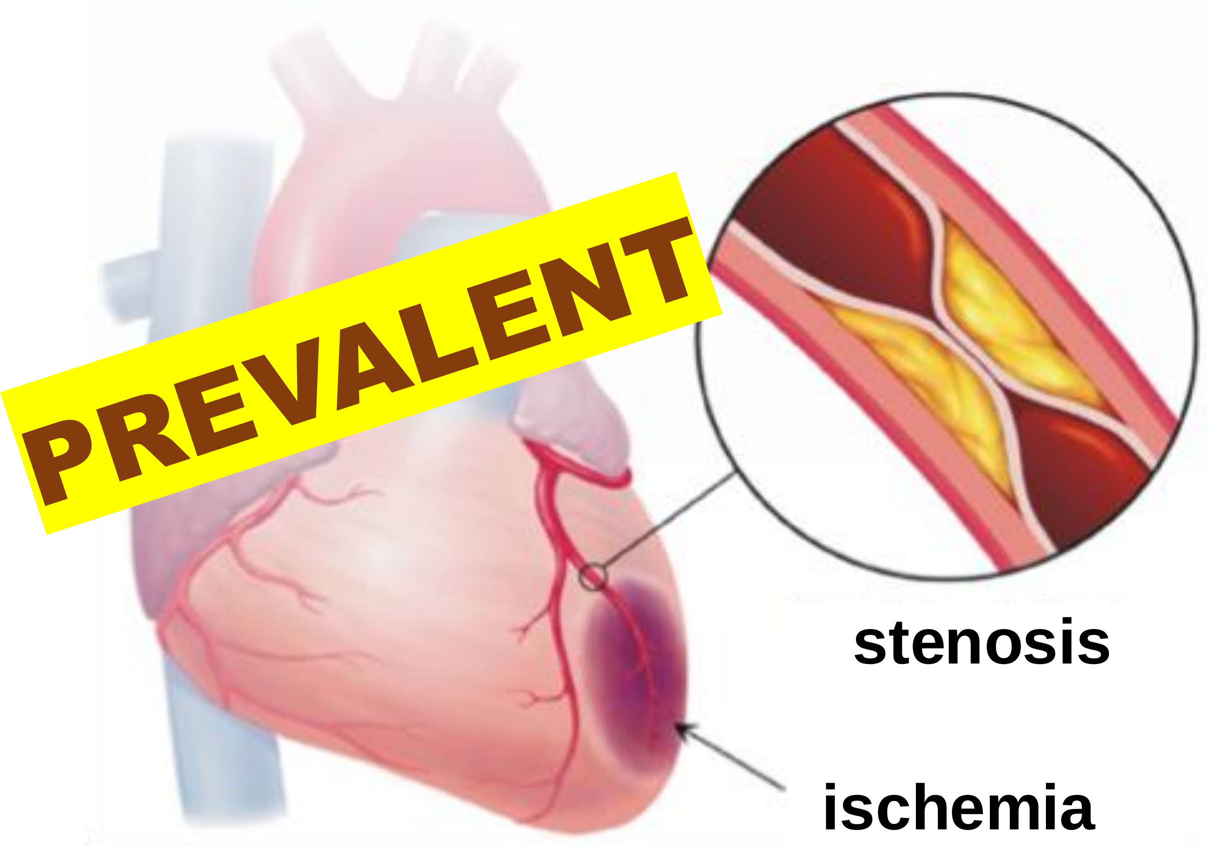
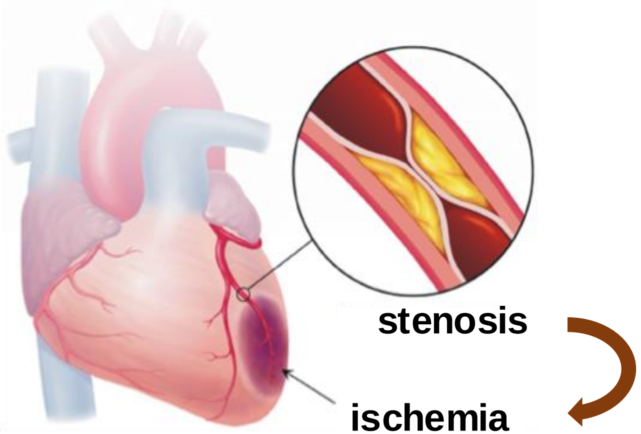
Can we "see" more from cardiovascular medical images with modeling?

