INDOOR $^{222}$Rn AND $^{220}$Rn CONCENTRATIONS AND DOSES IN BANGALORE, INDIA

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$^{222}$Rn and $^{220}$Rn levels have been measured using passive detector technique by employing time integrated solid-state nuclear track detector-based dosimeters in various types of houses at 10 different locations in and around Bangalore Metropolitan, India. The measured geometric mean concentration values of $^{222}$Rn and $^{220}$Rn levels in 200 dwellings of different types of construction were found to be $32.2 \pm 1.6$ and $21.4 \pm 1.0$ Bq m$^{-3}$, respectively. The dose rate received by the population of Bangalore ranged between 0.2 and 3.5 mSv y$^{-1}$ with an average and the geometric mean of $1.14 \pm 0.05$ and $1.06$ mSv y$^{-1}$, respectively. Overall, the result does not show much significant radiological risk for the inhabitants and the $^{222}$Rn levels are well within the limits of global average concentration of 40 Bq m$^{-3}$. However, the $^{220}$Rn levels observed were found to be higher than the global average of 10 Bq m$^{-3}$.

INTRODUCTION

Radon is the important natural source and contributes nearly 50 % of total effective dose received by the population from all natural sources(1). Radon emanates to a certain degree from all types of soil and rocks. The radiological importance of radon does not lounge on the concentration of radon gas itself, but on its short-lived decay progenies such as polonium, bismuth and lead. During breathing, radon comes out while exhale, but the short-lived progenies being material particles gets deposited onto the lungs, tracks of breathing etc(2). Factors influencing the diffusion of radon from soil into the air are: existence of $^{238}$U and $^{226}$Ra in soil and rock, emanation capacity of the ground, porosity of the soil and/or rock, pressure gradient at the interface, soil moisture and water saturation grade of the medium(3). The concentration of indoor radon depends on ventilation rate of dwellings. It is important to note that even though reduced ventilation rate aids to enhance the concentration of radon and its daughters in air. Subba Ramu et al.(4) carried a survey by making use of solid-state nuclear track detector (SSNTD) technique for indoor levels of radon daughters in some higher background areas in India, and have reported the value of $^{222}$Rn concentration in the range from 35.3 to 86.0 Bq m$^{-3}$ and with a geometric mean of 9.4 mWL (milli working level) concentration of the potential alpha energy exposure level from radon daughters with an annual effective dose equivalent value of 3.1 mSv. They have also reported that, the dose equivalent estimated for the studied locations were 2.4 times higher than the annual back ground value of 1.3 mSv y$^{-1}$ given by Environmental Protection Agency. The track-etch detector technique is being recognised as the most reliable for integrated and long-term measurement of indoor radon concentrations(5). As a part of the measurements initiated in India for a nationwide mapping, the measurement for $^{222}$Rn and $^{220}$Rn concentrations were instigated by using plastic track detectors in and around Bangalore metropolitan and results are discussed in detail. The data are obtained for a period of 3 y since 2007, covering 200 dwellings for all the four seasons of the calendar year. The work presented is first of its kind for the environment of Bangalore and carry interesting results.

Area of present study

The area of present study is Bangalore metropolitan, India and is shown as locative map in Figure 1. The geology of this part forms predominantly a granite terrain with numerous varieties of granites, granitic gneiss, pegmatite and charnockites. The rocks around the study area are closepet granites(6), which are younger than the peninsular gneiss, made up of several types of potassium granites with variable colour, 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 of 15–25 km. The soil radioactivity for this region has been reported in earlier studies(7). The radioactivity
reported for the building materials collected from this region were higher compared with soil radioactivity\(^{(8)}\). However, major quantity of bricks used for the construction of buildings are brought from places from the outskirts of city, Nelamangala, Magadi etc., and a small portion from Hoskote, Ramanagara and Channapatana of radial distance 60 km. The average activity concentrations of \(^{226}\text{Ra}\), \(^{232}\text{Th}\) and \(^{40}\text{K}\) in the soil samples of Nelamangala and Magadi were reported as \(31.3 \pm 0.6\), \(52.6 \pm 0.9\) and \(303.1 \pm 6.1\) Bq kg\(^{-1}\) and \(16.9 \pm 0.6\), \(57.5 \pm 1.1\) and \(1073.0 \pm 15.6\) Bq kg\(^{-1}\), respectively\(^{(9)}\). The occurrence of radon in the groundwater samples of the study area\(^{(10)}\) is ranging from 55.9 to 1189.3 Bq l\(^{-1}\), with concentration exceeding the permissible limit of 11.8 Bq l\(^{-1}\) and at some places it is as high as hundred times\(^{(10)}\). All the monitored houses were on ground floor. About 20 houses of different construction types were chosen each in all the monitored locations.

