

**Numerical Model of Cilia-Driven Transport of Inhaled Particles in the
Periciliary Layer of the Human Tracheobronchial Tree**

By

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DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Mechanical and Aeronautical Engineering

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

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2022

Dedicado a mi familia, cuyos sacrificios fueron mayores que los míos
Dedicated to my family, whose sacrifices were greater than mine

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Numerical Model of Cilia-Driven Transport of Inhaled Particles in the Periciliary Layer of the Human Tracheobronchial Tree

Abstract

The human respiratory system has evolved to maintain critical functions for survival despite being vulnerable to threats in the environment that are inhaled as part of the necessary gas exchange process. In the respiratory tract, ciliated cells line the tracheal-bronchial tree where mucus producing cells create a barrier that captures inhaled particles. The ciliated cells have hair like protrusions that beat in complex beat patterns in order to move the mucus towards the throat where it is expectorated or swallowed. The system complexity has made it difficult to properly measure particle clearance *in-vivo*. The subject of this dissertation is to numerically study the interaction of inhaled particles with the ciliated cell population. More specifically, the numerical modeling effort builds on work analyzing mucosal layer clearance by addition of arbitrary shaped finite-sized particles in the mucosal layer. In our work, we show that finite-sized particles compared to massless tracers have non-trivial clearance paths, challenging and enriching previous modeling assumptions that massless tracer particles are sufficient for measuring clearance.

We consider one specific simplified model, a single cilium infinitely repeating, and a more representative model, a cilium patch, to understand the effect that biophysical airway parameters have on particle-cilia interaction. We consider the effects that the configuration parameters have on clearance and, in addition, how the dynamics of a finite-sized particle differ from massless tracers. Second, we broaden our model to consider a patch of cilia that represent a two-dimensional cross section of the upper airway. The effect of multiple cilia structures are studied by varying arrangement and synchrony. Next, we quantify in detail the effect that these parameters have on the transport of any arbitrary shaped particles. This dissertation is concluded with a thorough analysis of the flow dynamics in the periciliary layer by incorporating three distinct measures of mixing.

Acknowledgements

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Chapter 1

Introduction

1.1 Respiratory Inhalation and Dysfunction

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1.2 Research Goals and Dissertation Structure

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Chapter 2

Governing Equations and Numerical Methodology

2.1 Problem Formulation

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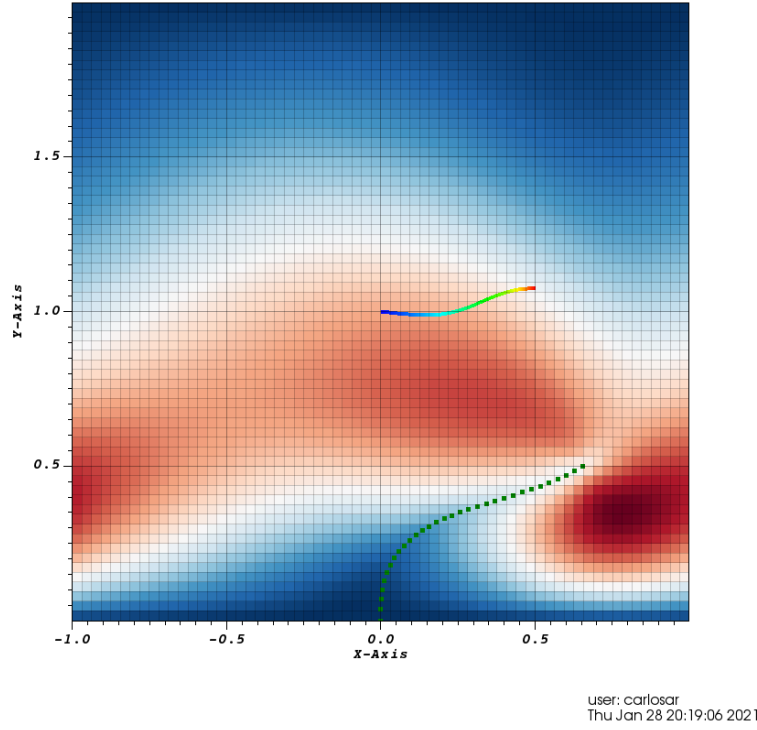


Figure 2.1: Simulation of single cilium.

