EFFECTIVE DOSE EQUIVALENT RATE FOR THE RESPIRATORY TRACT FROM DAUGHTER PRODUCTS OF RADON

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SUMMARY: Using standard models, the dose and dose equivalent received by tracheobronchial (T-B) and pulmonary (P) regions of human lung from exposure to radon daughter products have been estimated. Effective dose equivalent rates determined by OECD, ICRP and UNSCEAR have been compared and the conversion factor of (7-17) nSv h^{-1} per Bq m^{-3} recommended by ICRP has been adapted to find out dose equivalent rate for the house dwellers in the Pakistani cities of Islamabad/Rawalpindi and Lahore. In the bed rooms of these cities an estimated dose equivalent rate of 2 mSv per year was found. For mine workers the conversion factor of 10 mSv y^{-1} per WLM was adapted. The mine workers of Makarwal Coal Mines (Pakistan) receive 8-12 mSv y^{-1} which is 4 to 6 times higher than the value for houses in the cities of Islamabad, Rawalpindi and Lahore.

Key Words: Radon daughter products, tracheobronchial and pulmonary regions, effective dose equivalent rate, dwellings, coal mines.

INTRODUCTION

The daughter products of radon are present in air either as attached with the aerosols or as free atoms (unattached). The attachment of the daughter products with the aerosols in air depends upon the size of aerosols which varies with ventilation rate, cleanliness and living styles of the inhabitants (1, 2). The free fraction of ions or atoms, when inhaled along with air, is mostly removed in the upper part of the respiratory tract; whereas, the attached fraction of the aerosols is deposited in the tracheobronchial (T-B) and pulmonary (P) regions (3). The deposited ions are cleared from the respiratory system by various processes (4-6).

The radon daughter products decaying in the lungs will dissipate their energy in the lung cells. The basal cells are affected by the decaying daughter products and become a cause of lung cancer (7). The probability of lung cancer depends upon the amount of energy dissipated per unit mass, i.e. dose received by different regions of the lung. The dose received depends upon the amount of radon daughters inhaled. This dose depends upon the breathing rate and it is different for children, occupational workers and non occupational public (8).

Taking into account the above mentioned factors, a method has been described for calculation of dose received by the T-B and P regions of human lung. A factor has been chosen for the conversion of Equilibrium Equivalent Concentration (EEC) of radon into effective dose equivalent rate. This factor has been applied for the determination of dose equivalent rate for the residents of the cities of Islamabad/Rawalpindi and Lahore. For the mine workers of Makarwal Coal Mine, the dose equivalent rate has also been calculated using the ICRP recommendations based upon annual limit of exposure to the daughter products of radon as a result of their inhalation.

CALCULATIONS FOR DOSE EQUIVALENT

Calculation of dose due to radon and its daughter products to different parts of a lung is based upon various lung dosimeter models which are based upon various lung models. The important among these are the ICRP, Weibel A and Yeh-Schum lung models (9-11).

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These models differ from each by: (a) the division of lung into different part (generations), (b) the air ways dimensions of the generations, and (c) the transfer mechanism of radon daughter from lung to other parts of the human body (6).

The most commonly used lung dosimeter models are: (a) the Jacobi-Eisfeld (J-E) dose model which uses Weibel A lung model, (b) the James-Birchall (J-B) dose model which considers Weibel A and Yeh-Schum models and (c) the ICRP dose model which takes into account the ICRP lung model. The other quantities differentiating the dose models are (6):

(a) the deposition of unattached fraction of the daughter products which depends upon the airways dimensions and is a function of the age of the breathing person,

(b) the deposition of attached fraction which is a three step process of diffusion, impaction and sedimentation which in turn depends upon the size distribution of aerosols on which the daughter products are attached,

(c) the removal mechanism which is either physical decay or biological removal by sorption or absorption,

(d) the location of basal cells in a lung.

Dose to lung is defined as the energy absorbed per unit mass of the lung tissue. The dose from the daughter products inhaled from air is calculated by energy absorbed by the basal cells of the tracheo-bronchial (T-B) and pulmonary (P) regions of the lung. The energy absorbed in the lung regions is calculated as follows:

If N_i is the number of atoms inhaled in the lung of a nuclide i (i is the index for ^{218}Po, ^{214}Pb or ^{214}Bi= ^{214}Po), the fraction of N_i which decays in the region R (T-B or P) is given by (5):

$$Z^R_{i,k} = d^R_i N_i \prod_{j=i}^{k} \lambda_i \tau^R_j \qquad (1)$$

where,

k= index for the nuclide consideration.