presenter Sijie Li
instructor Ju Liu

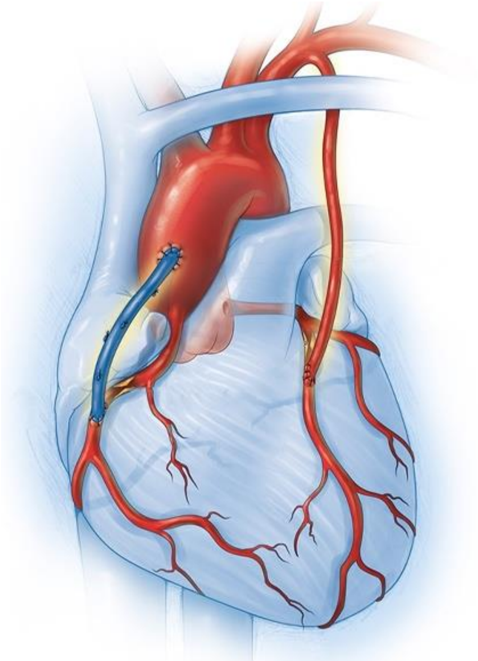
Clinical need



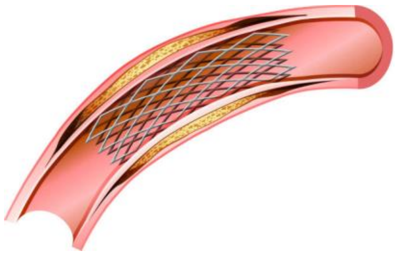
Clinical need



Surgery

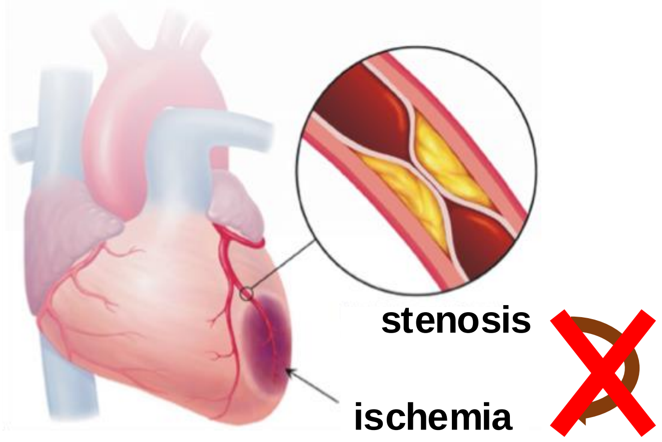


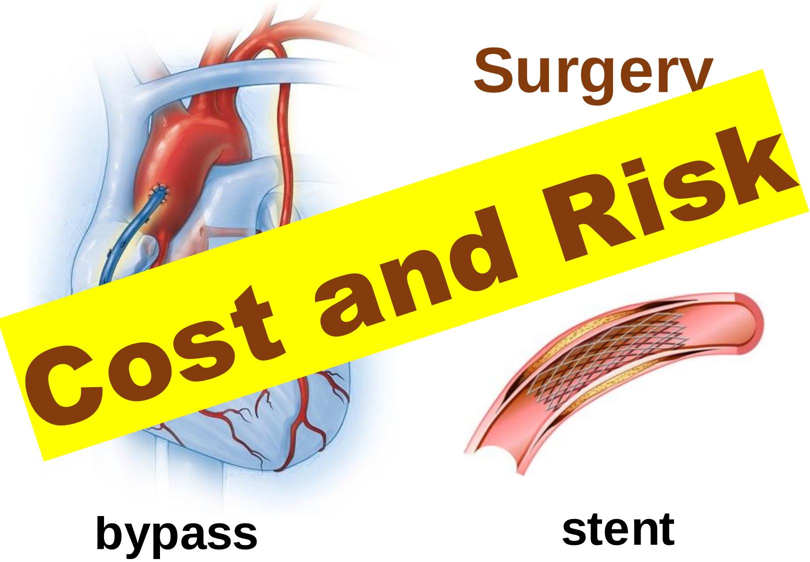
bypass



stent

Clinical need





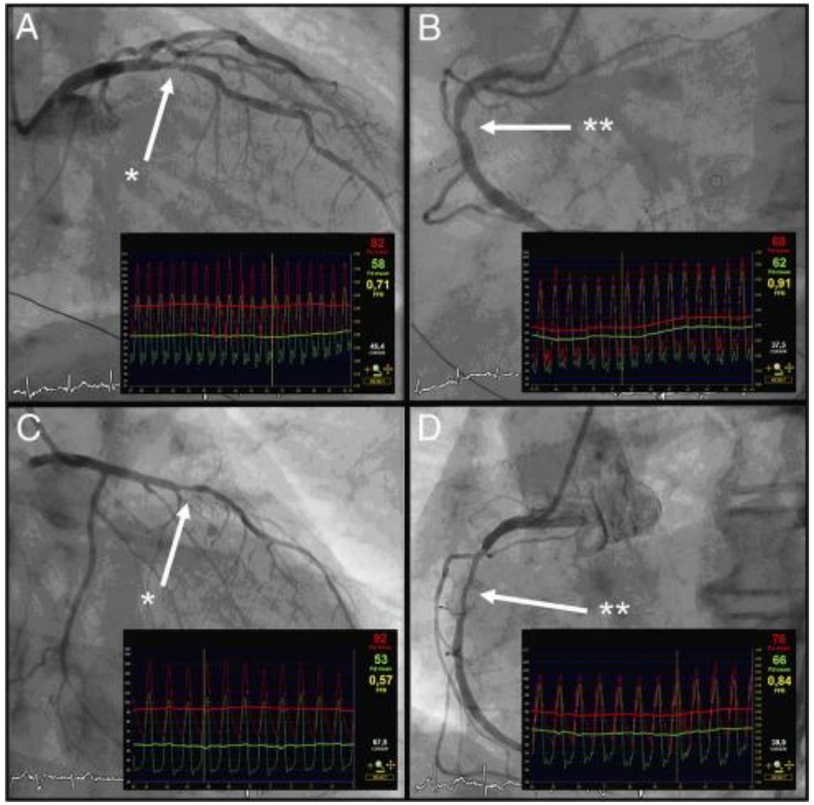
Just stablize it!

Anatomical VS functional

stenosis

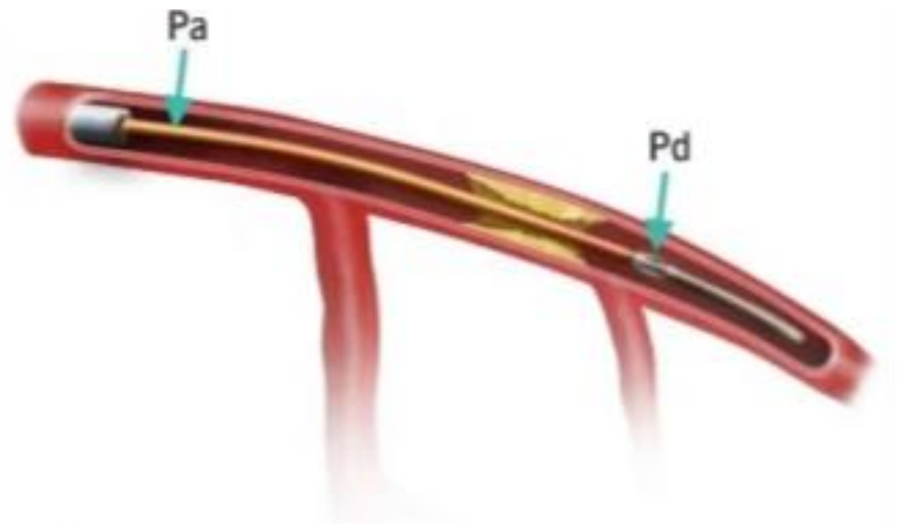
ischemia

CTA (computed tomography angiography)



(Tonino et al., 2010)

FFR (fractional flow reserve)



$$FFR = \frac{\text{Distal Coronary Pressure (Pd)}}{\text{Proximal Coronary Pressure (Pa)}}$$

(During Maximum Hyperemia)

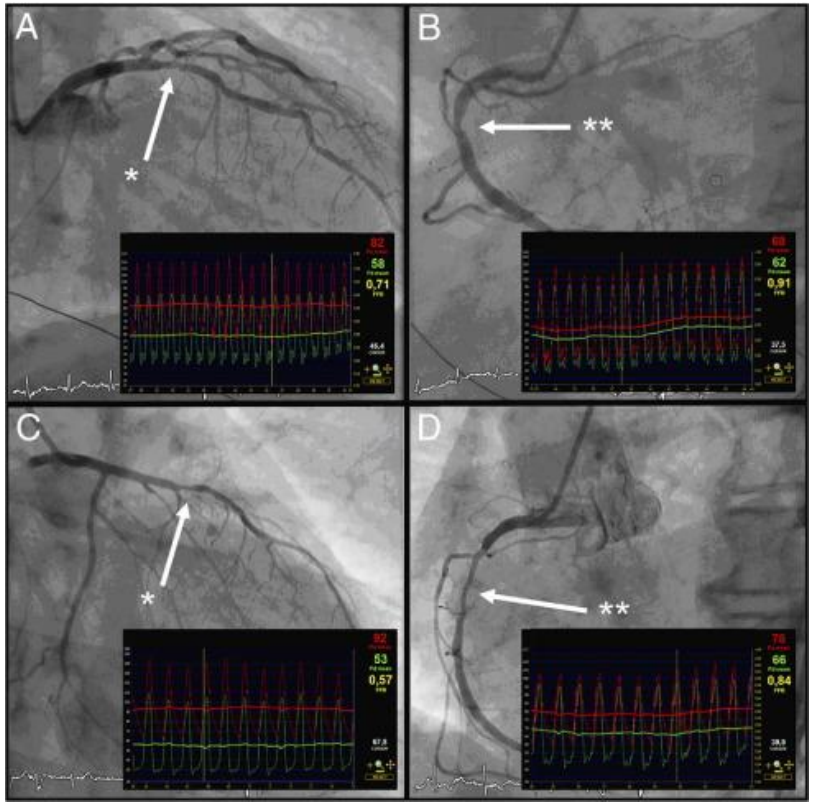
Anatomical VS functional

stenosis

?

