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ASSESSMENT OF DOSE DUE TO EXPOSURE TO INDOOR RADON AND THORON PROGENY

by

***Ganesh PRASAD*[1], *Gurupad S. GUSAIN* [1], *Veena JOSHI* [2], *and Rakesh C. RAMOLA*[1*]**

[1]Department of Physics; [2]Department of Chemistry,
H.N.B. Garhwal University, Tehri Garhwal, India

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The components of the effective dose through inhalation from radon and its progeny are important for human health since they contribute to more than 50% of the total radiation dose from natural sources. As a consequence, radon has been identified as the second leading cause of lung cancer after smoking. Radon and its short lived decay products (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po) present in dwellings are a radiation hazard, particularly if such sources are concentrated in the enclosed areas like poorly ventilated houses and underground mines. The indoor radon, thoron, and progeny concentrations were measured in a small hilly town of Budhakedar and the surrounding area of Tehri Garhwal, India, by using LR-115 Type II plastic track detector in a twin cup radon dosimeter. The concentrations of radon progeny were measured as the highest in winter and the lowest in summer while the thoron progeny concentration was found maximum in rainy season and minimum in autumn. The annual exposure to the potential alpha energy of radon and thoron were found to vary from 0.04 WLM to 0.69 WLM with an average value of 0.29 WLM, and 0.03 WLM to 0.37 WLM with an average value of 0.16 WLM, respectively. The annual effective dose due to the exposure to indoor radon and progeny in Budhakedar homes was found to vary from 0.16 mSv to 2.72 mSv with an average value of 1.14 mSv and the effective dose due to the exposure to thoron and progeny was found to vary from 0.18 mSv to 2.49 mSv with an average value of 1.05 mSv. The results of systematic study have been obtained by considering the room as a space in which the radon and thoron levels are directly related to the dynamic and static parameters.

Key words: radon, thoron, expose, effective dose

INTRODUCTION

Health hazards from radon (^{222}Rn) and thoron (^{220}Rn) and their progeny are of considerable concern to the general population. It is now accepted that there is an appreciable correlation between radon exposure and some types of cancer [1-4] (and kidney diseases [2, 5]).There is a risk of a lung cancer from the inhalation of radon due to the alpha radiation emitted by the short-lived radon decay products. To estimate the annual average equivalent dose, a number of indoor radon surveys have been carried out around the world [6]. The inhalation exposure of the general population to the ambient radon progeny constitutes the most significant health hazard of the natural radiation environment [7]. It is generally accepted by the scientific community that a considerable fraction of all naturally occurring lung tumors is caused by the inhalation of the short-lived radon progeny [8]. This risk is exacerbated for certain identifiable subpopulations, such as tobacco smokers and uranium miners [9-14]. The assessment of radiological risk related to the inhalation and ingestion of radon and radon progeny is based mainly on the integrated measurements of radon [15-18]. Dose calculations indicate that the effective dose would be 20-50% higher for children than that for adults [19, 20]. However, the sensitivity of the children to radon exposure is not known. According to the mine data, the relative risk coefficient decreases with age and with the time since the exposure. The miner data support the presence of an inverse dose-rate effect as well as a lower relative risk coefficient at low total dose [21].

The exposure of a person to a high concentration of radon and its short-lived progeny for a long period of time leads to pathological effects like respiratory functional change and the occurrence of a lung cancer [22-24]. In some countries, the radiation dose to man caused by inhaled radon daughters constitutes more than 50% of the total dose [24]. Any inhaled gas, in-

* Corresponding author; e-mail: rcramola@gmail.com

cluding radon, is slightly soluble in body tissues. Radon in lungs diffuses to blood and is transported to other organs, where the gas and the decay products that build up in tissues deliver a radiation dose. In a study of inhaled radon, Harley *et al*. [25] determined the solubility of radon in the body. Two persons were in a controlled, relatively high-radon atmosphere for about a day. Sequential exhaled-breath samples were used to infer retention times in the five major body-compartments: lungs, blood, intracellular and extra cellular fluid, and adipose tissue. The data were used in the metabolic modeling of the dose to other organs from inhaled radon [26]. The dose to organs other than the lungs had been calculated previously by Jacobi and Eisfeld [27]. Radon, thoron and their short-lived decay products contribute to the population annual average effective dose equivalent of about 1 mSv per person [28, 29]. This amount is often higher in the uranium and thorium rich areas, especially near the mines and mille. Therefore it is necessary to monitor the environmental radioactivity around these objects and to asses the influence of radiation to the population.

