COMPUTATIONAL FLUID DYNAMIC MODEL OF THE CARDIOPULMONARY SYSTEM

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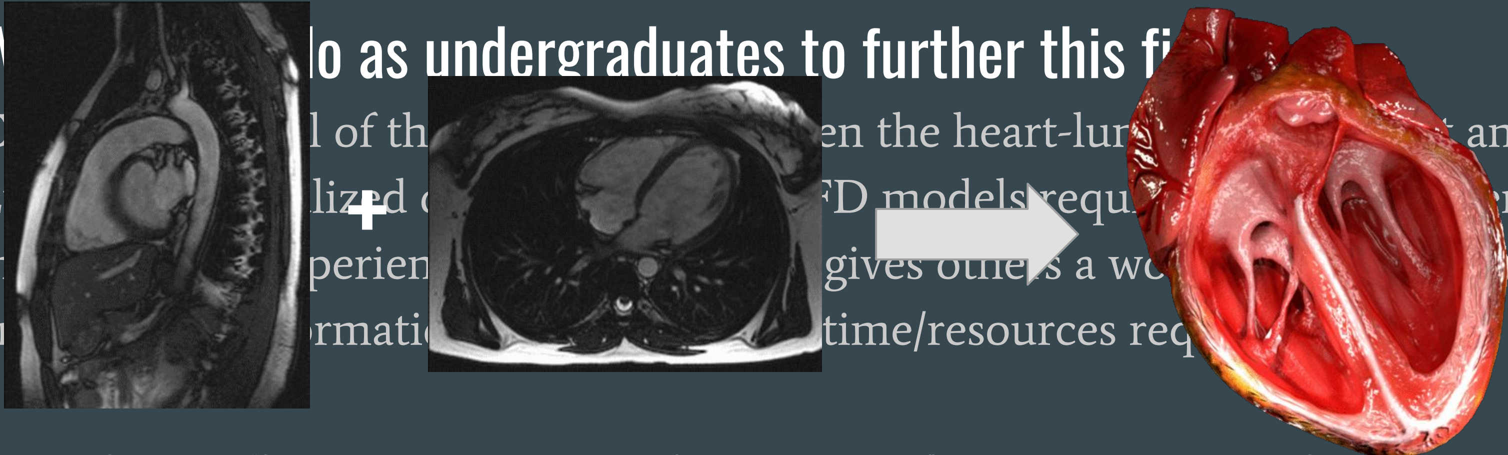
Domain Science: BioMedical CFD

Image-based CFD is the future of cardiovascular [and pulmonary] medical treatment[1]. It has only recently become a feasible option for researchers [note: not physicians], for example a December 2016 study by Virginia Commonwealth University researchers accurately modeled pulmonary drug delivery of an inhaler within 10% accuracy of clinical data[2].



W lo as undergraduates to further this fi

C l of th en the heart-lur an easy task. E lized c FD models requ ring and m perien gives othe s a wo amework ar rmati time/resources req

