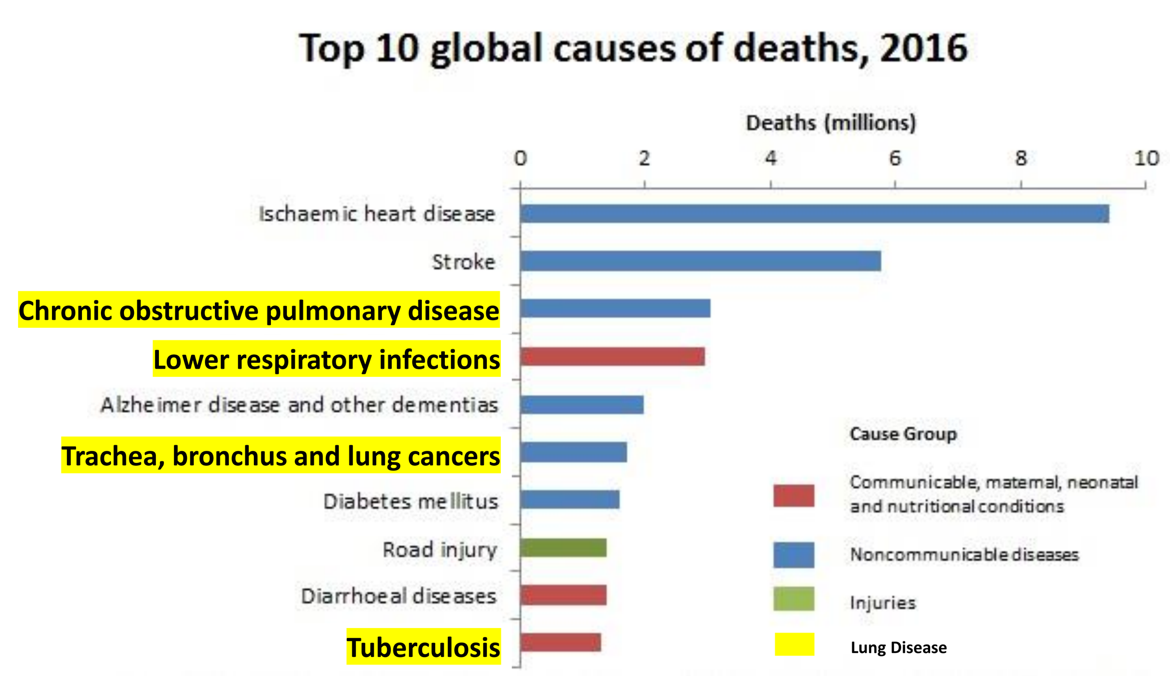
Inhaled Particle Dynamics at the Air/Mucus Interface using DPM-VOF Modeling

Blake Bartlett[1], Yu Feng[1]
[1]School of Chemical Engineering, Oklahoma State University

Objectives

- Create a physics-based volume-of-fluid model of the conducting airways
- Include the mucus layer and mucociliary clearance
- Simulate the deposition of inhaled particles and their modes of clearance