ischemia

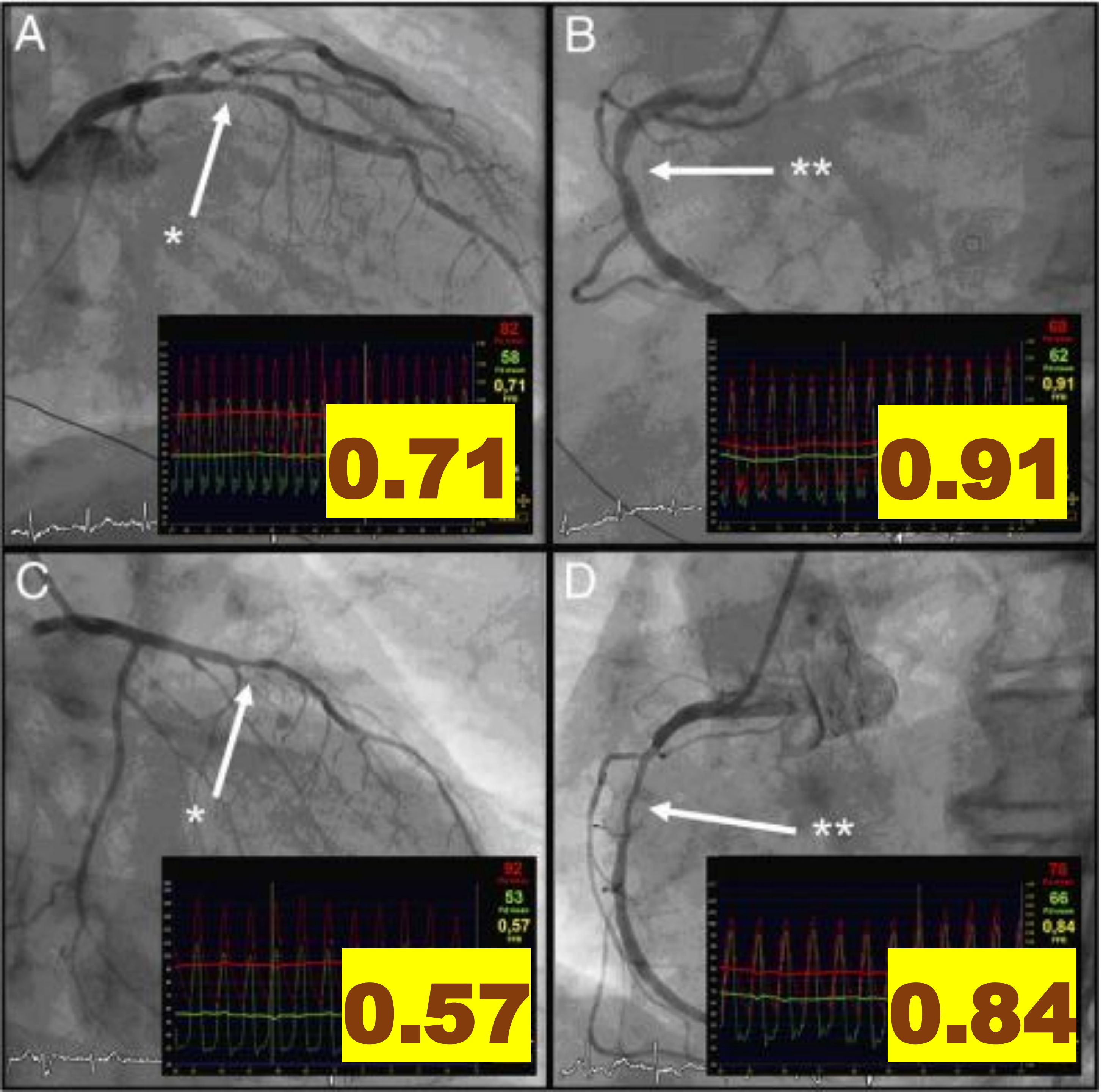
CTA (computed tomography angiography)

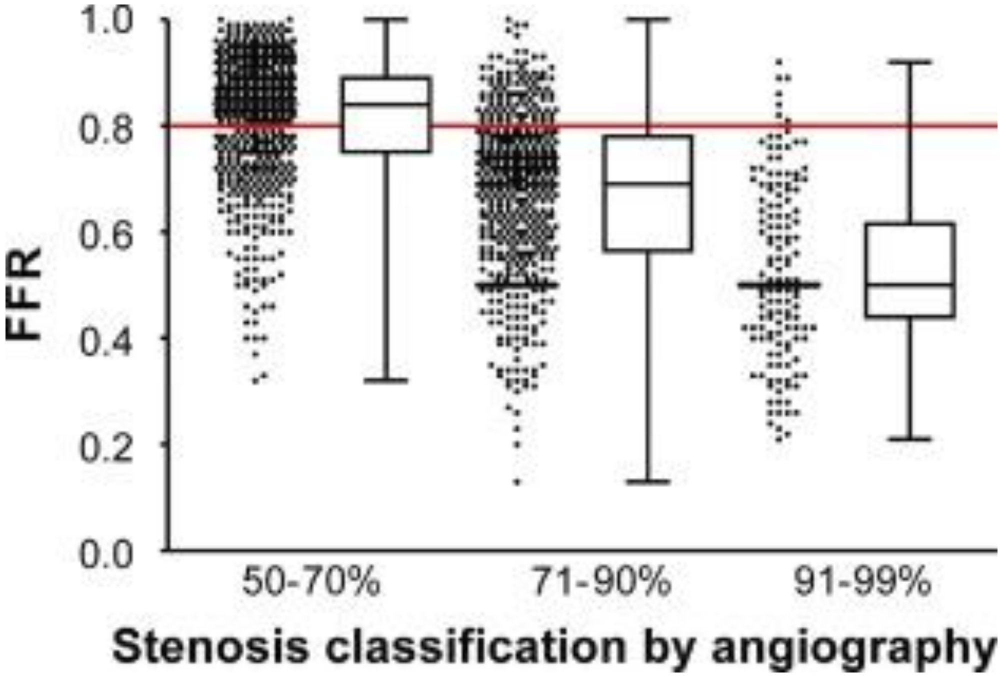


(Tonino et al., 2010)

FFR (fractional flow reserve)