τ^R_j = effective mean residence time of nuclide i in air which can be evaluated from the lung model taking into account the elimination pathways of the considered lung region.

d^R_i = effective deposition probability of nuclide i.

$$d^R_i = \eta\, d^{R,f}_i + (1-\eta)\, d^{R,a}_i \qquad (2)$$

where,

f = index for free atoms.

a = index for attached atoms.

η = relative fraction of the free radioactive atoms in inhaled air.

If E^R_k is the absorbed energy in region R per decay of k-atoms, the absorbed energy W^R_i in the region R arising from N_i atoms inhaled i

$$W^R_i = \sum_{k=i}^{3} E^R_k Z^R_{i,k} = d^R_i N_i \omega^R_i \qquad (3)$$

with

$$\omega^R_i = \sum_{k=i}^{3} \left(E^R_k \prod_{j=i}^{k} \lambda_i \tau^R_j \right) \qquad (4)$$

where,

ω^R_i = the absorbed energy in the region R per deposited atom of the nuclide i.

The total absorbed energy W^R in the region R due to inhalation of all daughter nuclides in a decay chain is given by:

$$W^R = W^{R,f} + W^{R,a} \qquad (5)$$

with

$$W^{R,f} = A_o \eta\, d^{R,f} \sum_{i=1}^{3} \omega^R_i k^f_i / \lambda_i \qquad (6)$$

and

$$W^{R,a} = A_o (1-\eta)\, d^{R,a} \sum_{i=1}^{3} \omega^R_i k^a_i / \lambda_i \qquad (7)$$

where N_i has been replaced by A_o/λ_i and k_i is a function of air exchange rate, aerosol size, etc. (5).

The substitution of Eqs. (6) and (7) in Eq. (5) gives

$$W^R = A_o \sum_{i=1}^{3} \frac{\omega^R_i}{\lambda_i} \left[\eta\, d^{R,f} k^f_i + (1-\eta)\, d^{R,a} k^a_i \right] \qquad (8)$$

If f_p is the fraction of the total potential alpha energy that is unattached, B is the breathing rate, m^R is the mass of region R then from energy absorbed as given by Eq. (8), the absorbed dose rate can be estimated by multiplying it with breathing rate, B and dividing with the mass, m^R .The absorbed dose D^R in region R of mass m^R can be calculated as follows:

$$D^R = A_o B\left[f_p D^{R,f} + \left(1-f_p\right)D^{R,a}\right] \qquad (9)$$

where the first factor is due to free fraction and second term is due to fraction attached to aerosols.

Since almost all the unattached activity of the daughter products is removed in and above the T-B region, the contribution of the unattached fraction is negligible in the P region of the lung. The radon dose in the T-B and P regions of the lung will be

$$D^{T-B} = A_o B\left[f_p D^{T-B,f} + \left(1-f_p\right)D^{T-B,a}\right] \qquad (10)$$

and

$$D^P = A_o B\left(1-f_p\right)D^{P,a} \qquad (11)$$

The contribution to the regional lung dose from the free atoms and attached fraction of the potential alpha energy can be combined to derive an effective dose equivalent H_E using the quality factor for alpha particles and the concept of weighting factor of ICRP (12). The total weighting factor for lung can be split up into two equal weighting factors for the T-B and P regions. Here the dose to tissues other than lung can be neglected (8). The effective dose equivalent H_E, therefore, will be

$$H_E = A_o Q B\left\{W^{T-B}\left[f_p D^{T-B,f} + \left(1-f_p\right)D^{T-B,a}\right] + W^P\left(1-f_p\right)D^{P,a}\right\} \qquad (12)$$

The effective dose equivalent per unit of intake will be

$$\frac{H_E}{A_o B} = Q\left\{W^{T-B}\left[f_p D^{T-B,f} + \left(1-f_p\right)D^{T-B,a}\right] + W^P\left(1-f_p\right)D^{P,a}\right\} \qquad (13)$$

CONVERSION FACTORS

The effective dose equivalent H_E can be obtained b using the quality factor Q=20 for alpha particles and weighting factor $W^{T-B}=W^P=0.06$ for T-B and P regions of lung in Eq. (13). ICRP (1) and OECD (2) have given the functions derived from the dosimetric models relating the effective dose equivalent to potential alpha energy exposure in terms of aerosol activity median diameter (AMD) and free atom fraction of potential alpha energy, f_p. For house dwellers, the OECD has given the range of effective dose equivalent per unit of potential alpha energy exposure, for AMD=0.1-0.2, f_f=0.05-0.02 and B=0.75 m^3 h^{-1}, and for occupational exposure to ^{222}Rn daughters the ICRP has given the range of effective dose equivalent per unit of potential alpha energy exposure, for AMD=0.2-0.3, ≤0.05 and B=1.2 m^3 h^{-1} . The range of effective dose equivalent per unit of potential energy exposure obtained from the OECD and ICRP is given in Table 1. The range of these quantities has also been reported by UNSCEAR (8) and is given in Table 1.