Lung Diseases

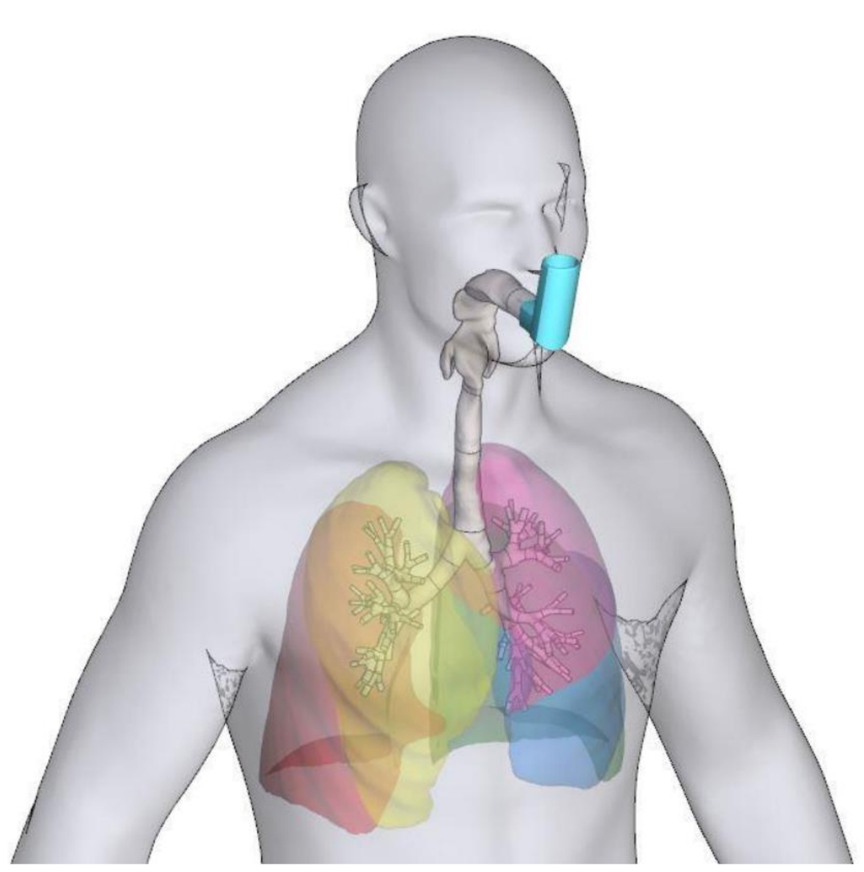


https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death

Sources of Lung Disease

- Occupational Hazard Exposure
- Pathogenic infection
- Genetic predisposition

Aerosol Treatment Potential

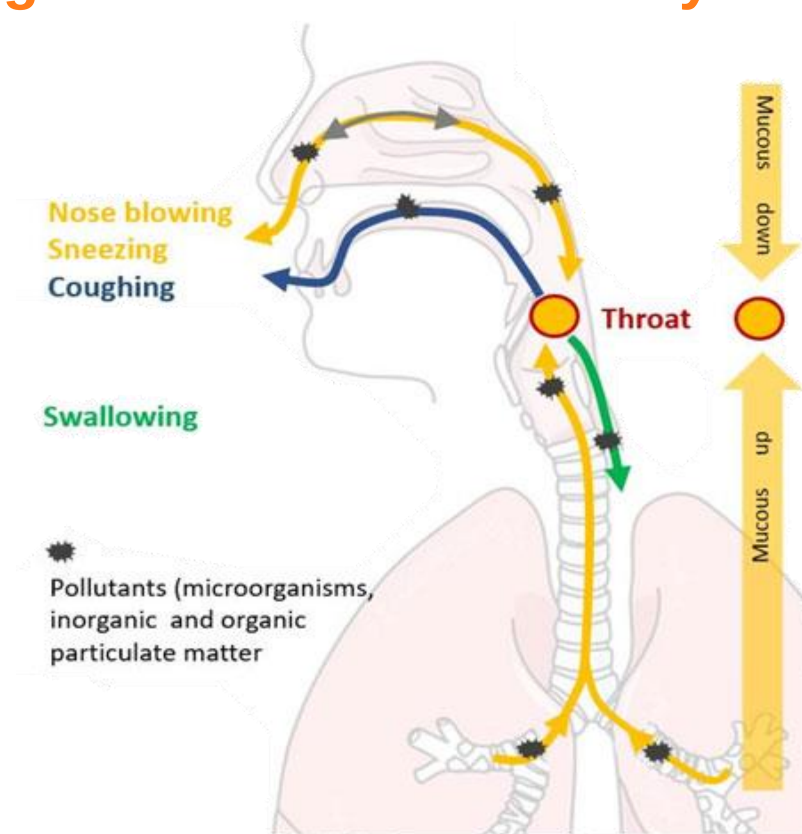


Localized Treatment of Lung

- Maximize the amount of drug that reaches the diseased portion of the lung
- Reduce off-target side effects
- Take advantage of large lung surface area
- Minimize administration inconveniences