**MATERIALS AND METHODS**

SSNTD-based dosemeters are being used to obtain the time-integrated measurements\(^{(11)}\) of indoor \(^{222}\text{Rn}\), \(^{220}\text{Rn}\), their progenies and dose rates in dwellings. The dosemeter system has two cylindrical cups of equal volumes of radius 3.1 cm and height 4.1 cm with the inner volume of 124 cubic centimetres as shown in Figure 2. Dimensions of the dosemeters are 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. The dosemeter is designed to discriminate \(^{222}\text{Rn}\) and \(^{220}\text{Rn}\) in the mixed field situations, where both the gases are present like in monazite rich deposit areas. Track detector used in the dosemeter is 12-μm thick pelliculable cellulose nitrate films, commercially called LR-115 films, made by Kodak Pathe. LR-115 Type II films were suitable for spark counting and spark counter was used for counting the alpha tracks. These films of size 3 cm × 3 cm were affixed at the bottom of each cup as well as on the outer surface of the dosemeter. The exposure of the detector inside the cup is termed as the cup mode and other one exposed openly is termed as the bare mode. One of the cups has its entry covered with a glass fibre filter paper of thickness 0.56 mm that permeates both \(^{222}\text{Rn}\) and \(^{220}\text{Rn}\)
gases into the cup and is called filter cup. The other cup covered with a semi-permeable membrane sandwiched between two glass fibre filter papers called membrane cup\(^{(12)}\). The semi-permeable membranes have a diffusion coefficient for \(^{222}\)Rn gas in the range of \(10^{-2} \text{ to } 10^{-7} \text{ cm}^2 \text{ s}^{-1}\) that permeates >95% of the \(^{222}\)Rn gas, while it suppress >99% entry of \(^{220}\)Rn gas\(^{(13)}\). Thus, the SSNTD films inside the membrane cup register tracks that attributes to \(^{222}\)Rn gas alone, while the filter film records tracks due to both \(^{222}\)Rn and \(^{220}\)Rn gases. The third film exposed in the bare mode registers alpha tracks produced by both the gases and their alpha-emitting progeny. Eappen and Mayya\(^{(14)}\) reported that LR-115 (12 \(\mu\)m) film does not register tracks from deposited activity because \(E_{\text{max}}\) for LR-115 is 4 MeV and all the progeny isotopes of \(^{222}\)Rn, \(^{220}\)Rn emit alphas with energies >5 MeV.

There are two energy limits of alpha particles, \(E_{\text{max}}\) and \(E_{\text{min}}\), striking the surface of SSNTD films above and below no etchable tracks were formed. Alpha particles passing through a medium lose its energy along the path; say \(dE/dt\) and the gradient will be minimum, if alpha particles have high incident energy. The energy imparted to the medium will be minimum along the path, resulting in less damage to a medium along the path of alpha particles. Thus, it does not cause an etchable track along the path of the alpha particle. This incident energy is called \(E_{\text{max}}\) energy. Thus, uncertainty due to deposited activity on film surface is removed for the bare detector estimate, a reason to choose LR-115 (12 \(\mu\)m) film for bare card estimate.

The dosemeters were kept at a height of \(\sim 1.5 \text{ m}\) from the ground, considering minimal disturbances to the occupants. A single dosemeter per house is deployed for a period of 90 d to cover individual seasons of the calendar year. After exposure, the dosemeters were retrieved, and SSNTD films were removed from the dosemeter for etching. The films were then etched in 10% NaOH solution at 60°C for 90 min\(^{(14)}\).

