The ubiquitous radon

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Over half of the total effective dose from natural background radiation to every member of the human population comes from inhalation of the naturally present radon, thoron and their daughter products. The occurrence of radon, thoron and their daughters in the outdoor and indoor environment, and their behaviour are discussed. Risk factors for lung cancer from their inhalation are indicated. Methods for controlling excessive indoor radon exposures are outlined. From an examination of the radon levels encountered in various parts of India, it is concluded that indoor radon exposure is not *a significant health risk in India.*

Background

RADIOGENIC lung cancer is the oldest type of radiation-induced malignancy known[1]. It was recorded in the 15th and 16th centuries among miners in the Schneeberg region of central Europe. The so-called 'Schneeberger Krankheit' was diagnosed as lung cancer in 1879. Possible association with radon was suggested around 1924 when high levels of radon were discovered in these mines. In the 1950's, it was recognized that it was the inhalation of shortlived radon daughter products that was the responsible agent.

During the last two decades we have come to realize that over half of the total effective dose to every member of the human population from natural background radiation comes from inhalation of the naturally present and ubiquitous radon, thoron and their daughter products. Further, the contribution from this source is highly variable, depending on a variety of factors. In many countries, there are some individuals who receive doses from this natural source which are substantially higher than those that would be permitted in occupational exposure.

Several international scientific bodies, particularly the International Commission on Radiological Protection (ICRP) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) are devoting considerable attention to radon exposures, both to occupational workers and to members of the public.

Radon in the environment[1, 2]

Radon, ^{222}Rn, is a noble gas produced by the decay of radium which is a member of the ^{238}U decay series, while thoron, ^{220}Rn, is a member of the ^{232}Th decay series (Figure 1). Some of the radionuclides in these series are α-emitters, and are the chief source of biological risk. Table 1 (taken from ref. 3) gives the typical levels of natural radioactivity in rocks, soil, and building materials. Inside rock and soil the daughters will be in equilibrium with the parents. Radon exhaled from ore bodies migrates through rock and is exhaled from the earth's surface or mine surfaces continuously. Radon exhaled into the free atmosphere is rapidly dispersed and diluted by vertical convection and turbulence. Considerably higher levels can occur if the radon is released in confined air spaces such as underground mines, homes, natural caves or tunnels. The radon level in the free atmosphere is about one-thousandth of that in the soil air.

Behaviour of radon and its daughters in the environment[2]

When an atom of ^{218}Po is formed through the decay of a radon atom, it is a free ion. Molecules of water vapour or trace gases coalesce almost immediately around the ion, forming a molecular cluster of 2–20 nm in diameter. The ion and the cluster are referred to as the 'unattached decay products'. Unattached ^{218}Po is highly mobile, and after 10–100 seconds, it attaches itself to aerosol particles in the 50–500 nm range, dust particles, or solid surfaces. In aerosol form the particles tend to remain suspended, although they are subject to electrostatic, inertial and diffusive forces by which they can be removed. Some of the unattached ^{218}Po may plate out on to surfaces (particularly indoors), or be transported with the air circulation, or decay into unattached ^{214}Pb. Attached ^{218}Po is relatively immobile and its plateout is negligible. The attached and unattached fractions behave differently in the environment and in the respiratory passage. When an attached ^{218}Po atom decays, the ^{214}Pb then created may remain on the aerosol or become unattached as a result of the recoil energy. Subsequently, the behaviour of ^{214}Pb is similar to that of ^{218}Po. On decay of ^{214}Pb, the ^{214}Bi remains typically attached due to the low recoil energy of the beta decay.

