Uncertainty of Image Segmentation on Pulmonary Hemodynamics

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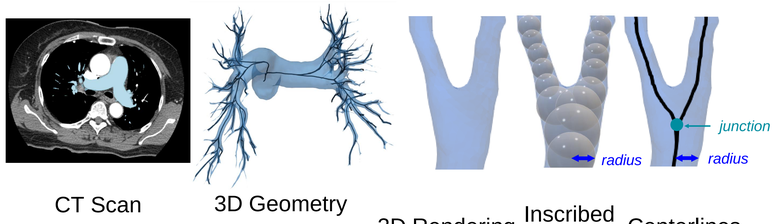
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Overview

- Computed tomography (CT) images of the lung are used for qualitative diagnosis of vascular health
- Right heart catheterization provides 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



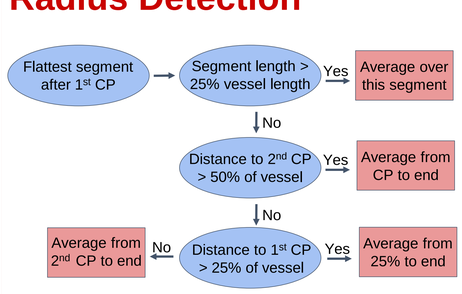
CT Scan | 3D Geometry | 3D Rendering | Inscribed Spheres | Centerlines

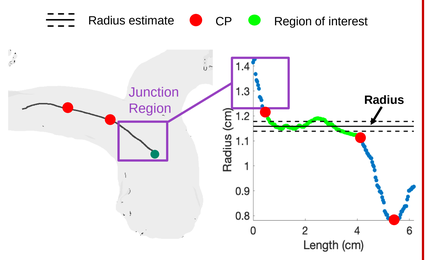
Volumetric model of the pulmonary arteries obtained using 3D Slicer

Vascular Modeling Toolkit (VMTK) creates centerlines such that each point has a radius and each line connecting points has a length

Vessel Data Corrections

Radius Detection

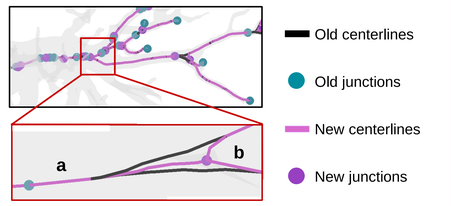




For each vessel, identify the region that best describes the vessel's radius

Junction Adjustment

- Combine vessels if the normalized distance between daughter vessels is smaller than ε
- New vessel determined by averaging daughter paths



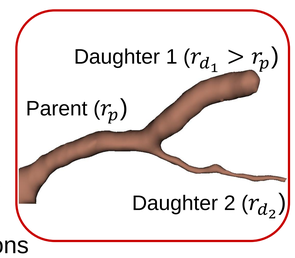
Radius Correction

Assumptions

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

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

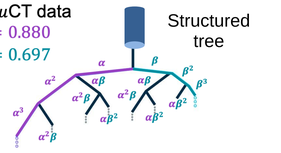
Due to manual segmentation, daughter radii may become too large, violating assumptions



From μCT data

$\alpha = 0.880$

$\beta = 0.697$



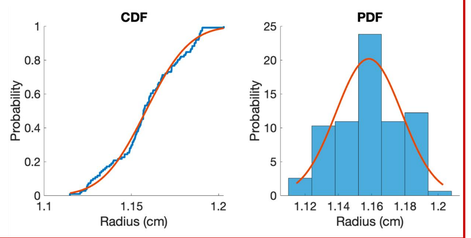
Vessels that violate assumptions are assigned a radius using known structured tree branching valid for small vessels

