Note

QUALITY FACTORS FOR ALPHA PARTICLES IN THE HUMAN RESPIRATORY TRACT

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Abstract—**Quality factors of alpha particles emitted by radon progeny in the human lung have been calculated by using the formula recommended by the International Commission on Radiological Protection. Calculations have been carried out for different combinations of sources, energies, and targets. The values obtained are between 20 and 26, with an average of about 24. These are comparable to previously published results for the human lung and for the general consideration of alpha particles emitted in tissue.**
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Key words: alpha particles; lungs, human; respiratory system; radiation effects

INTRODUCTION

RECENTLY, BORAK (2002) discussed the quality factor Q for alpha particles emitted in tissue, where the radioactivity was assumed to be distributed uniformly in a tissue or organ for which Q was to be calculated. A mathematical formalism was developed to calculate the alpha-particle fluence and the average quality factor $\bar{Q}$. Stopping of alpha particles was considered in the tissue just next to the location where they were emitted, without any consideration of possible targets. It was shown that $\bar{Q}$ depended on the initial energies of alpha particles.

In the present work, calculations of $\bar{Q}$ for alpha particles emitted in the human respiratory tract are presented. Here, the radioactivity is not uniformly distributed in the tissue, and, furthermore, the sources and the targets are physically separated. Alpha-particle sources are in the mucus layer in either the fast or slow clearance phase, while the targets are the nuclei of basal and secretory cells (ICRP 1994). An additional complication is that the medium in which the alpha particles are stopped is not homogeneous, i.e., the path of an alpha particle can be partially in air and partially in tissue. Since our considered scenario is different from that of Borak (2002), his mathematical formalism has not been applied here.

The average value of Q is calculated by

$$\bar{Q} = \frac{1}{D}\int Q(L)\,D(L)dL, \qquad (1)$$

where D is total absorbed dose, $D(L)$ is the absorbed dose from the particles with linear energy transfer between L and $L + dL$, and $Q(L)$ is the quality factor calculated from the following equations:

$$Q(L) = 1 (L < 10\ \text{keV}/\mu\text{m}) \qquad (2a)$$

$$Q(L) = 0.32L - 2.2$$

$$(10\ \text{keV}/\mu\text{m} \le L \le 100\ \text{keV}/\mu\text{m}) \qquad (2b)$$

$$Q(L) = 300/\sqrt{L} (L > 100\ \text{keV}/\mu\text{m}) \qquad (2c)$$

as proposed by the ICRP (1990) and re-published in 1996 (ICRP 1996).

METHODS

The model and computer programs used for our calculations are the same as those described earlier by Nikezic and Yu (2001, 2002), so they will not be fully repeated here.

The lung model adopted for our calculations is the ICRP66 model (ICRP 1994), since this model is the most comprehensive and updated one in this field. The morphometric model of the airway wall was proposed earlier by the National Research Council (1991). These models are followed as much as possible in our calculations. Moreover, the ICRP66 nomenclatures, BB for bronchial region and bb for bronchiolar region, are also adopted.

Two types of cells, the secretory and basal cells, are considered equally sensitive to alpha radiation according

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to ICRP66 and the National Research Council (1991). In this work, therefore, we consider irradiation of the nuclei of these cells by alpha particles emitted from short-lived radon progeny and calculate the corresponding quality factors.

The physical sub-model is related to the stopping powers of alpha particles in striated tissue and air. The data were given in the ICRU49 report (International Commission of Radiation Units and Measurements 1993) where the stopping power was given as a function of energy of alpha particles. These data were fitted and converted into tables where the energy E and the stopping power S were given as functions of the "tissue equivalent" distance d traveled by the alpha particles. The path length of an alpha particle in air was multiplied with the ratio, S_{air}/S_{tissue}, between the stopping power in air and that in tissue, to give the tissue equivalent path length. The functions $S(d)$ and $E(d)$ were given in tables in steps of distance, and the values corresponding to intermediate values of d were found by linear interpolation. Two tables were produced (not shown here), one for 6 MeV initial energy and the other for 7.69 MeV (corresponding to alpha energies from the radon progeny ^{218}Po and ^{214}Po, respectively). Calculations of E and S were performed with the continuous slowing down approximation (or CSDA).

