STOCHASTIC MODEL OF RADON DAUGHTER DEPOSITION AND CLEARANCE IN HUMAN BRONCHIAL AIRWAYS

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INTRODUCTION

Morphometric measurements of human airway casts have revealed that the human bronchial tree is an asymmetrically dividing network, exhibiting individual variations of airway dimensions within a given airway generation (1). Thus, a statistical correlation exists between the linear dimensions of a given parent airway and those of the asymmetrically dividing daughter branches (2). This statistical relationship, however, is constrained by correlations among various geometrical parameters, i.e., the human lung is not a fully stochastic system. From a statistical analysis of these morphometric data, the following geometrical parameters could be obtained for each airway generation or bifurcation: (i) probability distributions for diameters and lengths, ratios of parent cross section to the combined cross section of both daughters, ratios of major to minor daughter diameters, and branching angles for major and minor branches; (ii) correlations of diameters and lengths; and (iii) the probability of terminating the bronchial region as a function of both diameter and generation number (2). Since the original lung morphometry refers to total lung capacity (1), airway diameters and lengths were scaled down to functional residual capacity (3).

STOCHASTIC BRONCHIAL DEPOSITION AND CLEARANCE MODEL

The stochastic deposition model used in the present study refers to the transport of inhaled particles through this stochastic lung structure by selecting randomly the sequence of airways for each individual particle, applying Monte Carlo techniques (4). For the computation of particle deposition within a selected airway bifurcation, however, the average deposition behavior of many particles is assumed, i.e., deposition probabilities are calculated by the commonly used deposition equations (4). In other words, the stochastic deposition model used here reflects the effects of a stochastic airway system on particle transport and deposition. In this model, deposition is computed for individual airway bifurcations (consisting of half of the parent and the major and minor daughter lengths) in a given lung lobe, considering the filtering effect of nose or mouth (5). The stochastic deposition model has been validated by comparison with total and regional deposition data in human test subjects for a wide range of particle sizes (6).

In the present study, a bronchial mucociliary clearance model has been implemented into the above described stochastic deposition model, based on the following assumptions: (i) the average mucus velocity in the trachea is assumed to be 5.5 mm min^{-1} (7); (ii) at a given airway bifurcation, average mucus velocities in the asymmetrically branching daughter airways are proportional to their respective diameters (7); (iii) mucus transport is delayed at central bifurcation zones (delay time Δt is uniformly distributed between 0 and 30 min) (8); and, (iv) the slow bronchial clearance fraction, f_s, with a half-life of about 10 days, decreases in a linear fashion with the particle's diameter, d, according to the equation: $f_s = 0.77 - 0.12\ d\ (\mu m)$ (9).

RESULTS

Experimental data on particle retention in the lungs after shallow bolus inhalation for 1.7, 3.2. and 6.7 μm geometric diameter particles are plotted in Figure 1 (10) (note: the volumetric front depth of 55 cm^3 refers to a bolus inhalation time of 3.78 s during a 4 s inspiration time, with an initial dispersion of 0.1 s). Except for the first four hours, in which the stochastic clearance simulations predict a higher retention than has been observed in the experiments, the agreement between experiment and model predictions is quite satisfactory, considering potential effects of inter-subject variability in lung dimensions and structure.

In the simulations presented here, bronchial deposition patterns, normalized to the number of particles entering the trachea are computed for 0.2 μm unit density particles under resting breathing conditions, i.e., for a tidal volume of 1000 cm^3, a cycle time of 4 s (2 s inspiration, 2 s expiration, no breath-hold period), and uniform inhalation during the 2 s inspiration time. The initial activity of the inhaled radon decay products is 9 Bq (^{218}Po), 6 Bq (^{214}Pb), and 4 Bq ($^{214}Bi/^{214}Po$), representing typical decay product ratios in domestic environments (8).

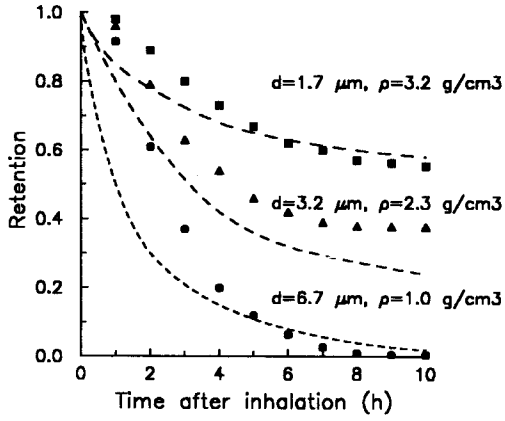

Figure 1. Particle retention as a function of time after shallow bolus inhalation for three different particle sizes. The symbols denote the theoretical predictions, while the fits to the measured data (10) are represented by the broken lines.