EXPERIMENTAL METHOD

A twin cup radon dosimeter is used in the present study for the measurements of indoor radon and thoron concentrations. The radon dosimeter system is a cylindrical plastic chamber divided into two equal compartments each having an inner volume of 135 cm^3 and height of 4.5 cm (fig. 1). It has been designed and developed by the Department of Atomic Energy, Government of India.

The exposure of the detector inside the cup is termed as the cup mode and the one exposed to the open is termed as the bare mode. One of the cups has its entry covered with a glass fiber filter paper which permeates both radon and thoron gases into the cup and is called the filter cup. The other cup is covered with a semi-permeable membrane [30] sandwiched between two glass fiber filter papers and is called the membrane

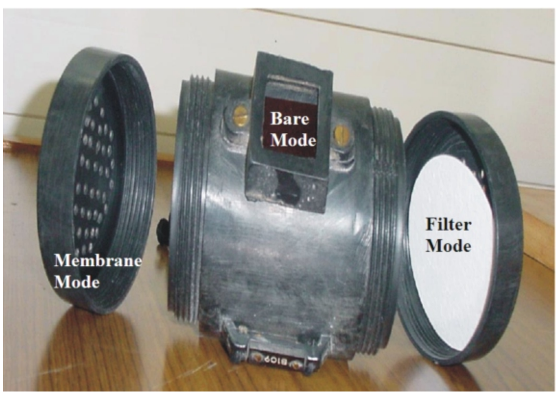

Figure 1. Twin cup radon dosimeter

cup. This membrane has permeability constant in the range of 10^{-8} -10^{-7} cm^2/s [31-33] and allows more than 95% of the radon gas to diffuse while it suppress the entry of thoron gas almost completely. Thus, the SSNTD film inside the membrane cup registers tracks contributed by radon only, while that in the filter cup records both radon and thoron. The third SSNTD film exposed in the bare mode registers alpha tracks contributed by the concentrations of both gases and their alpha emitting progeny.

The dosimeter is kept at a height of 1.5 m from the floor of the room and care is taken to keep the bare card at least 10 cm away from any wall surface. This ensures that the errors due to tracks from the deposited activity from nearby surfaces are avoided, since the ranges of alpha particles from radon/thoron progeny fall within 10 cm distance. After the exposure period of 90 days, the SSNTD films are retrieved and chemically etched in 2.5N NaOH solution at 60 °C for 60 minutes with mild agitation throughout [34]. The tracks recorded in all the three SSNTD films are counted using a spark counter. A methodology has been developed to derive the equilibrium factors separately for radon and thoron using the track densities based on the ventilation rates in the dwellings [35, 36]. The recorded track densities were converted in Bq/m^3 by using an appropriate calibration factor [37]. The measurements were repeated over time integrated four quarterly cycles to cover the four seasons of a calendar year.

RESULTS AND DISCUSSION

The values of radon progeny concentration in the houses of Budhakedar for the four different seasons of a year are given in tab. 1. The concentration of radon progeny was found to be the highest in winter and the lowest in summer. Radon progeny concentration in summer was found to vary from 0.86 mWL to 13.41 mWL with an average value of 4.60 mWL and in winter season from 0.65 mWL to 23.14 mWL with an average value of 8.93 mWL. The highest radon concentration in winter is mainly due to the poor ventilation conditions of houses during this season. Since the study area is located in the cold region, people keep the doors and windows closed during winter to conserve the energy inside the house. The building material in mud houses also contributes to the additional radon inside the room, which also influences the indoor radon and progeny concentrations.

