Annales Univ. Sci. Budapest., Sect. Comp. 44 (2015) 37–47

DEPOSITION AND CLEARANCE OF INHALED RADON PROGENIES IN THE BRONCHIAL AIRWAYS

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Communicated by Antal Járai

(Received December 30, 2014; accepted March 23, 2015)

Abstract. Majority of lung cancers in the case of former uranium miners were developed in the central airways where the deposition densities of inhaled radon progenies have the highest values. Up to the present no one has compared the radiation burden of primarily deposited radon progenies in the central airways with the radiation burden of radon daughter elements cleared up into the central airways from the more distal bronchial regions. In this paper, this comparison has been realized. Published dosimetric models compute only the primarily deposited fractions and neglect the concomitant effect of clearance.

In the present work, the deposition distribution of inhaled radon progenies was computed by the Stochastic Lung Model in each bronchial airway generation. A clearance model was developed to compute the mucociliary clearance of deposited particles. In addition, a dosimetric model was elaborated to determine the radiation burden of primarily deposited and the radiation burden of up-cleared radon progenies in each bronchial airway generation.

Based on the results, in the first few airway generations, the burden of the up-cleared radon progenies is about two–three times higher than that of the primarily deposited particles. Thus, the concomitant effect of clearance should not be neglected in this region at the dosimetric and health effects considerations of inhaled radon progenies.

Key words and phrases: Bronchial airways, clearance, lung deposition, numerical modeling, radon progenies.

2010 Mathematics Subject Classification: 34A05, 37-04, 37A50, 37A60, 60A99.

This work has been carried out in the frame of VKSZ_14-1-2015-0021 Hungarian project supported by the National Research, Development and Innovation Fund.

1. Introduction

Large scale histopathological studies [11], [5], [8], [9] have demonstrated that inhaled radon progenies induced pre-neoplastic and neoplastic lesions in addition lung carcinomas predominantly in the large bronchi, especially in airway generations 3–5 in the case of the former uranium miners. Three-dimensional computational fluid dynamics calculations depicted high primary deposition density values in this region of the thoracic airways [3]. Thus, in this region, there is a strong correlation between local burden and neoplastic lesions.

The dose contributions of the primary deposited and the dose contributios of the up cleared radon progenies in the large bronchial airways are not compared with each other in the literature. It seems to be a reasonable task to calculate the primary deposition fractions in the whole bronchial region as a function of airway generation number, to compute the clearance of deposited particles, to estimate the radiation burden of both the deposited and the up-cleared fractions, and compare these two components of radiation burden as a function of airway generation number.

The main input data of the new clearance model were the mucus velocities as a function of airway generation number, the half-life of radon progenies (^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po), the lengths of the airways and the deposition fraction values in each airway generation. Before the application of the clearance model, lengths and deposition fraction values were computed by the Stochastic Lung Model.

The radiation burden in each airway generation were determined both for the primary deposited and the up-cleared radon progenies by computing the absorbed energy of emitted α-particles divided by the surface area of the airway generation for a large number of attached radon progenies. The ratios of the inhaled different radon daughter elements were characteristic to the former New Mexico uranium mine.

The main objective of this study was to compare the radiation burden of the primarily deposited and the up-cleared radon progeny fractions in the central human airways as a function of airway generation number.

2. Methods

2.1. Mathematical background

The decay of a radioactive isotope can be written with the differential equation:

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} + \lambda N(t) = 0,$$

where $N(t)$ is the number of particles as a function of time and λ is the decay constant. This is a homogenous linear first order linear differential equation with solution

$$N(t) = N_0 \cdot e^{-\lambda t},$$

where N_0 is the number of radon progeny particles at the starting moment $t = 0$.