The tracks recorded on LR-115 films were counted using a spark counter\(^{(15, 16)}\). Tracks are converted to gas concentrations using relations given below:

\[
C_{\text{R}} (\text{Bq m}^{-3}) = \frac{T_m}{d \times S_m} \quad (1)
\]

\[
C_{\text{T}} (\text{Bq m}^{-3}) = \frac{T_f - d \times C_{\text{R}} \times S_{\text{rf}}}{d \times S_{\text{tf}}} \quad (2)
\]

where \(T_m\) is the track density of the film in membrane compartment (Tr cm\(^{-2}\)), \(d\) is the period of exposure in number of days (d), \(S_m\) refers to the sensitivity factor of membrane compartment (Tr cm\(^{-2}\)/Bq dm\(^{-3}\)), \(T_f\) is the track density of the film in filter compartment (Tr cm\(^{-2}\)), \(S_{\text{rf}}\) and \(S_{\text{tf}}\) are the sensitivity factor for \(^{222}\)Rn and \(^{220}\)Rn in filter compartment (Tr cm\(^{-2}\)/Bq dm\(^{-3}\)) and, \(C_{\text{R}}\) and \(C_{\text{T}}\) are the concentrations (Bq m\(^{-3}\)) of \(^{222}\)Rn and \(^{220}\)Rn, respectively.

The authors followed the protocols given by Eappen and Mayya\(^{(14)}\) for processing the exposed films; hence sensitivity factors \(S_m\) and \(S_{\text{rf}}\) are taken from their work for computing the gas concentrations. The progeny concentrations in terms of WL can be written as

\[
R_{\text{m}}(\text{mWL}) = \frac{C_{\text{R}} \times F_{\text{R}}}{3.7} \quad (3)
\]

\[
R_{\text{T}}(\text{mWL}) = \frac{C_{\text{T}} \times F_{\text{T}}}{0.275} \quad (4)
\]

where \(F_{\text{R}}\) and \(F_{\text{T}}\) are equilibrium factors for \(^{222}\)Rn and \(^{220}\)Rn, respectively and can be equated with
progeny fractions of respective gases as shown in the following equations:

\[ F_R = 0.104F_{RA} + 0.514F_{RB} + 0.37F_{RC} \]  
\[ F_T = 0.91F_{TB} + 0.09F_{TC} \]

where \( F_{RA}, F_{RB}, F_{RC}, F_{TB} \) and \( F_{TC} \) are activity fractions of \(^{210}\text{Po}, ^{214}\text{Pb}, ^{214}\text{Bi}, ^{212}\text{Pb} \) and \(^{212}\text{Bi} \), respectively. Mayya et al.\(^{(17)}\) have obtained these activity fractions through ventilation parameters, applying a root finding method using the deposition velocities for attached and unattached fractions of the progeny nuclides. The calibrations of the dosimetric system are being carried out in a calibration system and are discussed in detail elsewhere\(^{(14)}\). In the present study, the calibration factors and the detection limits were followed as discussed elsewhere\(^{(14,17)}\).

Inhalation dose estimates

Absorbed dose rates to the critical cells of the respiratory tract due to \(^{222}\text{Rn}, ^{220}\text{Rn} \) and their progeny are estimated on the basis of aerosol characteristics, its size distribution, unattached fraction, breathing fraction, fractional deposition in the airways, mucous clearance rate and location of the target cells in the airways\(^{(18,19)}\). Lung dose distribution assessment carried out by different researchers for the years from 1956 to 2000 show a large variation in dose conversion factors\(^{(1,2)}\). The estimated dose conversion factors varied drastically based on the breathing rate as well as the target tissue mass. In the present study, the inhalation dose is computed using UNSCEAR\(^{(14)}\) equilibrium factors, and the values for \( F_R \) is 0.4 and \( F_T \) is 0.03. Indoor occupancy factor for the population is taken as 0.8, and the annual inhalation dose (mSv y\(^{-1}\)) is calculated using the following equation:

\[ D(\text{mSv y}^{-1}) = 0.8 \times 24 \times 365 \times [(0.17 + 9F_R)C_R + (0.11 + 40F_T)C_T] \times 10^{-6} \]

where 0.17 and 9 are the dose conversion factors for indoor \(^{222}\text{Rn} \) and its progeny concentration in terms of nSv Bq\(^{-1}\) h\(^{-1}\) m\(^{-3}\). 0.11 and 40 are the dose conversion factors for indoor \(^{220}\text{Rn} \) and its progeny in nSv Bq\(^{-1}\) h\(^{-1}\) m\(^{-3}\). Since the data in this study are not sufficient for deriving ventilation dependent \( F_{xx} \) factors, bare card results are not used in deriving \( F \) values. Such an exercise will be tried later after large number of measurements data are collected from future study. The inhalation dose is computed using UNSCEAR\(^{(14)}\) \( F \) values. The overall errors in the detector preparation, calibration and standardisation are estimated to be \( \sim 30\% \). The minimum detection limit of the dosimetric configuration used is estimated to be 7.5 Bq m\(^{-3}\) for 90 d exposure\(^{(14)}\).

