Fluid-Structure Interaction Studies of Coronary Artery Disease Biomechanics

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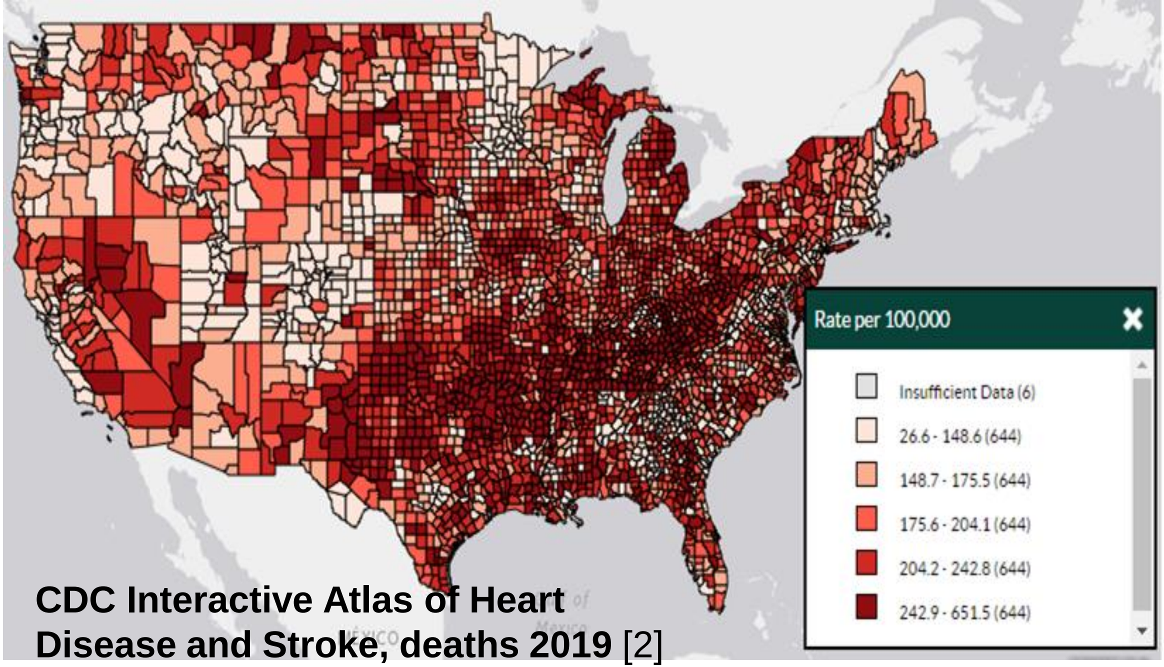
Coronary Artery Disease kills 1 in 7 in the United States

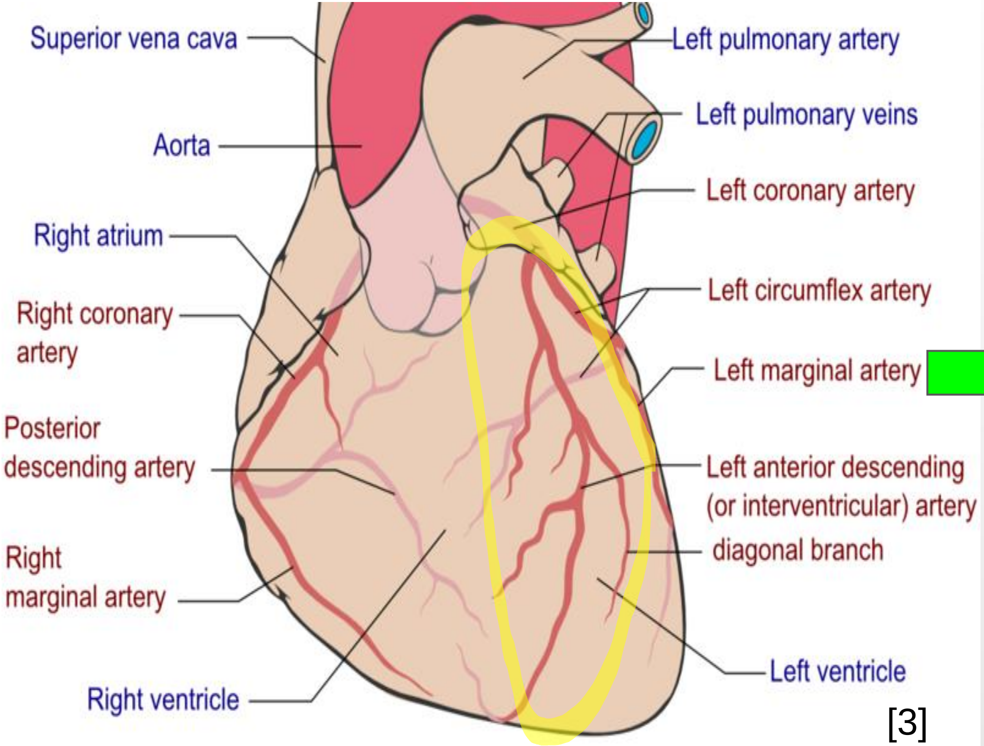
- Coronary artery disease is the most common form of heart disease[1] which can result in heart attack or other serious thrombotic events



