



Numerical simulation of micro-particle deposition in a realistic human upper respiratory tract model during transient breathing cycle

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ABSTRACT

An more reliable human upper respiratory tract model that consisted of an oropharynx and four generations of asymmetric tracheo-bronchial (TB) airways has been constructed to investigate the micro-particle deposition pattern and mass distribution in five lobes under steady inspiratory condition in former work by Huang and Zhang (2011). In the present work, transient airflow patterns and particle deposition during both inspiratory and expiratory processes were numerically simulated in the realistic human upper respiratory tract model with 14 cartilaginous rings (CRs) in the tracheal tube. The present model was validated under steady inspiratory flow rates by comparing current results with the theoretical models and published experimental data. The transient deposition fraction was found to strongly depend on breathing flow rate and particle diameter but slightly on turbulence intensity. Particles were mainly distributed in the high axial speed zones and traveled basically following the secondary flow. "Hot spots" of deposition were found in the lower portion of mouth cavity and posterior wall of pharynx/larynx during inspiration, but transferred to upper portion of mouth and interior wall of pharynx/larynx during expiration. The deposition fraction in the trachea during expiration was found to be much higher than that during inspiration because of the stronger secondary flow.

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1. Introduction

Inhaled particle deposition is a hot topic on air pollution and human health. The transportation and deposition in human respiratory tract have been investigated broadly by experimental measurements and numerical simulations. Utilizing steady air-particle flow, particle deposition was deeply studied on realistic replicas from cadavers (Cheng, Zhou, & Chen, 1999; Zhou, Su, & Cheng, 2008), idealized oropharyngeal model (Heenan, Matida, Pollard, & Finlay, 2003; Zhang, Kleinstreuer, & Kim, 2002), symmetric bronchial models (Zhang, Kleinstreuer, & Kim, 2009) and reconstructed model from CT-scans (Choi, Tu, Li, & Thien, 2007; Sandeau et al., 2010).

The transient breath patterns have already been considered in some work. The temporary and spatial deposition in symmetric

bronchial lung of first two bifurcations was studied during a full breathing cycle (Moskal & Gradon, 2002). By setting the axial symmetric inspiration velocity profile at the trachea inlet, the instantaneous airflow pattern and particle deposition were studied in an asymmetric tracheo-bronchial (TB) airway during inspiratory process (Li, Kleinstreuer, & Zhang, 2007a; Li, Kleinstreuer, & Zhang, 2007b), and symmetric bronchial airway from three to six generations during typical breathing cycle (Zhang & Kleinstreuer, 2002). But few of them considered the breathing cycle in the whole region of human upper respiratory tract (URT). Study in the whole region will avoid the assumption of boundary conditions in separate parts.

In the present work, a realistic human URT model is constructed and validated by comparing particle deposition with several theoretical models and experimental data under three steady inspiratory flow rates. The instantaneous airflow structure and particle deposition during the inspiratory and expiratory processes are investigated. This contribution is an extension of former work by Huang and Zhang (2011) in which the particle deposition pattern and mass distributions of five lobes on steady airflow were investigated.