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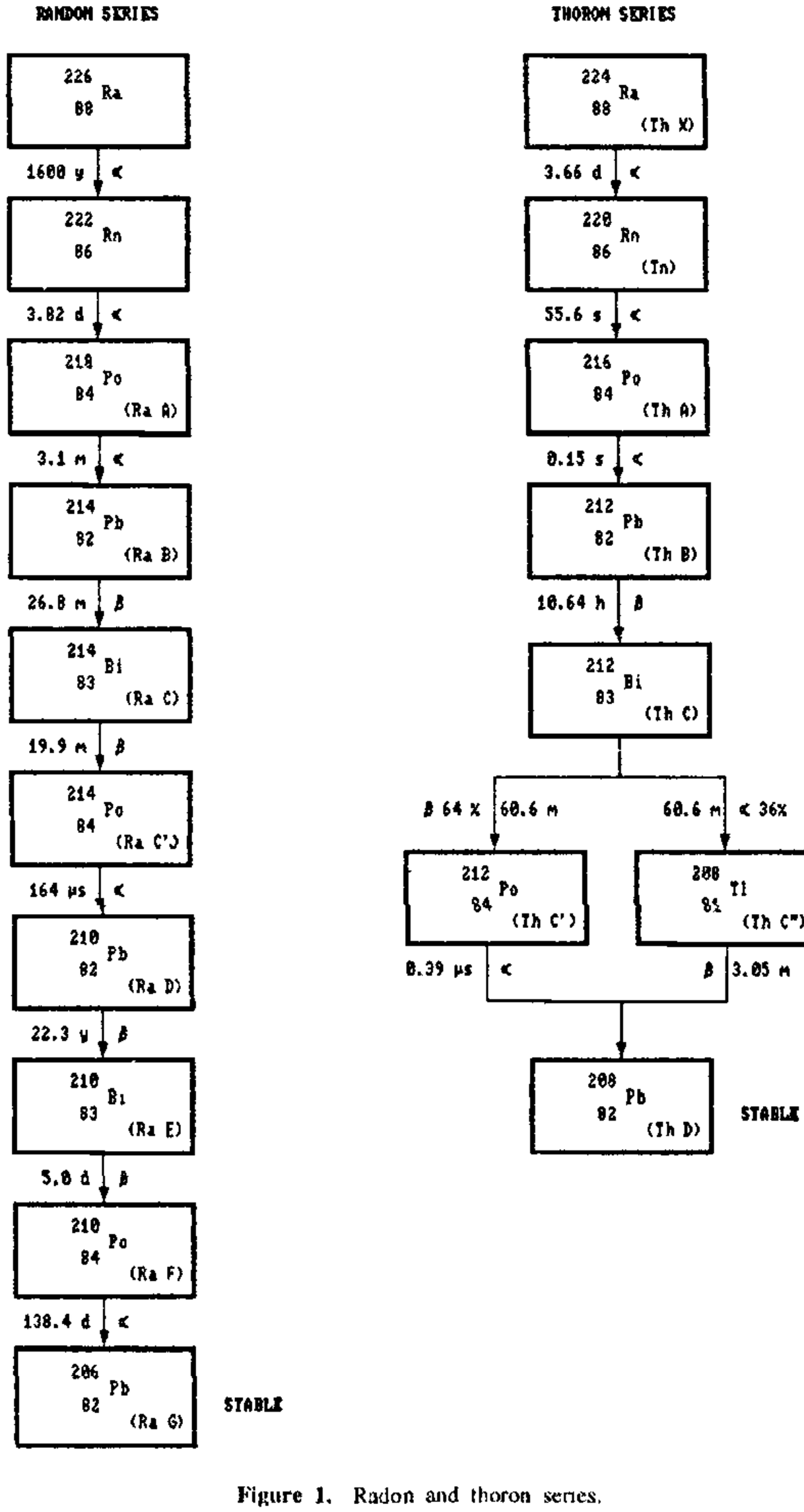

Figure 1. Radon and thoron series.

Special quantities and units used in radon exposures[4]

Due to historical reasons, s veral special quantities and units have been developed in relation to radon exposures in mines and this terminology has also been carried over in discussions on all radon exposures in general.

The *potential* α *energy*, ε_p, of an atom of radon or thoron is the total α energy emitted during the decay of this atom along its decay chain of shortlived daughters in equilibrium with it down to ^{210}Pb or ^{208}Pb respectively.

The *potential* α *energy concentration* in air, PAEC, of any mixture of shortlived radon or thoron daughters, c_p, (expressed in Jm^{-3}) is the sum of the potential α energies of all daughter atoms present per unit volume of air.