FFR < 80%
Gold standard

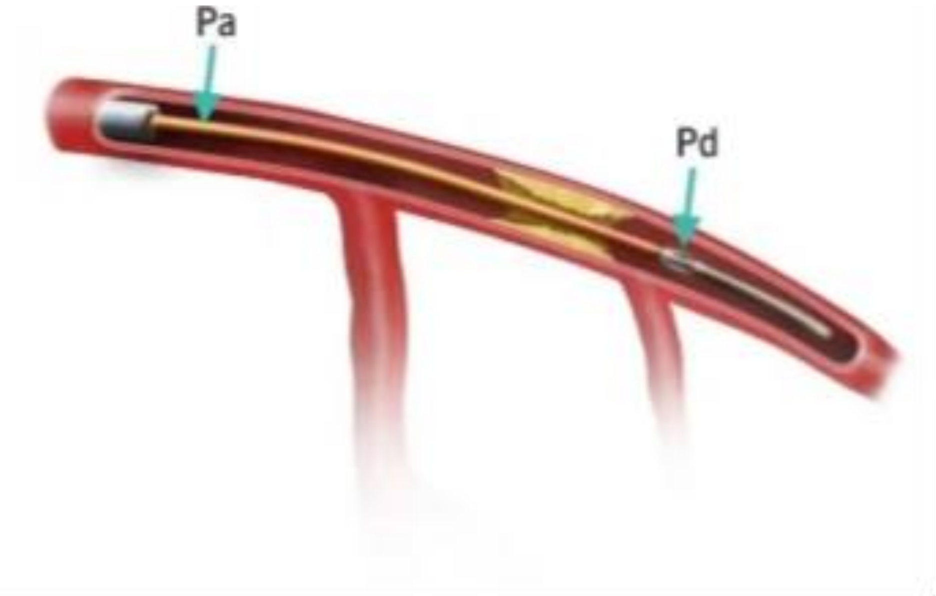




(Tonino et al., 2010)

ICA_{FFR} VS CTA_{FFR}

ICA_{FFR} (invasive coronary angiography)



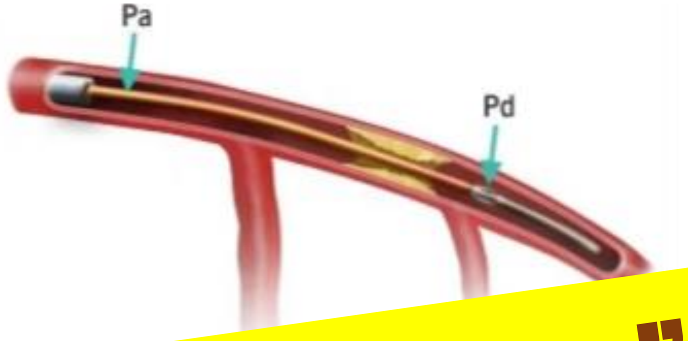
- **Hyperemia**
- **Pressure**

require →

- **Adenosine administration**
- **Catheter invasion**

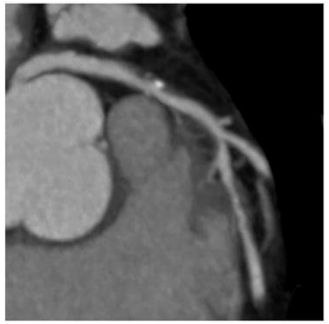
ICA_{FFR} VS CTA_{FFR}

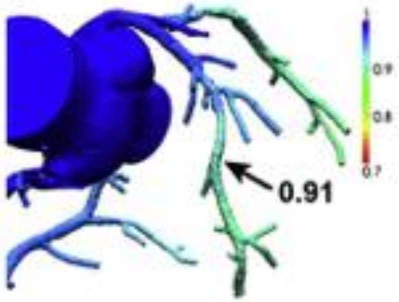
ICA_{FFR} (invasive coronary angiography)



Can we "see" more from cardiovascular medical images?

CTA_{FFR}

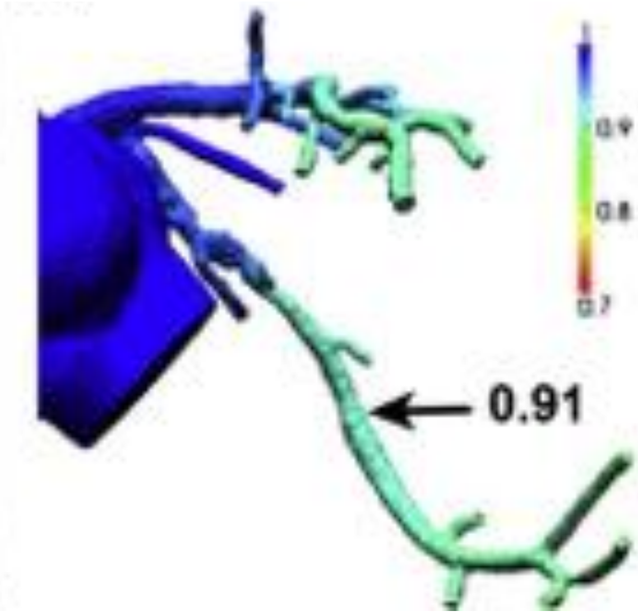




Modeling!

Modeling?

HOW?



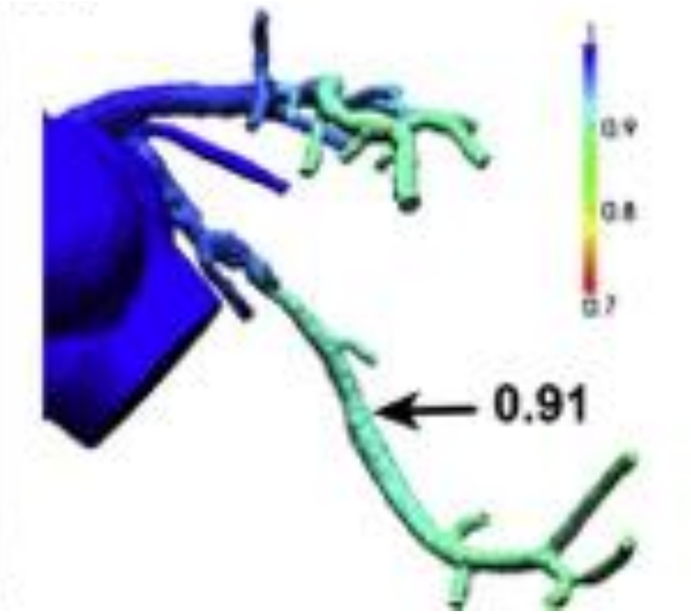
- Anatomical
- static

- Functional
- complicated

Modeling?

