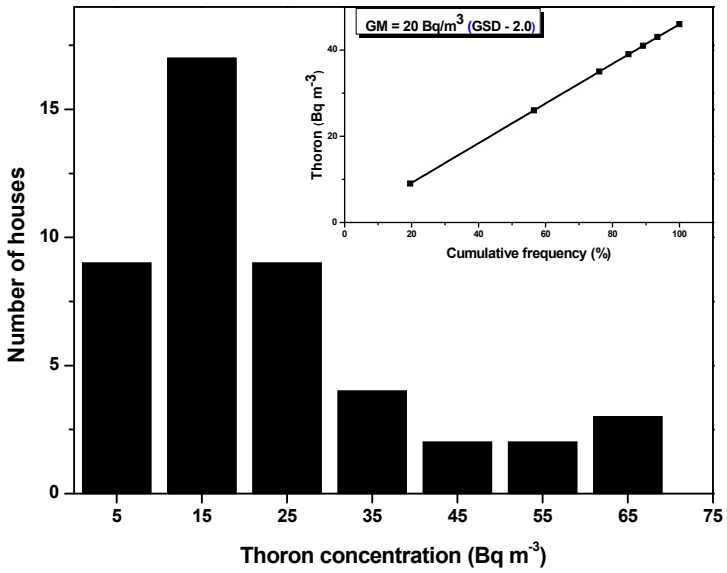

Fig. 12. ^{220}Rn levels in dwellings

Inhalation dose is computed using UNSCEAR (2000) dose conversion factors. Inhalation dose calculated from the total results varied from 0.27 to 4.45 mSvy^{-1} with a geometric mean of 1.34 mSvy^{-1} (GSD 2.1).

Table 10 shows 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.

Table 10. ^{222}Rn and ^{220}Rn levels in category of rooms

Volume of room (m^3)	^{222}Rn (Bqm^{-3}) Range		AM ± SD	^{220}Rn (Bqm^{-3}) Range		AM ± 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

A plot of ^{222}Rn and ^{220}Rn concentrations is made against room volume in Fig. 13. It is seen from the figure that 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.

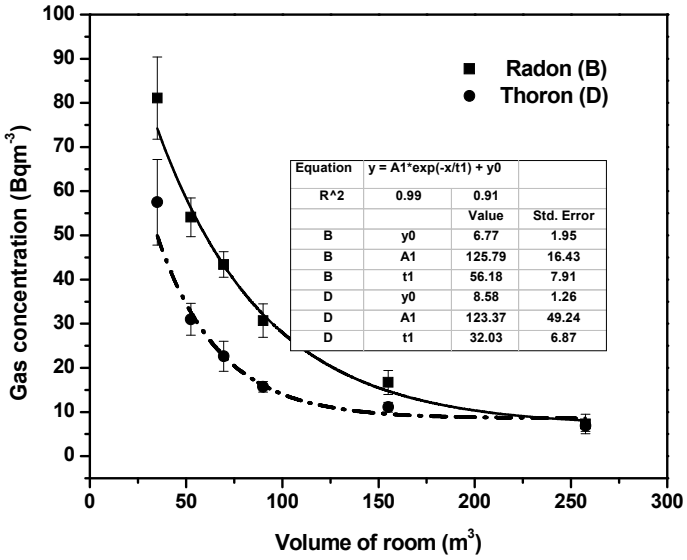

Fig. 13. Gas concentrations with volume of dwellings

A plot of volume against ratio of area to volume (A/V) is shown in Fig. 14. It could be seen from the plot that the A/V ratio also showed an exponential fit in decreasing order with a correlation coefficient 0.99. It is interesting to note that the fitting parameter *t* in Fig. 14 is 61.4 which closely match with effective decay value for radon (56.2) in Fig. 13. This clearly indicates that the radon values inside dwellings covered under the study is predominantly depended on A/V ratio inside the houses.

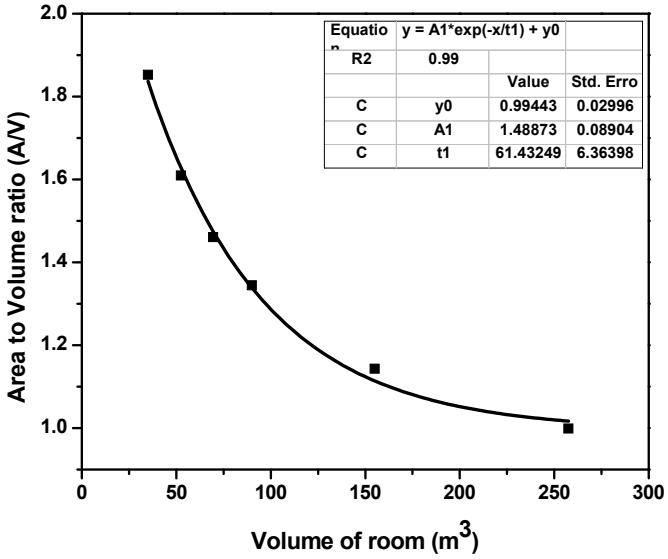

Fig. 14. Correlation between A/V ratio and volume of dwellings

Effect of ventilation seems negligible when the measurement was carried out for longer 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.