The *equilibrium-equivalent concentration* in air, EEC (expressed in Bqm^{-3}), of a non equilibrium mixture of

Table 1. Levels of natural radioactivity in common materials[3]

Material	Typical concentration (Bq/kg)			
	^{238}U	^{226}Ra	^{232}Th	^{40}K
Rocks				
Igneous	48	48	48	800
Granite		90	80	
Sedimentary sandstone	24	26	14	330
Sedimentary shales	15	40	40	800
Limestones	15	16	5	80
Phosphate ore		1400	50	260
General soil	24	70	40	440
Bricks		60	46	600
Gypsum & cement		300	25	90
Sands & gravels	20–90	4	20–200	30
Concretes		60	30	500
Coal (UK)	14	15	12	170
Fly ash	200	200	200	500

radon (or thoron) daughters in air is that activity concentration of radon (or thoron) in equilibrium with its daughters which has the same potential α energy concentration as the actual non-equilibrium mixture.

The *equilibrium factor in air*, F, is the ratio of EEC to the actual activity concentration of the parent nuclide in air, and characterises the disequilibrium between the mixture of the shortlived decay products and their parent nuclide in air in terms of potential α energy.

The *radon daughter exposure*, E (expressed in Jhm^{-3}), of an individual is the time integral of the PAEC of the daughter mixture in air, or the corresponding EEC of radon (expressed in $Bqhm^{-3}$), to which the individual is exposed over a given time period.

The special unit *working level* (WL) is often used for the PAEC. One WL corresponds approximately to the potential α energy concentration of shortlived daughters in air in equilibrium with a radon activity concentration of 100 pCi/l (or 3.7 Bq/l), or a PAEC of 1.3×10^5 MeV/l or 2.08×10^{-5} Jm^{-3}. (For thoron daughters, 1 WL corresponds to a thoron concentration of 7.43 pCi/l or 0.275 Bq/l). One *working level month* (WLM) corresponds to an exposure at 1 WL for 170 working hours per month.

Methods of measurement[5]

The methods may be active (involving pumping of air containing the gases and/or their progeny into or through a detecting system), or passive (where the concentrations integrated over a period of time are measured under natural conditions by exposing the detector for a fixed period of time). Solid state nuclear track detectors (SSNTD) are simple, sensitive, convenient and inexpensive passive devices consisting of thin sheets of dielectric material like polycarbonates, cellulose nitrate (Kodak LR-115) or CR-39 (composition $C_{12}H_{18}O_7$). The small diameter (< 0.1 μm) tracks produced by the alphas can be increased in size by chemical etching, enabling them to be counted under a microscope or using a spark counter.

The active methods are used mostly for short-term sampling, while the passive methods do not need constant attention, can give time-integrated concentrations (so that fluctuations during the sampling period are averaged out), and are hence ideal for measurements inside dwellings.

Outdoor and indoor concentrations of radon and daughters[2]

Outdoor concentrations

Radon enters the atmosphere by crossing the soil-air interface; other sources are the ocean, ground water, natural gas, geothermal fluids and coal combustion. The atmospheric concentrations at ground level are governed by the exhalation rate and by atmospheric diffusion.

Following the decay of a ^{228}Ra atom in the soil particle, the resulting radon atom can escape to the air-filled pores through recoil. Typical values for the emanating power (fraction of the radon formed that escapes to the surface) are: soil, 0.2; rock, 0.1; brick, 0.02; concrete, 0.2; cement. 0.05; fly ash, 0.005. Radon atoms can enter the free atmosphere by convection induced by pressure differences, or by diffusion.

Radon concentration generally decreases with increasing height. Concentrations are, as a rule, lower over locations such as islands and coastal sites (by a factor of 2–4) and Arctic areas which have less soil capable of emanating radon than over continental temperate regions.

There is a seasonal variation showing a summer (August) maximum with a value thrice that of the winter (February) minimum. The diurnal variation shows a maximum in the night which is twice the minimum value at noon.

