

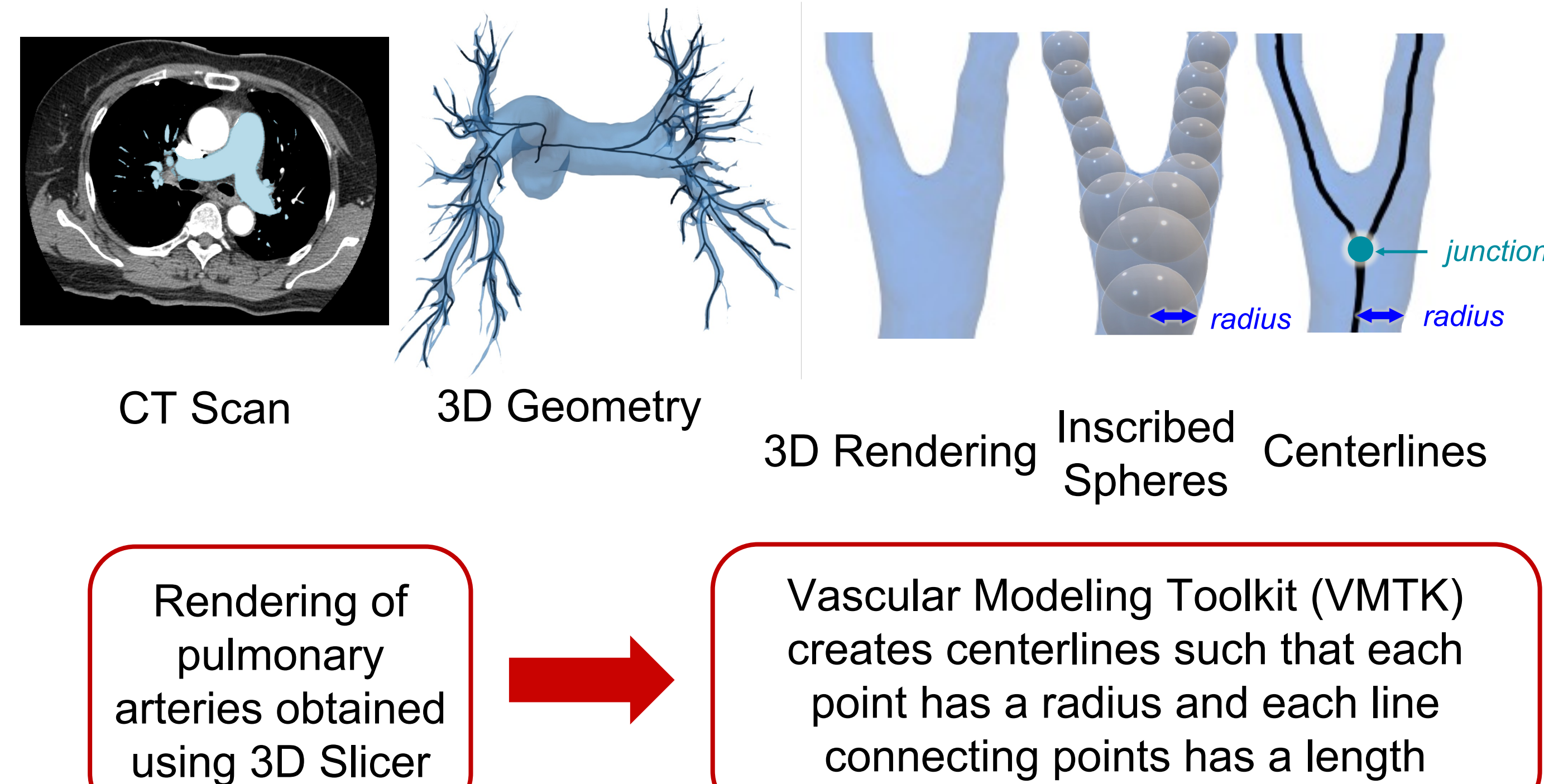
Uncertainty of Image Segmentation on Pulmonary Hemodynamics

