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SHORT COMMUNICATION

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Comparison of dose conversion factors for radon progeny from the ICRP 66 regional model and an airway tube model of tracheo-bronchial tree

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Abstract Current epidemiological approaches to radon dosimetry yield a dose conversion factor (DCF) of 4 mSv WLM^{-1} while the dosimetric approaches give a value closer to 13 mSv WLM^{-1}. The present study investigated whether the application of compartment models for the bronchial (BB) and bronchiolar (bb) regions, rather than more anatomically realistic airway tube models, has brought the dosimetric DCF to the higher values. The airway tube model of the tracheo-bronchial tree was used to calculate the effective dose per unit radon exposure. All other elements of the human respiratory tract from the reports of the ICRP or NRC were adopted. A dosimetric derivation of the radon DCF using the airway tube model yielded a value of 14.2 mSv WLM^{-1}. This value is slightly larger than, but not significantly different from, the result obtained through the ICRP 66 approach. It is concluded that utilization of the airway tube model instead of the regional ICRP 66 compartmental model cannot reconcile the gap between dose conversion factors derived from epidemiological and dosimetric approaches.

Introduction

Inhalation of radon progeny ^{218}Po, ^{214}Pb, and ^{214}Bi (^{214}Po) in homes and working places constitutes the highest exposure to natural radiation for members of the general public. The dose conversion factor (DCF) given in mSv WLM^{-1}, is defined as the effective dose per potential alpha energy exposure. Two methods, namely, the dosimetric and the epidemiological approach, are used to estimate the DCF. The epidemiological approach, based on the data obtained from Japanese atomic bomb survivors and uranium miners, gives a value of approximately 4 mSv WLM^{-1}. In contrast, the dosimetric approach based on ICRP Publication 66 [1] gives this same quantity as 13.4 mSv WLM^{-1} which is approximately three times larger than that derived from the epidemiological approach. The discrepancy led the ICRP to recommend a conversion convention factor based on epidemiological considerations to relate radon progeny exposures and lung cancer risk [2].

There are two groups of parameters in the ICRP 66 human respiratory tract model (HRTM); namely, (a) aerosol-related parameters and (b) subject-related parameters. Marsh and Birchall [3] recently analyzed the effects of different parameters on the DCF. The best estimates and realistic ranges for all parameters were defined. All parameters were then kept at their best-estimated values except the one being considered, which was varied over its realistic range. In this way the most important parameters were identified, and all parameters were categorized according to their influence on the radon DCF. In this analysis, the DCF values calculated using the ICRP 66 method were almost always larger than 10 mSv WLM^{-1}. In a second ''sensitivity'' analysis performed by Marsh et al. [4], all parameters were changed simultaneously according to some distributions. The main conclusion of both these analyses was that the variability of the parameters could not explain the difference between the results from the epidemiological and dosimetric approaches.

ICRP Publication 66 considers the HRT as a sequence of five filters in series, with two filters representing the extrathoracic (ET1 and ET2) regions. The tracheo-bronchiolar (T-B) part of the human lung is represented by another two filters, one for the bronchial or BB region (generations 1–8) and another one for the bronchiolar or bb region (generations 9–16). A fifth filter

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presents the alveolar interstitial region (AI). An algebraic model was developed to calculate deposition in all these filters. Although the airway tube structure of the T-B tree was described in ICRP Publication 66, including airway diameters, radii, branching angle, gravity angle, etc., the tube structures of BB and bb regions were ignored during the calculations of deposition, clearance, and the resultant regional tissue absorbed dose. In addition, an expression for calculating the deposition of airborne aerosols in a given airway tube was given in ICRP Publication 66 (p. 263), but was not used.

The objective of the present work is to investigate whether the application of compartment models for the BB and bb regions, instead of the realistic tube models, has brought a DCF value much higher than the value derived epidemiologically.

Calculation model

The main part of the computer software employed in this study was written based on the ICRP Publication 66 model. A brief review of the model can be found in [5]. Some parts of the model are also adopted from NRC [6].

Deposition

Aerosol deposition in airway tubes was calculated using the Ingham equation given in ICRP Publication 66 (p. 263 in [1]). Ingham [7] gave the following expression for the deposition efficiency in a cylindrical tube for a parabolic and laminar flow:

$$\eta_{\mathrm{th}} = 1 - 0.819\mathrm{e}^{-14.63\Delta} - 0.097\mathrm{e}^{89.22\Delta} - 0.0325\mathrm{e}^{-228\Delta} - 0.0509\mathrm{e}^{-125.9\Delta^{2/3}} \quad (1)$$

$$\Delta = \frac{\pi l D}{4V}, \quad (2)$$

where l is the airway length, D the diffusion coefficient and V is the flow rate.