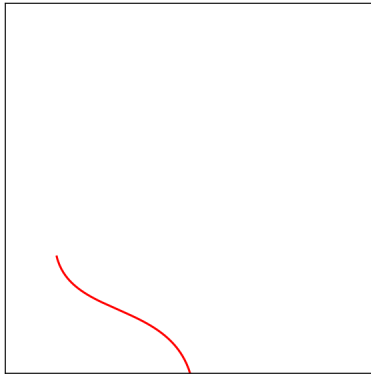
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You also probably need the NS equations. The governing equations of motion for the periciliary fluid are the incompressible Navier-Stokes equations given by Equations 2.1-2.2.

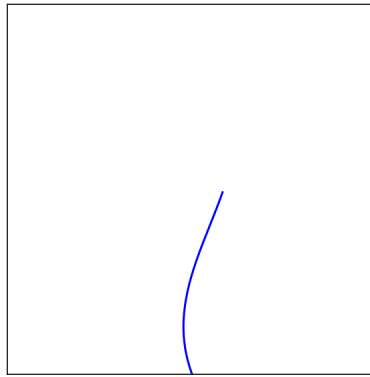
$$\vec{\nabla} \cdot \vec{v}(\vec{x}, t) = 0 \quad (2.1)$$

$$\rho_p \left(\frac{\partial \vec{v}}{\partial t}(\vec{x}, t) + \vec{\nabla} \cdot (\vec{v}(\vec{x}, t) \otimes \vec{v}(\vec{x}, t)) \right) = -\vec{\nabla} p(\vec{x}, t) + \mu_p \vec{\nabla}^2 \vec{v}(\vec{x}, t) + \vec{f}_b(\vec{x}, t) \quad (2.2)$$

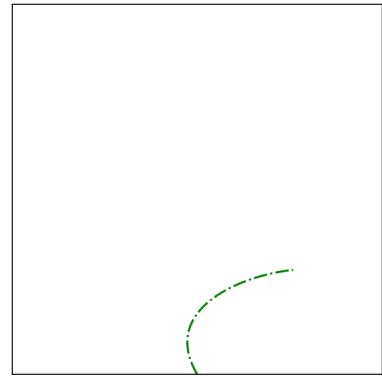
Equation 2.1 is the incompressible mass continuity equation, and Equation 2.2 is the momentum equation, where the parameters...



(a) Start of stroke. Long sentence to display the caption margin limits, if it is off, it looks like Figure 2.2c and 2.2b.



(b) Forward stroke. Long sentence to display the caption margin limits, if it is off, it looks like...wait that's us!



(c) Backward stroke. Long sentence to display the caption margin limits, if it is off, it looks like...wait that's us!

Figure 2.2: Some subfigures.

2.2 More testing of things

I also used subcaption to get some subfigures (Figure 2.2), and changed the caption margin to add some spacing between the figure subcaptions. Figure 2.2b and 2.2c the caption margin makes it look like one continuous caption between the two figures. Downside is that then you might need to add extra lines with invisible text to line them all up. Figure 2.2a is not aligned with all of them.

Chapter 3

A title for chapter 3 that is very long and needs to exist in two lines

3.1 Methodology

A chapter with typical sections with some citations sprinkled around.

3.1.1 Data Generation

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3.1.2 Data Analysis

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3.2 Results

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3.2.1 Cool Results

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3.2.2 Surprising Results

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3.2.3 Other Results

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3.3 Discussion and Conclusions

The section that says "I am ready to graduate" as described in Ruvalcaba [1].

Chapter 4

Conclusions and Future Work

4.1 Conclusions and Contributions

Throughout this body of work, several important contributions have been made to the field. We summarize these contributions.

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4.2 Future Work

Future graduate students, see me for ideas!

Appendix A

Long Title of Appendix A

Observations of non-wet rain have recently appeared in the literature. In this Appendix, we briefly consider the implications of these observations for the analysis offered in this dissertation.

Appendix B

Long Title of Appendix B

Observations of non-wet rain have recently appeared in the literature. In this Appendix, we briefly consider the implications of these observations for the analysis offered in this dissertation.

References

- [1] Carlos Abraham Ruvalcaba. Writing my dissertation. *A Journal that Accepts my Paper*, 1(19):1211–1248, 2021.