- Anatomical
- static

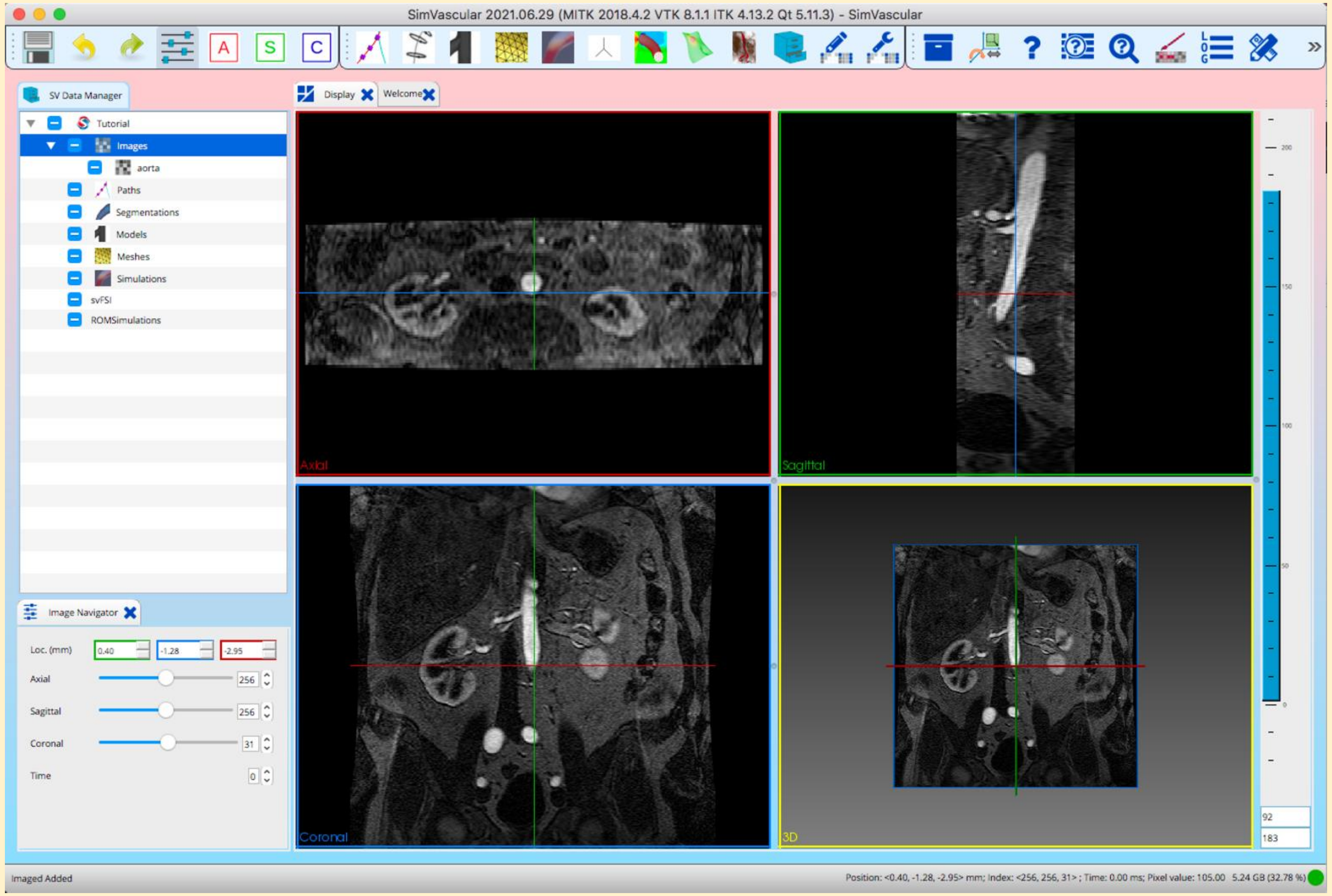
- **Form-function relationships**
- **Physical laws**



- Functional
- complicated

Modeling…

CTA

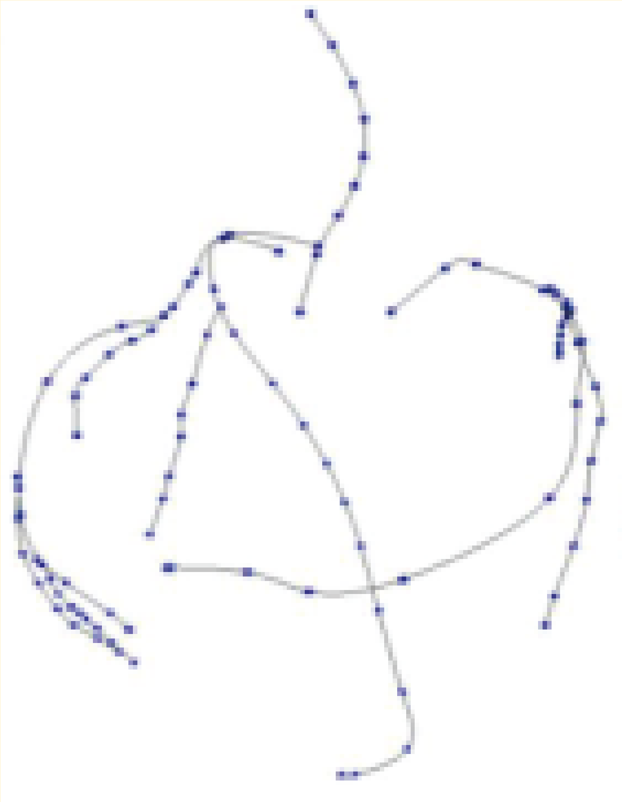


SimVascular

Modeling...

CTA

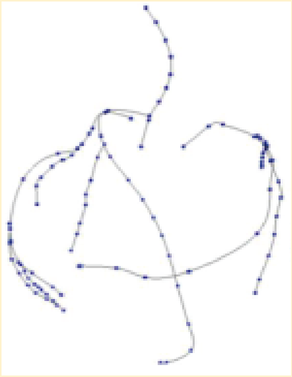
path



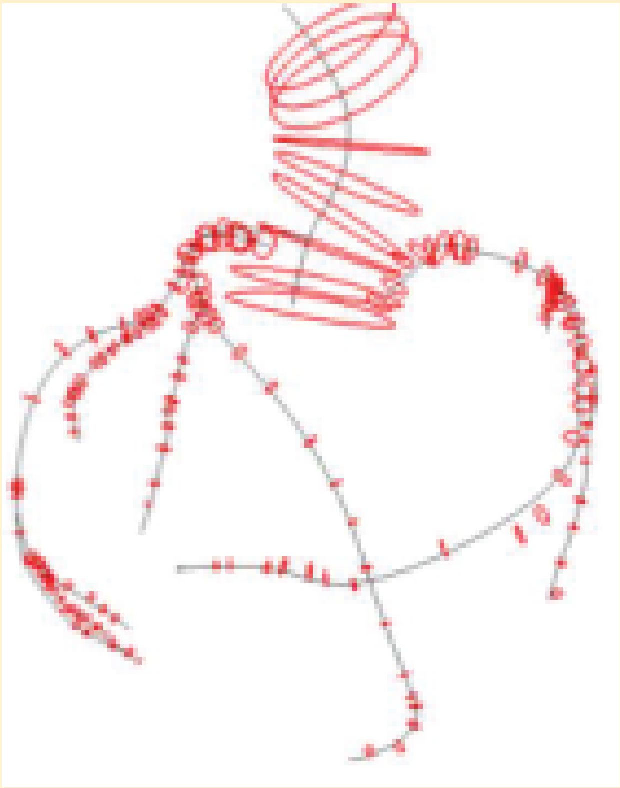
Modeling...