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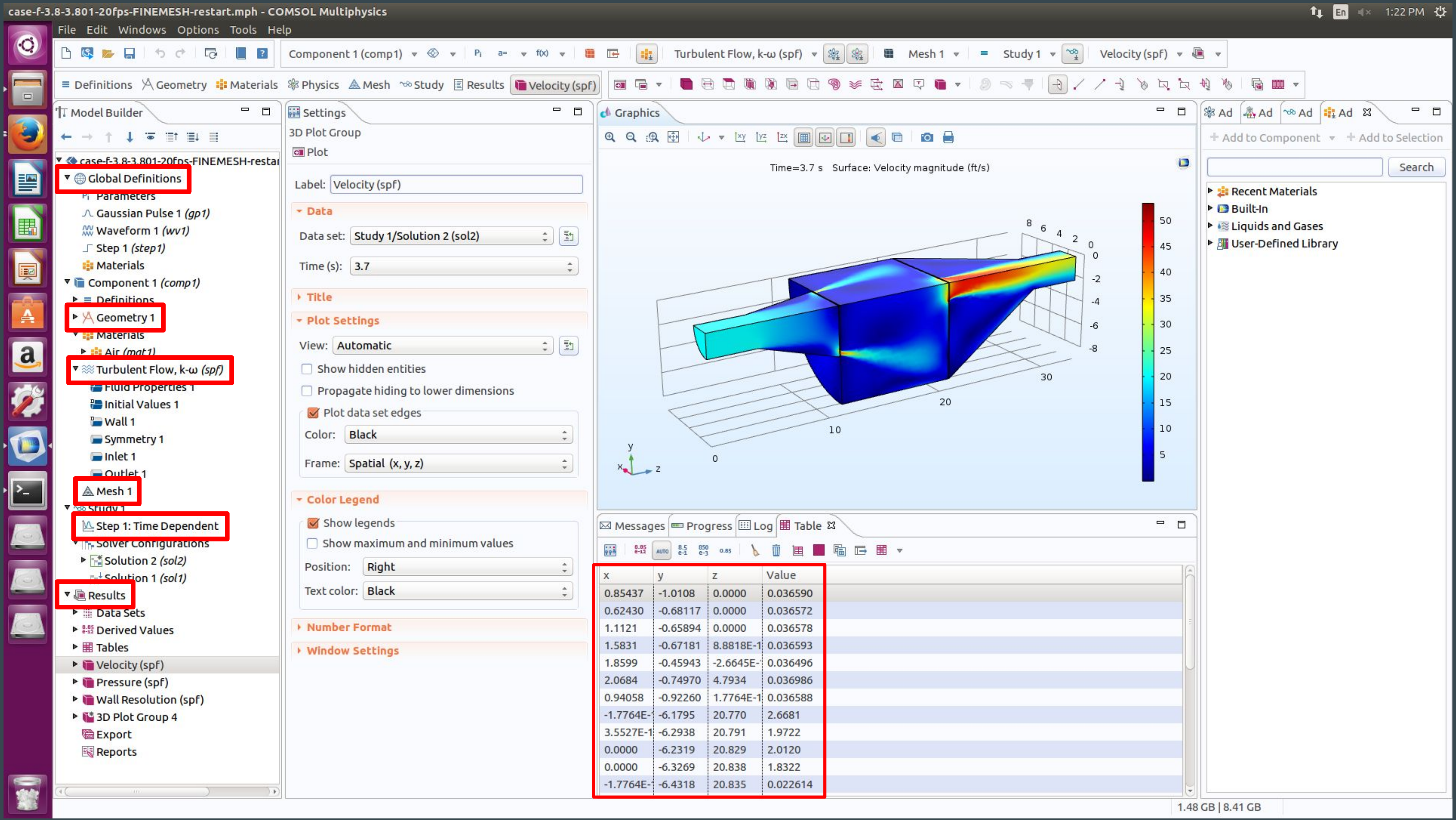
[1] Pennati, Giancarlo et al. “Computational Fluid Dynamics Models and Congenital Heart Diseases.” *Frontiers in Pediatrics* 1 (2013): 4. *PMC.* Web. 12 June 2017.
[2] Longest P. Worth, Tian Geng, Khajeh-Hosseini-Dalasm Navvab, and Hindle Michael. Journal of Aerosol Medicine and Pulmonary Drug Delivery. December 2016, 29(6): 461-481.
Heart model by DrJanaOfficial (Own work) [CC BY-SA 4.0 (http://creativecommons.org/licenses/by-sa/4.0)], via Wikimedia Commons



Label: Velocity (spf)

Data

Data set: Study 1/Solution 2 (sol2)

Time (s): 3.7

Title

Plot Settings

View: Automatic

☐ Show hidden entities

☐ Propagate hiding to lower dimensions

☑ Plot data set edges

Color: Black

Frame: Spatial (x, y, z)