The values of thoron progeny concentration in the houses of Budhakedar for four different seasons of a year are shown in tab. 2. The concentration of thoron progeny was found to be the highest in rainy season and the lowest in autumn. Thoron progeny concentration in autumn was found to vary from 0.11 mWL to 1.73 mWL with an average value of 0.61 mWL and in rainy

Table 1. Radon progeny concentration in Budhakedar homes for different seasons

Location	Radon progeny concentration [mWL]					Room volume [m^3]	Building material
	Autumn	Winter	Summer	Rainy	Average		House
Niwalgaon	2.49	1.95	0.86	1.73	1.76	19.44	Cement
Niwalgaon	1.41	2.59	2.49	2.38	2.22	14.21	Cement
Niwalgaon	1.41	0.65	0.86	0.86	0.95	20.41	Cement
Agar	6.59	7.35	2.49	11.68	7.03	11.23	Mud
Rashagrom	6.05	7.68	6.59	9.30	7.41	17.01	Mud
Ghordhi	n. a.	12.76	3.14	4.22	6.71	35.64	Cement
Rashagram	8.76	15.57	7.46	8.43	10.06	17.49	Mud
Bhigum	23.46	8.76	6.27	3.35	10.46	22.68	Mud
Agunda	2.16	5.73	5.95	4.11	4.49	20.79	Cement + Mud
Agunda	1.62	6.05	3.89	n. a.	3.85	16.20	Mud
Bishan	12.32	13.73	5.51	22.59	13.54	27.72	Mud
Bishan	4.65	4.76	1.19	7.57	4.54	15.12	Mud
Budhakedar	4.22	4.86	3.14	7.46	4.92	27.12	Cement
Budhakedar	5.51	6.38	2.27	4.22	4.60	34.02	Cement
Budhakedar	13.41	23.14	13.41	16.54	16.63	33.85	Cement
Vinayakal	6.59	19.78	8.76	4.11	9.81	45.36	Mud
Kamlanagar	9.41	10.16	4.00	14.38	9.49	17.01	Mud
Average	6.88	8.93	4.60	7.68	6.97		
Minimum	1.41	0.65	0.86	0.86	0.95		
Maximum	23.46	23.14	13.41	22.59	16.63		

Table 2. Thoron progeny concentration in Budhakedar homes for different seasons

Location	Thoron progeny concentration [mWL]					Room volume [m^3]	Building material
	Autumn	Winter	Summer	Rainy	Average		House
Niwalgaon	0.30	0.16	0.27	0.46	0.30	19.44	Cement
Niwalgaon	0.46	0.59	0.38	1.70	0.78	14.21	Cement
Niwalgaon	0.14	0.22	0.19	0.24	0.20	20.41	Cement
Agar	0.62	0.24	0.46	3.35	1.17	11.23	Mud
Rashagrom	0.24	2.00	0.68	7.08	2.50	17.01	Mud
Ghordhi	n. a.	0.54	1.57	0.22	0.78	35.64	Cement
Rashagram	0.57	3.95	1.51	0.81	1.71	17.49	Mud
Bhigum	1.54	1.59	0.27	0.73	1.03	22.68	Mud
Agunda	0.11	0.27	0.22	0.62	0.31	20.79	Cement + Mud
Agunda	0.27	0.65	0.46	n. a.	0.46	16.20	Mud
Bishan	1.73	4.46	2.73	1.73	2.66	27.72	Mud
Bishan	0.49	3.51	0.65	1.00	1.41	15.12	Mud
Budhakedar	0.14	1.97	1.03	1.59	1.88	27.12	Cement
Budhakedar	0.27	0.62	0.22	0.35	0.37	34.02	Cement
Budhakedar	0.59	0.27	0.54	3.84	1.31	33.85	Cement
Vinayakal	1.73	0.54	0.51	0.35	0.78	45.36	Mud
Kamlanagar	0.65	2.73	0.86	5.03	2.32	17.01	Mud
Average	0.61	1.43	0.74	1.82	1.17		
Minimum	0.11	0.16	0.19	0.22	0.20		
Maximum	1.73	4.46	2.73	7.08	2.66		

season from 0.22 mWL to 7.08 mWL with an average value of 1.82 mWL. A majority of the houses in the area are mud houses, which also influences the radon, thoron, and progeny concentrations in the houses of the study area. The observed values of radon, thoron, and progeny concentrations in mud houses were found comparably higher than those in other houses.