Table 1: The recommendations of the radiation protection agencies for the conversion of potential alpha energy exposure (Bq h m^{-3}) to effective dose equivalent (nSv).

Agency	Conversion factor (nSv/Bq h m^{-3})	Breathing rate (m^3 h^{-1})	AMD (μm)	f_p	References
ICRP	7-17	1.2	0.2-0.3	0.05-0.00	(1)
OECD	8-16	0.75	0.1-0.2	0.05-0.02	(2)
UNSCEAR	9-17	0.8	0.1-0.2	0.05-0.025	(8)

As can be seen from Table 1, the range recommended by ICRP covers the values recommended by OECD and UNSCEAR. Therefore, ICRP value of (7-17) nSv per Bq h m^{-3} will be used for conversion of potential alpha energy exposure to dose equivalent. If one wants to use a single value, the UNSCEAR value of 10 nSv per Bq h m^{-3} will be used (13).

It may be noted that all the dosimetric coefficients given above refer to adult members of the public. Correction factors should be applied for infants and children to account for the age dependent change in lung mass and breathing rate. The effective dose equivalent for the age group of up to ten years might, on the average, be a factor of 1.5-2 higher than for the adults (8).

DOSE EQUIVALENT RATE FOR THE RESIDENTS OF VARIOUS CITIES

Internal dose rate

Radon concentration was measured in different types of rooms in the cities of Islamabad/Rawalpindi and Lahore (14). To determine the range of dose equivalent rate for the people living in these cities, the minimum and the maximum values were chosen from all categories of rooms. A conversion factor of (7-17) nSv h^{-1} per Bq m^{-3} of ICRP was used for calculating the range of internal effective dose equivalent rate for the population of these cities. While calculating the effective dose equivalent rate, the radon concentration measured in these cities was multiplied with the equilibrium factor (F) of 0.5 (13) to convert it to equilibrium equivalent concentration of radon. Moreover, it was assumed that 80% of the time is spent indoors.

The range of dose equivalent rate versus radon concentration has been shown in Figure 1. For internal dose due to radon it is very difficult to specify a particular value, rather one has to take into account a wide range of values. As can be seen from the figure, the area subtended by the dose equivalent rate for the dwellers of the city of Lahore is more than that for the cities of Islamabad and Rawalpindi.

The size of bedrooms is mostly about 4 m x 5 m x 2.5 m and wall thickness is about 0.2 m, the external dose equivalent rate $\mathring{H}$ (mSv / y) at the center of the room assuming that 80% of the total time is spent indoors is given by (17):

$$\mathring{H} = 4.9 \times 10^{-3} \sum C_j A_j \qquad (14)$$

where, C_j are the coefficients of dose equivalent rate (nGy h^{-1}) for different isotopes having A_j (Bq kg^{-1}) concentration. For calculation of external dose equivalent rate, the coefficients based upon mesh adoptive approach by Mirza *et al.* (18) and Tufail *et al.* (19) have been used. The dose equivalent rates for the walls made of bricks fixed with mud have been calculated using Eq. (14) and the values so obtained are given in Table 2 for the rooms in the cities of Islamabad/Rawalpindi and Lahore. The values of external dose equivalent rate for the bedrooms of the city of Lahore is about 20% more than that found for the rooms in the cities of Islamabad and Rawalpindi.