A well-defined geometrical model, which enables consideration of transport of particles, is needed for the Monte Carlo simulations. In the course of the simulations, starting points of alpha particles were sampled in the mucus layer covering the epithelium, in the fast and slow clearing phases, in which the alpha emitters were distributed. According to ICRP66, the fast source in BB is 0 to 5 μm and the slow source is 5 to 11 μm below the top of the mucus. In bb, the fast source is 0 to 2 μm and the slow source is 2 to 6 μm below the top of the mucus. In the ICRP66 approach, the dose is calculated for the layer containing the sensitive cells, thereby neglecting their distribution and abundance. In BB, secretory cells are 21 to 51 μm and basal cells are 46 to 61 μm below the top of the mucus. In bb, the only targets are secretory cells, which are 10 to 18 μm below the top of the mucus.

Information on the distribution and relative volume abundance of sensitive cells was given by Mercer et al. (1991). In the present work, we have employed the ICRP66 geometrical model but at the same time adopted the volume abundance of sensitive-cell nuclei given by Mercer et al. (1991).

The cell nuclei are assumed to be uniformly distributed in the sensitive-cell layer. The diameter of the cell nuclei was 9 μm for both types of cells in BB and 8.1 μm for secretory cells in bb (Hofmann et al. 2000).

The first step in our calculations is the "construction" of cell nuclei in a given layer according to their volume abundance as given by Mercer et al. (1991). The number of nuclei is computed through division of the layer volume by the volume abundance. These nuclei are programmed to randomly distribute within the layer, and their positions are stored in the computer memory.

The second step refers to the Monte Carlo simulations of alpha-particle propagation in the airway tube. It consists of generating alpha-particle "histories" and examination of possible hits of cell nuclei. In the case of a hit, the incident energy, linear energy transfer L and energy ϵ imparted to the cell nucleus are determined based on geometrical and other relevant parameters (stopping power in tissue and air). The procedures have to be repeated many times to get a small statistical error. In our study, the number of alpha hits was 10^4 and the statistical error was 1%.

A modification of the previously written computer program was performed at this point in order to calculate the average quality factor. A table consisting of values of imparted energy as a function of L was first generated. When the number of simulations, given as an input parameter, has been completed, the total energy imparted to the cell nuclei is converted to the absorbed dose by dividing with the mass of the cell nuclei. In the same way, the imparted energies in different intervals of L, $L + \Delta L$ are converted to the absorbed dose in the same interval of L to facilitate calculations of the average quality factor according to eqn (1).

RESULTS AND DISCUSSION

Calculations have been performed for the various source-target combinations listed in Table 1. The sources include fast and slow mucus in BB and bb and for the two alpha energies, 6 MeV and 7.69 MeV. The targets are nuclei of basal and secretory cells in BB, and of secretory

Table 1. Average quality factors $\bar{Q}$ for different combinations of sources and targets in the human respiratory tract.

Source (fast or slow mucus)	Target cell	Energy (MeV)	$\bar{Q}$ (Sv Gy^{-1})
BB fast	Secretory	6	22.9
BB fast	Secretory	7.69	25.7
BB slow	Secretory	6	24.0
BB slow	Secretory	7.69	25.6
BB fast	Basal	6	22.2
BB fast	Basal	7.69	23.9
BB slow	Basal	6	20.4
BB slow	Basal	7.69	25.0
bb fast	Secretory	6	26.7
bb fast	Secretory	7.69	24.3
bb slow	Secretory	6	26.0
bb slow	Secretory	7.69	24.1

cells in bb. Results of these calculations are given in Table 1. It can be observed that the average quality factor ranges between 20.4 and 26.7, and is always larger than 20, and the overall average is about 24.2.

The quality factor for alpha particles in the human lung was also calculated by Hofmann et al. (1994). In their work, the dependence of Q with the cellular depth was given. Their calculations were based on ICRU40 where Q was given as a function of the micro-dosimetric quantity, lineal energy y, but not on L. Despite the different lung model and different formulae employed by them, the values for Q were also between 24 and 26, which are commensurate with our results. Three independent calculations of the quality factor of alpha particles in tissue (Hofmann et al. 1994; Borak 2002; present work) using different models and approaches have brought similar results, which exceed significantly the radiation weighting factor of alpha particles w_R of 20 as recommended by ICRP.

ICRP recommended use of radiation weighting factor w_R to calculate equivalent dose and effective dose that would be used for risk estimation. However, the ICRU system of radiation units is still based on the quality factor, Q, and that is the reason for these calculations.

Although the quality factor and radiation-weighting factor are not the same quantities, both of them are used to calculate equivalent dose, and we feel that some consistency between these two quantities should be established.

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