Fig. 15 shows the variation of concentration with inverse volume. It is interesting to note that the variation of concentration against change in the volume of the room leads to a straight line.

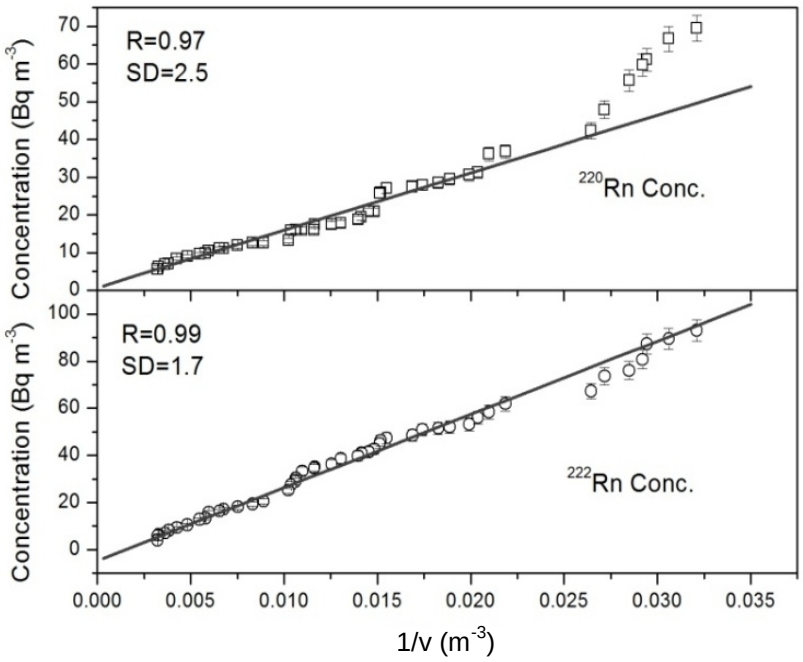

Fig. 15. Behavior of radon with inverse volume of room

The correlation between concentration and volume is more than 90% in all cases and envisages that there is a direct dependence of concentration with volume. The annual effective inhalation dose due to ^{222}Rn, ^{220}Rn and their progenies from the study ranged between 0.2 – 4.4 with an arithmetic mean of 1.7 ± 1.1 mSvy^{-1}. The concentration (Nazaroff, 1988) *C* of ^{222}Rn/^{220}Rn may be written as: $C = \frac{JA}{V(\lambda_0 + \lambda_v)}$ where, *J* is the area averaged emission flux, *A* and *V* are the surface area and the volume of the room respectively, λ_0 is the radioactive decay constant and λ_v is the air-exchange rate. For ^{222}Rn, air exchange rates are of the order of 0.1-1 h^{-1}, whereas the decay constant is 0.0076 h^{-1} then $\lambda_v >> \lambda_0$ by neglecting the decay of ^{222}Rn. Therefore, for all the houses in a particular location, *J* is approximately same and different combination of λ_v, *A* and *V* will result in different concentrations. However, for ^{220}Rn, the decay constant is 45 h^{-1} whereas air exchange rates are 0.1-1 h^{-1}, $\lambda_0 >> \lambda_v$ by neglecting the ventilation. Then the concentration will depend upon *A/V*. As a first effort, an attempt is made to interpret the data with respect the volume of the room and its fitting parameters.

5. CONCLUSIONS

Depending on the experimental studies conducted during the period 2007 to 2011, subsequent conclusions are drawn.

The estimated concentration of ^{222}Rn and ^{220}Rn for the environment of Bangalore, India varied from 17.2 ± 1.2 to 85.8 ± 2.3 Bqm^{-3} and 8.3 ± 1.2 to 38.3 ± 5.4 Bqm^{-3} with a mean of 32.2 ± 1.6 and 21.4 ± 1.0 Bqm^{-3}, respectively. The lower concentration of ^{222}Rn is observed in Rajajinagar and higher in Government Science College of Gandhinagara. Whereas, ^{220}Rn is lower in Vijayanagar and higher in Government Science College. The investigation shows no significant radiological risks for the inhabitants and is well within the limits prescribed by UNSCEAR.

Higher values of ^{222}Rn and ^{220}Rn are observed for lower volume house, granite flooring house, bath room, mud wall houses and during winter season. Among these the inhabitants of lower volume rooms, and granite flooring house are exposed to higher dose. It is alarming that the dwellers of lower volume and granite floorings receive relatively a higher dose rate and the result shows significant radiological risk. Hence, it is recommended that the lower volume houses should have good ventilation and the dwellings should be granite free flooring, to reduce the effective dose rate.

Volumetric variations of indoor ^{222}Rn, ^{220}Rn and their progeny levels reveals higher concentrations in lower volume room compared to higher volume at the monitored locations. For this environment, the levels of indoor ^{222}Rn and ^{220}Rn are higher than the acceptable values for the population prescribed by UNSCEAR. Hence, the lower volume room should be well ventilated to reduce the health effects. Further, the frequency distributions of ^{222}Rn and ^{220}Rn levels in dwellings reveal the higher concentrations in lower volume houses and lower in higher volume houses.

More detailed studies on the evaluation of public exposure from the natural radiation; particularly the exposure from ^{220}Rn and their progeny should be planned and performed in this region and in the country.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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