Other deposition mechanisms like sedimentation and impaction can be important in the ICRP 66 HRTM. Impactional deposition in an airway tube, η_{ID}, was calculated by using the Gurman expression [8] as follows (see also p. 262 in [1]):

$$\eta_{\mathrm{ID}} = aS_{\mathrm{tk}}^{b}, \quad (3)$$

where $a = 6.4$ and $b = 1.43$ for generations 1–3, and $a = 1.78$ and $b = 1.25$ for other generations [9], and S_{tk} is the stokes number. Calculations have shown that impactional deposition is small after the fifth generation in comparison to diffusional deposition in the entire range of aerosol diameters of interest.

Deposition by sedimentation was calculated using the expression of Chang et al. [10]:

$$\eta_{\mathrm{sed}} = 1 - \mathrm{e}^{\frac{4gC\rho Lr^2\cos\Phi}{9\pi\mu Rv}} \quad (4)$$

where η_{sed} is the sedimentation deposition probability, g the acceleration due to gravity, ρ the density of the particle, Φ the inclination angle relative to the horizontal, C the Cunningham slip correction factor, r the radius of the particle, R the radius of the airway, μ the viscosity of air and v is the mean flow velocity of air. Impaction and sedimentation are more important for larger particles, while diffusion deposition is dominant for very small particles.

The effect of inertial and sediment deposition were combined to give an overall aerodynamic deposition η_{ae} according to ICRP Publication 66 (formula D.10 in [1]):

$$\eta_{\mathrm{ae}} = 1 - (1 - \eta_{\mathrm{IM}})(1 - \eta_{\mathrm{sed}}) \quad (5)$$

Finally, thermodynamic and aerodynamic depositions were combined as (formula D.16 in [1]):

$$\eta = \sqrt{\eta_{\mathrm{th}}^2 + \eta_{\mathrm{ae}}^2} \quad (6)$$

Deposition in other regions of the HRTM, namely, ET1, ET2, and AI, were calculated by using the algebraic model of ICRP Publication 66 (Table 12, p. 45 of ICRP Publication 66). Depositions in generations 1–16 were calculated using Eqs. (1)–(6), assuming the tube structure of airways in the BB and bb regions. Each airway generation in the BB and bb regions was considered a filter, which collected radon progeny from the air stream passing through the tubes.

Clearance, transfer to blood, and equilibrium activity calculation

To calculate the equilibrium activity in each generation, a clearance model is needed. The main clearance mechanisms in the T-B tree are through mucus movement and transfer to blood.

ICRP Publication 66 did not make a recommendation on the mucus transit time for generations 1–16 in the T-B tree [1]. Comparisons among mucus velocities and clearance time from different authors were given on page 343 of ICRP Publication 66 (Table E.10 in [1]). Two values for the particle transport rate, i.e., 10 days^{-1} ($t_{1/2}$ = 100 min) and 2 days^{-1} ($t_{1/2}$ = 8 h) for the BB and bb regions, were given in ICRP Publication 66 (p. 71 in [1]). Since the data for the mucus transit time through the generation were missing in ICRP Publication 66, the mucus clearance rates through the T-B tree were calculated based on the mucus transit time given by NRC (p.206 in [6]), which are also presented here in Table 1. The mucus transit time in generation 1 (trachea) and 17 were not given by NRC, and were estimated here based on the trends of the data of NRC [6].

The clearance to blood depends on the physical–chemical form of the carrying aerosol. The ICRP 66 model for transfer to blood was rather complicated and

Table 1 Mucus transit time as a function of the branching generation the in T-B tree [6]. The mucus transit time in generation 1 (trachea) and 17 are not given by NRC, and were estimated based on the trends of the data of NRC [6]

Generation	Mucus transit time (min)
1	5
2	11
3	9
4	7
5	10
6	11
7	13
8	16
9	22
10	22
11	28
12	45
13	91
14	143
15	417
16	1,667
17	1,940

The mucus transit time in generation 1 (trachea) and 17 are not given by NRC, and were estimated based on the trends of the data of NRC [6]

no single value for the transport rate was given. It was stated that due to the lack of information one has to assume equal transport rates in all regions except ET. In the sensitivity analysis mentioned above [3], 10 h was used as the half time for transfer to blood. This value was derived from the work of Booker et al. [11] and Greenhalgh et al. [12], and was also applied in the present study.

