ON THE FATE OF INHALED PARTICLES IN THE HUMAN: A COMPARISON OF EXPERIMENTAL DATA WITH THEORETICAL COMPUTATIONS BASED ON A SYMMETRIC AND ASYMMETRIC LUNG

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An analytical model is used to describe the behavior of inhaled particulate matter in the human respiratory tract. Three different geometries, symmetric and asymmetric, are utilized to simulate the tracheobronchial (TB) tree. The suitability of each geometry for representing the human is evaluated by comparing calculated aerosol deposition probabilities with experimental data from inhalation exposure tests. A symmetric, dichotomously branching pattern is found to be a reliable description of the TB tree for studies of factors affecting aerosol deposition in the human lung. Calculations with the theoretical model are in excellent agreement with measured aerosol deposition efficiencies. Furthermore, the model accurately predicts experimentally observed features of inhalation exposure data, such as effects of inter-subject lung morphology differences and relative efficiencies of specific deposition mechanisms, on aerosol deposition patterns in the TB tree.

Introduction. Knowledge of the sites of deposition of inhaled particulate matter within the tracheobronchial (TB) tree is of importance in assessing the health effects of atmospheric pollutants and in aerosol therapy procedures where medicinal agents are administered to patients. Early experimental inhalation exposure studies established that particle deposition probabilities within the human respiratory system can be expressed as a function of the mass median aerodynamic diameter (MMAD) and geometric standard deviation ($\sigma_g$) of an inspired aerosol (Task Group on Lung Dynamics, 1966; Lippman and Albert, 1969). A detailed experimental investigation of the regional dispersion of inhaled particles in the human conducted by Lippmann et al. (1971) has shown that deposition in ciliated airways of the TB tree is related to an 'impaction parameter' defined in terms of particle parameters (size and density) and a breathing parameter (inspiratory flow rate).

A theoretical model of aerosol behavior in the human respiratory tract that permits factors which influence deposition to be studied is presented here. The model requires definition of a system of deposition probability formulae and a description of human TB morphology. The system of equations describing the deposition efficiencies of the inertial impaction,
sedimentation and diffusion mechanisms proposed by Martonen (1982) is used. There are several morphologies available for use in such a theoretical aerosol deposition model. Different TB morphologies have been proposed by Weibel (1963), Horsfield et al. (1971) and Soong et al. (1979). The latter two will hereafter be referred to as the ‘Horsfield’ and ‘Soong’ geometries respectively. The Weibel and Horsfield descriptions are based on extensive anatomical measurements of the human lung. The Soong geometry is a Weibel-type TB morphology, with dimensions modified from the original to account for variation in lung dimensions among a population.

The three TB descriptions were incorporated into the theoretical aerosol deposition model, and calculated particle losses within the different TB trees compared with the experimental data of Lippmann et al. (1971). Findings indicated that the symmetric, dichotomously branching pattern proposed by Weibel (1963), with airway dimensions modified by the statistical work of Soong, is a suitable description of the human lung for the study of aerosol behavior.

**Human Tracheobronchial Morphology.** The Weibel Model A morphology is the simplest TB description proposed for the human lung. It is a symmetric, dichotomously branching network of cylindrical tubes. There are 17 generations of conducting airways (tubes) numbered from 0 through 16, with generation $I = 0$ being the trachea and generation $I = 16$ the last unalveolated bronchiole. Each generation $I$ consists of $2^I$ identical airways. A description of the morphology is given in Table I. The dimensions given, which were measured from a cast of large-bore airways and histological sections of small-bore bronchioles, correspond to a lung volume of $3/4$ total lung capacity (TLC), or $4800 \text{ cm}^3$. The Weibel conception of the TB network, because of its simplicity and the fact that it is based on anatomical measurements, has been widely used in experimental (Ferron, 1977; Scherer et al., 1979) and theoretical (Gerrity et al., 1979; Martonen and Patel, 1981) studies of aerosol deposition in the human lung.

The Soong branching scheme is identical to that of Weibel; airway dimensions, however, are different. Since Raabe et al. (1976) discussed the significance of inter-subject differences in the structure and dimensions of the human TB tree, the Soong morphology, a statistical description, was intended to account for such variabilities. From morphometric measurements of airway lengths and diameters as functions of TB generation reported in the open literature, statistical parameters of each such distribution were determined. Mean airway dimensions $\mu$ and coefficients of variation $\sigma/\mu$ of distributions of standard deviations $\sigma$ are