CTA

path



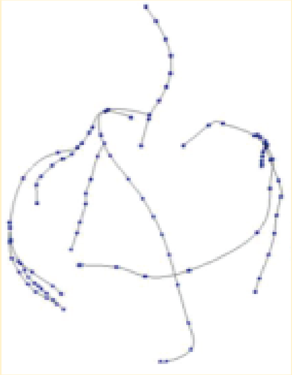
segmentations



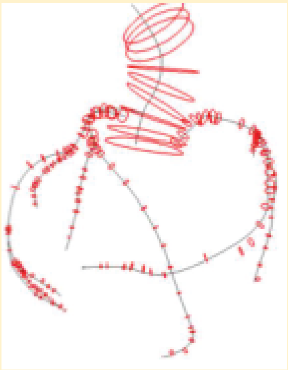
Modeling...

CTA

path



segmentations

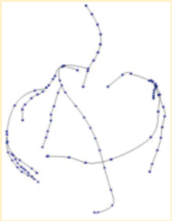


Model

Modeling...

CTA

path



segmentations

Model

Form-function relationships

$$Q = \frac{\pi}{32\mu}\tau_w d^3$$

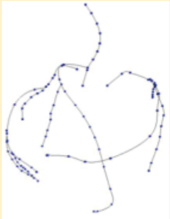
$$p = QR$$

$$R \propto d^{-3}$$

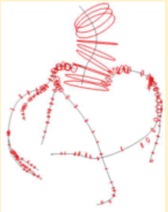
Modeling...

CTA

path



segmentations



Model

Form-function relationships

$$Q = \frac{\pi}{32\mu}\tau_w d^3 \quad p = QR \quad R \propto d^{-3}$$

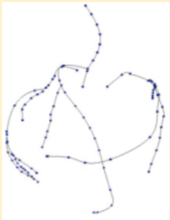
$$Q_{total} \propto M_{myo}^{\beta} \propto V^{\alpha} \qquad P_{aortic} \propto P_{brachial}$$

$$R_{hyperemia} \approx 0.24 \times R_{total} = 0.24 \times \frac{P_{aortic}}{Q_{total}}$$

Modeling...

CTA

path



segmentations

Model

Form-function relationships

$$Q = \frac{\pi}{32\mu}\tau_w d^3 \qquad p = QR$$

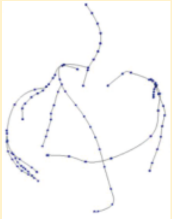
$$Q_{total} \propto M_{myo}^{\beta} \propto V^{\alpha} \quad P_{aortic} \propto P_{brachial} \longrightarrow P_{inlet}$$

$$\left.\begin{aligned} & R \propto d^{-3} \\ & R_{hyperemia} \approx 0.24 \times R_{total} = 0.24 \times \frac{P_{aortic}}{Q_{total}} \end{aligned}\right\} R_{outlet}$$

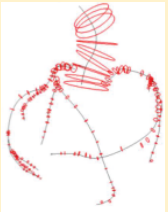
Modeling...

CTA

path



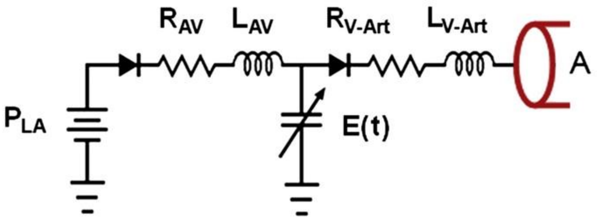
segmentations



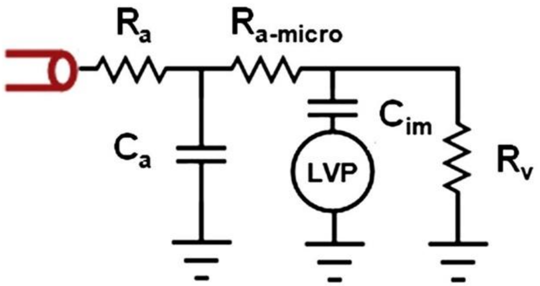
Model

Form-function relationships

P_{inlet}



R_{outlet}



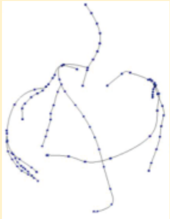
- **Dynamic**
- **Detail**

(Taylor et al., 2013)

Modeling...

CTA

path



segmentations

Model

Form-function relationships

P_{inlet} R_{outlet}

Boundary Conditions

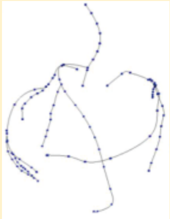
Pysical laws

No-slip condition

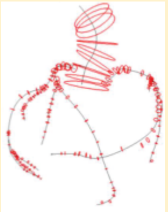
Modeling…

CTA

path



segmentations



Model

Form-function relationships

P_{inlet} R_{outlet}

Pysical laws

No-slip condition

Blood $\approx$ Newtonian fluid

rigid vessel wall

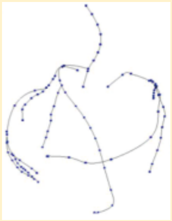
$$\tau = \mu \frac{dv}{dy}$$

Constitutive relationship

Modeling...


CTA

path



segmentations

Model

Form-function relationships

$$P_{inlet} \qquad R_{outlet}$$

Pysical laws

No-slip condition

Constitutive relationship + mass and momentum conservation:

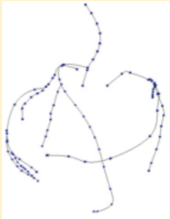
$$\rho\left(\frac{\partial \vec{u}}{\partial t} + (\vec{u}\cdot\nabla)\vec{u}\right) = -\nabla p + \mu\nabla^2\vec{u} + \vec{f} \qquad \nabla\cdot\vec{u} = 0$$

Navier-Stokes equation – **local behavior!**

Modeling...