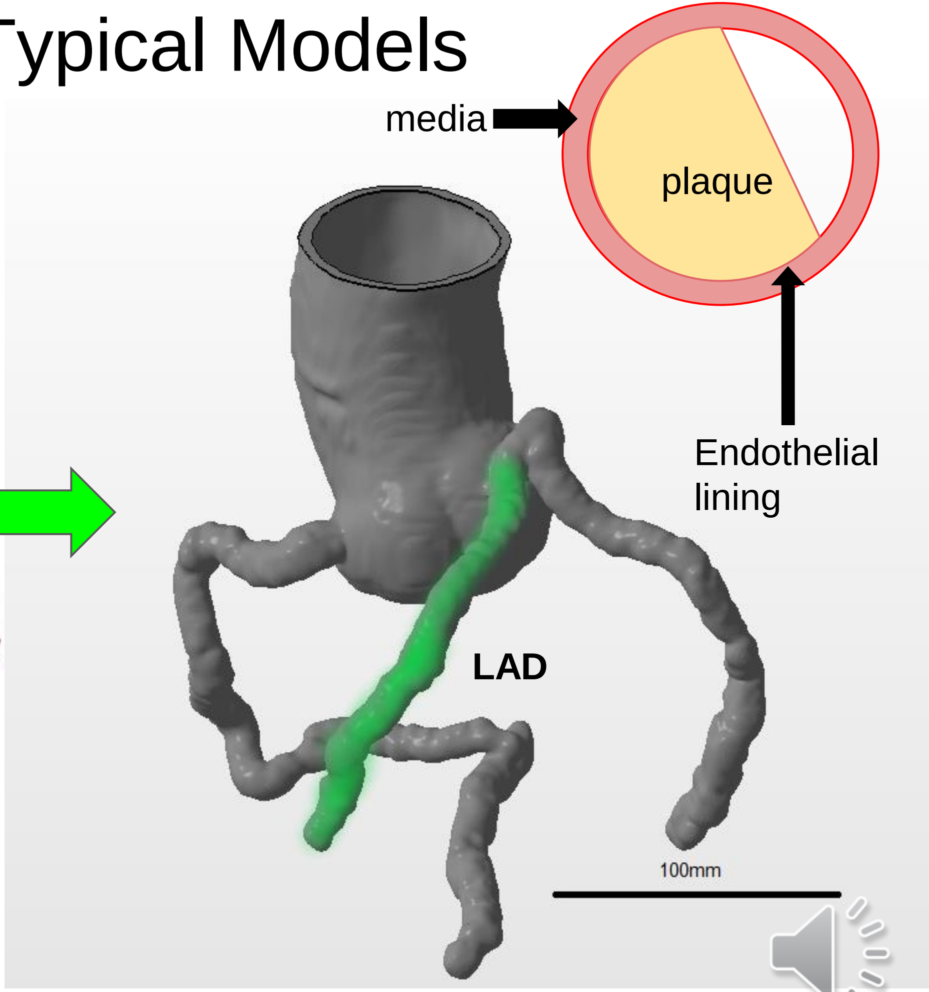
CDC Interactive Atlas of Heart Disease and Stroke, deaths 2019 [2]

- Cells in the blood and blood vessels are known to respond to alterations of the mechanical forces of their environment
    - Wall shear stress
    - Tensile strain
- Computational Models of the coronary arteries are commonly used to estimate these parameters to evaluate disease development