It is more complex to calculate with isotopes being together with their parent element. In this case, the decay of the parent element increases while the decay of the progeny decreases the quantity of the daughter element. This can be written by the equation

$$\frac{\mathrm{d}N_2(t)}{\mathrm{d}t} + \lambda_2 N_2(t) = \lambda_1 N_1(t) = \lambda_1 N_1^0 e^{-\lambda_1 t}.$$

Here N_1 and N_2 are the quantity of the parent element (e.g., ^{218}Po) and the progeny (e.g., ^{214}Pb), respectively. We assume that the parent of the parent element is not present in the system. Therefore, the solution of the equation is:

$$N_2(t) = N_2^0 \cdot e^{-\lambda_2 \cdot t} + \frac{\lambda_1}{\lambda_2 - \lambda_1} N_1^0 (e^{-\lambda_1 \cdot t} - e^{-\lambda_2 \cdot t}).$$

If this radon progeny (N_2) can decay further to another radioactive isotope then the amount of the new daughter element (N_3) can be expressed by the following equation:

$$\frac{\mathrm{d}N_3(t)}{\mathrm{d}t} = \lambda_2 N_2(t) - \lambda_3 N_3(t),$$

which has the solution

$$N_3(t) = N_3^0 \cdot e^{-\lambda_3 \cdot t} + \frac{\lambda_2}{\lambda_3 - \lambda_2} N_2^0 (e^{-\lambda_2 \cdot t} - e^{-\lambda_3 \cdot t}) + \\ + \frac{\lambda_2 \cdot \lambda_1}{\lambda_2 - \lambda_1} N_1^0 \left(\frac{e^{-\lambda_1 \cdot t} - e^{-\lambda_3 \cdot t}}{\lambda_3 - \lambda_1} - \frac{e^{-\lambda_2 \cdot t} - e^{-\lambda_3 \cdot t}}{\lambda_3 - \lambda_2} \right).$$

We need to calculate how many α-particles are emitted within a certain time interval. These functions are to be integrated on the corresponding intervals.

Three functions have been applied though the current study assumes the series of ^{218}Po → ^{214}Pb → ^{214}Bi → ^{214}Po. Because the half life of ^{214}Po (164 μs) is very short compare to that of ^{214}Bi (19.7 min), therefore, if ^{214}Bi decays it can be assumed that ^{214}Po immediately emits an α-particle, that is, ^{214}Bi and ^{214}Po are in equilibrium.

2.2. Biophysical and physiological background

In the present work, the primary deposition distributions of the inhaled radon progenies were computed in the whole respiratory system by the newest version of stochastic lung deposition model [7]. Particle deposition simulations were performed at four different breathing conditions characteristic of sleeping, sitting, light exercise and heavy exercise physical activities. Functional residual capacity (FRC), tidal volume, and breathing cycle times characteristic of an adult man during these four types of breathing activities were applied from ICRP66 [1] publication. The FRC is 3300 cm^3, the other values are represented in Table 1. For the heavy exercise breathing condition deposition distributions both for mouth and nose breathing modes were calculated and in the final computations the average of the two deposition values were used; this corresponds the 50% mouth and 50% nose breathing. For the other three breathing modes only nose breathing was supposed.

	Sleeping	Sitting	Light exercise	Heavy exercise
Tidal volume (cm^3)	625	750	1250	1923
Breath cycle (min^{-1})	12	12	20	26

Table 1. The breathing parameters of the four breathing conditions according to ICRP66 [1].

A new bronchial clearance model has been elaborated to simulate the up clearing fractions of particles deposited from the deeper airway generations. Particles trapped by the high viscosity mucus were assumed to move together with the mucus layer. Mucus velocity values were derived from the available literature.

Figure 1 presents the velocity of the mucus layer as a function of airway generation number.

Further input data of the clearance model are furthermore the average tube length and surface area of each generation which were also calculated by the Stochastic Lung Model (see Table 2).