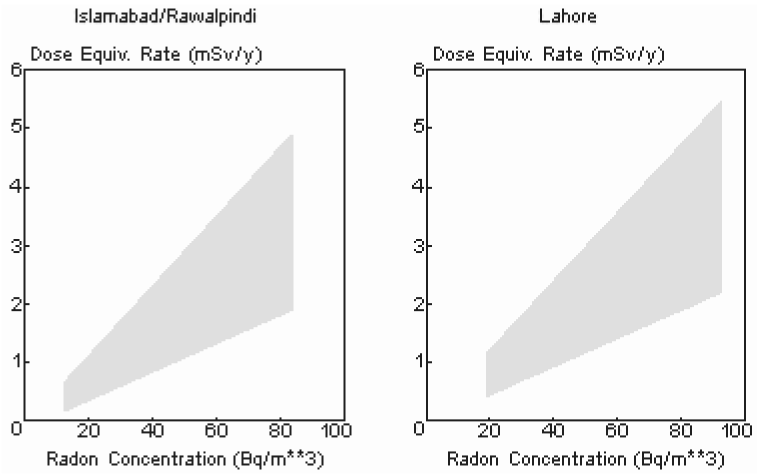

Figure 1: Dose equivalent rates for the population living in the cities of Islamabad/Rawalpindi and Lahore.

External dose rate

In the cities of Islamabad/Rawalpindi and Lahore, most of the buildings are constructed by fixing the clay bricks with mud or cement-sand mixture and plastering them with cement-sand mixture. The volume ratio for mud, cement-sand mixture and bricks in such a construction is 1:1.5:22. Therefore, for practical purposes it can be considered that the walls are made of bricks. The activity concentration in the bricks used in the cities of Islamabad/Rawalpindi and Lahore was measured and reported elsewhere (15, 16).

Comparison

For comparison purposes we have taken the average values of radon concentration in the bedrooms of the cities of Islamabad/Rawalpindi and Lahore. As stated earlier, the internal dose cannot be specified as one particular value because it depends upon various

Table 2: The external dose equivalent rate from the walls of a room and the internal dose equivalent rate from radon in the bedroom of the cities of Islamabad/Rawalpindi and Lahore.

Conversion factor 1 Bq m^{-3} = (7-17) nSv y^{-1}		
Location	Dose Equivalent (mSv y^{-1})	
	External	Internal
Islamabad/Rawalpindi	0.9	1.8
Lahore	1.1	2.0

factors. However, a dose equivalent rate conversion factor of 10 nSv hr^{-1} per Bq m^{-3} (13) has been applied to the average values of radon concentration in bedrooms. The values of internal dose equivalent rates in the bedrooms of the cities of Islamabad/Rawalpindi and Lahore are given in Table 2. The internal dose equivalent rate value found in the city of Lahore is about 10% higher than those found in the cities of Islamabad and Rawalpindi. The reasons of higher values have been given elsewhere (14).

The internal and external dose equivalent rates cannot be directly related because the radon concentration in a room depends not only upon the material type and dimensions of the rooms but also upon factors such as infiltration and ventilation rates, meteorological parameters, etc. But the external dose depends on the material type and the room dimensions. Therefore, as a rough guess one can say that the internal dose is by a factor two more than the external dose in a standard size room.

DOSE EQUIVALENT RATE FOR THE WORKERS OF MAKARWAL COAL MINES

Concentration of radon daughter products was measured in the Coal Mines of Makarwal using the air sampling techniques of Thomas and Kusnetz (20, 21). The sul have been published elsewhere (22). The average value of the concentration of radon daughter products as given in Table 3 has been considered for estimation of dose equivalent rate.

As far as the conversion of exposure (WLM) to dose is concerned a factor is derived from the annual limit of potential alpha energy exposure (ALE_p). ICRP recommend an ALE_p of 4.8 WLM for the occupational workers which corresponds to a dose equivalents rate of 50 mSv per year. Therefore, the annual exposure to dose conversion factor of 10 mSv per WLM, based upon the recommendations of ICRP is adapted.

From the radon exposures given in Table 3, annual dose equivalent rate has been calculated and is given in the same table. The dose equivalent rate in the mine is about 9 mSv /y provided the mine workers spend 170 hours per month and work 12 months in a year.

Table 3: Dose equivalent rate for the people working in the Coal Mines of Makarwal, Pakistan.

Conversion factor IWLM = 10 mSv y^{-1}		
Method	Radon Exposure WLM	Dose Equivalent rate (mSv y^{-1})
Kusnetz	0.952	9.5
Thomas	0.834	8.3

Therefore, it is recommended that in these mines a mine worker must not spend more than 2000 hours per year, otherwise, he will get more dose equivalent rate which is not desirable.

CONCLUSIONS

The dose equivalent rate calculated in the bedrooms of the cities of Islamabad/Rawalpindi and Lahore was found to be about 2 mSv y^{-1}. The dose received by the mine workers is about 4 to 6 times more than that received by the population living in cities of Islamabad/Rawalpindi and Lahore.

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