RESULTS AND DISCUSSION

Area wise variations

About 200 dwellings in 10 different locations of Bangalore metropolitan, India were chosen on the basis of types of construction, age of the building, nature of walls and floorings, rooms and different volume of the dwellings to see the effective dose rates due to indoor \(^{222}\text{Rn}, ^{220}\text{Rn} \) and their progeny levels during different seasons of the year. Further, houses were categorised on the basis of ventilation which depends on number of windows, doors and usage pattern (such as closed, open, partially open/close) to identify them as poor (no or one-window), moderate (two-windows), good (three-windows), very good (four-windows) and excellent (five-windows) ventilated houses. The levels of \(^{222}\text{Rn}, ^{220}\text{Rn} \) and their short-lived progeny levels were observed simultaneously for a period of 3 y by covering a large area of Bangalore metropolitan. The measured average values of \(^{222}\text{Rn} \) and \(^{220}\text{Rn} \) found in the different locations during 2007–10 showed the lower concentrations of \(^{222}\text{Rn} \) at Rajajinagar and relatively higher concentrations at Government Science College of Gandhinagara and the lower and higher concentrations of \(^{220}\text{Rn} \) were observed at Vijayanagar and Government Science College of Gandhinagara, respectively. This is may be due to the activity concentrations of \(^{226}\text{Ra}, ^{232}\text{Th} \) and \(^{40}\text{K} \) in soil around the respective areas\(^{(9)}\). The observations made for Bangalore region were in the same range as reported elsewhere in India\(^{(7)}\).

The mean values of \(^{222}\text{Rn} \) and \(^{220}\text{Rn} \) with different ventilation condition are given in Table 1. Results show the concentration levels are little higher in poor ventilated houses than in excellent ventilated houses. Comparisons of indoor \(^{222}\text{Rn} \)

<table>
<thead>
<tr>
<th>Number of windows</th>
<th>Nature of ventilation</th>
<th>AM \pm SE</th>
<th>222Rn concentration (Bq m(^{-3}))</th>
<th>220Rn concentration (Bq m(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Excellent</td>
<td>7.9 \pm 0.8</td>
<td>9.4 \pm 0.9</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Very good</td>
<td>16.6 \pm 0.9</td>
<td>10.6 \pm 1.7</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Good</td>
<td>31.3 \pm 1.4</td>
<td>19.7 \pm 2.0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
<td>42.7 \pm 1.1</td>
<td>29.5 \pm 6.4</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Partial</td>
<td>54.0 \pm 1.5</td>
<td>33.9 \pm 7.5</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>Poor</td>
<td>81.0 \pm 3.5</td>
<td>38.6 \pm 6.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Arithmetic mean values of \(^{222}\text{Rn} \) and \(^{220}\text{Rn} \) with different ventilation condition.
concentration for different seasons are also made. The winter-to-summer ratio was found to be maximum, while the winter-to-autumn ratio was minimum. The higher values during winter season are mainly due to less ventilation factor. Indoor radon is influenced mainly by the ventilation condition of the dwellings. In most of the class rooms of the Government Science College, high $^{222}\text{Rn}$ concentration in summer seasons were recorded than in winter season. This observed anomaly may be due to the fact that the class rooms were closed for a longer duration in summer holidays (April to June). Further, the higher concentrations in Gandhinagar may be due to the higher activity concentrations$^9$ of $^{226}\text{Ra}$, $^{232}\text{Th}$ and higher concentrations of radon gas in ground water in the surrounding area$^{10}$. The winter to summer ratio in different locations were found to vary between 1.9 and 3.7, and this ratio is high compared with the ratio of winter to rainy and winter to autumn season. This again depends on ventilation condition of the dwellings. The concentrations of $^{222}\text{Rn}$ and its progeny also follow the same trend as it was recorded maximum in summer and minimum during winter season$^{20}$. To get a clear idea of the spatial variations, the observed values are compared with the surveys made in different areas; the range (minimum to maximum) values of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ are plotted in Figure 3.