The balance of the radon progeny in a tube, determined by different mechanisms (decay, clearance, deposition), is described by a set of differential equations summarized as:

$$\frac{\mathrm{d}N_{i,j}}{\mathrm{d}t} = \frac{B_{i,j}}{\lambda_i} + A_{i-1,j} + 2\lambda_{c,j+1}N_{i,j+1} - \left(\lambda_i + \lambda_b + \lambda_{c,j}\right)N_{i,j} \tag{7}$$

where $N_{i,j}$ is the number of atoms of the ith radon progeny in the jth generation of the T-B tree, $B_{i,j}$ the activity of the ith radon progeny deposited in the jth generation per unit time (in Bq $s^{-1}m^{-2}$), $A_{i,j}$ the equilibrium activity (in Bq m^{-2}), λ_i the decay constant of the ith Rn progeny, $\lambda_{c,j}$ the mucus clearance rate in the jth generation and λ_b is the transfer rate to blood (all λ values in s^{-1}). As a final result, the equilibrium activity of radon progeny in the mucus of the airway is obtained.

Translocation of activities from the AI region to the bb region was also taken into account with the transfer rate given in ICRP Publication 66. In the ICRP 66 terminology, there are clearance paths m_{14}, m_{24}, and m_{34} with half times of 35, 700 and 7,000 days, respectively. This transport route increased the radioactivity in the 16th generation of T-B tree.

Input parameters

Input parameters used in the calculations were as follows: equilibrium factor between radon and its short lived progeny = 0.4; particle density ρ = 1g cm^{-3}; particle shape factor χ = 1; hygroscopic particles growth = 1; fraction of breathing through the nose = 1; breathing rate = 0.78 m^3 h^{-1}; one modal log-normal distribution of attached radon progeny with AMTD = 0.17 μm and geometrical standard deviation σ_g = 2.31; unattached fraction = 0.08; unattached radon progeny distributed according to the log-normal distribution with $AMTD_u$ = 0.9 nm and $\sigma_{g,u}$ = 1.3.

Absorbed dose calculation

Here, the conversion factor is defined as the absorbed dose per one disintegration of a radon progeny per unit surface on the inner airway tube wall (in Gy disintegration^{-1} m^{-2}). NRC previously used the same quantity (p. 198, 200 in [6]). To determine the conversion factors, the airway wall models of ICRP Publication 66 were adopted (p. 15–17 in [1]), which provided information on the structure of the wall, thickness and depths of various cell layers, and the geometry of target and source tissues. The targets were the basal and secretory cells in the BB region and secretory cells in the bb region. Conversion factors were calculated in this study for each T–B generation using the approach described by Nikezic et al. [13]. The results are given in Figs. 1 and 2 along with the data from NRC [6] given for comparison.

In Fig. 1, the data for basal cells are presented. Since these cells are present only in the BB region, the data are given up to the eight-generation. The data from NRC are shown as a horizontal solid line. A low conversion factor for 6 MeV (bottom of the Fig. 1) is obtained because the basal-cell layer is very deep within the epithelium. The distance from the source tissue (i.e., mucus)

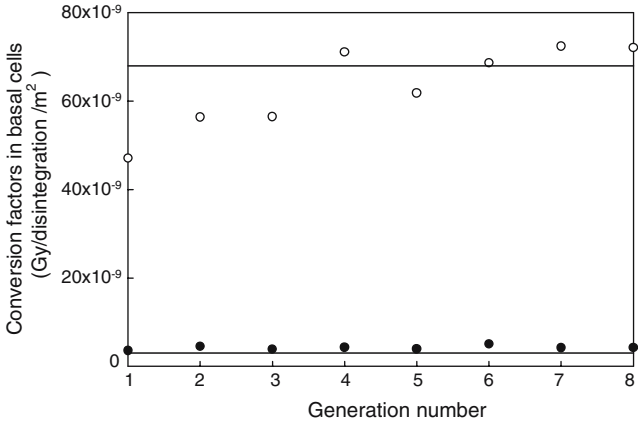

Fig. 1 Conversion factors for basal cells. Our calculations for each generation are shown by the scattered data, while the NRC results are shown as *solid lines*. *Filled circles* 6 MeV, *open circles* 7.69 MeV

to the basal cells is close to the range of the 6 MeV alpha particles in tissue. The conversion factor for 7.69 MeV alpha particles is much larger. The NRC data are good representations of the points obtained by our computational model.

