A Computational Framework for Patient-Specific Vascular Modeling

Darsh Gandhi[1], Alexandria Johnson[2], Emma Slack[3], Isaiah Stevens[4], Zachary Turner[5]; Mentors: Michelle Bartolo[4], Mette Olufsen[4]

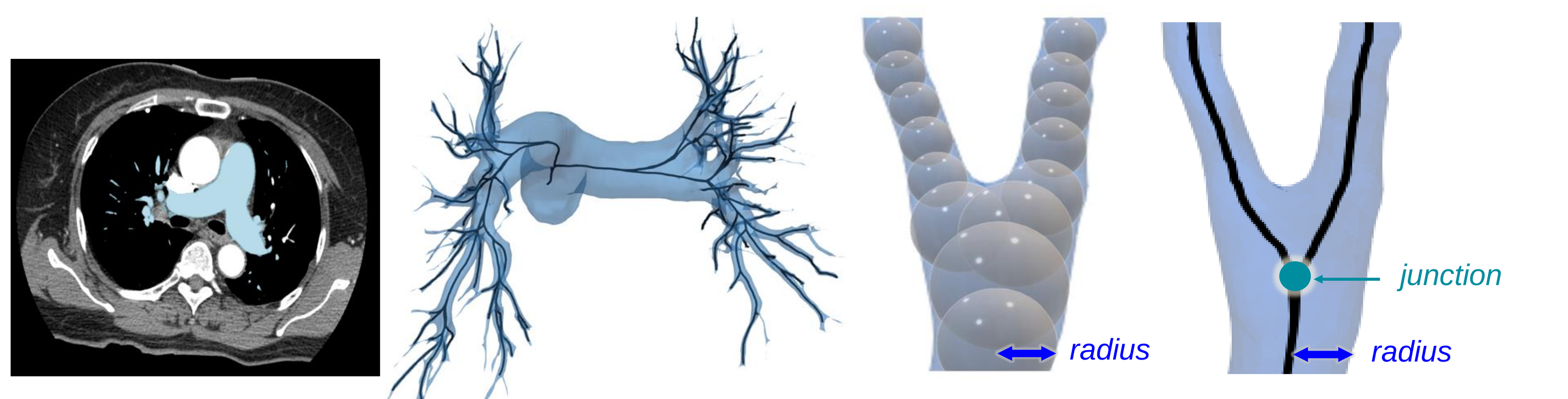
[1]University of Texas at Arlington, [2]University of South Florida, [3]Colorado State University, [4]North Carolina State University, [5]Arizona State University

NC STATE UNIVERSITY

Overview

- Computed tomography (CT) images of the lung are used for qualitative diagnosis of vascular health
- Right heart catheterization provide dynamic quantitative data measuring blood pressure in the main pulmonary artery
- Using fluid dynamics modeling, we superimpose dynamic data on geometric domains extracted from CT images providing a predictive tool to simulate the effect of treatments
- The overall objective of this study is to determine uncertainty associated with geometric domains extracted from CT images
- We investigate the uncertainty in hemodynamics associated with image segmentation, vessel radius, and junction detection