Elevated levels of concentrations were seen in poor ventilated houses in all 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 were observed in Rajajinagar area. This may be due to the lower activity concentrations$^9$ of $^{226}\text{Ra}$ and lower radon concentration in ground water in surrounding area$^{10}$. However, the higher concentration may be due to the higher activity concentrations of $^{226}\text{Ra}$ and higher concentrations of radon in water in all monitored locations. Shiva Prasad et al$^9$ and Hunse et al$^{10}$ have reported the activity concentrations of $^{226}\text{Ra}$ in the surrounding area of Rajajinagar (Mallathalli) and Gandhinagara (Lalbagh) were $23.7 \pm 0.7$ and $111.6 \pm 1.2$ Bq kg$^{-1}$, respectively, whereas the activity concentrations of $^{232}\text{Th}$ in the surrounding areas of Vijayanagar (Mallasandra) and Gandhinagara (Lalbagh) were $29.5 \pm 0.9$ and $95.4 \pm 1.5$ Bq kg$^{-1}$. Levels of $^{222}\text{Rn}$ in water of Nagarbhavai (Vijayanagar), Rajajinagar and Lalbagh area were reported as $97.2 \pm 5.7$, $166.6 \pm 8.1$ and $887.7 \pm 34.1$ Bq l$^{-1}$, respectively.

The frequency distributions of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ are depicted in Figure 4, $\sim 60\%$ of indoor $^{222}\text{Rn}$ levels were found to vary between 20 and 39 Bq m$^{-3}$. Higher levels ($> 80$ Bq m$^{-3}$) were observed in 6% of the studied houses. Nearly 23% of buildings showed the concentrations of 50–79 Bq m$^{-3}$ and they were of 40-y-old dwellings, poorly constructed, with several cracks in foundation, walls and basic slabs, thorough which radon could easily enter into the rooms. About 85% of dwellings have shown that the $^{220}\text{Rn}$ concentrations were <30 Bq m$^{-3}$, and 15% of them had the concentrations >50 Bq m$^{-3}$. The estimated $^{222}\text{Rn}$ levels at different locations of India

![Figure 3. Area wise range of $^{222}\text{Rn}$ and $^{220}\text{Rn}$](http://rpd.oxfordjournals.org/)
varied from 6.4 to 95.4 Bq m$^{-3}$, with a geometric mean (GM) of 25.5 Bq m$^{-3}$ [geometric standard deviation (2.1)], whereas for $^{220}$Rn they were ranged between 3.5 and 42.8 Bq m$^{-3}$ with a GM of 12.2 Bq m$^{-3}$ (GSD 3.22) with the effective annual dose of 0.94 mSv y$^{-1}$. The observed values of $^{222}$Rn (17.2–85.8 Bq m$^{-3}$) and $^{220}$Rn (8.3–38.3 Bq m$^{-3}$) concentrations for the environment of Bangalore were found to be comparable with the observation made elsewhere in India$^{(8)}$. In general, radon concentrations were found to be higher in mud houses compared with cemented houses$^{(21)}$. Such houses on the ground floor are 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 the materials used$^{(22)}$.

**Seasonal variations and dose rates**

The mean values of $^{222}$Rn and $^{220}$Rn concentrations in studied locations during different seasons are shown in Figure 5a and annual effective dose rates in Figure 5b. The concentrations show clear trends of seasonal variations. The concentrations were found maximum during winter and minimum in summer months as observed elsewhere$^{(23)}$. Radon levels in closed environment were also found to be affected both by the degree of exchange with outdoor air as measured by ventilation rate, and also by the changes in entry of excess of radon from soil and rocks underneath the ground. With possible temperature variations, majorly of the houses were well ventilated in summer season, and indoor radon concentrations might be expected to be lower for summer than in winter seasons$^{(20)}$. The higher concentrations observed during winter season may be due to trapping of radioactive gases near to the surface because of temperature inversions. In summer, the higher rate of vertical mixing and dispersions lift the aerosols to higher altitudes resulting in a decrease in the concentration near to the ground$^{(24)}$. Magalhaes et al.$^{(25)}$ have observed a two order of magnitude of variability, with a maximum of 50 Bq m$^{-3}$ in winter and a minimum of 0.5 Bq m$^{-3}$ 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$^{(26)}$ of $^{222}$Rn and $^{220}$Rn. A correlation of 0.97 and 0.77 is observed between $^{222}$Rn and its progeny and $^{220}$Rn and its progeny, respectively. Looking at the seasonal correlation coefficients, wind speed may play an important 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$^{(27)}$.