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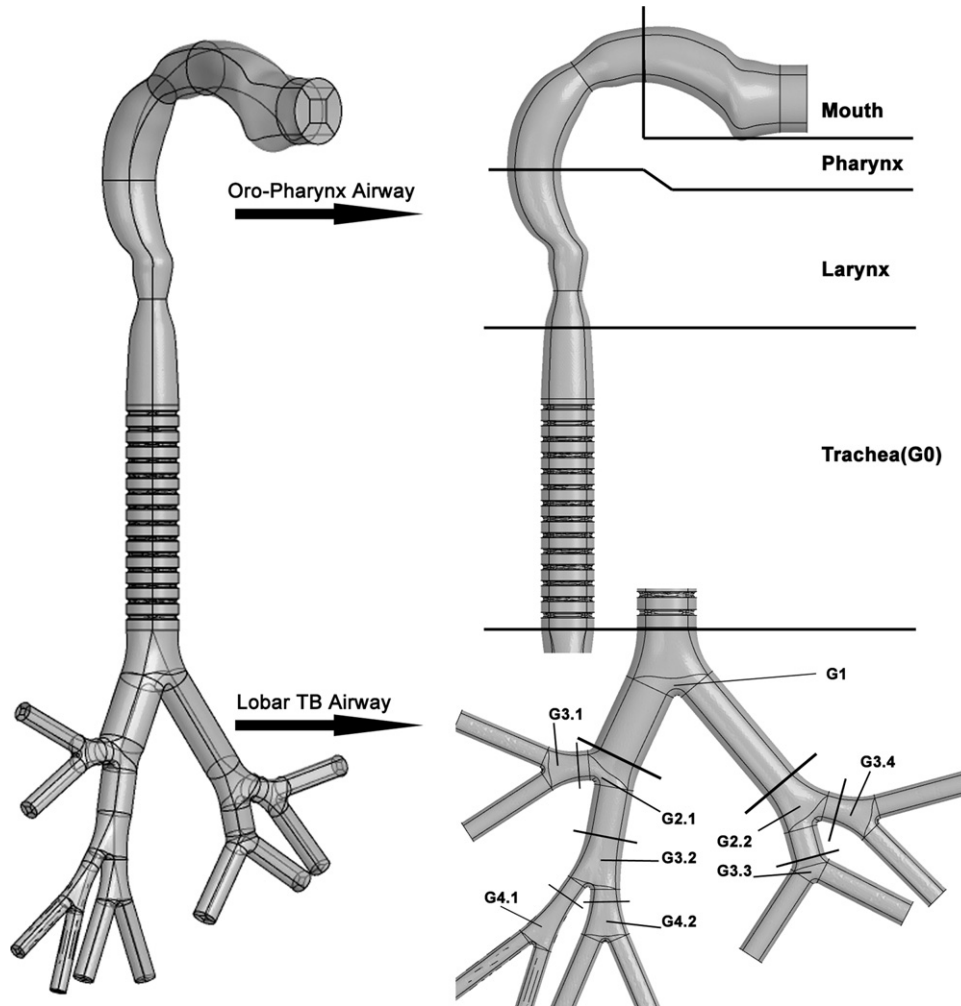


Fig. 1. The human upper respiratory tract model.

2. Numerical models

2.1. The human upper respiratory tract model

The present human upper respiratory tract (URT) model shown in Fig. 1 consists of two parts: an oropharyngeal region and 4 generations of asymmetric TB airway. The oropharyngeal region including oral cavity, pharynx and larynx was constructed from a realistic replica (Cheng et al., 1999), and has been validated in published work (Huang & Zhang, 2011; Zhang et al., 2002). The dimensions of the asymmetric TB airway are adopted from “the typical path lung model” (Yeh & Schum, 1980). The “typical path lung model” considers the human lung to consist of five parts, i.e. two left lobes and three right lobes. The airway segment diameters, lengths, branching angles are employed to construct the asymmetric bronchial bifurcations; the angles of inclination to gravity are ignored in this study. For the tracheal tube, 14 cartilaginous rings of semicircular cross-sections with diameter of $0.1D_{\text{trachea}}$ were adopted. Table 1 lists the dimensions of the asymmetric TB airway including the angles of each bifurcation θ .

2.2. Governing equations and boundary condition

For the viscous, isothermal and incompressible flows in human URT, the Reynolds averaged Navier–Stokes (RANS) equations are modeled employing the eddy viscosity hypothesis and eddy dif-

fusivity hypothesis. These hypotheses assumed that the Reynolds stresses in the RANS equations can be related to the mean velocity gradients and turbulent viscosity. The Wilcox $k-\omega$ turbulence model (Wilcox, 1998) was adopted to simulate the airflow field in the URT model.

Micro-particle transported in the URT model is considered as dilute monodisperse rigid sphere suspensions, with large particle-to-air density ratio and negligible particle rotation. In this case, based on order-of-magnitude arguments (Clift, Grace, & Weber, 1978), the drag force is dominant. The particle trajectory equation can be written as:

$$m_p \frac{d\mathbf{u}^p}{dt} = \frac{1}{8} \pi \rho d_p^2 C_{Dp} |\mathbf{u} - \mathbf{u}^p| (\mathbf{u} - \mathbf{u}^p) + \frac{\pi}{6} d_p^3 (\rho_p - \rho) \mathbf{g}, \quad (1)$$

where m_p , $\mathbf{u}^p$, ρ_p and d_p are the one spherical particle mass, velocity vector, particle density and diameter, respectively; ρ is the air density and $\mathbf{g}$ is the gravity vector; C_{Dp} is the drag force coefficient given as

$$C_{Dp} = \frac{C_D}{C_{\text{slip}}}, \quad (2)$$

where

$$C_D = \max \left(\frac{24}{Re_p} (1 + 0.15 Re_p^{0.687}), 0.44 \right), \quad (3)$$

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