Image Segmentation



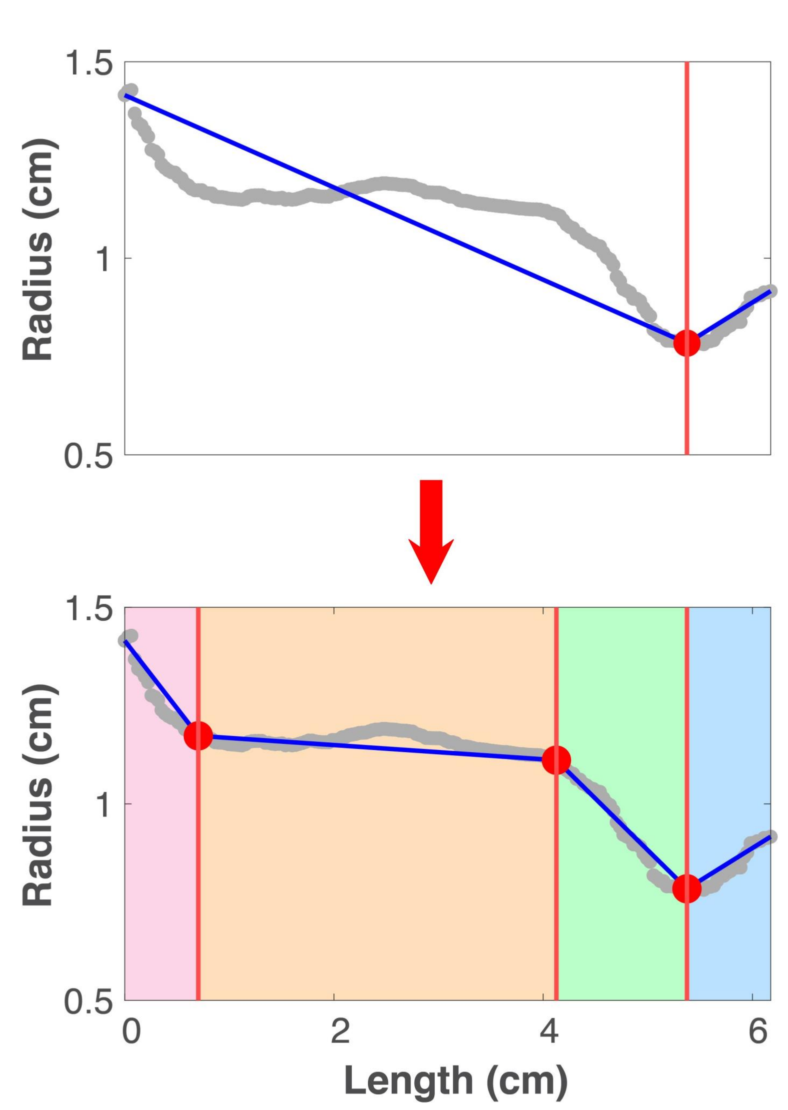
CT Scan | 3D Geometry | Inscribed Spheres | Centerlines

Volumetric model of the pulmonary arteries obtained using 3D Slicer → Vascular Modeling Toolkit (VMTK) creates centerlines such that each point has a radius and each line connecting points has a length

Change Point Analysis

- For each vessel, change points (CP) detect significant changes in the data's mean and variance
- We conduct a hypothesis test on the existence of a single CP

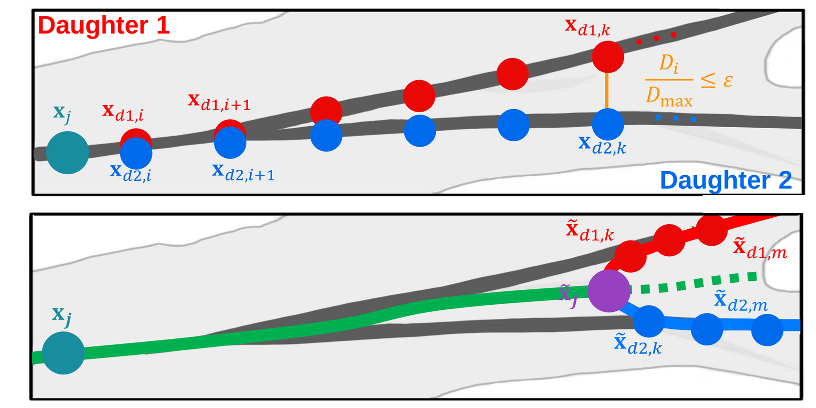
  H_0: $m = 0$; H_a: $m = 1$
- Rejection of the null hypothesis leads to placement of a CP at highest maximum likelihood
- Multiple CPs are detected with binary segmentation, splitting data into sections and running hypothesis tests in each segment
- To prevent overfitting, we allow a maximum of 3 CPs