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Overview

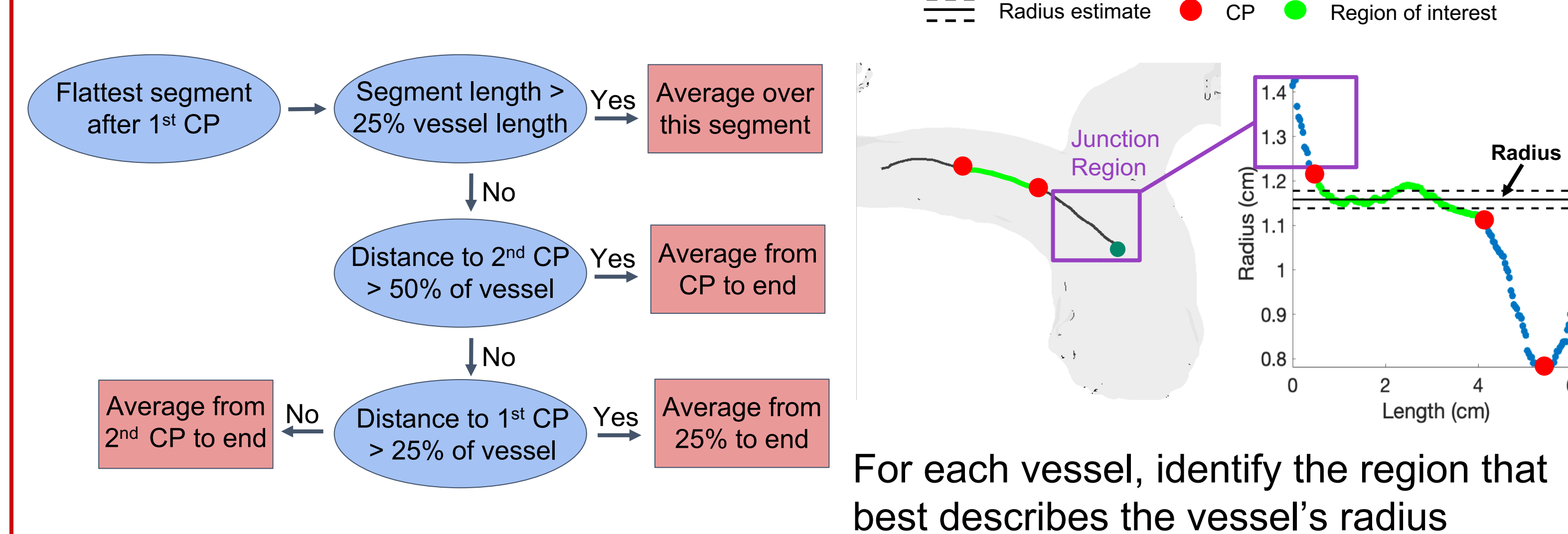
- Computed tomography (CT) images of the lung are used for qualitative diagnosis of vascular health
- Right heart catheterization provide dynamic quantitative data measuring blood pressure in the main pulmonary artery
- Using fluid dynamics modeling, we superimpose dynamic data on geometric domains extracted 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



