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Global and local transport properties of steady and unsteady flow in a symmetrical bronchial tree

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ABSTRACT

The branching structures and bifurcation flows in human lung are crucial factors for the functioning of the respiratory system. In this paper, both steady and unsteady flow in a symmetrical bronchial tree have been investigated, and the global and local transport properties are explored by fractal geometry and computational fluid dynamics method, respectively. Firstly, total flow properties for steady laminar flow and pulsatile flow in a fractal tree-like network are derived, and the global fluid dynamics behavior under volume constrain is discussed accordingly. And then, a mathematical model is developed for the steady and unsteady gas flow as well as gas-particle two-phase flow in a four-generation bifurcation in order to study the local transport characteristics of bronchial tree. The results indicate that the critical successive diameter ratio for the first few generations is below the prediction of Murray's law while small airways follow Murray's law. It has been also shown that the asymmetrical and non-uniform flow distribution can be realized through a symmetric branching structure with increased Reynolds number. The asymmetric ratio is found to be scaled with the Reynolds number as $\chi \sim \mathrm{Re}^{0.00124}$ in the steady respiratory condition. The effect of Reynolds number and respiratory frequency on the flow distribution and particle deposit efficiency are studied for different respiratory conditions, which show that the particle deposit efficiency can be increased with increased Stokes number. The present work is important for the morphology of the bronchial tree and understanding the physical mechanism of the bifurcation flow.

1. Introduction

The air convection in human lung organ can directly affect the ventilation function and gas exchange efficiency of the respiratory system. Human lung contains a tree-like branching network of airway tubes that start at the trachea and become shorter, narrower, and more numerous as they penetrate deeper into the lung. The tree-like branching structure is believed to be a very efficiently natural transport system, and the problem of heat and mass transfer through it is of considerable current interests [1–5]. It has also provided useful hints for optimal solutions of many engineering problems [6–10]. Although a large number of investigations have been made on the characteristics of the single- and multi-phase flow within the airways of the respiratory system [11–13], there are still perspectives that are not completely understood, in particular, in terms of global transport properties and time-dependent transitional flow in the branching structures.

The discovery of association between morphology and function of bronchial tree has been the research focus of biologists [14–17]. The notion of optimality has been employed in understanding the bifurcation flows, and bronchial tree is believed to follow Murray's law in the view of natural selection [18]. However, the scaling exponent for the first few generations of bronchial tree is a little smaller than the predictions of Murray's law ($2^{-1/3}$). While, the scaling exponent of deep bronchi in human lung is larger than that in Murray's law. Mauroy et al. proposed a safety factor to explain the difference between the optimized and practical values of the homothety ratio [19]. The branching patterns in the organism are governed by general physical laws as well as by specific physiological requirements, and the dominant optimum principle designing natural bronchial tree remains elusive [18–21]. The fluid flow in the bronchial tree is frequently unsteady, especially in the former human airways. However, fully-developed laminar flow has been generally assumed in most previous work. Thus, the transport properties of unsteady fluid flow need to be studied in order to understand the morphology of the bronchial tree.

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Nomenclature

Latin symbols

c	Korteweg–Moens velocity ($\mathrm{m\,s^{-1}}$, Eq. (7))
C	constant (Eq. (12))
d	diameter (m)
D	fractal dimension
f	frequency of pulsation (Hz)
F	additional acceleration term (Eq. (12))
g	gravity acceleration ($\mathrm{m\,s^{-2}}$)
l	length (m)
n	branching number (integer)
N	particle number (integer)
m	total generation number (integer)
p	pressure (Pa)
q	mass flow rate ($\mathrm{kg\,s^{-1}}$)
Q	respiratory rate ($\mathrm{ml\,s^{-1}}$)
r	particle deposition efficiency (Eq. (15))
R	resistance
Re	Reynolds number
s	branching tube label
St	Stokes number (Eq. (16))
t	time (s)
u	velocity ($\mathrm{m\,s^{-1}}$)
V	volume ($\mathrm{m^3}$)
x	Cartesian coordinates (m)
z	generation level (integer)
Z	impedance