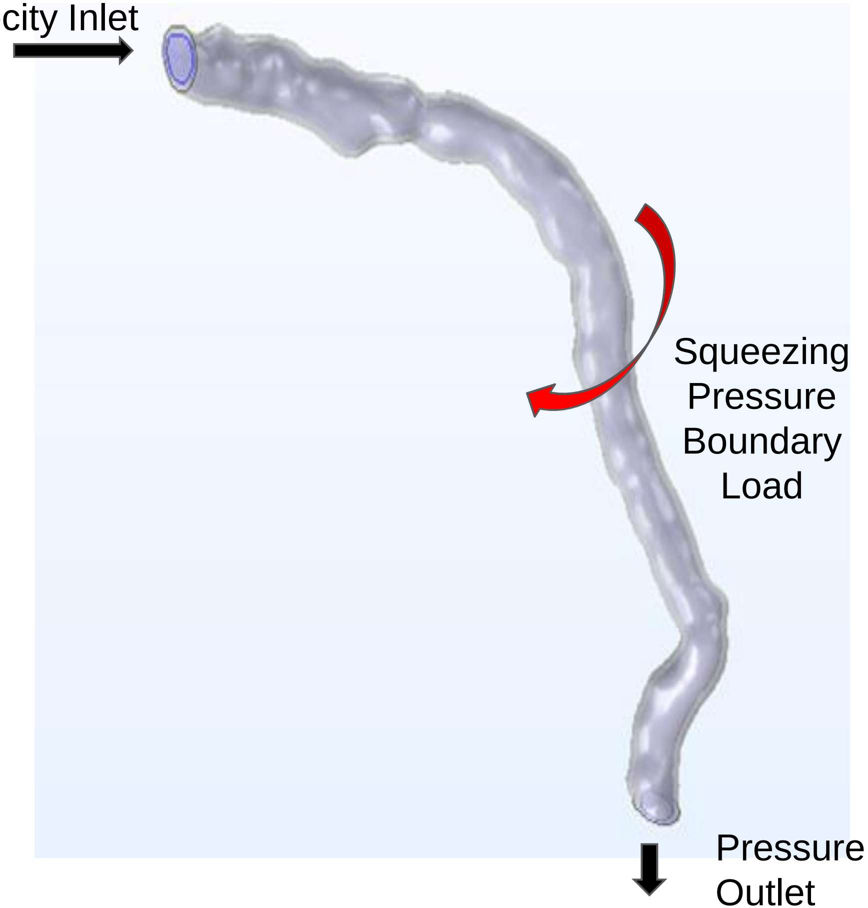
Background of Typical Models



[3]



General FSI Set Up and Boundary Conditions



Velocity Inlet

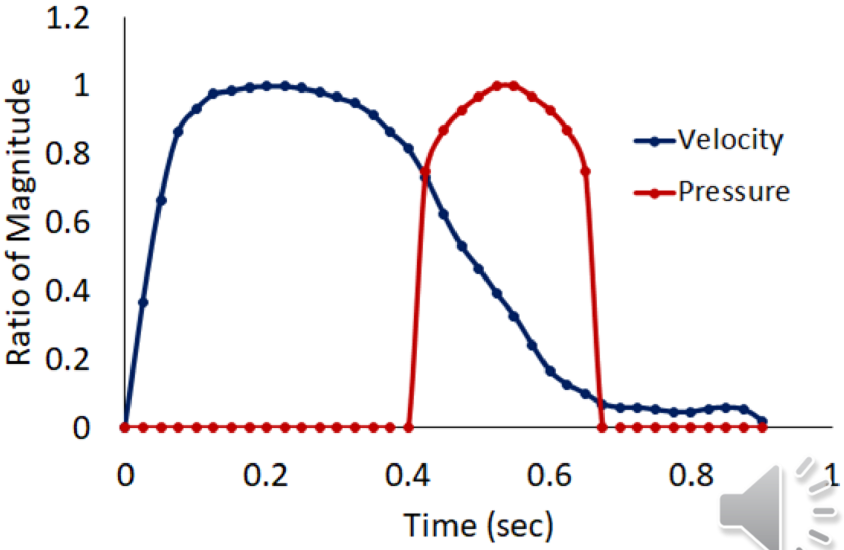
Squeezing Pressure Boundary Load

Pressure Outlet

$$\rho \frac{\partial \mathbf{u}}{\partial t} - \nabla \cdot \eta\left(\nabla \mathbf{u} + \left(\nabla \mathbf{u}\right)^{T}\right) + \rho\left(\mathbf{u} \cdot \nabla\right)\mathbf{u} + \nabla p = 0$$

