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Particle deposition in the human tracheobronchial airways due to transient inspiratory flow patterns

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Abstract

Considering realistic tracheobronchial airways, transient airflow structures and micro-particle deposition patterns were simulated with an in-house finite-volume code for typical inhalation waveforms and Stokes numbers, i.e., the average flow rates at the trachea inlet, $Q_{\mathrm{in,av}}$, are 15 and 60 L/ min and the mean Stokes number at the trachea inlet, $St_{\mathrm{mean,trachea}}$, is in the range of $0.0229 \leqslant St_{\mathrm{mean,trachea}} \leqslant 0.0915$, respectively. While the overall airflow fields exhibit similar characteristics, the local flow patterns which influence particle deposition are largely affected by secondary flows (for both $Q_{\mathrm{in,av}} = 15$ and 60 L/ min) as well as airflow turbulence (when $Q_{\mathrm{in,av}} = 60$ L/ min). The particle deposition fraction is a strongly transient function according to a given inhalation waveform.

In light of the importance of targeted drug-aerosol delivery, it is shown that the relation between particle-release positions at the trachea inlet and particle depositions at specific lung sites are greatly influenced by the complex airway geometry and the flow-rate magnitude. For laminar flow, the particle-release points are deterministic and unique, as required for optimal drug-aerosol targeting.

Keywords: Transient inhalation; Laminar flow; Turbulent flow; Local flow pattern; Micro-particle deposition; Deposition fraction; Drug-aerosol targeting

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1. Introduction

People may inhale 100 millions of particles each day, ranging from toxic particulate matter to drug aerosols, where some of those deposited can be either harmful or therapeutic to humans depending upon the aerosol material, deposition site and local concentration. These aspects and parameters, in turn, are greatly determined by the airflow field, particle properties, breathing pattern and geometric airway characteristics. Complementary to the idealized, i.e., planar and symmetric, lung airway model published by Weibel (1963), Horsfield, Dart, and Olson (1971) provided geometric data sets for asymmetric airways obtained from a resin cast model. Recently, modern imaging techniques allowed for even

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Table 1
Model geometry

Branch[a]	Diameter (mm)	Length (mm)	In-plane branching half angle (degree)	Out-of-plane spatial angle (degree)
Trachea	16	100	0	0
L_1	11.1	22.00	35	0
L_2	7.3	15.60	63	25
L_3	8.9	26.00	15	25
L_4	6.67	11.27	18	60
L_5	4.27	10.81	33	60
L_6	5.2	21.00	61	5
L_7	6.4	8.00	15	5
R_1	12.0	50.00	73	0
R_2	8.0	11.00	44	15
R_3	7.5	16.00	48	15
R_4	7.00	9.70	28	0
R_5	5.35	9.70	70	0
R_6	4.27	10.81	25	35
R_7	6.67	11.27	65	35

[a] The position of segmental extents L_i and R_i, $i = 1, \ldots, 7$ is shown in Fig. 1(a).

more detailed mapping of the human respiratory system (see Cebral & Summer, 2004; Ley et al., 2002; Sera et al., 2003; among others).

For example, using a mouth-to-trachea replica plus three generations of the Weibel Type A configuration, Kleinstreuer and Zhang (2003) as well as Zhang, Kleinstreuer, Donohue, and Kim (2005) and Zhang, Kleinstreuer, and Kim (2006) investigated numerically steady nano- and micro-particle transport and deposition. They focused on laminar-to-turbulent flow effects as well as different deposition patterns between nanomaterial, micro-particles and micro-droplets. Employing a Weibel-type bifurcation and considering chronic obstructive pulmonary disease (COPD), Yang, Liu, So, and Yang (2006) and Liu, So, and Zhang (2003) compared the resulting airflow structures under different inlet conditions. In contrast, Calay, Kurujareon, and Holdo (2002) and Ertbruggen, Hirsch, and Paiva (2005) relied on modified versions of Horsfield's model to simulate airflow fields and micro-particle depositions. Both research teams assumed steady-state, uniform inlet velocity conditions and sharp carinal ridges.

Experimental measurements of particle deposition have been provided by Johnston, Isles, and Muir (1977), and Kim and Iglesias (1989) and Kim, Fisher, Lutz, and Gerrity (1994) for single bifurcations. Sudlow, Olson, and Schroter (1972) measured the velocity profile in a large-scale symmetric bronchial model. Olson and Sudlow (1973) measured the flow patterns in a realistic human upper and central airway model under steady inhalation condition. Snyder and Olson (1989) discussed the suppression of flow separation in pulmonary bifurcation models. Based on Weibel's model, Kim and Fisher (1999) studied the particle deposition in a glass tube replica of a symmetric double bifurcation airway. Zhou and Cheng (2005) measured the particle deposition in a cast of a human lung airway model with nine branches. Zhang and Finlay (2005) showed experimentally that the presence of cartilaginous rings in the trachea affects local micro-particle deposition.

All main contributions so far assumed either steady air-particle flow and/or symmetric airways representing the tracheobronchial tree. In this work, using data provided by Horsfield et al. (1971), Raabe, Yeh, Schum, and Phalen (1976) and Zhang et al. (2005), transient inhalation was simulated in a realistic human upper airway model. Two average inhalation flow rates, i.e., $Q_{\text{in,av}} = 15\,\text{L/min}$ (at rest) as well as $Q_{\text{in,av}} = 60\,\text{L/min}$ (during moderate exercise), were considered. This contribution is an extension of the two-part paper by Li, Kleinstreuer, and Zhang (2007a, 2007b), in which the impacts of different airway configurations and inlet velocity profiles on steady and quasi-steady airflow fields and micro-particle transport were analyzed.

2. Theory

2.1. Airway geometry

Human lung airway structures are complex and quite variable; but, there are some common geometric characteristics. For example, Horsfield et al. (1971) measured a resin cast of a representative human respiratory system from the trachea