Lung Environment

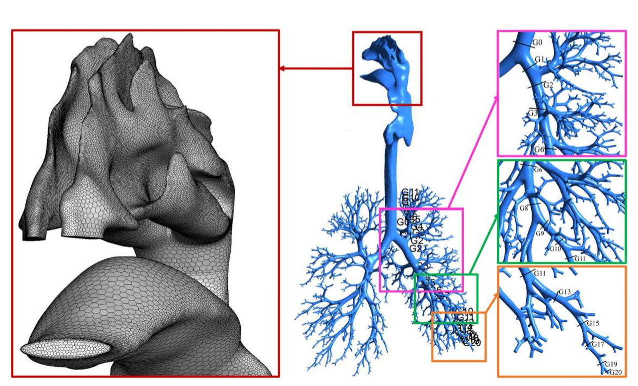
Lung Mucus and Mucociliary Clearance



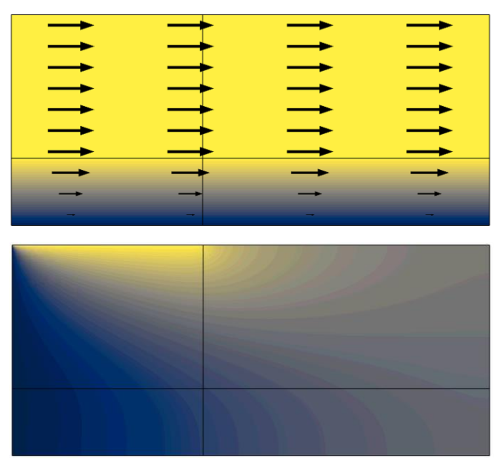
https://www.condair-group.com/humidity-health-wellbeing/how-dry-air-affects-our-immune-system

Simulation Novelty

- Handful of existing models for airflow in bifurcating airways, straight tubes
- Small number of simulations for transport of particles through mucus, similar fluids
  - Often on micron scale
- No existing model can study both phenomena simultaneously