In Fig. 2, the data for the conversion factors for secretory cells for generations 1–16 are given. The conversion factor for 6 MeV alpha particles is not negligible in the BB region because these cells are closer to the source tissue. There is a discontinuity in the data between the 8 and 9 generations, which is caused by the different models of the airway wall used in the calculations (see Figs. 5, 6, pp. 15 and 17 in [1]). The conversion factor can be recalculated as the absorbed fraction (AF), which was used in ICRP Publication 66. The AFs are given for different combinations of sources and targets, but they are defined only for these tissue regions. Here we need the conversion factor for each airway tube in the T–B tree for generations 1–16.

Dose weighting

The outputs from the computer program are the absorbed doses to the basal and secretory cells in different generations of the T–B tree. The absorbed dose values are first weighted according to the surface area of different generations; this weighting was not mentioned in ICRP Publication 66, but can be implied. The absorbed doses calculated for basal cells, $D_{BB,bas}$, and those for secretory cells, $D_{BB,sec}$, in the BB region are further weighted assuming the same sensitivity of these cells, so that the dose D_{BB} in the BB region was determined as $D_{BB} = 0.5D_{BB,bas} + 0.5D_{BB,sec}$. Marsh and Birchall [3] previously employed the same weighting scheme [3]. These weighting coefficients of 0.5 were used because there are no data on the relative sensitivities of the basal cells and secretory cells to alpha radiation and induction of lung cancer. The dose D_{bb} in the bb region is equal to the dose for secretory cells, because there are no basal cells in this region. The absorbed dose in the T–B tree is then found as $D = 0.333 \times D_{BB} + 0.333 \times D_{bb}$. The weighting coefficients, 0.333, for the BB and bb regions were recommended in ICRP Publication 66 (p. 35 Table 10 in [1]). These are assumed because of the lack of confident experimental data regarding the origin of lung cancers within the respiratory tract tissues. The effective dose E is finally calculated as $E = 0.12 \times 20 \times D$, where 0.12 is the tissue-weighting factor for the lung and 20 is the radiation weighting factor for alpha particles. The described weighting procedures were suggested in ICRP Publication 66 [1].

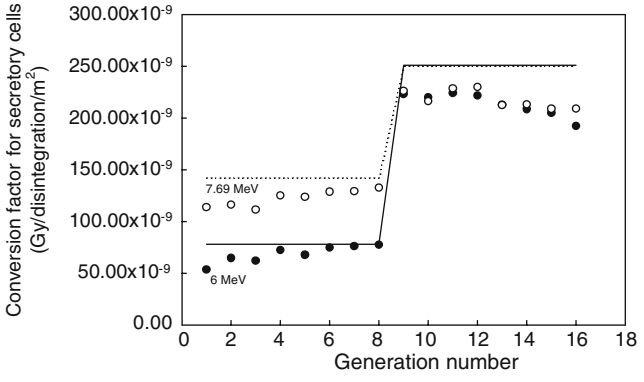

Fig. 2 Conversion factors for secretory cells. Our calculations for each generation are shown by the scattered data, while the NRC results are shown as *solid* and *dotted lines*. *Filled circles* 6 MeV, *open circles* 7.69 MeV

Results and conclusions

In the present work, the ICRP 66 dosimetric model of the human respiratory tract was applied. The only modification made in the present work was that the BB and bb regions (generations 1–16) were now considered as a system of airway tubes while these were considered as two separate compartmental regions in ICRP Publication 66. All other elements of the model were kept consistent as much as possible with those recommended in ICRP Publication 66, including the deposition in the ET1, ET2, and AI compartments, the clearance model, as well as procedures in calculating and weighting the regional tissues absorbed doses. The doses in the BB and bb regions were calculated by multiplying the dose conversion factors with the equilibrium surface activities in each airway generation, while ICRP Publication 66 recommended multiplying the total activities in the BB and bb regions with the absorbed fractions.

Only one calculated result is presented here. We obtained the DCF as 14.2 mSv WLM^{-1} based upon the computational model of the present study. This value is slightly larger than, but not significantly different from, the result obtained through the ICRP Publication 66 approach presented in Marsh and coworkers [3, 4]. From this result, we conclude that utilizing the airway tube model for the BB and bb regions, instead of the compartment models used by ICRP Publication 66, does not resolve the difference between DCF values derived from the epidemiological and dosimetric approaches.

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