Numerical Study of Mucociliary Clearance in the Airway

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Abstract: **We study the mucociliary clearance in human airway using numerical simulations. In our model, the beating cilia immersed in the viscous mucus provide the driving force. Each cilium is modeled as a rigid rod with prescribed motions. Parameters, such as fluid viscosity, cilia length, cilia beating frequency, and the orientation of cilium, are examined in order to understand their effects on the transport property of the mucociliary flow. Deviation of these parameter values from normal physiological range corresponds to various respiratory problems, e.g., primary cilia dyskinesia, cystic fibrosis.**

Keywords: **mucociliary clearance, cilia, mucus, Navier-Stokes**

I. Introduction

Mucociliary clearance is one important mechanism that our body uses to fight off the constant attack on our airway surface. Important factors that maintain good mucociliary clearance include the density of the cilia, the coordinated movements of cilia, and the viscosity of the mucus layer. Deviation of these parameters from the normal range, either as a genetic defect or as a result of infection, would lead to various respiratory diseases, for example, pneumonia, cystic fibrosis. In our work, we developed a mathematical model to simulate mucociliary clearance. This model is applied to study key factors that affect the transport of the mucociliary flow.

II. Mathematical model

Our two dimensional mucociliary flow model simplifies some biological processes of the mucociliary clearance in order to focus on the study of biomechanics. We treat the cilium as a rigid rod, and model the microtubule-dynein activation of the cilium using prescribed periodic motions. The shape change of the cilium during the effective and recovery stroke is described as the length change between the tip and base of the rod. The viscoelastic mucus layer is assumed to be Newtonian and incompressible. The motion of the mucus layer is governed by Navier-Stokes equations. In the simulation, the transport of the mucus layer is driven by the beating cilia. We examine effects of a list of disease-relevant parameters of the mucus flow, including the viscosity of the mucus, the coordinated motion, the beating frequency and the orientation of the cilia.

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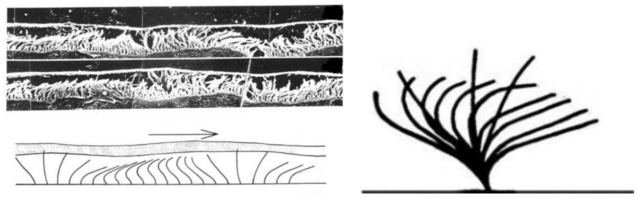

Figure 1: *Left:* an illustration of mucociliary clearance using cultured tracheal epithelium of rabbit[2]. *Right:* Snapshots of the cilium motion in a whole cycle at a sequence of equally spaced times[2].

III. Result and Discussion

Our numerical simulations show that 1) asymmetry in the cilium motion is essential to the uni-directional movement of the mucociliary flow; 2) the trace of fluid particles follow a periodic pattern. The periodicity depends on the beating frequency, the phase shift and the number density of the cilia; 3) an increase of mucus viscosity causes an significant decrease in the particle transport; 4) the bending of the cilia during the recovery stroke increases the efficiency of the mucociliary transport.

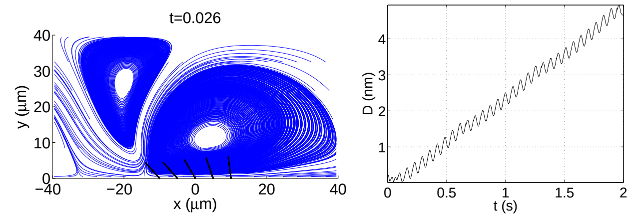

Figure 2: *Left:* streamlines of the fluid flow using 5 rods whose motions are out of phase. The length of the rod is changed during the recovery stroke to mimic the cilium bending. *Right:* the displacement of the particle from its original position at (0, 6.5)μm.

Reference

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