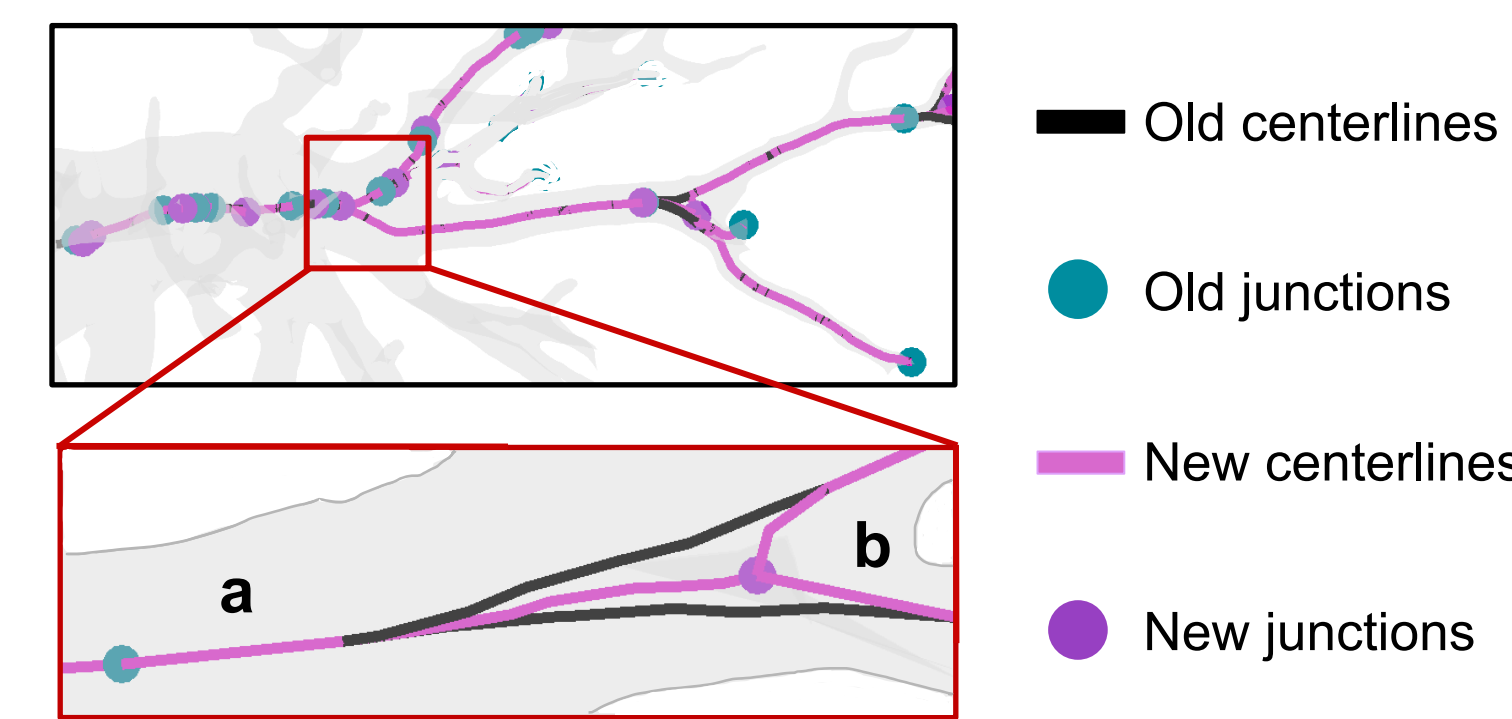
Vessel Data Corrections

Radius Detection



Junction Adjustment

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



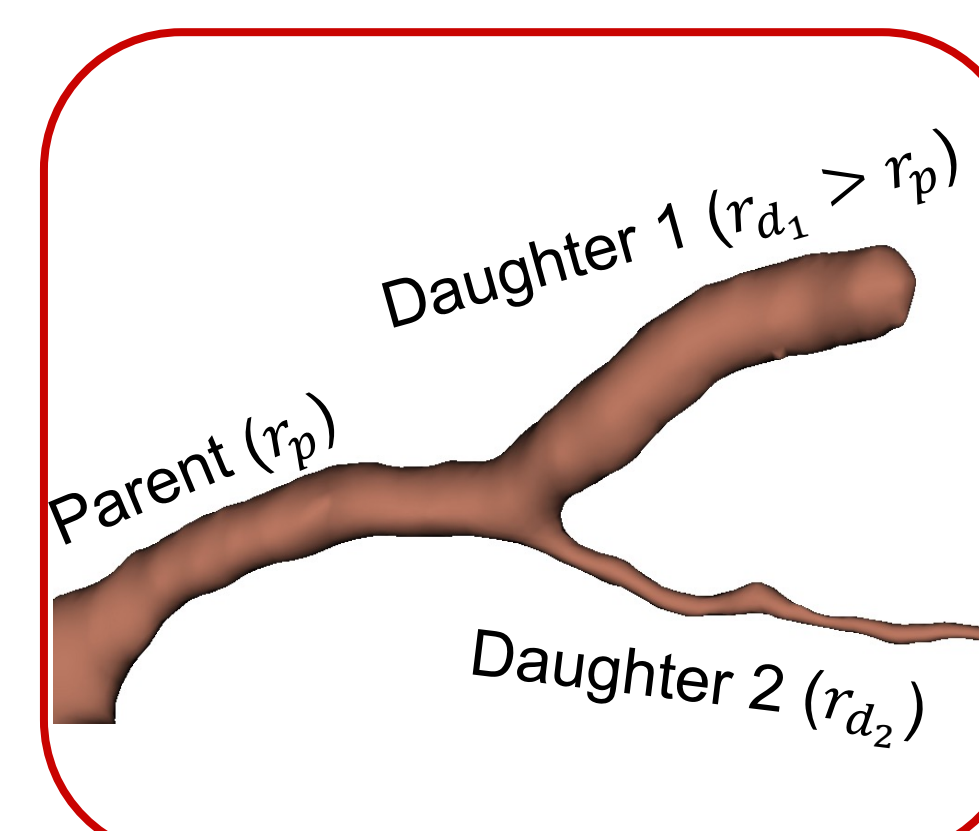
Radius Correction

