A Numerical Study of Structure and Function Relationships in Normal and Severe Asthmatic Lungs

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Abstract

Rationale: Computational fluid dynamics (CFD) has become a popular tool for studying particle deposition in the lungs because it can be used to track individual particle motion and quantify particle deposition in a region of interest. In this study, we apply a high-fidelity CFD model together with computed tomography (CT) image-based airway models to study airway resistance and particle deposition in both normal and severe asthmatic lungs. The objective of this study is to investigate numerically the effect of constricted airways (structure), as in the asthmatic lung, on airway resistance and particle deposition (function).

Methods: The human airway models were constructed from CT volumetric images of a normal subject and a severe asthmatic subject. Each subject was scanned during breath-hold at two lung volumes. A subject-specific physiological flow boundary condition was derived from air volume difference by registering two lung images of the same subject. An in-house parallel large eddy simulation (LES) technique was adopted to capture turbulent-transitional-laminar flows in the central airways because a turbulent laryngeal jet is induced at the glottal constriction in the trachea. A constant inspiratory flow rate of $Q=3.42\times10^{-4}$ m^3/s was imposed at the inlets of the two airway models. In order to understand the characteristics of deposition of pharmaceutical aerosols or bacteria in both airway models, particle transport simulations were performed using LES-predicted air flow fields. Particle size of 2.5 μm was considered. Airway resistance ($R = \Delta p/Q$, where Δp is the pressure drop and R in $Pa/(m^3/s)$) was calculated for various generations of airway segments in both normal and asthmatic models.

Results: Pressure drop of ~ 200 Pa and airway resistance of ~7420 $Pa/(m^3/s)$ are observed in the asthmatic lung, especially in the right upper lobe (RUL) and the left lower lobe (LLL). Local high pressure drop is associated with local high air speed caused by airway constriction. High concentrations of particles are also found in the branches of RUL and LLL. That is, we find that local airway constriction induces high air speed and increases particle deposition in the constricted regions and at their downstream bifurcations.

Conclusion: The obstructed airways can induce high airway resistance and subsequently increase particle deposition in the constricted regions and at their downstream bifurcations.

Acknowledgments:

This work was supported in part by NIH grants R01-HL094315 and S10-RR022421.