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

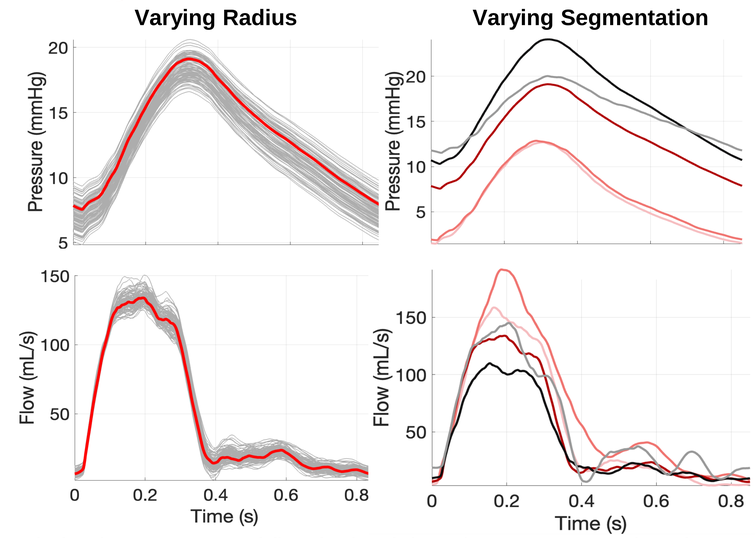
Results

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



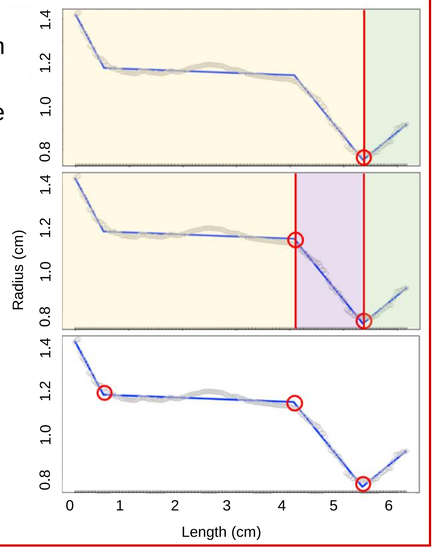
Variation in pressure and flow in the right pulmonary artery show how radii and image segmentations affect uncertainty in model predictions

Change Point Analysis

- Change points (CP) detect significant changes in the mean and variance of data
- Using a Bayesian algorithm, we conduct a hypothesis test on the existence of a single CP

$$H_0: m = 0;\ H_a: m = 1$$

- When the null hypothesis is rejected, place first 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 change points



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:

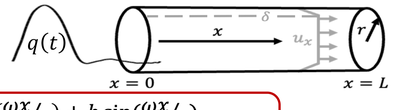
- solve linearized 1D models to quantify pressure and flow as functions of frequency

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

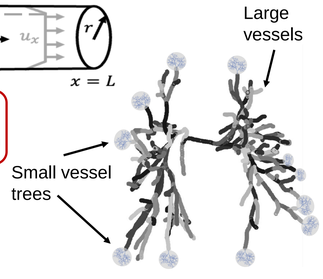


Flow: $Q(x,\omega) = a\cos(\omega x/c) + b\sin(\omega x/c)$

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

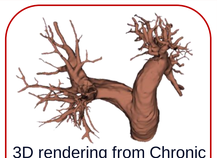
Pressure continuity: $p_p(L_p,t) = p_{d_1}(0,t) = p_{d_2}(0,t)$

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



Conclusions and Future Work

- Network generation, including radius selection and segmentation source, has a significant impact on fluid dynamics in the pulmonary arteries
- Varying segmentation has more of an impact on the pressure and flow simulations than the radius selection
- Future studies will quantify differences between control and CTEPH patients



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

References and Acknowledgments

[1] Colebank, M. J. (2021). *Computational modeling of patient specific pulmonary hemodynamics* (thesis).

[2] Killick, R. and Eckley, I. (2014). "Changepoint: An R package for changepoint analysis." *Journal of statistical software, 58*(3), 1-19.

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