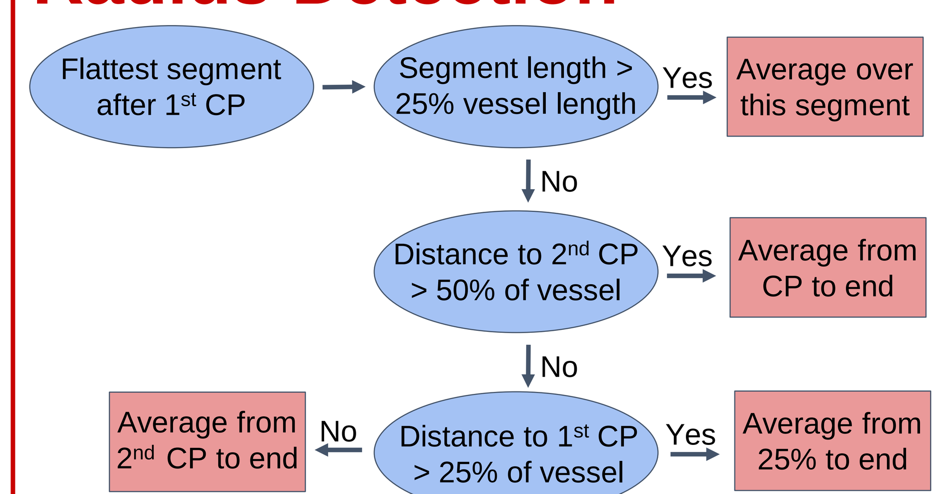
Vessel Data Corrections

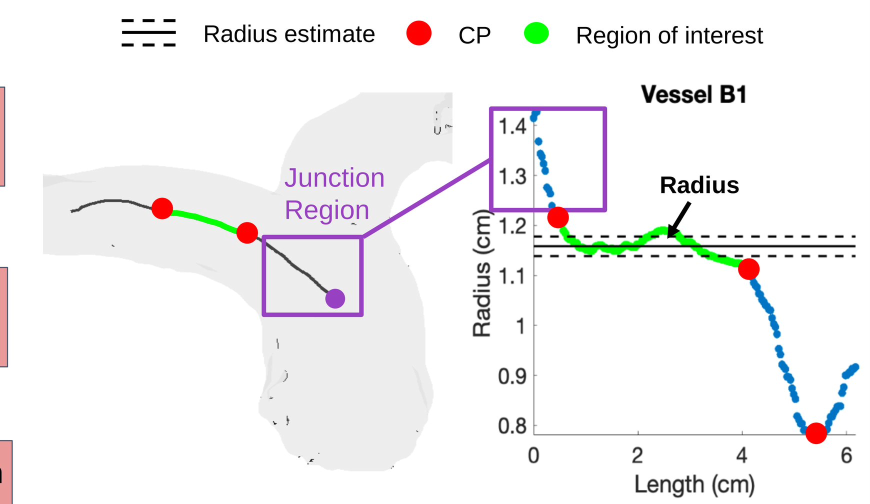
Junction Adjustment

- Starting at terminal VMTK detected junction nodes, recursively correct node-placement if the distance between daughter vessels $< \varepsilon$
- Generate new smooth parent and daughter vessels by averaging



Radius Detection





Identify the region that best describes the radius with standard deviation for each vessel