**Wall-wise variations and dose rates**

The observed mean concentrations of $^{222}$Rn and $^{220}$Rn in different walls reveals the higher concentrations and dose rates in mud wall houses and lower in concrete walls houses. The concentration depends on type of walls. The variations may be due to the random distribution of radioactive rock species used ignorantly in the construction of houses$^{(28)}$. Correlation coefficient of 0.98 and 0.93 is observed.
between $^{222}\text{Rn}$ and its progeny and $^{220}\text{Rn}$ and its progeny. Sreenath Reddy et al.\textsuperscript{(29)} have reported the similar observation for the environment of Hyderabad, India and states that the dwellings with mud floor are exhibited relatively higher dose, this establishes the fact that sub surface soil is predominating source of indoor $^{222}\text{Rn}$ and $^{220}\text{Rn}$. 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 $^{226}\text{Ra}$ and $^{232}\text{Th}$ content. Ramachandran et al.\textsuperscript{(20)} and Folkerts et al.\textsuperscript{(30)} 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.

### Floor wise variations and dose rates

The mean concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ levels in different type of floorings have shown the higher levels 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\textsuperscript{(31)}. Granite samples show higher radon exhalation rate than mosaic. There is a positive correlation between radium content in granite with radon exhalation and its concentration\textsuperscript{(32)}. The elevated dose rates were observed in the granite floorings and the lower in mosaic floorings. A positive correlation of 0.98 between $^{222}\text{Rn}$ and its progeny and 0.81 between $^{220}\text{Rn}$ and its progeny were observed. The lower correlation might be due to the fact that many physical and meteorological factors affect the variation of 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\textsuperscript{(33)}.

### Room wise variations and dose rates

Variations of indoor $^{222}\text{Rn}$ and $^{220}\text{Rn}$ concentrations in different rooms of houses have shown higher concentrations in bath room, bed room and lower in living rooms. One can clearly see that there is a soaring concentration in bathroom compared with 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 additional $^{222}\text{Rn}$ due to $^{222}\text{Rn}$ dissolved in water\textsuperscript{(22)}. The $^{222}\text{Rn}$ is shown to be released in spray from faucets or shower fixture\textsuperscript{(34)}. Air in living rooms on the other hand is most readily diluted due to outdoor air blow. The variations of dose rate in different rooms of the houses revealed the higher dose rates in bed room and bath rooms. The correlation between $^{222}\text{Rn}$, $^{220}\text{Rn}$ and their progenies were 0.74 and 0.94, respectively.
Volume wise variations and dose rates

Rooms were classified broadly into six groups on the basis of volume ranged between 30 and 310 m³ such as 30–40, 45–60, 65–75, 80–100, 110–120 and 200–310. Minimum of seven rooms were selected for each dimension and this is covered for 10 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 x 10 locations = 420 rooms. These 420 rooms have been analysed for four seasons and lead to 1680 measurements. The total number of films (LR-115 detectors) exposed during this period of measurement is > 5000. The volumetric variations of ²²²Rn and ²²⁰Rn are shown in Figure 6a. Higher concentrations were observed in lower volume room than in the higher volume room. The estimated concentrations in a dwelling of volume 30–310 m³ ranged from 4 to 93 Bq m⁻³.

The observations clearly indicate 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 for the house of volume above 150 m³. The regression coefficients for the exponential drop for ²²²Rn and ²²⁰Rn were 0.99 and 0.98, respectively. The variations of dose rates are shown in Figure 6b. 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. A correlation of 0.79 and 0.96 between ²²²Rn, ²²⁰Rn and their progenies were observed respectively. The frequency distribution indicated the higher concentrations in lower volume rooms and lower concentration in higher volume rooms.

CONCLUSIONS

The estimated concentration of ²²²Rn and ²²⁰Rn for the environment of Bangalore, India varies from 17.2 ± 1.2 to 85.8 ± 2.3 Bq m⁻³ and 8.3 ± 1.2 to 38.3 ± 5.4 Bq m⁻³ with a geometric mean of 32.2 ± 1.6 and 21.4 ± 1.0 Bq m⁻³, respectively. The dose rate received by the population of Bangalore estimated by using UNSCEAR dose conversion factors and equilibrium factors ranged between 0.2 and 3.5 mSv y⁻¹ with the AM and GM of 1.14 ± 0.05 and 1.06 mSv y⁻¹, respectively. The lower concentration of ²²²Rn is observed in Rajajinagar and higher in Government Science College of Gandhinagara. Whereas ²²⁰Rn 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. The study on estimations of dose rates in dwellings of different features reveals the higher values 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. Hence, it is recommended that the lower volume houses should have good ventilation to reduce the effective dose rate.

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