UNSCEAR[2] assumes the following population weighted world-wide average values: radon concentration in outdoor air: 5 Bqm^{-3}; equilibrium factor; 0.8; corresponding EEC: 4 Bqm^{-3}. Annual averages of this value (excluding extreme values) will vary in the range 1–10 Bqm^{-3}.

Indoor concentrations

Sources of radon entry into buildings are: soil or rock under or surrounding the buildings, building materials, outdoor air, water supplies and natural gas.

UNSCEAR[2] has arrived at a mean indoor entry rate of 50 Bqm^{-3} h^{-1} from all sources into a 'reference house' (pressure-driven flow from underlying soil: 75%; building

materials: 12%; outdoor air: 9%; diffusion from underlying soil: 3%; natural gas: 0.6%; water: 0.2%). High rates can be traced to high flow rate of soil gas from underlying soil, use of alum shale as building material, or high radon concentration in tap water (which may be thousands of times the average value of 1 kBqm^{-3}). In apartments, entry from the soil is less important, and levels are generally lower than for houses; building materials play a greater role here.

Indoor concentrations of radon and its daughters vary roughly as ventilation rate (air changes per hour). In addition, radon daughters can be removed by plateout mechanisms. Human activities like closing or opening of doors and windows, turning ventilation system on or off, and meteorological conditions result in considerable variations in indoor levels. Much less information is available about thoron entry rates indoors.

Results of indoor surveys

UNSCEAR[2] has arrived at a population-weighted mean indoor concentration of 51 Bqm^{-3}, a log-normal distribution and a geometric standard deviation of 2.5 for the temperate and high latitudes representing 750 million people. Values as high as 10,000 Bqm^{-3} have been observed in thousands of buildings, particularly in Finland and Sweden. There is much less information available for the tropical regions. The levels will be lower than in temperate latitudes.

A population-weighted world average arithmetic mean of 40 Bqm^{-3} for the indoor concentration, with a corresponding EEC of 15 Bqm^{-3} (geometric mean 25 Bqm^{-3}) has been assumed by UNSCEAR[2]. For this average value, the percentage of houses exceeding specified levels would be as follows[1]:

50 Bqm^{-3}—5%; 100 Bqm^{-3}—1%; 200 Bqm^{-3}— 0.1%. For thoron daughters, the mean EEC values for indoor and outdoor air are respectively 0.5 and 0.2 Bqm^{-3}. The average indoor and outdoor occupancy factors of 0.8 and 0.2 respectively have been assumed.

On this basis the total annual per caput exposure to the world population is 0.19 WLM (0.66 mJhm^{-3}) from radon daughters and 0.09 WLM (0.30 mJhm^{-3}) from thoron daughters[1].

Epidemiology of radiation-induced lung cancer

In countries with a high mean life expectancy of 70–80 years, the integral natural incidence of lung cancer is in the range of 400–800 and 80–200 cases per million per year for males and females respectively[6].

The two main sources of quantitative information about radiation-induced lung cancer are the Japanese atomic bomb survivors and several groups of underground miners (mainly uranium miners) exposed to radon and its daughters. Studies on the correlation of lung cancer incidence with indoor radon levels in dwellings have been, by and large, supportive of the risk estimates arrived at by the other studies, but provide no quantitative confirmation.

The epidemiological approach is fairly straightforward and gives an upper estimate for the risk. As of 1990, in all the studies of uranium and non-uranium miners combined, with an average follow-up of about 30 years, a total of about 26,600 workers have been followed up for 520,000 person-years at risk; the average per capita cumulative exposure was around 120 WLM. A total of about 940 lung cancer deaths have occurred[7] as against an expected number of 260. The studies indicate a linear non-threshold relation between lung cancer risk and cumulative radon exposures up to 500 WLM. Below 50 WLM the level of statistical significance of the relation is somewhat less. For indoor exposures, we are interested in life-time exposures of around 20 WLM.

It appears that the risk of radon-daughter-induced lung cancer for heavy smokers may be 6–10 times higher than for non-smokers[8].

Dosimetry

The cells at risk appear to be those in the basal layers of the bronchial and the pulmonary epithelia. The dose to the bronchial epithelium is considerably higher than the mean dose to the pulmonary region or to the total lung. The main type of radiation-induced cancer is anaplastic or oat cell cancer with a short latency period.