Radon exposure

The exposure to the potential alpha energy (E_p) is the quantity related to the inhalation dose. However, the monitoring of the exposure to radon gas from the time integral of the radon concentration in air is relatively straightforward [38]. Thus, the additional parameter, F, known as the equilibrium factor, has been devised for practical application [39]. This expresses the airborne concentration of the potential alpha energy as a fraction of the highest possible value achieved when the progeny has the same activity concentration as the measured radon gas. Thus, the potential alpha-energy concentration is 1 WL when the radon concentration is 3700 Bq/m^3. F is the equilibrium factor and is calculated independently for each measurement. The annual exposure to the potential alpha energy, E_p, is then related to the average radon concentration, C_{Rn}, by the following expression [40]

$$E_p \frac{WLM}{y} \quad \frac{8760 \quad n \quad F \quad C_{Rn}}{170 \quad 3700}$$

where C_{Rn} is the radon concentration in Bq/m^3, n – the fraction of time spent indoors (occupancy factor), 8760 is the number of hours per year, and 170 – the number of hours per working month. Taking the occupancy factor to be 0.8 [39, 41], the annual exposure to the potential alpha energy is given by 0.011 FC_{Rn} in the conversion unit WLM per Bq/m^3. The annual exposure to the potential alpha energy was found to vary from 0.04 WLM to 0.69 WLM with an average value of 0.29 WLM (tab. 3).

Thoron exposure

There is relatively little information on the characteristics of the thoron progeny aerosol in room air and the degree of radioactive equilibrium. The first progeny, Po-216, will always be close to the equilibrium with the thoron gas because of its very short half-life (0.16 s). The second progeny, Pb-212, will not approach the equilibrium with thoron, because its half-life of 10.6 h is much longer than the effective rate of removal from room air by ventilation or loss to surfaces. The estimates of the activity of Pb-212 in indoor air relative to that of the thoron gas have ranged from approximately 2% [38, 42] to about 10% [43]. The activity of the third progeny, Bi-212 (half-life 61 minutes), again will be only a fraction of that of its parent. In general, therefore, more than 90% of the potential alpha energy associated with thoron progeny in indoor air is carried by Pb-212. Although the activity concentration of Po-216 may be 50 times higher, the associated fraction of the potential alpha energy is minute and the dosimetric consequence of inhaling this activity (even as unattached particles) is negligible. The quantity related primarily to the dose is the intake of the potential alpha energy in air [38]. The annual exposure to the potential alpha energy can be related adequately to the mean activity concentration of Pb-212 in air by the following expression

$$E_p \frac{WLM}{y} \quad \frac{8760 \quad n \quad C^{212}\text{Pb}}{170 \quad 300}$$

where $C_{\text{Pb-212}}$ is the concentration of ^{212}Pb in Bq/m^3, n – the fraction of time spent indoors (occupancy factor), 8760 – the number of hours per year, 170 – the number of hours per working month, and 300 is the concentration of ^{212}Pb in Bq/m^3 per WL.

Taking n to be 0.8, the annual exposure to the potential alpha energy of thoron progeny was found to vary from 0.03 WLM to 0.37 WLM with an average value of 0.16 WLM (tab. 3). The thoron progeny exposure value in WLM is comparable to the radon progeny exposure value in the indoor atmosphere of Budhakedar The average concentration of ^{212}Pb in indoor air may be typically about one-fortieth of that of the radon gas [39]. However, in the present study, the thoron annual exposure potential alpha energy is found to be roughly half of the radon annual exposure potential alpha energy, which shows the importance of the thoron monitoring in the study area.

Effective dose

The estimates of the absorbed dose to the critical cells of the respiratory tract per unit ^{222}Rn exposure applicable to the general population can be derived from an analysis of information on aerosol size distribution, unattached fraction, breathing rate, fractional deposition in the airways, mucous clearance rate, and location of the target cells in the airways. For both radon-exposed underground miners and those exposed to other carcinogenic aerosols such as cigarette smoke, 75% of lung tumors are found in the branching airways of the bronchial tree and 15% in the gas exchange region, or parenchyma [14]. The dosimetry of the inhaled radon and decay products is therefore directed to the cells of the bronchial epithelium. The most important variables affecting the alpha dose to the nuclei of these cells are the aerosol size distribution, the unattached fraction, the breathing rate, and the depth in tissue of the target cell nuclei. The effective dose due to the exposure to radon and progeny may be calculated by the relation [24]