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

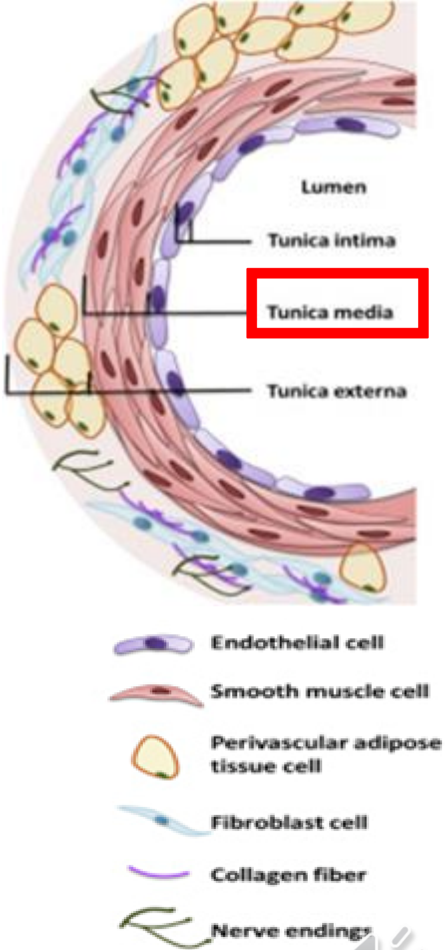
Navier Stokes Equations for incompressible fluids.



Modeling the Arterial Wall Material Properties

5-Parameter Mooney Rivlin model	**C_{10} (kPa)**	**C_{01} (kPa)**	**C_{11} (kPa)**	**C_{20} (kPa)**	**C_{02} (kPa)**
Media	9.26	3.50	1183.00	305.46	504.50
Fibrous Plaque	28.49	8.63	56.75	150.48	2721.00

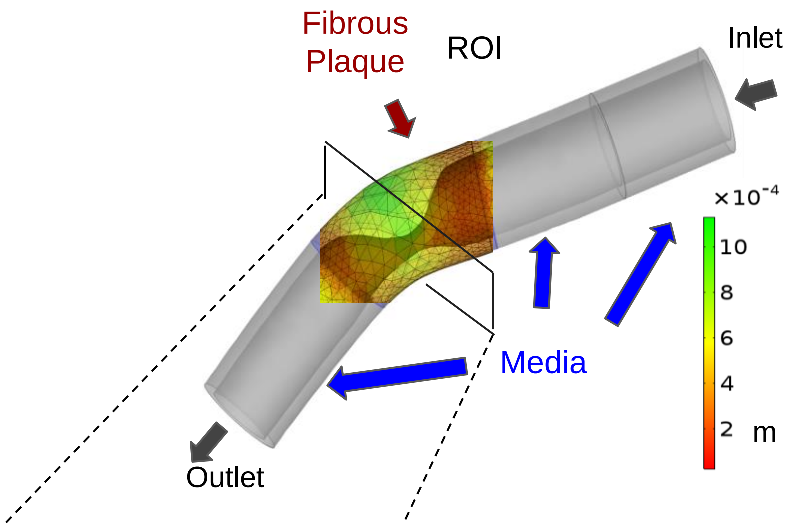
Mooney Rivlin constants for LAD media layer [4]

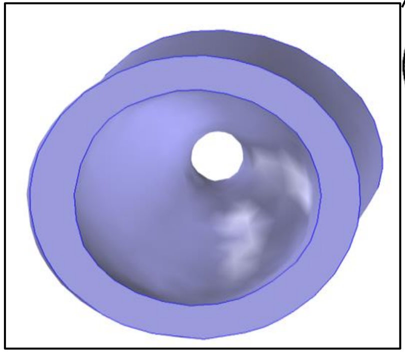


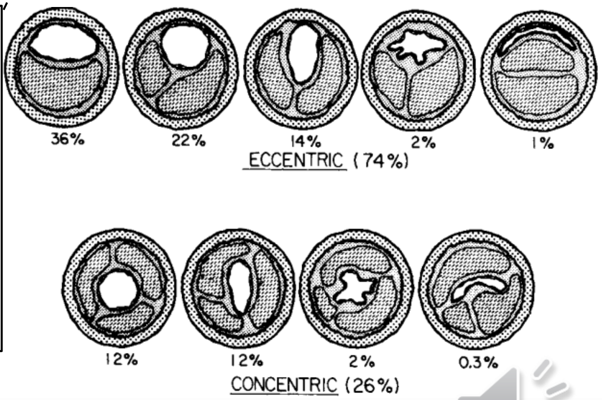
Vascular Wall Cross section [5]