CTA

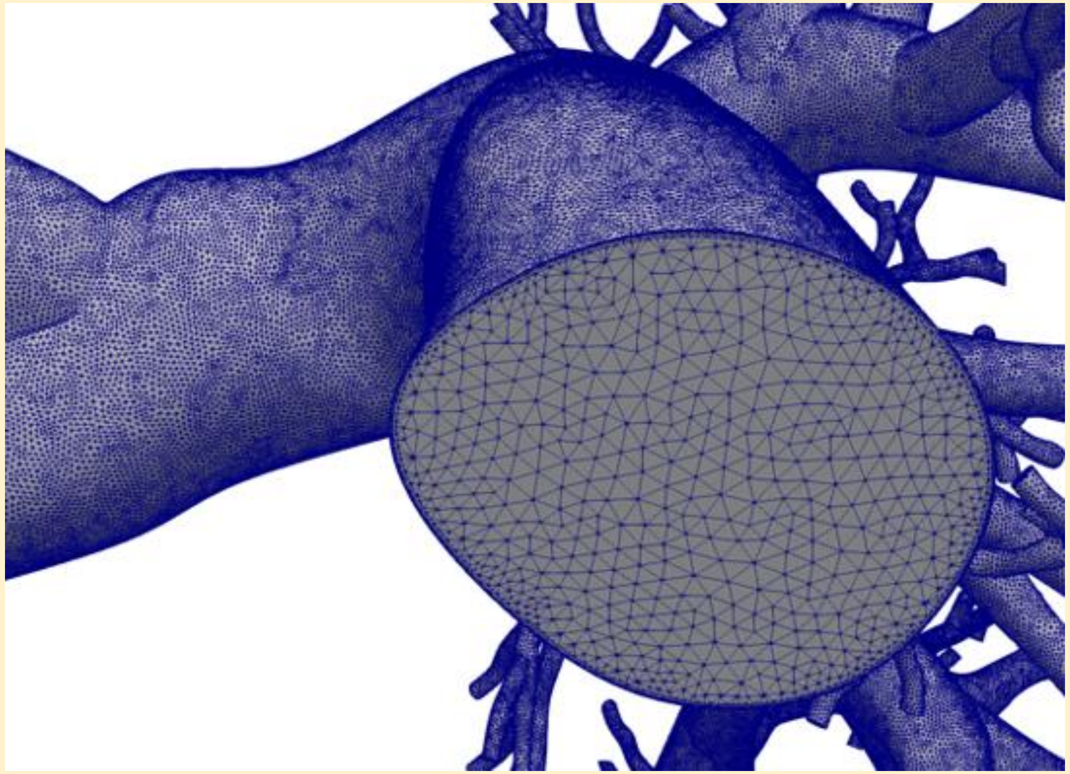
path



segmentations

Model

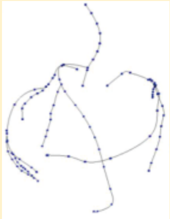
meshing



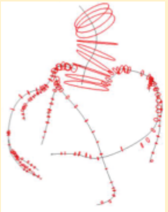
Modeling...

CTA

path

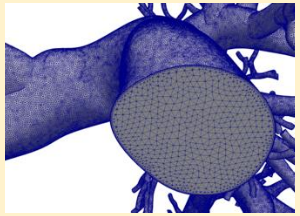


segmentations



Model

meshing



Form-function relationships

$$P_{inlet} \quad R_{outlet}$$

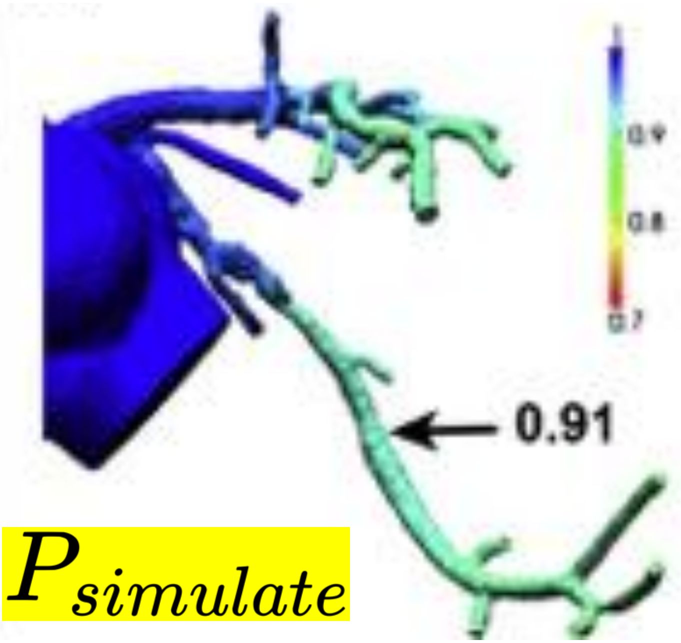
No-slip condition

Pysical laws

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + (\vec{u}\cdot\nabla)\vec{u}\right) = -\nabla p + \mu\nabla^2\vec{u} + \vec{f}$$

$$\nabla \cdot \vec{u} = 0$$

simulation

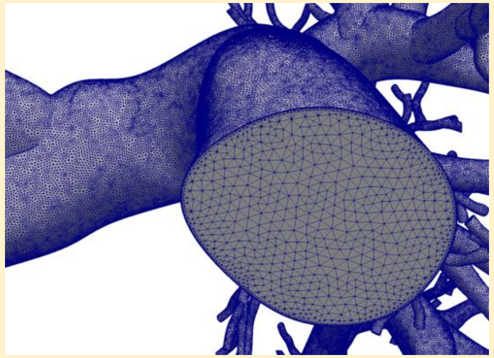


$$P_{simulate}$$

$$FFR = \frac{P_{simulate}}{P_{inlet}}$$

Modeling...

meshing



$$P_{inlet}$$

$$R_{outlet}$$

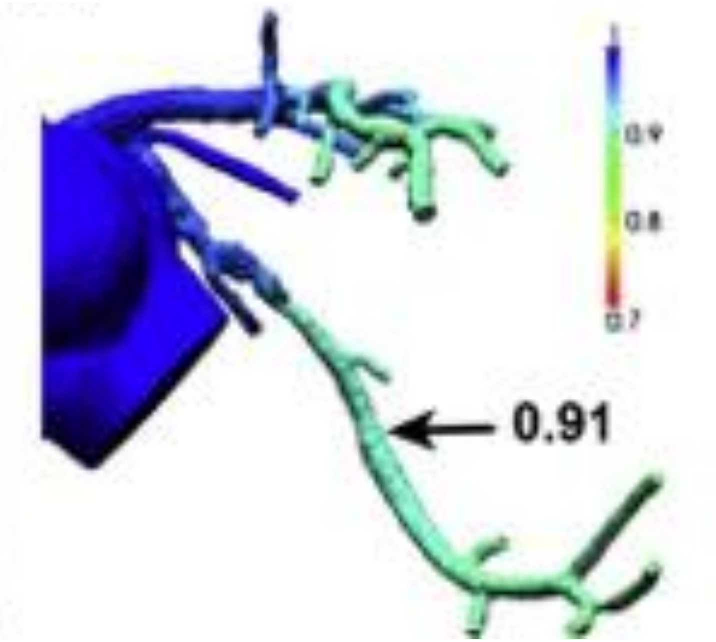
No-slip condition

$$\nabla \cdot \vec{u} = 0$$

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u}\right) = -\nabla p + \mu \nabla^2 \vec{u} + \vec{f}$$

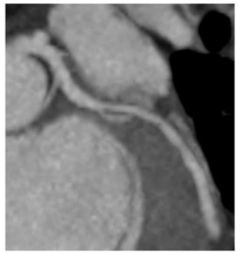
FEM

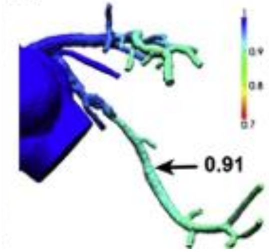
(finite element method)