Table 3. Calculated annual dose due to the exposure to radon and thoron daughters in the Budhakedar homes

Location	House type	Room volume [m^3]	Radon progeny exposure [WLM]	Thoron progeny exposure [WLM]
Niwalgaon	Cement	19.44	0.07	0.04
Niwalgaon	Cement	14.21	0.09	0.11
Niwalgaon	Outside	20.41	0.04	0.03
Agar	Mud	11.23	0.29	0.16
Rashagrom	Mud	17.01	0.31	0.34
Ghordhi	Cement	35.64	0.28	0.11
Rashagrom	Mud	17.49	0.41	0.24
Bhigum	Mud	22.68	0.43	0.14
Agunda	Cement + Mud	20.79	0.19	0.04
Agunda	Mud	16.20	0.16	0.06
Bishan	Mud	27.72	0.56	0.37
Bishan	Mud	15.12	0.19	0.19
Budhakedar	Cement	27.21	0.20	0.26
Budhakedar	Cement	34.02	0.19	0.05
Budhakedar	Cement	33.85	0.69	0.18
Vinayakal	Mud	45.36	0.40	0.11
Kamlanagar	Mud	17.01	0.39	0.32

$$\text{Effective dose} = C_{\text{Rn}}\,(\text{Bqm}^{-3}) \times 20.8 \times 7000\ \text{h} \times 9\ \text{nSv}\,(\text{Bqhm}^{-3})^{-1}$$

where C_{Rn} is the annual average of the measured radon concentration in the houses of Budhakedar and 0.28 is the average of the equilibrium factor for radon and progeny measured in the houses of Garhwal Himalaya [44]. The effective dose due to the exposure to indoor radon and progeny in Budhakedar homes was found to vary from 0.16 mSv to 2.72 mSv with an average value of 1.14 mSv (tab. 4).

The effective dose due to the exposure to thoron and progeny may be calculated by the relation [24]

$$\text{Effective dose} = C_{\text{Tn}}\,(\text{Bqm}^{-3}) \times 0.09 \times 7000\ \text{h} \times 40\ \text{nSv}\,(\text{Bqhm}^{-3})^{-1}$$

where C_{Tn} is the annual average of the measured thoron concentration in the houses of Budhakedar and 0.09 is the average of the equilibrium factor for thoron and progeny measured in the houses of Garhwal Himalaya [44]. The effective dose due to the exposure to thoron and progeny in the houses of Budhakedar was found to vary from 0.18 mSv to 2.49 mSv with an average value of 1.05 mSv (tab. 4).

Table 4. Estimated annual effective dose due to the exposure to radon and thoron in the Budhakedar homes

Location	Effective dose (radon) [mSv]	Effective dose (thoron) [mSv]
Niwalgaon	0.28	0.28
Niwalgaon	0.37	0.73
Niwalgaon outdoor	0.16	0.18
Agar	1.15	1.08
Rashagram	1.22	2.34
Ghordhi	1.09	0.73
Rashagram	1.64	1.59
Bhigun	1.71	0.96
Agunda	0.74	0.28
Agunda	0.64	0.43
Bishan	2.21	2.49
Bishan	0.74	1.31
Budhakedar	0.81	1.11
Budhakedar	0.76	0.35
Budhakedar	2.72	1.23
Sounla	1.61	0.73
Kamal Nagar	1.55	2.17

CONCLUSIONS

The results of the systematic study are obtained by considering the room as a space in which the radon and thoron levels are directly related to the dynamic and static parameters. The main dynamical variables, *i. e.*, the ventilation rate of the system could not be defined at every state but the data were analyzed on the basis of the ventilation conditions of the room. Unpredictable and uncontrolled disturbing parameters of the dwellings set a limit to the precession of the measured data. Minor modification in the houses is usually neglected during the measurements. Our earlier study shows that the indoor radon and thoron concentrations in the study area are below the recommended action level set by various organizations, while the radon concentration is high in soil-gas and groundwater of the area [45]. It was observed that the indoor radon and thoron progeny concentrations follow a specific trend of seasonal variation. The indoor radon progeny concentration in Budhhakedar was found to be the highest in winter and the lowest in summer while the thoron progeny concentration was maximum in rainy season and minimum in autumn. Based on these results, it is concluded that the seasonal variations should be taken into account to calculate the precise values of the annual effective dose.