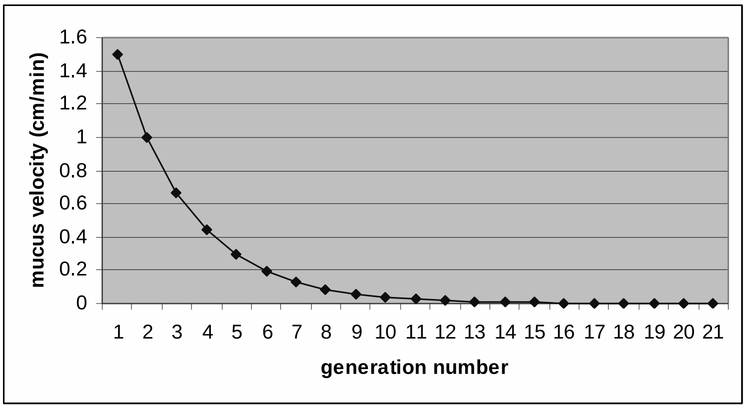

Figure 1. Mucus velocity in the bronchial region according to Chopra [4], and Hofmann and Sturm [6].

Generation number	**Length (cm)**	**Surface (cm^2)**
1	10.93	72.2
2	2.81	23.6
3	1.13	22.5
4	1.54	30.3
5	1.14	45.6
6	0.97	59.3
7	0.80	84.7
8	0.76	124
9	0.56	168
10	0.39	227
11	0.50	293
12	0.30	375
13	0.34	480
14	0.26	609
15	0.16	758
16	0.13	959
17	0.13	1170
18	0.12	1310
19	0.11	1400
20	0.10	1450

Table 2. The length of the tubes and the surface of the airway generations according to Koblinger and Hofmann [7].

The applied particle diameter is considered to be 200 nm which is the most frequent aerodynamic diameter in the number distribution of the environment aerosols [1]. Based on the computations performed with the Stochastic Lung Model, the particles with diameter of 1 nm deposit over 90% in the extra thoracic region, so we did not calculate with the burden of the unattached fraction which consists of particles with this size.

In each of the Stochastic Lung Model computations we have selected 100 000 particles. According to UNSCEAR 2000 [10], the ratio of ^{218}Po, ^{214}Pb and ^{214}Bi concentrations is 6:4:3, respectively in the New Mexico uranium mine. For ^{218}Po we have to calculate with quasi double burden: an atom of this radon progeny emits an α-particle becoming ^{214}Pb with energy of 6 MeV, from this particle we get ^{214}Bi with β-decay, and finally a ^{214}Po. However, the ^{214}Po emits an α immediately (after 164 μs) with 7.69 MeV.

Regarding the radioactive burden of the bronchial epithelium, in the cases of ^{214}Pb and ^{214}Bi radioisotopes, which are β-emitters, we only need to calculate with a single α-emission with 7.69 MeV which originates from the decay of ^{214}Po.

Finally, we divided in each airway generation the emitted energy by the surface area and thus, we have received the emitted energy on a unit surface (radiation burden) in MeV/cm^2 in each airway generation.

3. Results

The Stochastic Lung Model has been applied for sleeping, sitting, light exercise and heavy exercise breathing conditions to compute the total, regional and airway generation level deposition fractions of inhaled attached radon progenies.

The computed radiation burden as a function of airway generation number (MeV/cm2) values originated from deposition and clearance for the four breathing patterns are summarized on Figures 2–5. The extrathoracic deposition values are listed in Table 3.

Breathing mode	Sleeping	Sitting	Light exercise	Heavy exercise		
				mouth	nose	average
Extrathoracic deposition fractions	11.1%	10.5%	8.11%	1.58%	6.74%	4.16%

Table 3. The extrathoracic deposition fractions for different breathing modes.