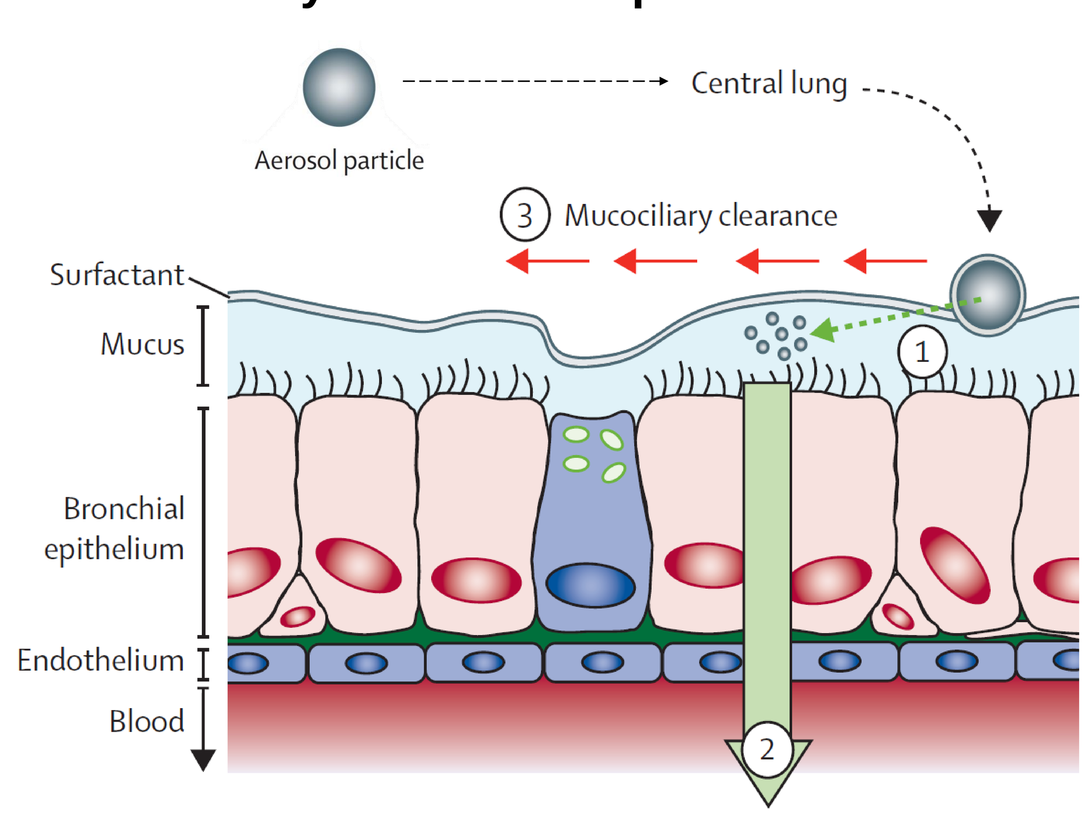
Hayati et al., J Aerosol Sci, 2021



Bartlett et al., bioRxiv, 2021

Particle Impaction and Clearance

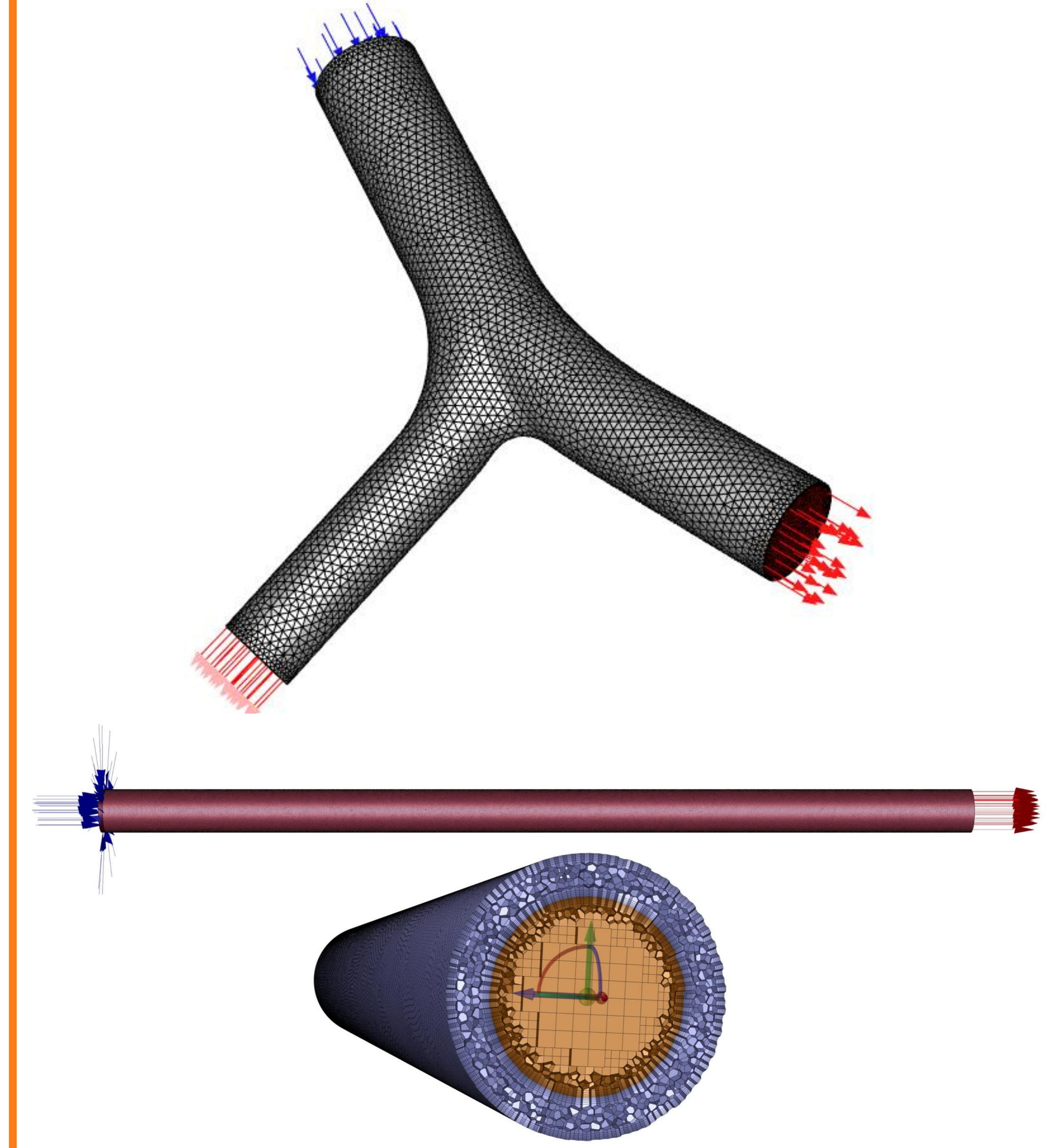
1. Particle contact with the mucus
2. Transport of the particle across the epithelium to target tissue
3. Mucociliary clearance of particle



Adapted from Ruge et al., Lancet Respir Med, 2013

Computer Model

Simulation Domain



Two studied domains: single bifurcation and simplified straight cylinder. Rigorous implementation of liquid layer more difficult in complex geometries

Equations

Momentum equation governs velocity profile, effect of viscosity

$$\frac{\delta}{\delta t}(\rho\vec{v} + \nabla\cdot(\rho\vec{v}^2) = -\nabla p + \nabla\cdot(\overline{\overline{\tau}}) + \rho\vec{g} + \vec{F}$$

$$\overline{\overline{\tau}} = \mu\left[(\nabla\vec{v} + \nabla\vec{v}^T) - \frac{2}{3}\nabla\cdot\vec{v}I\right]$$