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REFERENCES

[1] Archer, V. E., Wagoner, J. K., Lundin, Jr. F. E., Lung Cancer Among Uranium Miners in United States, *Health Phys, 23* (1973), pp. 351-371
[2] Henshaw, D. L., Eatough, J. P., Richardson, R. B., Radon as a Causative Factor in Induction of Myeloid, Leukaemia and other Cancers, *The Lancet*, *335* (1990), 8696, pp. 1008-1012
[3] Pershagen, G., Liang, Z. H., Hrubec, Z., Svenson, C., Boice, Jr. J. D., Residential Radon Exposure and Lung Cancer in Swedish Women, *Health Phys, 63* (1993), pp. 179-186
[4] Sevc, J., Kunz, E., Tomasek, L., Placek, V., Horacek, J., Cancer in Man after Exposure to Radon Daughters, *Health Phys,* 54 (1988), pp. 27-46
[5] Waxweiler, R. J., Roscoe, R. J., Archer, V. E., Thun, M. J, Wagoner, J. K., Lundin, Jr. F. E., Mortality Fol-Low-Up through 1977 of the white Underground Minors Cohort Examined by the United States Public Health Services, in: Radiation Hazards in Mining, Control, Measurement and Medical Aspects (Ed. M. Gomexz), American Institute of Mining, Metallurgical and Petroleum Engineers, New York, USA, 1981
[6] ***, United Nations Scientific Committee on the Effects of Atomic Radiation, Sources and Effects of Ionizing Radiation, United Nations, New York, E. 94. IX. 2, 1993
[7] Pohl, E., Steinhausler, F., Hofmann, W., Pohl-Ruling, J., Methodology of Measurements and Statistical Evaluation of Radiation Burden to Various Population Groups from all Internal and External Natural Sources, in: Biological and Environmental Effects of Low-Level Radiatiohn, IAEA, Vienna, 1976, pp. 305-315
[8] ***, National Council on Radiation Protection and Measurements, Evaluation on Occupational and Environmental Exposures to Radon and Radon Daughters in the United States, NCRP Report No. 78 National Council on Radiation Protection and Measurements, Bethesdam, Md., USA, 1984
[9] Ochsner, A., Ochsner, A., Jr., H' Doubler, C., Blalock, J., Bronchogenic Carcinoma, *Dis. Chest, 37* (1960), pp. 1-12
[10] Wagoner, J. K., Archer, V. E., Lundin, F. E., Jr., Holaday, D. A., Lloyd, J. W., Radiation as the Cause of Lung Cancer among Uranium Miners, *N. Engl. J. Med., 278* (1965), pp. 181-188
[11] Sevc, J., Kunz, E., Placek, V., Lung Cancer in Uranium Miners and Long Term Exposure to Radon Daughter Products, *Health Phys., 30* (1976), pp. 433-437
[12] ***, American Cancer Society, Cancer Facts and Figures, ACS, New York, USA, 1981
[13] Whittemore, A. S., McMillan, A., Lung Cancer Mortality Among U. S. Uranium Miners, A Reappraisal, *J. Nalt. Cancer Inst, 71* (1983), pp. 489-499
[14] Saccomanno, G., Auerbach, O., Kuschner, M., A Comparison of the Localization of Lung Tumors in Uranium Miners with Non-Miners, *Cancer, 77* (1996), pp. 1278-1283
[15] ***, International Commission on Radiological Protection, Protection Against Radon-222 at Home and at Work, ICRP Publication 65, Annals of the ICRP 23(2), Pergamon Press, Oxford, UK, 1993
[16] Ramola, R. C., Kandari, M. S., Rawat, R. B. S., Assessment of Health Risk Due to Exposure of Radon and its Daughter Products in the Lower Atmosphere, *Current Science, 73* (1997), pp. 771-774
[17] Samuelsson, C., Johansson, J., Long-Lived Radon Decay Products as a Long Term Radon Exposure Indicator, *Radiat Prot Dosim., 56* (1994) pp. 123-126
[18] Solomon, S. B., A Radon Progeny Sampler for the Determination of Effective Dose, *Radiat Prot Dosim, 72* (1997), pp. 31-42
[19] Hofmann, W., Dose Calculations for the Respiratory Tract from Inhaled Natural Radioactive Nuclides As a Function of Age, *Health Phys, 43* (1982), pp. 31-44
[20] ***, US National Research Council, Comparative Dosimetry of Radon in Miners and Homes, Washington, National Academy Press, Washington DC, 1991
[21] Lubin, J. H., Boice, Jr, J. D., Edling, C., Hornung, R. W., Howe, G., Kunz, E., Kusiak, R. A., Morrison, H. I., Radford, E. P., Samet, J. M., Tirmarche, M., Woodward, A., Yao, S. X., Pierce, D. A., Lung Cancer in Radon Exposed Miners and Estimation of Risk from Indoor Exposure, *J. Natl. Cancer Inst., 87* (1995), pp. 817-827
[22] Lubin, J. M., Boice, Jr. J. D., Lung Cancer Risk from Residential Radon: Meta-Analysis of Eight Epidemiological Studies, *J. Nat. Can. Inst., 89* (1993), pp. 49-57
[23] Ramola, R. C., Singh, M. S., Choubey, V. M., Radon and Thoron Monitoring in the Environment of Kumaun Himalaya: Survey and Outcomes, *J. Environ Radioactivity, 79* (2005), pp. 85-92
[24] ***, United Nation Scientific Committee on the Effect of Atomic Radiation Exposures from Natural Radiation Sources, Annex B, 2000
[25] Harley, J. H., Jetter, E. S., Nelson, N., Elimination on Rn-222 from the Body, HASL-32, U. S. Atomic Energy Commission, New York Operations Office, New York, USA, 1958
[26] Harley, N. I. I., Robbins, E. S., Radon-222 Alpha Dose to Organs other Than the Lung, *Radiation Protection Dosimetry, 45* (1992), pp. 619-622
[27] Jacobi, W., Eisfeld, K., Dose to Tissues and Effective Dose Equivalent by Inhalation of Radon-222, Radon-220 and Their Short-Lived Daughters, GSF Report S-626, Gesellschaft fur Strahlen-und Umweltforschung, Munich-Neuherberg, Germany, 1980
[28] Sinnaeve, J., Clemente, G., O'Riorden, M., The Emergence of Natural Radiation, *Rad. Prot. Dos., 7* (1984), pp. 15-17