Assumptions

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

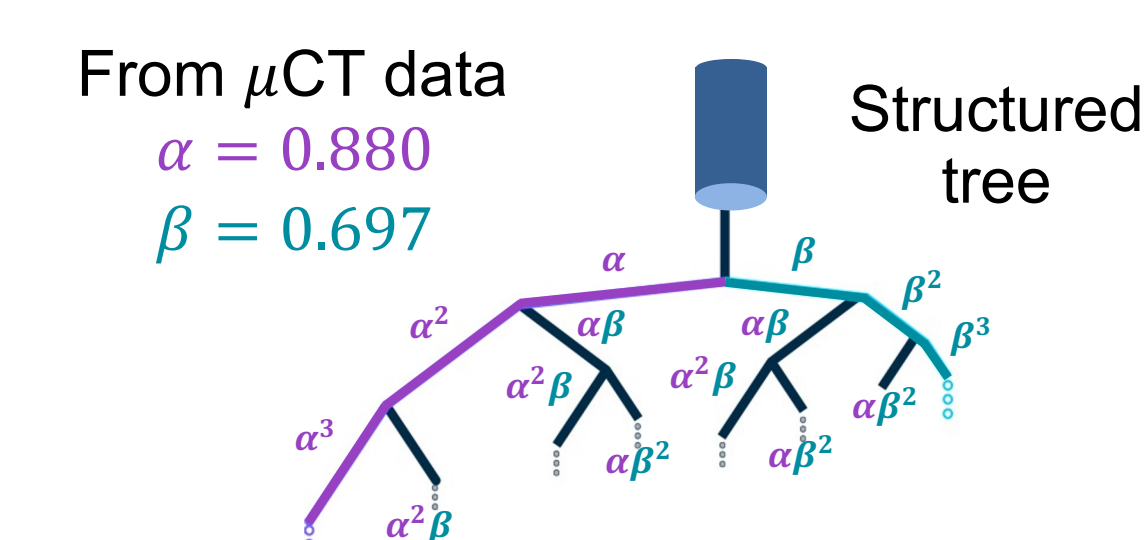
$$A_p < A_{d_1} + A_{d_2}$$

3D Slicer may make daughter radii too large in some vessels, violating assumptions