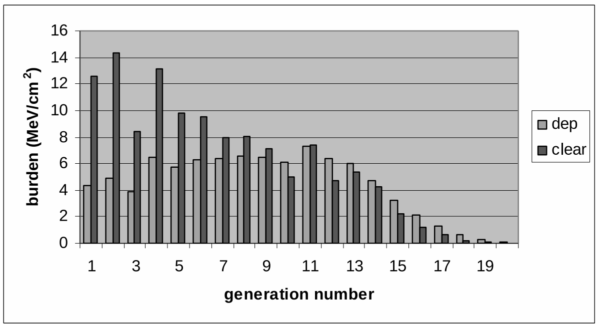

Figure 2. Radiation burden (MeV/cm^2) of the radon progenies from the primarily deposited (dep) and the up-cleared fractions (clear) during sleeping breathing condition.

In the case of sleeping breathing condition the air velocity is slow, so a particle spends relatively long time in an airway generation. Inspection of Figure 2 demonstrates that the radiation burden originating from primary deposition is rather uniform along the large bronchial airways. It is slightly increasing near linearly in airway generations 1–11. The curve decreases practically to zero at airway generations 19–20. The curve of the cleared-up fraction is quite different. It is the highest in the first six airway generations then it decreases till the end of the bronchial region (airway generations 19–20). As a consequence of relatively short or relatively long airways, the curve of the burden as a function of airway generation number may have local minima or local maxima, e.g., at generation 3 there is a local minimum and at generation 11 there is a local maximum. It seems to be an important and useful result that the radiation burden of the airways is higher with a factor of about two-three in the first four airway generations originating from clearance than deposition. It is the region of the lung where radon progeny induced lung cancer incidence has the highest probability. However, the models [11], [5], [8], [9] known by us in the literature calculate only the burden originating from deposition and neglect the concomitant effect of clearance.

At this particle diameter (200 nm) the main deposition mechanism is Brownian motion, accordingly the primary deposition mechanism is the diffusion and it is significant at all the selected parameter values.

At sitting breathing condition (Figure 3) the inhaled particles spend a little bit shorter time in a certain airway generation than at sleeping breathing pattern. Accordingly, slightly less time remains for diffusional deposition and thus the deposition fractions are a little bit less in the central airways. However, both the absolute values of deposition fractions and the distribution of deposition are very similar to the cases characteristic to the sleeping mode. Accordingly, the cleared up fractions are also very similar.

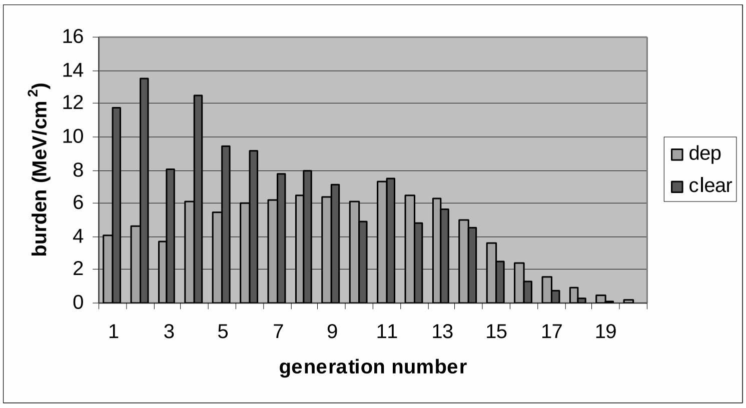

Figure 3. Radiation burden (MeV/cm^2) of the radon progenies from the primarily deposited (dep) and the up-cleared fraction (clear) during sitting breathing condition.

At light physical breathing mode (Figure 4) the air velocities are even higher than in sitting breathing condition and thus the deposition values which are dominantly caused by Brownian motion will be even less with about 30 percent. However, the shape of the curves both for deposition and clearance are similar to the previous two cases.

In the case of heavy exercise breathing condition, both deposition and clearance further decrease, as it is expectable, hence the air velocities further increase. The degree of decreasing is about 20% both in deposition fractions and clearance (Figure 5). The shape of the curves are similar as in the cases of the first three breathing modes. The reason why the shapes of the curves are similar is that the absolute value of the total deposition in the whole lung is not high and in this way the majority of the particles remain in the lumen of the airways without deposition, that is the exhaled fraction is high.