Color Legend

☑ Show legends

☐ Show maximum and minimum values

Position: Right

Text color: Black

Number Format

Window Settings

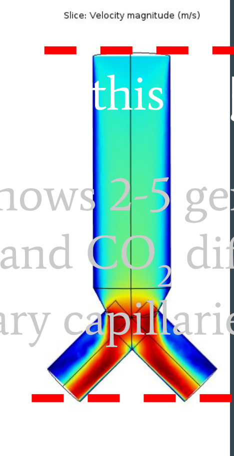
x	y	z	Value
0.85437	-1.0108	0.0000	0.036590
0.62430	-0.68117	0.0000	0.036572
1.1121	-0.65894	0.0000	0.036578
1.5831	-0.67181	8.8818E-1	0.036593
1.8599	-0.45943	-2.6645E-	0.036496
2.0684	-0.74970	4.7934	0.036986
0.94058	-0.92260	1.7764E-1	0.036588
-1.7764E-	-6.1795	20.770	2.6681
3.5527E-1	-6.2938	20.791	1.9722
0.0000	-6.2319	20.829	2.0120
0.0000	-6.3269	20.838	1.8322
-1.7764E-	-6.4318	20.835	0.022614

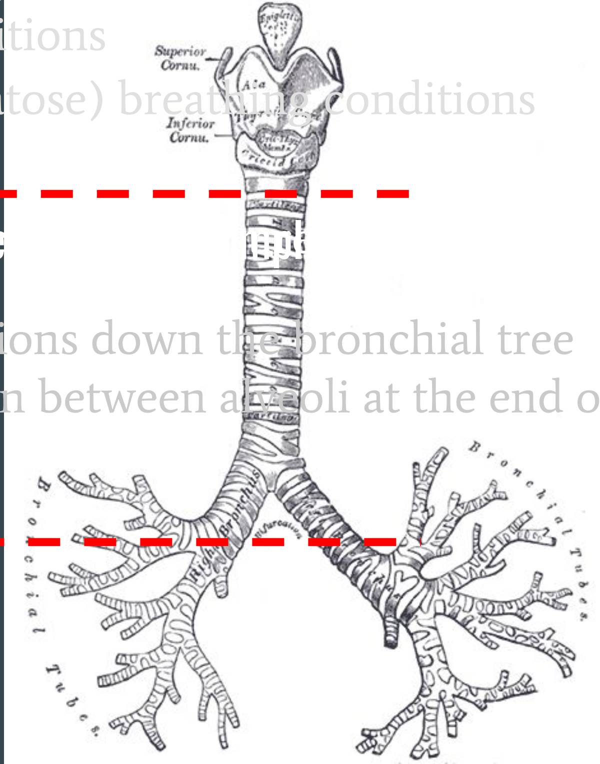
Research Plan

What we accomplished so far.

Using an idealized geometry

- Simulate “at rest” breathing conditions
- Simulate irregular (exercise/comatose) breathing conditions





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- Geometry that shows 2-5 generations down the bronchial tree
- Simulate the O_2 and CO_2 diffusion between alveoli at the end of the bronchial tree and the pulmonary capillaries

KEYS TO CARDIOPULMONARY SYSTEM

Main purpose of pulmonary system is the gas exchange of oxygen and carbon dioxide into/from the blood stream

Pulmonray system is pressure driven

Structure of pulmonary system breaks into generations that lead to the alveolar sacs

Steady State Simulation

Starting estimates for pulmonary pressure during a breath.

Where did we start?