[29] Wrixon, A. D., Bismuth Radionuclides in the Natural Background Gamma Radiation Spectrum, *Atom 352* (1986), pp. 2-7
[30] Ward, W. J. III., U.S. Patent 4, 004436, 1977
[31] Ramachandran, T. V., Lalit, B. Y., Mishra, U. C., Measurement of Radon Permeability Through Some Membranes, *Nucl. Tracks and Rad. Meas., 13* (1987) pp. 81-84
[32] Jha, G., Raghavayya, M., Padmanabhan, N., Radon Permeability of Some Membranes, *Rad. Meas., 19* (1982), pp. 307-308
[33] Wafaa, A., Permeability of Radon-222 through Some Materials, *Rad. Meas., 35* (2002), pp. 207-211
[34] Miles, J. C. H., Calibration and Standardization of Etched Track Detectors, in: Radon Measurements by Etched Track Detectors, Applications in Radiation Protection, Earth Sciences and the Environment (Eds: S. A. Durrani, R. Ilić), World Scientific, Singapore, 1997, pp. 143-176
[35] Mayya, Y. S., Eappen, K. P., Nambi, K. S. V., Methodology for Mixed Field Inhalation Dosimetry in Monazite Areas Using a Twin-Cup Dosimeter with Three Track Detectors, *Rad. Prot. Dosimetry, 77* (1998), pp. 177-184
[36] Eappen, K. P., Mayya, Y. S., Calibration Factors for LR-115 (Type-II) Based Radon Thoron Discriminating Dosimeter, *Radiation Measurements, 38* (2004), pp. 5-17
[37] Ramola, R. C., Rawat, R. B. S., Kandari, M. S., Ramachandran, T. V., Eappen, K. P., Subb Ramu, M. C., Calibration of LR-115 Plastic Track Detectors for Environmental Radon Measurements, *Indoor Built Environ., 5* (1996), pp. 364-367
[38] ***, Nuclear Energy Agency Group of Experts. Metrology and Monitoring of Radon, Thoron and Their Daughter Products, OECD, Paris, 1985
[39] ***, United Nations Scientific Committee on the Effects of Atomic Radiation. Ionizing Radiation: Sources and Biological Effects, Annex D, Report to the General Assembly, UN, New York, 1982, p. 141
[40] Anthony, C. J., Lung Dosimetry, in: Radon and its Decay Products in Indoor Air (Eds: W. W. Nazaroff, V. N. Jr. Anthony) 1987, pp. 259-303
[41] ***, Nuclear Energy Agency Group of Experts. Dosimetry Aspects of Exposure to Radon and Thoron Daugter Products, OECD, Paris, 1983
[42] Steinhausler, F., Long Term Measurements of ^{222}Rn, ^{220}Rn, ^{214}Pb, and ^{212}Pb Concentrations in the Air of Private and Public Buildings and Their Dependence on Meteorological Conditions, *Health Phys., 29* (1975), pp. 705-711
[43] Schery, S. D., Measurements of Airborne ^{212}Pb and ^{220}Rn at Varied Indoor Locations within the United States, *Health Phys., 29* (1985), pp. 705-712
[44] Ramola, R. C., Negi, M. S., Choubey, V. M., Measurement of Equilibrium Factor "F" between Radon and its Progeny and Thoron and its Progeny in the Indoor Atmosphere Using Nuclear Track Detectors, *Indoor Built Environ., 12* (2003), pp. 351-355
[45] Prasad, G., Prasad, Y., Gusain G. S., Ramola, R. C., Measurement of Radon and Thoron Levels in Soil, Water and Indoor Atmosphere of Budhakedar in Garhwal Himalaya, India, *Radiation Measurements, 43* (2008), S375-S379

