Mucociliary Clearance Efficiency: A Numerical Study

Ling Xu[1] and Yi Jiang[+]

Short Abstract — **Mucociliary clearance is an integral part of the first line of defense in our airways. The purpose of this study is to, using a mathematical model, identify and study the key factors that influence the transport ability of the mucociliary system.**

Keywords — **cilia, mucus, metachronal wave, computational fluid dynamics.**

I. Introduction

With breathing, the human respiratory tract is constantly in contact with potentially infective microorganisms and noxious substances in the air. Lung epithelium is our first line of defense against these potentially infective and damaging particles. On the other hand, aerosol inhalation is an effective means of drug delivery for respiratory problems. In order to better protect ourselves from these external harmful agents, or to design a more effective delivery device for aerosol drugs, we will need to understand how these particles are transported and redistributed through mucociliary clearance.

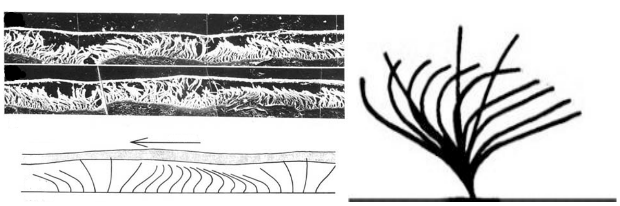

Fig.1: (Left) An illustration of mucociliary clearance using cultured tracheal epithelium of rabbit[1]. (Right) Snapshots of the cilium motion in a whole cycle at a sequence of equally spaced times[1] .

II. Mathematical Model

We developed a simple rod-propel-fluid model for mucociliary system, based on the following assumptions: (1) motion of the cilia is on a plane; (2) the mucus flow is homogeneous, incompressible and Newtonian; (3) the cilium is modeled as a rigid rod. Its complex shape variations during the effective and recovery strokes are treated as changes in the rod length; (4) the cilium motion is prescribed. The mucus motion is governed by the incompressible Navier Stokes equations. A formally second order immersed boundary method[2] was used to compute the impact of the moving mucus to the fluid flow.

III. Results and Discussion

Using the rod-propel-mucus model, we examined the effects of cilia density, beating frequency, metachronal wavelength, as well as the cilia bending functions.

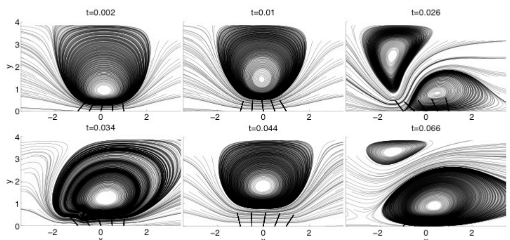

Fig.2: streamlines due to five beating cilia at consecutive times, as indicated in the plots.

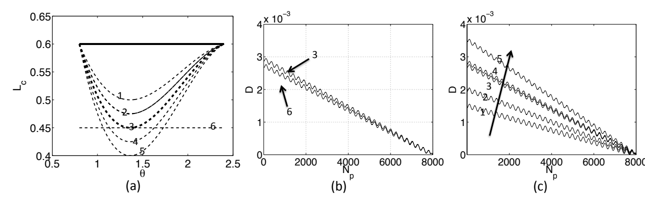

Fig.3: (a) Functions of the cilia tip orbit. (b) The transport ability *D* remains the same for very different tip orbits (functions 3 and 6 in (a)). (c) The transport ability *D* differs when the height difference change.

Our numerical simulations first verified that asymmetry in the cilia motion is key to develop the net transport in the mucus flow, as indicated in Fig.3. The cilium tip height difference between the active and recover strokes alone signifies the degree of asymmetry. The more deformed the cilium is during the recovery stroke, the more effective the transport is. We also found that the transport capacity saturates with increasing cilia density and cilia beating frequency. The contribution of the metachronal wave to the mucus transport ability is found to be significant, but, interesting, to depend little on the value of the phase lag among cilia. These findings offer new insights into mucociliary clearance in the airway.

References

[1] Sanderson M.J., Sleigh A. (1981) Ciliary Activity of Cultured Rabbit Tracheal Epithelium: Beat Pattern and Metachrony, *J.Cell Sci.,* **47:**331-347.

[2] Lai MC, Peskin CS (2000) An immersed boundary method with formal second- order accuracy and reduced numerical viscosity. *J Comput Phys.* **160(2):** 705-719.

[1] Department of Mathematics and Statistics, Georgia State University. E-mail: lxu9@gsu.edu

[+] Department of Mathematics and Statistics, Georgia State University. E-mail: yjiang12@gsu.edu