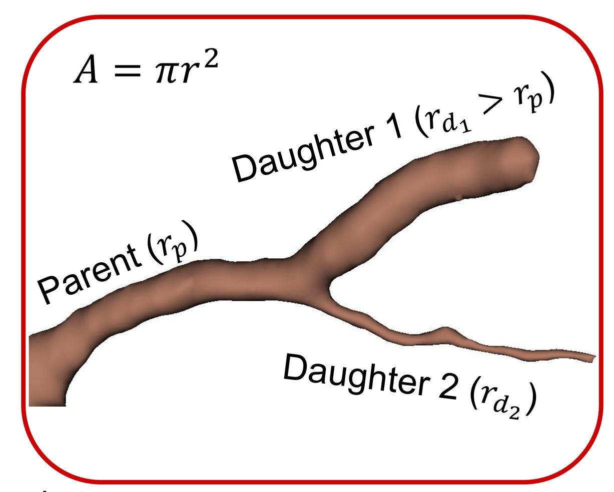
Radius Correction

Assumptions

$r_p > r_{d_1} > r_{d_2}$

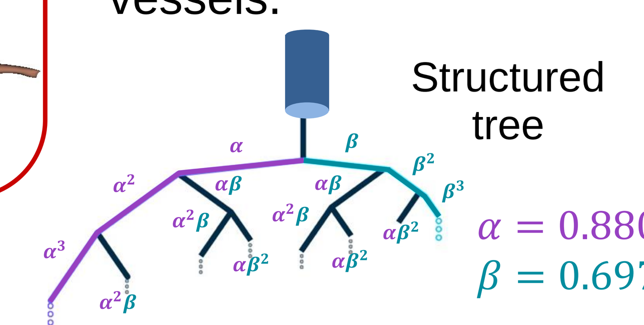
$A_p < A_{d_1} + A_{d_2}$

Segmentations have between 167 – 238 vessels. We *prune* by iteratively removing the smallest terminal vessels to standardize our networks.



$r_{d_1} = \alpha r_p$, $r_{d_2} = \beta r_p$

Daughter radii may violate assumptions. Vessels that violate assumptions are assigned a radius using known structured tree branching valid for small vessels.



Mathematical Model

Large vessels:

- solve non-linear 1D Navier-Stokes equations for flow q (mL/s), area A (cm^2), and pressure p (mmHg)

Small vessels (structured trees):

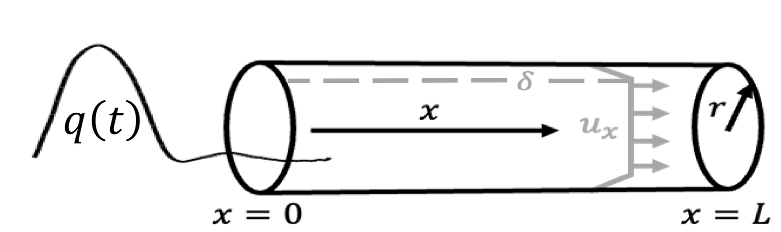
- solve linearized 1D models to quantify pressure P and flow Q as functions of frequency

Mass conservation: $$\frac{\partial A}{\partial t} + \frac{\partial q}{\partial x} = 0$$

Momentum balance: $$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q^2}{A}\right) + \frac{A}{\rho}\frac{\partial p}{\partial x} = -\frac{2\pi\nu R}{\delta}\frac{q}{A}$$

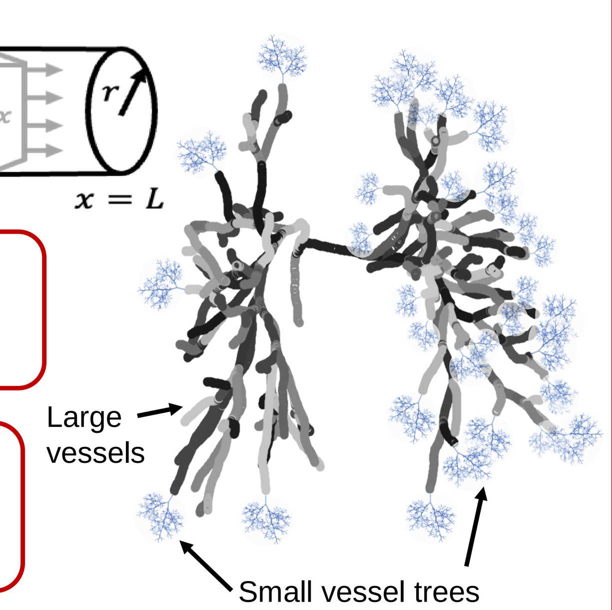
Pressure-area relation: $$p(x,t) = \frac{4}{3}\frac{Eh}{r_0}\left(\sqrt{A/A_0} - 1\right)$$