Greek symbols

α	successive length ratio (Eq. (1a))
β	successive diameter ratio (Eq. (1b))
ρ	density ($\mathrm{kg\,m^{-3}}$)
μ	dynamic viscosity ($\mathrm{kg\,m^{-1}\,s^{-1}}$)
θ	branching angle (°)
χ	asymmetrical ratio (Eq. (14))

Superscripts

+	dimensionless
‾	averaged

Subscripts

ave	time-averaged
b	branching structure
c	critical
C	captured particle
d	diameter
i, j	integer
l	length
max	maximum
p	solid particle
T	total injected particle
z	generation level
0	initial branch (trachea)

The unsteady nature of inhale–exhale breathing cycles further complicates the mass transfer problem in the branching structures. Under the normal breathing condition, quasi-steady could be assumed for the respiratory flow. However, the time-dependent transitional flow under abnormal breathing conditions may significantly affect the ventilation function and particle deposition of bronchial tree. Therefore, the unsteady airflow in the branching structures has attracted increasing interests [22–25]. Calay et al. [22] performed a numerical study on the unsteady respiratory airflow dynamics within a human lung based on a three-dimensional asymmetric bifurcation model by computational fluid dynamics method. Their numerical results for the resting and maximal exercise breathing conditions indicate that the airflow is strongly dependent on the geometry and Reynolds number, and the secondary motions are stronger for the normal breathing condition compared with the maximal exercise condition. Cui and Gutheil [23] investigated the flow field in a constricted tube with large eddy simulation and Smagorinsky sub-grid model. The numerical simulations of the flow field in the idealized model reveal that the unsteady flow field considerably differs from the time-averaged flow field with respect to the secondary flow, the recirculation zone and the laryngeal jet. Evegren et al. [24] studied both steady and unsteady flow through a three-generation system of non-symmetric bifurcations, and they concluded that the steady state solution is not representative for the unsteady cases. Sera et al. [25] investigated the effects of sinusoidal expansion and contraction during the respiratory cycle on gas dispersion in multi-branching airways with a 3D multi-branching airway model. They indicated that the steady streaming and unsteady flow behavior may enhance gas dispersion in multi-branching airways.

The motion and deposition of aerosol/particle in human airways have been of research interest for several decades [26–32]. Recently, several researchers have paid attentions on the particle deposition characteristics under unsteady airflow conditions. Zhang et al. [26] simulated the particle transport in a rigid and symmetric triple bifurcation lung airway model under transient and steady laminar flow conditions, and showed similar particle deposition results matching Stokes and Reynolds numbers for all inhalation modes and bifurcations. Nowak et al. [27] used a sinusoidal pressure profile with time period of 4 s to simulate a typical inhale–exhale cycle and indicated that particle deposition under time-dependent flow conditions are significantly different from the steady-state cases. Jin et al. [28] focused on the deposition efficiency of the inhaled particles with different size under an unsteady respiration mode at the breathing intensity of $Q = 60$ L/min, and their results indicate that the particle deposition efficiency in the unsteady respiration mode are higher than that of steady mode. Nazridoust and Asgharian [29] discussed the effect of inlet and outlet conditions on airflow and particle deposition in lung common airways. Predicted flows show similar trends but with a notable difference in magnitude, and the particle depositions are also different for different cases. Jedelsky et al. [30] measured the monodispersed aerosol particle motions in steady and cyclic flows in a realistic airway model, and reported negligible differences for the motion of particles in the inspected sized of 1–8 μm at frequency below 500 Hz. Soni and Aliabadi [31] compared steady-state inspiratory and unsteady flows with an inlet Reynolds number of 319 at an idealized ten-generation bronchial tube model via large-scale CFD simulations. A sinusoidal waveform was employed to represent inhale–exhale breathing. It was found that both the geometry of branching structures and unsteady nature of the breathing play an important role in particle deposition. As the inhaled nanoparticles may cause pulmonary inflammation, the transport and deposition of nanoparticles in airways have attracted more and more attention. Qiao et al. [32] presented a review on the transport and deposition of nanoparticles in respiratory system by inhalation, and discussed the methods and technique as well as influencing factors involved in particle transport and deposition.

Although many numerical simulations have been made on the fluid dynamics behavior of the bronchial tree, the comparison of