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

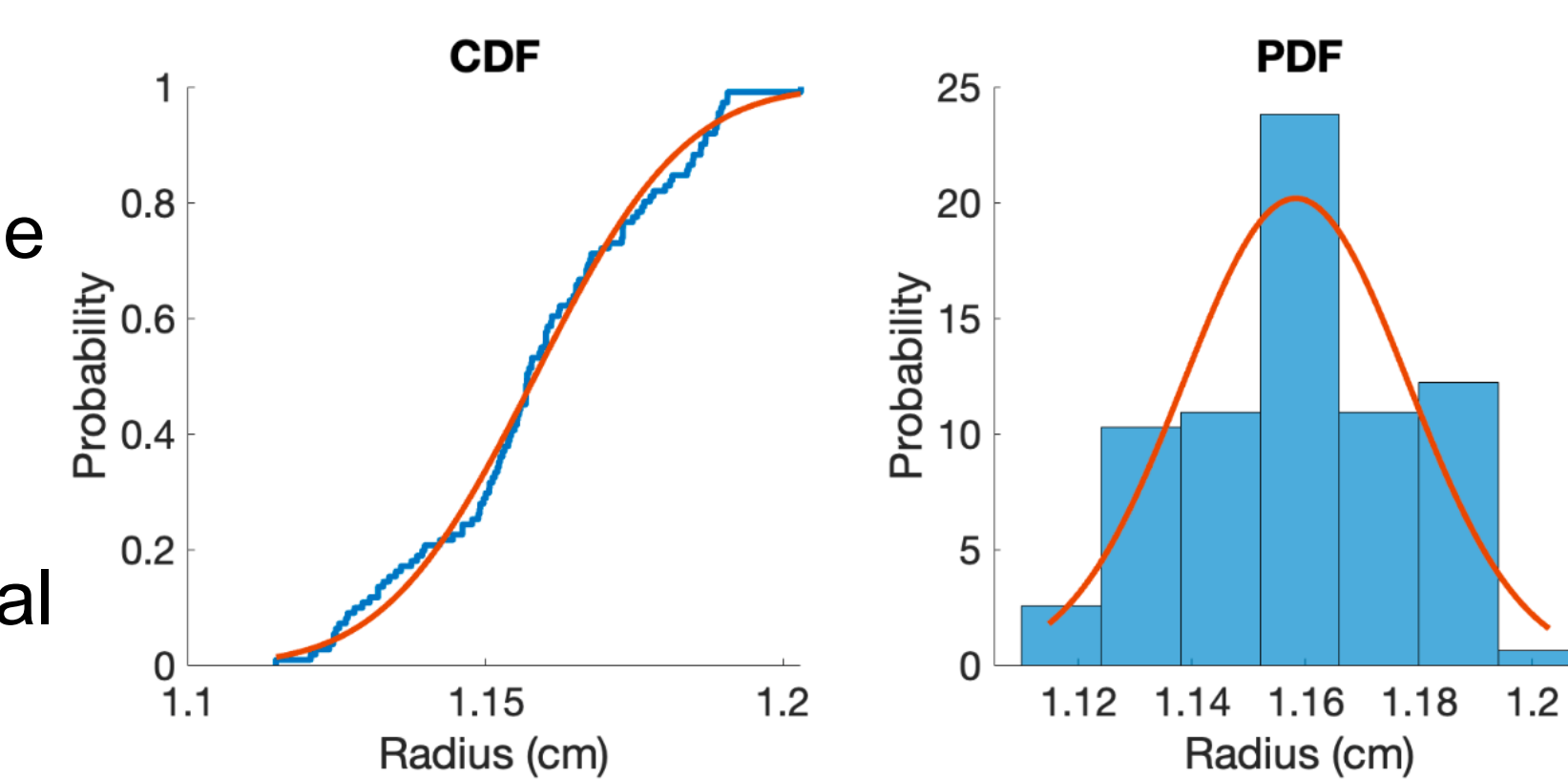
$$r_{d_1} = \alpha r_p, \text{ \& } r_{d_2} = \beta r_p$$