Wall stiffness: $$\frac{Eh}{r_0} = k_1 e^{k_2 r_0} + k_3$$



Flow: $Q(x,\omega) = a\cos(\omega x/c) + b\sin(\omega x/c)$

Pressure: $P(x,\omega) = i g_\omega^{-1}(b\cos(\omega x/c) - a\sin(\omega x/c))$



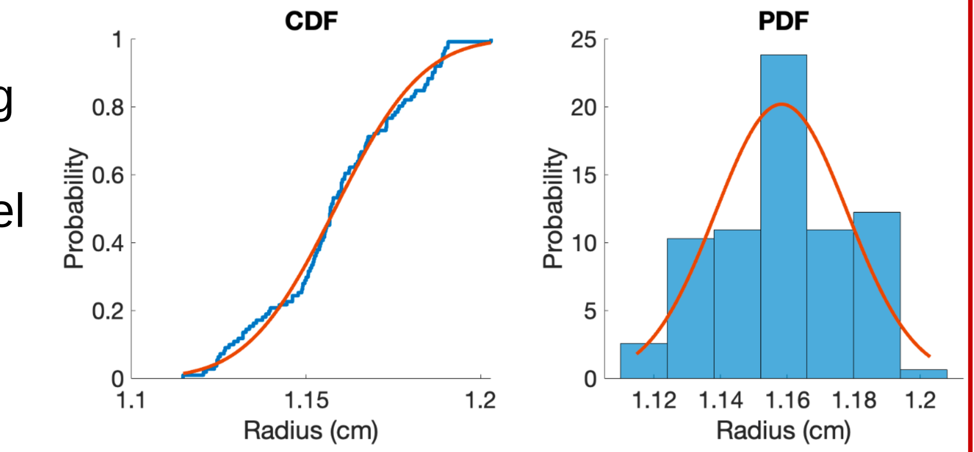
Pressure continuity: $p_p(L_p,t) = p_{d_1}(0,t) = p_{d_2}(0,t)$