Other factors that affect dosimetry are the equilibrium factor, the unattached fraction and the deposition pattern in the respiratory system. The dose increases linearly with the unattached fraction[1,4].

The effective dose can be taken[2] as 9 mSv/WLM (60 μSv per year per Bqm^{-3}). The lifetime risk coefficient for lung cancer is $1–4 \times 10^{-4}$ per WLM, averaged over all ages and both sexes[7].

For the reference values of mean indoor and outdoor concentrations and the occupancy factors discussed earlier, the weighted world means of the annual absorbed doses to the lungs and tracheo-bronchial cells add up to about 10 mGy and 0.80 mGy respectively. The annual effective dose per capita amounts to 1.1 mSv (7% from outdoor and 93% from indoor exposure). The excess lung cancer risk (cases per million per year) for the Reference World Population would be 79 for males, 16 for females and 47 for the average. It is concluded that about 12% of the total lifetime risk or frequency of lung cancer in the Reference Population might be due to exposure to indoor radon[1].

The relevance of microdosimetry

In view of the highly non-uniform nature of energy deposition in tissue from the short range α rays, for a

better understanding of the radiobiological effects, it becomes necessary to invoke microdosimetric concepts which take into account the stochastic nature of the interaction processes, with special reference to sub-cellular targets[9].

Methods for controlling excessive indoor radon exposures

There is a clear difference between *existing* exposure situations in present dwellings, where any action would have to be remedial (involving modifications to the dwellings or to the behaviour of the occupants), and *future* situations, which can be subjected to control at the stage of decision and planning. ICRP recommends the formulation of *action levels* to help in deciding when to institute remedial action in existing dwellings.

If the remedial action considered is fairly simple, an action level of 200 Bqm^{-3} might be considered. (Around 1% of dwellings in countries with high radon levels may exceed this value). For levels above 400 Bqm^{-3} intervention may become obligatory. For future buildings, an upper bound of 100 Bqm^{-3} has been suggested[10].

The technical measures for control include identifying cracks in the floor and sealing them, use of a small exhaust fan located in a porous area under the building, use of sealants to reduce exhalation from building materials and increasing the ventilation rate[2].

Work in India

The Department of Atomic Energy has a comprehensive countrywide programme on measurements of natural external radiation background levels as well as radon levels. A few other groups like those of Prof. H. S. Virk at Amritsar and Dr. Sudershan Kumar at Jodhpur have also been interested in the problem.

The terrestrial radiation profile has been drawn from estimates of the doses from typical abundances of U, Th and K of the relevant rock types in different parts of the country[11]. Shale, lignite, coal limestone and sandstone are rich in U, laterites in Th, and ultrabasic rocks and alluvial soils in K. The external radiation levels (cosmic ray plus terrestrial) have also been measured with thermoluminescent dosimeters. The results[12] are shown in Table 2.

Direct measurements of radon levels in the uranium mines at Jadaguda were first carried out by Raghavayya[13]. Subba Ramu and his colleagues[14] have made around 1500 countrywide measurements of outdoor and indoor radon levels (Table 2). The results can be summarized as follows:

(i) The overall national geometric mean concentration for indoor radon daughter exposure of the population is 4.2 ± 2.2 mWL (15.1 ± 8.1 Bqm^{-3}); the extreme values range from 0.6 to 15 mWL;

Table 2. State weighted average per caput total external (terrestrial + cosmic ray) radiation dose and radon daughter levels