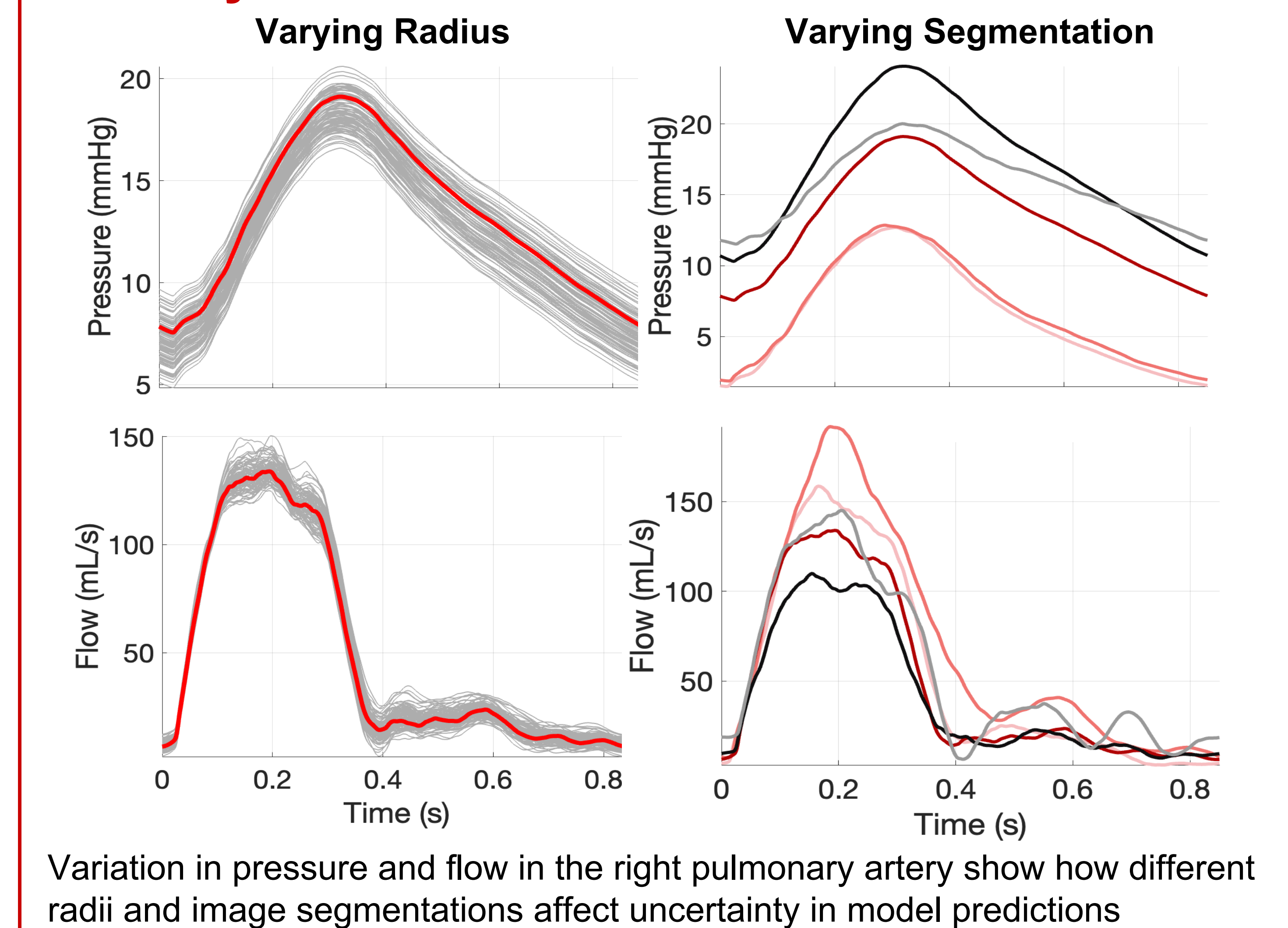
Results

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



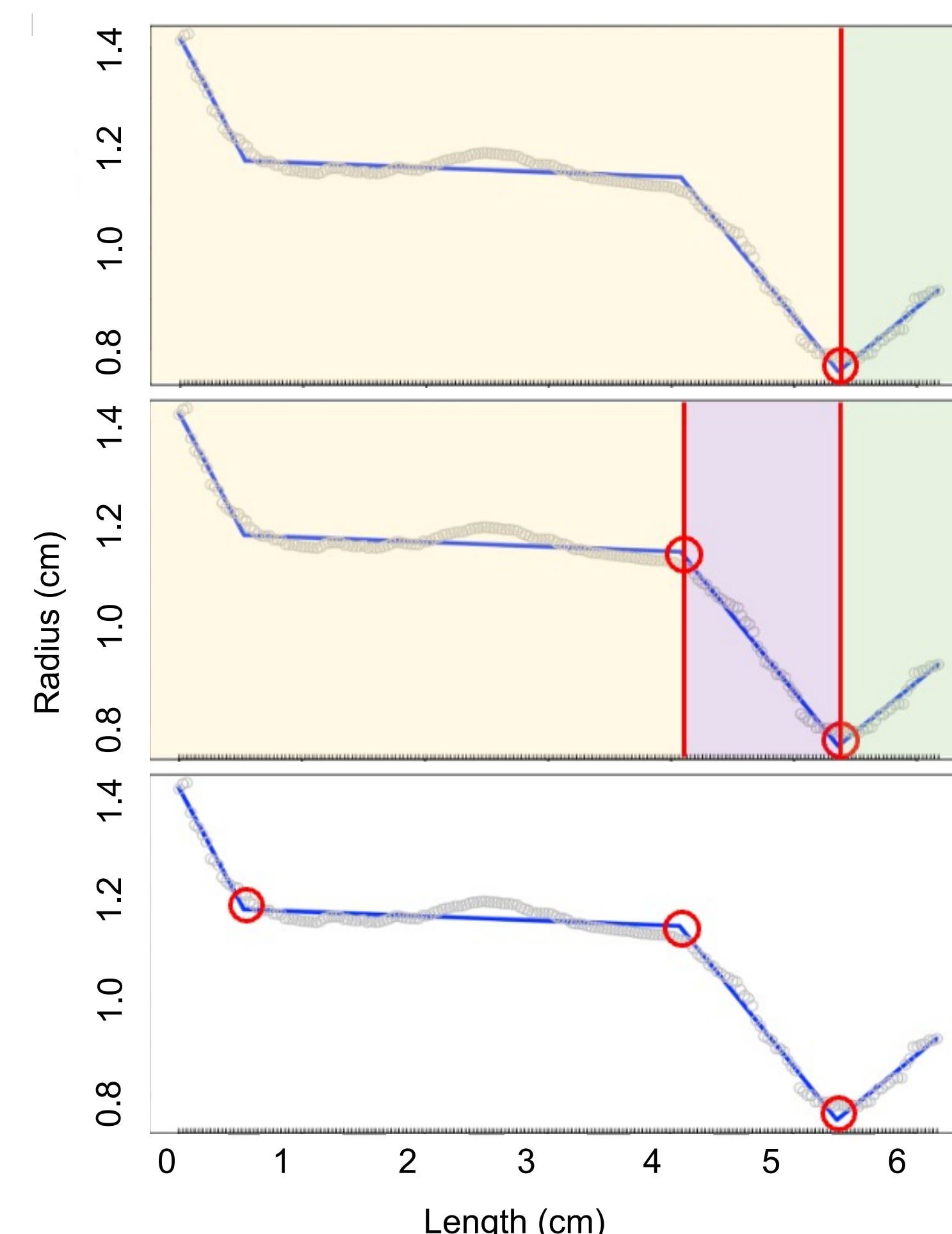
Hemodynamic Predictions



Change Point Analysis

- Change points (CP) detect significant changes in the mean and variance of data
- Use a Bayesian algorithm conducting a hypothesis test for m , 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 test for each segment
- To prevent overfitting we allow a maximum of 3 chance points



Mathematical Model