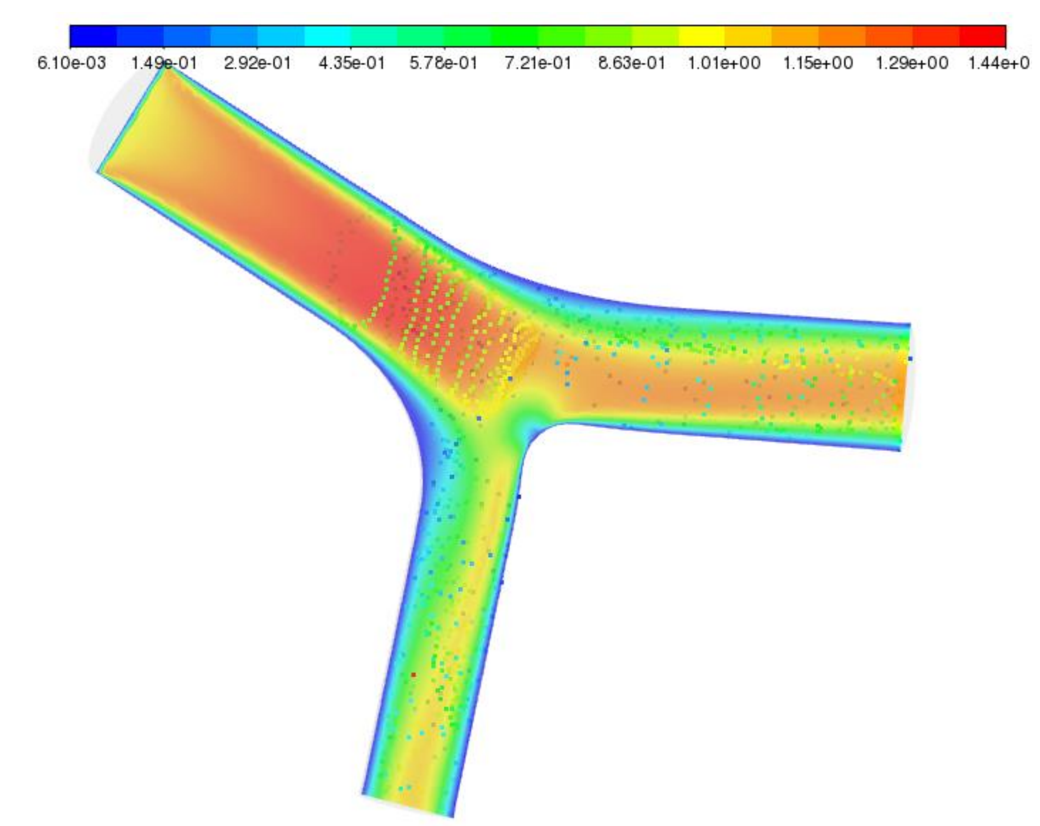
Continuity equation governs what portions of the volume are occupied by which phase, and how they interact

$$\frac{\alpha_q^{n+1}\rho_q^{n+1} - \alpha_q^n\rho_q^n}{\Delta t}V + \sum_f(\rho_q U_f^n \alpha_{q,f}^n) = \left[\sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp}) + S_{\alpha_q}\right]V$$

- Mucus clears at a rate orders of magnitude slower than airflow velocity
  - Does not significantly impact where particles are trapped, but does impact their final fate
- Volume fractions of air and mucus not expected to change significantly with time

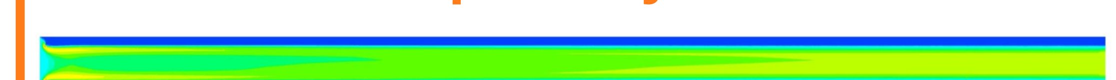
Results

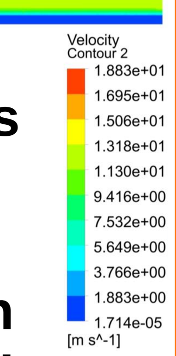
Airflow and Particle Deposition in Single Bifurcation



Deposition pattern varies with particle size, inhalation speed, orientation (due to gravity), and other factors

Airflow and Particle Deposition in Tube with Liquid Layer





Airflow is much faster than mucus flow. Velocity change is sharp at the liquid/air interface due to negligible viscous forces between the phases. Smaller, lighter particles are more likely to "ride the current" and impact the liquid layer further downstream than larger particles

Lung Environment

Skills Learned

- Modeling using ANSYS Fluent
- Generalized methods for optimized modeling
- Review of literature

Future Plans

- Apply non-Newtonian fluid models for mucus
- Simulate liquid layer as a hydrogel
- Final fate of particles when they reach wall rather than when they impact mucus
- Add mathematics for electrostatic interactions