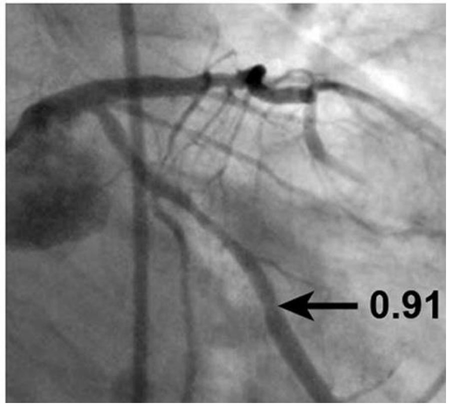


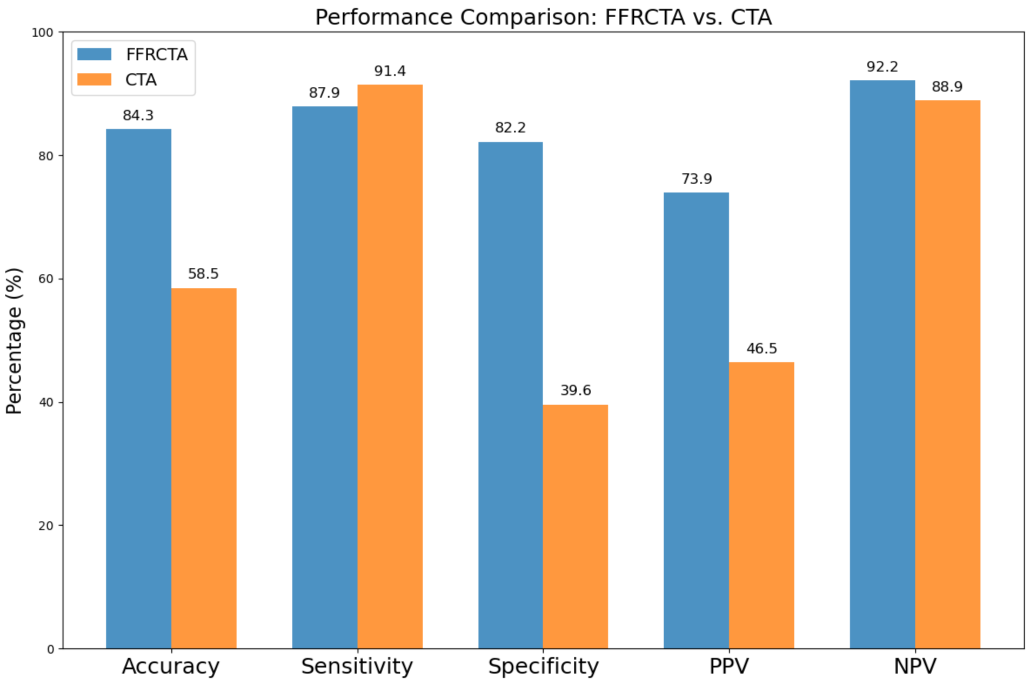
(Taylor et al., 2013)

Modeling!!!

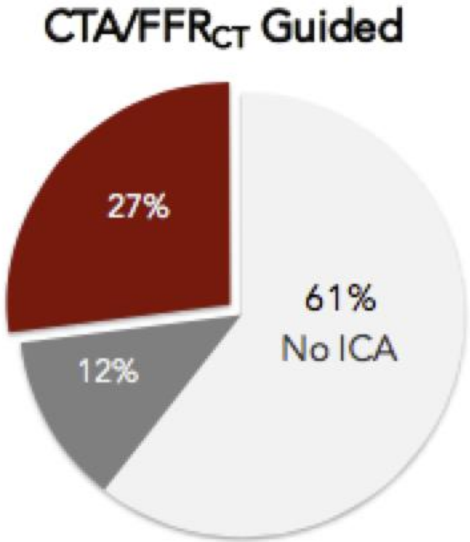








(Taylor et al., 2013)



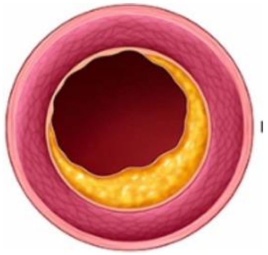
(Douglas et al., 2015)

More can be done...

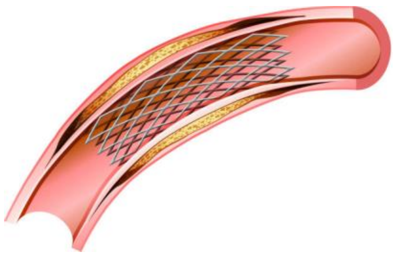
FSI

(fluid structure interaction)

Blood $\approx$ Newtonian fluid
elastic wall $\sigma = E \cdot \epsilon$



Mechanism of plaque



Influence of stent

More can be done...

FSI

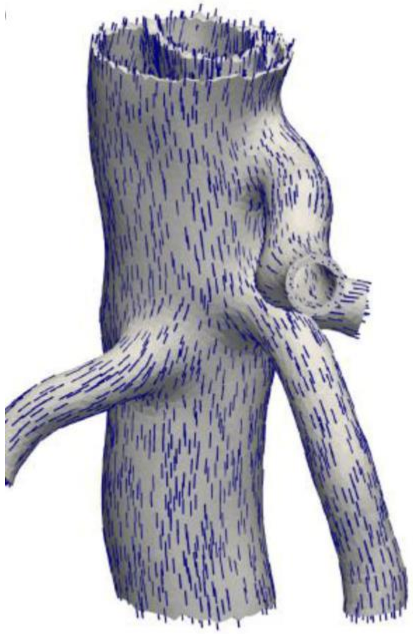
Blood ≈ generalized Newtonian fluid

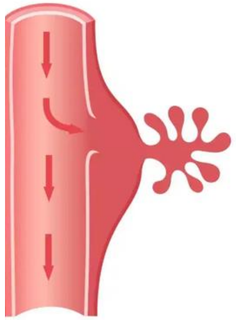
$$\tau = \mu(\frac{dv}{dy})\frac{dv}{dy}$$

Hyperelastic wall (fibrous tissue)

$$\sigma = \frac{W_{\text{iso}} + W_{\text{aniso}}}{\partial\epsilon}$$

W: strain energy density function





Aortic Dissection

(Schussnig et al., 2024)

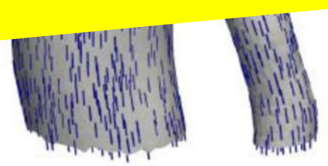
More can be done...

FSI

Blood ≈ generalized

"All models are wrong, but some are useful..."
—George E. P. Box

W: strain energy density function



Dissection

(Schussnig et al., 2024)

bioTechnology

technology

Development

need

Pay attention to technique details

Keep an eye on the real world's need

Reference list

Schussnig, R., Rolf-Pissarczyk, M., Bäumler, K., Fries, T., Holzapfel, G. A., & Kronbichler, M. (2024). On the role of tissue mechanics in fluid–structure interaction simulations of patient-specific aortic dissection. *International Journal for Numerical Methods in Engineering*, *125*(14), e7478. https://doi.org/10.1002/nme.7478

Taylor, C. A., Fonte, T. A., & Min, J. K. (2013). Computational Fluid Dynamics Applied to Cardiac Computed Tomography for Noninvasive Quantification of Fractional Flow Reserve. Journal of the American College of Cardiology, 61(22), 2233–2241. https://doi.org/10.1016/j.jacc.2012.11.083

Tonino, P. A. L., Fearon, W. F., De Bruyne, B., Oldroyd, K. G., Leesar, M. A., Ver Lee, P. N., MacCarthy, P. A., Van'T Veer, M., & Pijls, N. H. J. (2010). Angiographic Versus Functional Severity of Coronary Artery Stenoses in the FAME Study. *Journal of the American College of Cardiology*, *55*(25), 2816–2821. https://doi.org/10.1016/j.jacc.2009.11.096