Large vessels in the graph are extracted from the CT image, for which we solve non-linear 1D Navier Stokes equations for flow q mL/s, area A cm², and pressure p mmHg

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

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

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

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

Small vessels are represented by structured trees, so for these we solve linearized 1D models to quantify pressure P and flow Q as functions of frequency

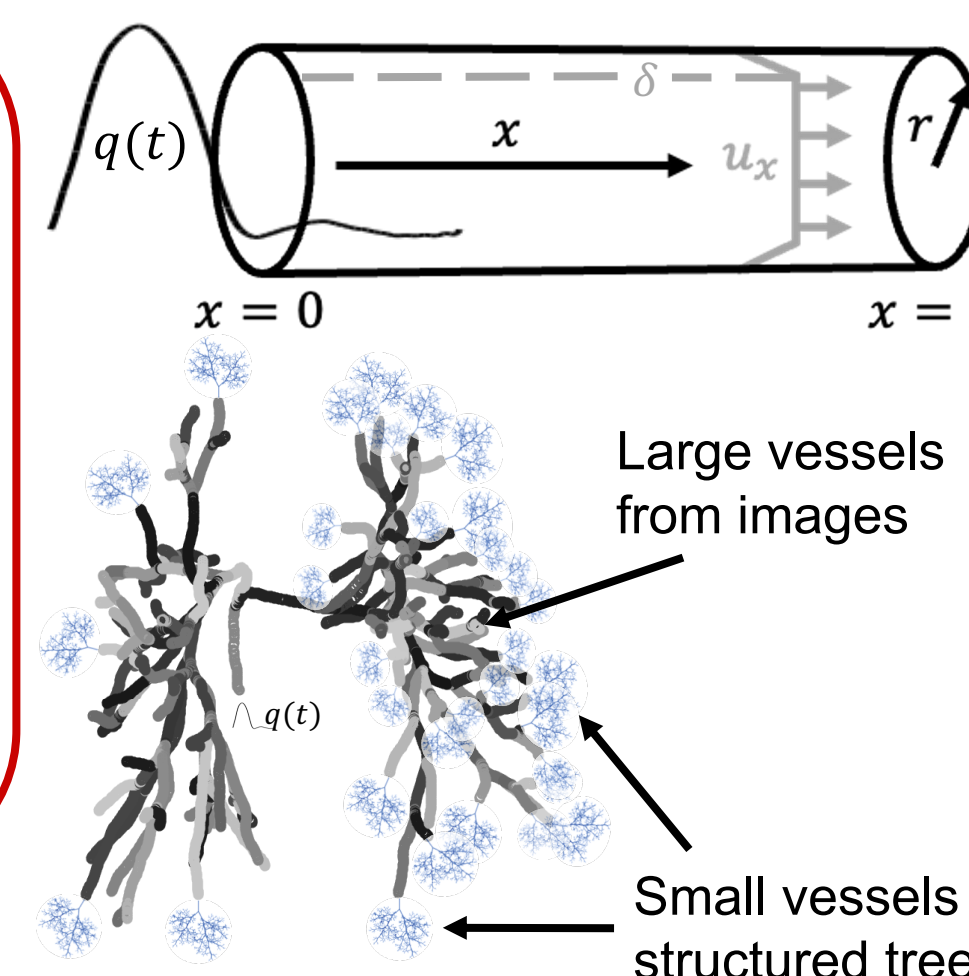
At junctions, flow is conserved and pressure is continuous