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Ганеш ПРАСАД, Гурупад С. ГУСАИН, Вина ЏОШИ, Ракеш Ч. РАМОЛА

ПРОЦЕНА ДОЗЕ УСЛЕД ИЗЛАГАЊА РАДОНОВИМ И ТОРОНОВИМ ПОТОМЦИМА У ЗАТВОРЕНИМ ПРОСТОРИЈАМА

Удео у ефективној дози услед инхалације који потиче од радона и његових потомака значајан је за људско здравље јер доприноси више од 50% укупној дози зрачења из природних извора. Отуда је, после пушења, радон означен другим водећим узроком рака грла. Радон и његови краткоживећи производи присутни у становима (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po) представљају радијациони ризик, посебно ако су ти извори концентрисани у затвореним просторима као што су слабо проветрене куће и подземни копови. Концентрације радона, торона и потомака мерене су у затвореним просторијама малог планинског града Будхакедара и околине, у Техри Гаврхвалу, Индија. Коришћен је LR-115, тип II, пластични траг детектор смештен у двојном радонском дозиметру. Измерене концентрације потомака радона биле су највише зими, а најниже лети, док су концентрације потомака торона биле максималне у кишној сезони, а минималне у јесен. Нађено је да годишње изалагање потенцијалној енергији алфа зрачења од радона и торона варира: за радон, од 0.04 WLM до 0.69 WLM, са средњом вредношћу од 0.29 WLM, а за торон, од 0.03 WLM до 0.37 WLM, са средњом вредношћу од 0.16 WLM. Годишња ефективна доза услед излагања радону и његовим потомцима у затвореним просторијама будхакедарских домова мењала се од 0.16 mSv до 2.71 mSv, са средњом вредношћу од 1.05 mSv. Резултати системског проучавања добијени су водећи рачуна да је соба простор у коме су нивои радона и торона непосредно повезани, са динамичким и статичким параметрима.

Кључне речи: радон, торон, излагање, ефективна доза