Flow conservation: $q_p(L_p,t) = q_{d_1}(0,t) + q_{d_2}(0,t)$

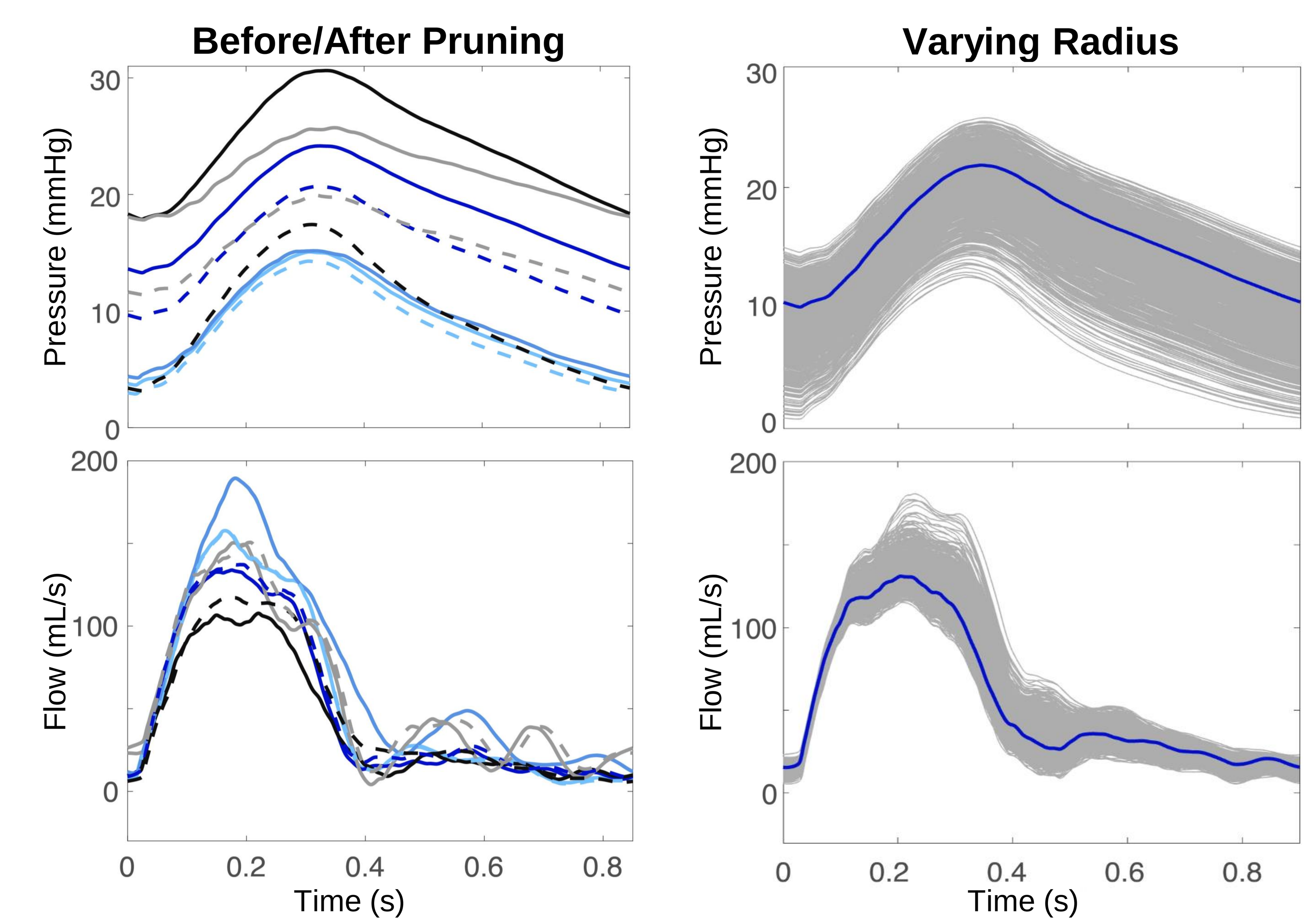
Results

Radius Sampling

From the segment representing the vessel radius, a probability distribution is generated. Vessel networks are generated by sampling vessel radii from a normal distribution



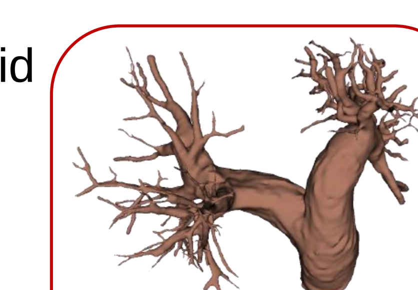
Hemodynamic Predictions



Variation in pressure and flow in the right pulmonary artery show how pruning and different radii affect uncertainty in the model predictions

Conclusions and Future Work

- Network generation, including radius selection and segmentation source, has a significant impact on fluid dynamics in the pulmonary arteries
- Our framework to prune networks, adjust junction nodes and extract radii using change points with uncertainty within expected measurement error
- Future studies will quantify differences between control and CTEPH patients, identify lesions from CT images, and investigate the impact on hemodynamics



3D rendering from Chronic Thromboembolic Pulmonary Hypertension (CTEPH) patient

References and Acknowledgements

[1] A computational framework for generating patient-specific vascular models and assessing uncertainty from medical images. Submitted 2023. https://arxiv.org/abs/2309.08779

[2] MJ Colebank (2021). *Computational modeling of patient specific pulmonary hemodynamics* (thesis).

[3] R Killick, I Eckley (2014). Changepoint: An R package for changepoint analysis. J Stat Soft. 58(3), 1-19

DMS-2051010 H98230-23-1-0009 NIH-HLBI RO1HL147590-02 NIH-5 T34 GM 131947-5

We acknowledge Dr. Mitchel Colebank, Alyssa LaPole, the McNair Scholars Program, and Kitware, Inc for contributions to this project