The subsequent upstream transport of the deposited radon progeny by mucociliary clearance is simulated for the same pathway which was selected upon inspiration, considering their radioactive decay. The transit times of the deposited particles in different bronchial airway generations, illustrating the effect of mucucs clearance, together with the initial deposition pattern are displayed in Figure 2. Because of the presumed relationship between mucus velocity and airway diameter, the decrease of diameters in peripheral bronchial airway bifurcations leads to increasing transit times. In the most distal genenerations, however, transit times decrease again due to the decreasing number of bronchial airways in these generations (note: in contrast to the commonly used symmetrical models, still 0.6 % of all airways in bifurcation 20 are terminal bronchioles).

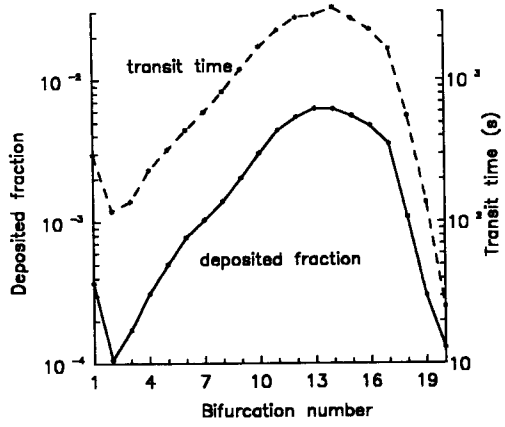

Figure 2. Initial deposition pattern for 0.2 μm unit density particles under resting breathing conditions, and the transit times of these particles in individual bronchial airway bifurcations due to mucociliary clearance.

The total number of radioactive decays, illustrating the combined effect of deposition, clearance and radioactive decay, and the number of radioactive decays per unit surface area, representing the radiation dose distribution, are plotted in Figure 3 as functions of the bifurcation number for both alpha-emitting radon progeny (only attached ^{218}Po nuclides have been considered here). Because of their relatively short half-lives,

the distributions of both nuclide transformations reflect the transit time distribution. On the other hand, the distribution of the number of nuclear transformations per unit surface hardly changes with penetration into the bronchial tree due to the larger total surface area in peripheral airway generations. Above about bifurcation 13, there is no further increase in total surface area due to a decreasing fraction of bronchial airways and the surface activities, therefore, drop parallelly to the decay pattern.

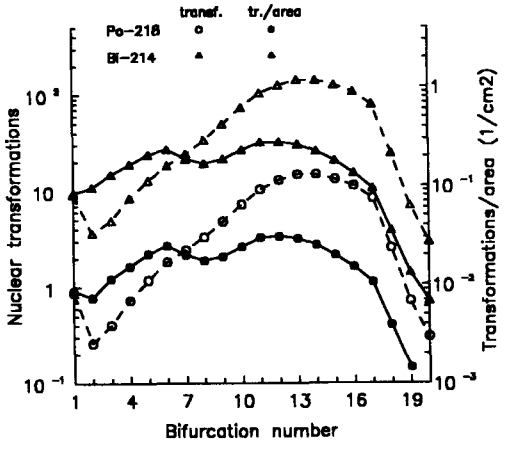

Figure 3. Number of nuclear transformations and number of decays per unit surface area in individual bronchial airway bifurcations for inhaled radon progeny with initial activities of 9 Bq (^{218}Po), 6 Bq (^{214}Pb), and 4 Bq (^{214}Bi/^{214}Po).

CONCLUSIONS

The results of the stochastic deposition and clearance calculations presented here reflect primarily the intra-subject variability of the human lung morphometry. In other words, the random walk of individual particles within a given bronchial bifurcation during inspiration and, if deposited, during mucociliary clearance has not yet been considered due to the lack of pertinent experimental information. Future incorporation of the random location of target cells in bronchial epithelium into the present stochastic deposition and clearance model will allow us to quantitate the effect of individual biological variability in cellular dose.

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