Figures 2–5 demonstrate that the contribution to the total radiation burden of the airways in the first few airway generations is significantly higher from clearance than from deposition. Thus, the negligence of the effect of clearance at the characterization of radiation burden or at the explanation of potential biological or health effects of inhaled radon progenies may cause a significant error and underestimation of the physical and biological effects. This is valid at all the studied breathing conditions.

The total burden is the highest in the large central airways, that is, in the large bronchi where most of the radon induced preneoplastic and neoplastic lesions were found. Comparing the relative contributions of the primarily deposited and up cleared isotopes it can be stated that in the most exposed re-

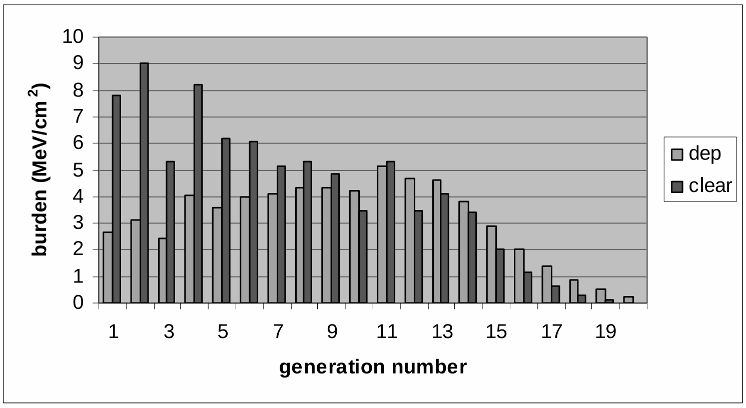

Figure 4. Radiation burden (MeV/cm^2) of the radon progenies from the primarily deposited (dep) and the up-cleared fraction (clear) during light exercise breathing condition.

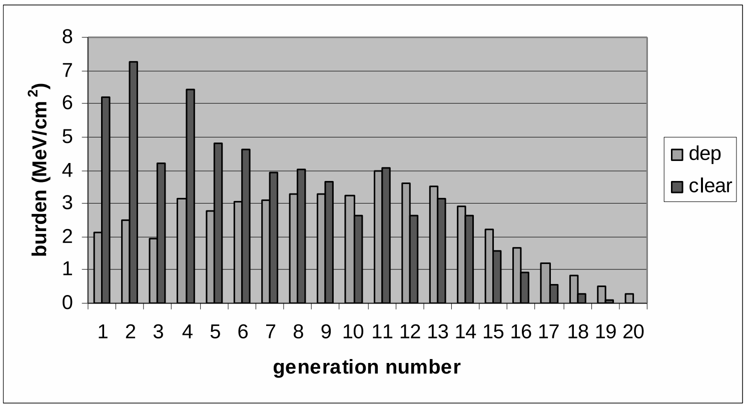

Figure 5. Radiation burden (MeV/cm^2) of the radon progenies from the primarily deposited (dep) and the up-cleared fraction (clear) during heavy exercise breathing condition.

gion (large bronchi) the up cleared fraction is dominant. This aspect is usually not considered in current computational dosimetry and risk modeling. Present computations may provide useful input for such models and thus contribute to a quantitatively better estimation of radiation burden and the related health consequence.

4. Conclusions

Based on the present results, in the central airways (first six airway generations), the radiation burden of the deeply deposited and up-clearing radon progenies is not negligible, even it is higher than the burden of deposition with a factor of up to three.

Physical activity, although affects the deposition and the related clearance fractions, does not seem to influence the above tendency very much. The results demonstrate that one of the reasons of the site specific radon induced lung cancer may be the dose contributions of the deeply deposited and up-cleared radon progenies.

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