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

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

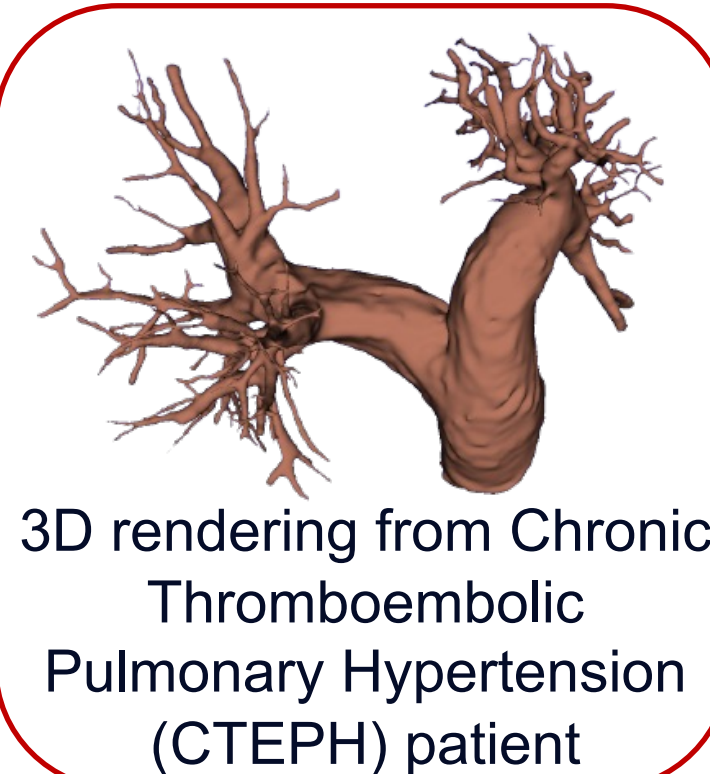
$$\text{Pressure continuity: } p_p(L_p, t) = p_{d_1}(0, t) = p_{d_2}(0, t)$$

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



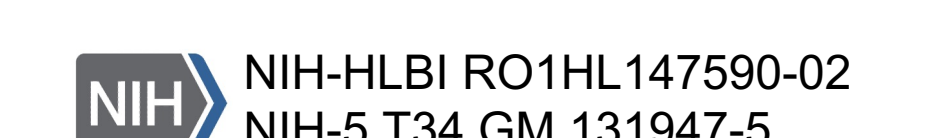
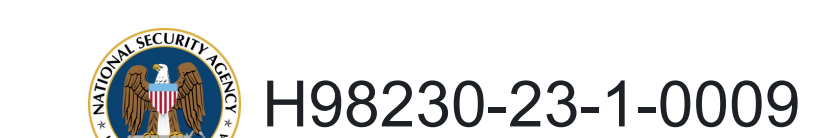
Conclusions and Future Work

- 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



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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