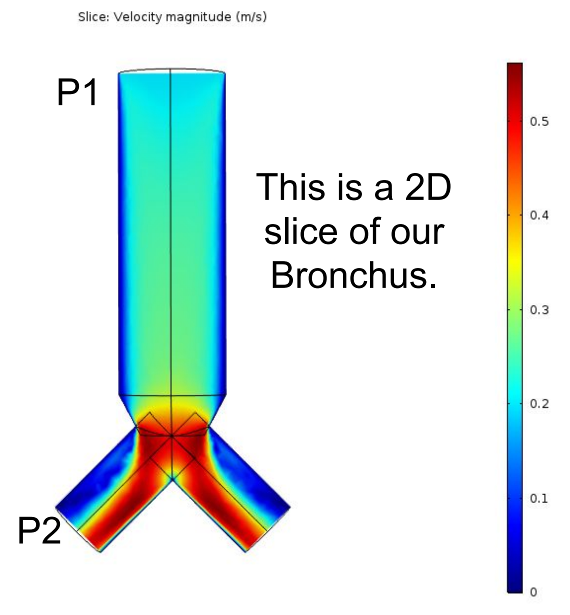
$$\mathcal{V} = \int Q \cdot dt$$

$$Q = \int V \cdot dA$$

Steady state means that the system has reached total equilibrium based off of a single set of initial and boundary conditions.

We care about this solution because it computes faster and gives a reliable snapshot of pressure and velocity.

For example, we know that the lungs can create a pressure difference of +/- 130 Pa. However, this pressure is found in the deepest parts of the lungs, we had to conduct numerical experiments to determine a ballpark estimate for the actual pressure in the bronchus.

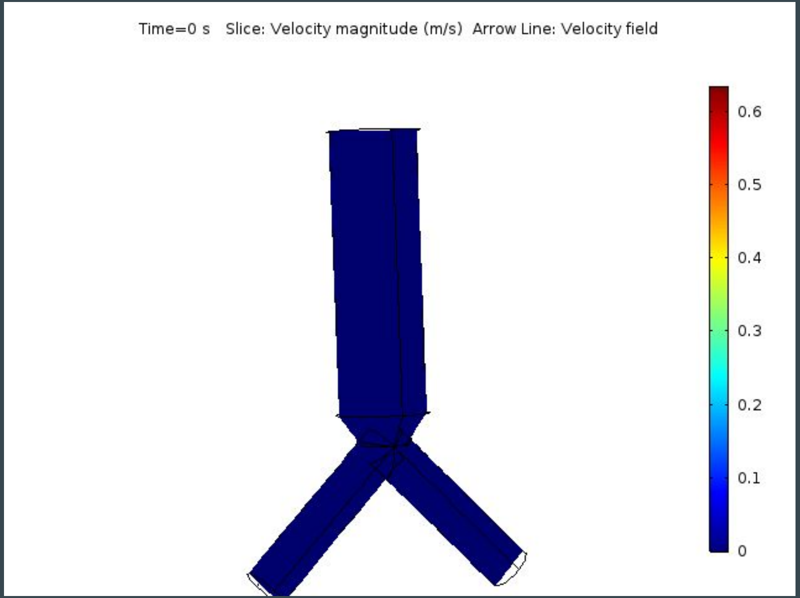

Slice: Velocity magnitude (m/s)

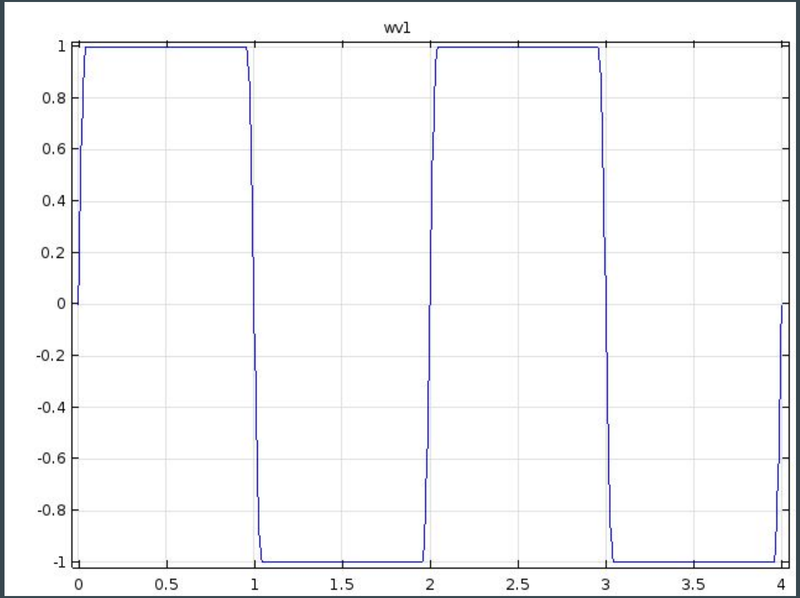
This is a 2D slice of our Bronchus.