State	State-weighted per caput exposure: Total external[12] mSv/y	Radon[14] mWL
Andaman	0.45	
Andhra Pradesh	1.07 ± 0.33	4.5 ± 2.4
Arunachal Pradesh		7.8 ± 1.1
Assam	0 82 ± 0.12	4 9 ± 2.0
Bihar	0 88 ± 0.21	4.5 ± 2.2
Chandigarh		8 1 ± 1.3
Daman	0.49	
Delhi	0.67 ± 0 00	3.9 ± 1.6
Diu	0 40	
Goa	0 60 ± 0 03	2.9 ± 2.5
Gujarat	0 49 ± 0.11	4 9 ± 2.4
Haryana	0 80 ± 0.05	5 0 ± 2.1
Himachal Pradesh	*0.96 ± 0.13*	4 5 ± 1.9
Jammu & Kashmir	0 76 ± 0.07	5 8 ± 2.2
Karnataka	0.59 ± 0 19	5 1 ± 1.8
Kerala	0 60 ± 0.18	3 2 ± 2.0
Lakshadweep	0.29 ± 0 06	7.3 ± 1 5
Madhya Pradesh	0.59 ± 0.20	2.4 ± 1 9
Manipur	0.30	
Maharashtra	0 37 ± 0.08	3 6 ± 2.4
Meghalaya	0.72 ± 0.15	3.6 ± 2.1
Mizoram		
Nagaland		2.3 ± 1.5
Orissa	0.86 ± 0.35	3.9 ± 2.3
Pondicherry	0.86 ± 0.35	
Punjab	*0.69 ± 0.09*	5 6 ± 1.9
Rajasthan	0.61 ± 0 11	3.7 ± 2.3
Sikkim	1.04	
Tamilnadu	0 71 ± 0.19	3.3 ± 2.4
Tripura	0.62 ± 0 02	8.3 ± 1 2
Uttar Pradesh	0 91 ± 0 13	5.1 ± 2 0
West Bengal	0.74 ± 0.11	9.5 ± 1.3
Monazite areas	5.760	
Areas not covered	0.690	
Average	0.69 ± 0.20	4.2 ± 2 2

*Excluding monazite areas.

(ii) About 52% of the total doses received by the Indian population is due to the inhalation of radon progeny[15];
(iii) For the high background areas the geometric mean is 9.4 ± 1.5 mWL;
(iv) The ratio of the winter peak to the monsoon minimum could be as much as 10;
(v) Rooms built with coal and fly ash bricks have higher radon levels (1.7 to 3.4 times the average);
(vi) The equilibrium factor is widely variable; the median value[16] is 0.30. (These values are lower than most values reported for the rest of the world);
(vii) The mean value[13] in uranium mines is 0.15 WL; for non-uranium underground mines it varies[17] from a few mWL to 100 mWL.

Kumar *et al*[18]., found that in Rajasthan the indoor levels were in the range 12–200 Bqm^{-3}, the average for the various cities being 40–135. The average levels in

the basements (which many houses in Rajasthan have) are twice the ground floor values.

In summary, we can note that in our country, due to the tropical climate and our living habits, we have plenty of ventilation in our houses, which is one of the factors that help in reducing indoor radon levels. Whether one considers the average level over the country, or even the maximum values recorded in the high background areas, the levels are below the ICRP recommended action level of 200 Bqm^{-3}, and hence indoor radon is *not* a significant health risk in our country.

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Electronic databases, networks and information support for scientific research

T. B. Rajashekar and A. Sreenivasa Ravi

Electronic databases and computer networks are bringing forth significant changes in both formal and informal information transfer mechanisms in science. More than 6,000 electronic databases are estimated to be available today, which include a large number of bibliographic and scientific hard databases. While a majority of these can be accessed 'online' using computer-communication networks, they can also be acquired on tapes, diskettes and CD-ROM discs and searched locally. Electronic databases are used predominantly to meet the current and retrospective information needs of scientists. While electronic databases facilitate a researcher in gaining rapid access to published or about-to-be published information, a variety of 'networked information services' have evolved on academic and research networks like BITNET, NSFNET, Internet and JANET. These include electronic discussion forums, data archives, electronic journals, library catalogues and databases. Network information services deliver information to the end-user right at his terminal and have the advantages of convenience, speed and informality. Although researchers in a few institutions in India are beginning to take advantage of these developments, there is need for more widespread awareness of these. This article is an attempt in this direction.

It is now widely acknowledged that the ability to access, transmit, share and disseminate information will make the difference between success and failure in the 21st century. If we have to improve productivity and innovation of our R&D activities and give competitive edge to our technological products, then convenient, economic

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