TRANSIENT SIMULATION

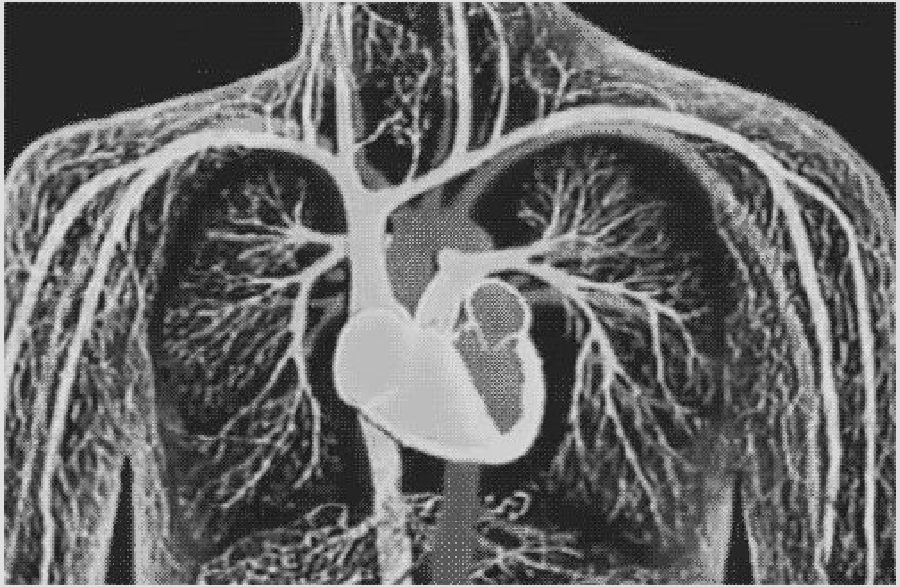
Transient solutions allow us to look at the behavior of the fluid during a breath cycle, rather than just a “snapshot” of the solution that we obtain from a steady state.

To create more breath-like simulations, we used a square Waveform function





Integrating



The Cardiovascular System

Computational __________ Mechanics

The Finite Element Method is a powerful tool when combined with HPC. FEM can be applied to many different disciplines of physics, not just fluid mechanics.

To model gas diffusion between the lungs and the blood, we apply Transport Mechanic equations to each element in our geometry.

Fick's Law of Diffusion

*Rate of Diffusion = Pressure Gradient * Area * Diffusion Coefficient*

The blood/lung pressure gradients of O_2 and CO_2 will be constantly changing because of two asynchronous periodic conditions, the heartbeat and the rhythm of the breath.

How do we idealize this system?

In reality, there are two driving forces behind gas transfer in the lungs, diffusion and the chemical reactions of oxygen and carbon dioxide binding and unbinding from their carriers (hemoglobin and bicarbonate, respectively)[1].

To avoid the requirement of applying an equation describing the equilibrium of a chemical reaction, such as the Hill equation, we are using “effective” diffusion coefficients[2] and applying them to Fick’s equation. These coefficients account for the extra time such reactions would take.

[1] Hlastala, Berger. Physiology of Respiration, Appendix B.
[2] Chang HK, Farhi LE. “Ternary diffusion and effective diffusion coefficients in alveolar spaces.” *Respiration Physiology*, 40(2), 1980, 269-279.

Questions?