Model 1: Mesoscopic Stenosis FSI Model

- Key Features and Improvements
  - Maximum resolution in the stenosis ROI: 26 µm; avg resolution 56 µm.
    - Comparable to vascular endothelial cells (20-100µm).
  - 2 materials: Media material in the healthy segments, and fibrous plaque material in the stenosis region representing increased stiffness of stenotic vessels.
  - A physiologically accurate stenosis morphology
    - 71% occlusion - severe stenosis, candidate for clinical intervention



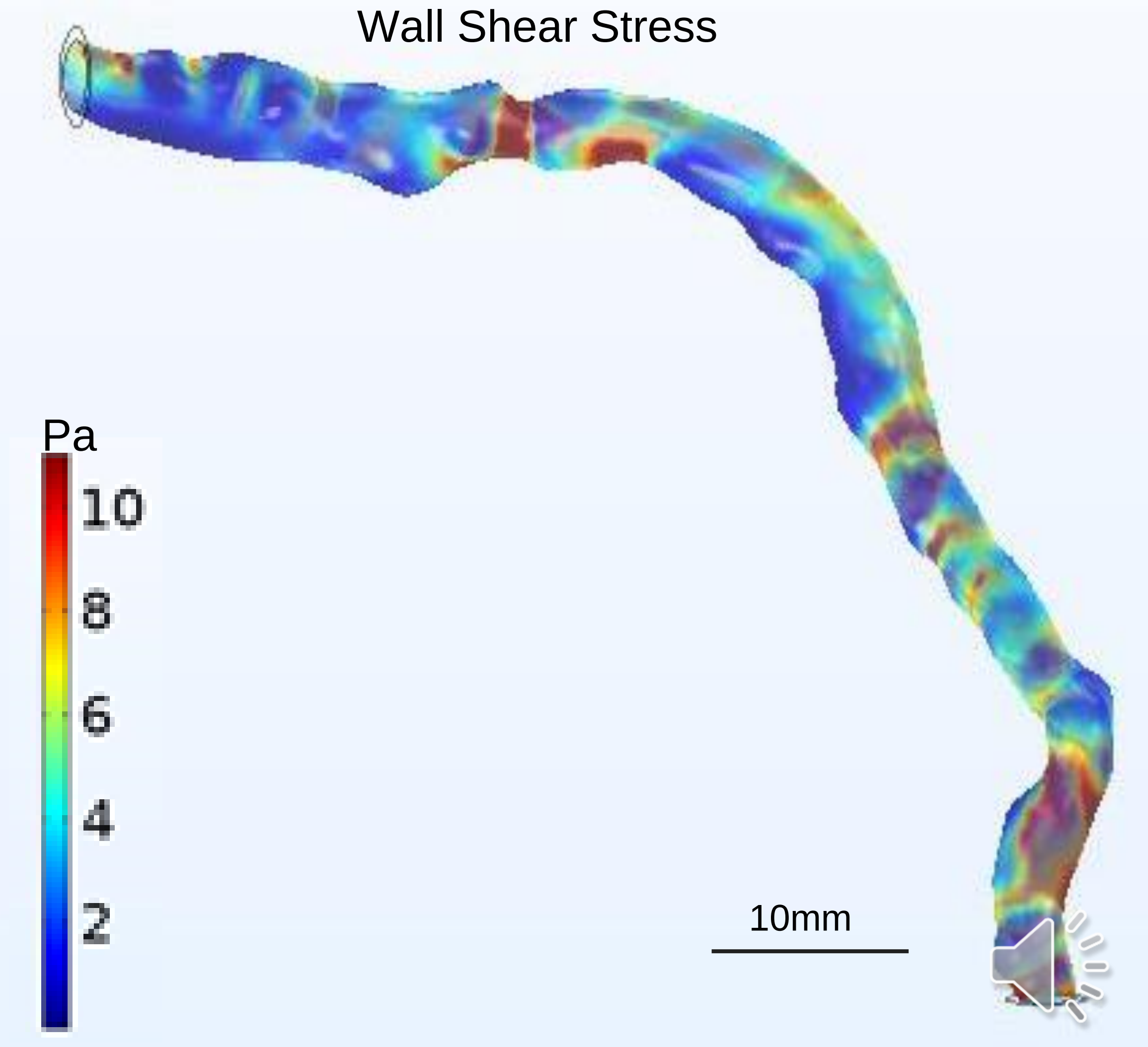




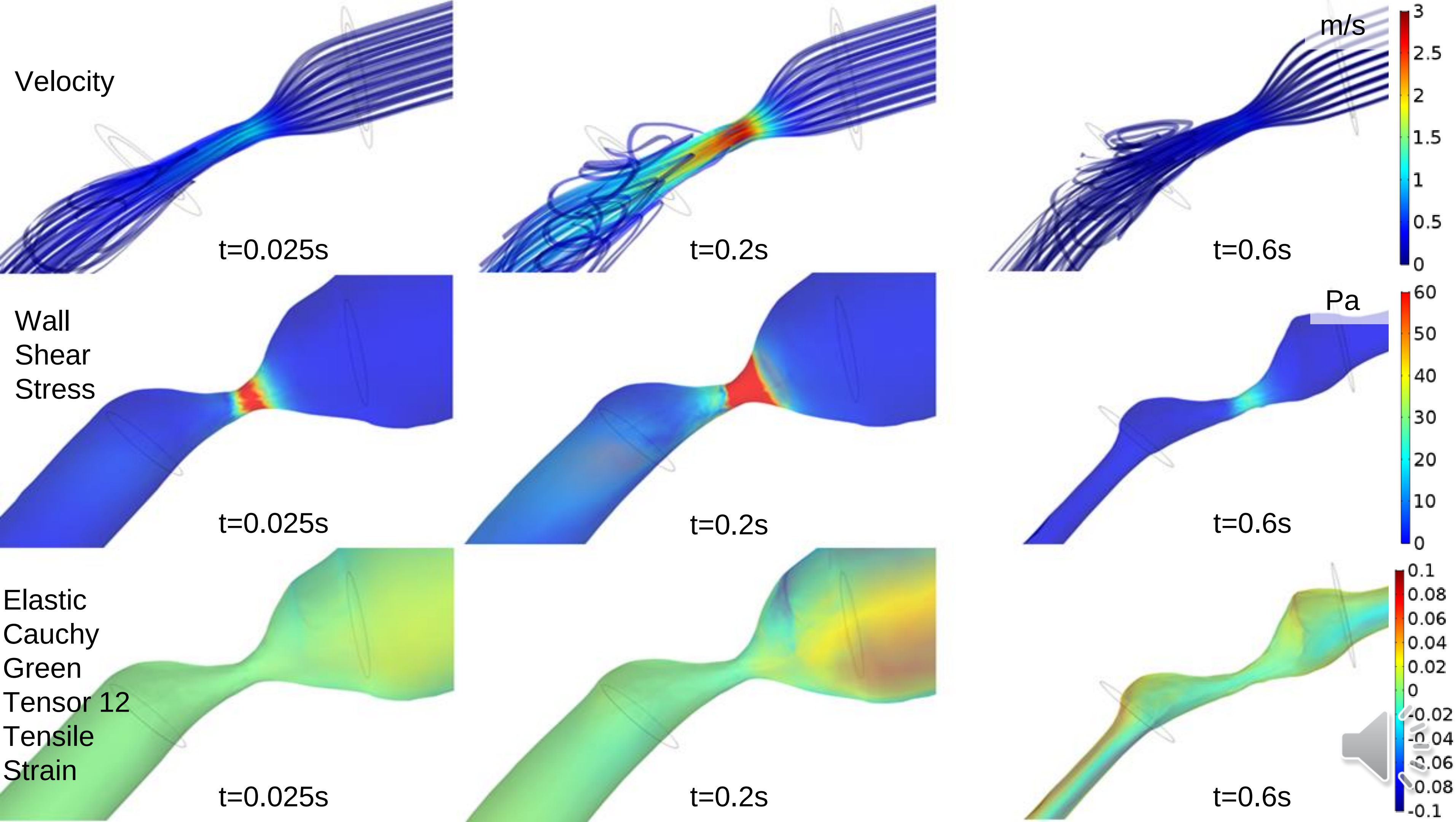
Types of atheorsclerotic lesion structures, from histological cross-sections. [6]

Model 2: Macroscopic Normal FSI Model

- Key Features and Improvements
  - Detailed geometry extracted from patient-specific CTA scan
  - Total length = 7.56cm with increased total volume compared to other coronary artery models
  - Average element size = 166μm



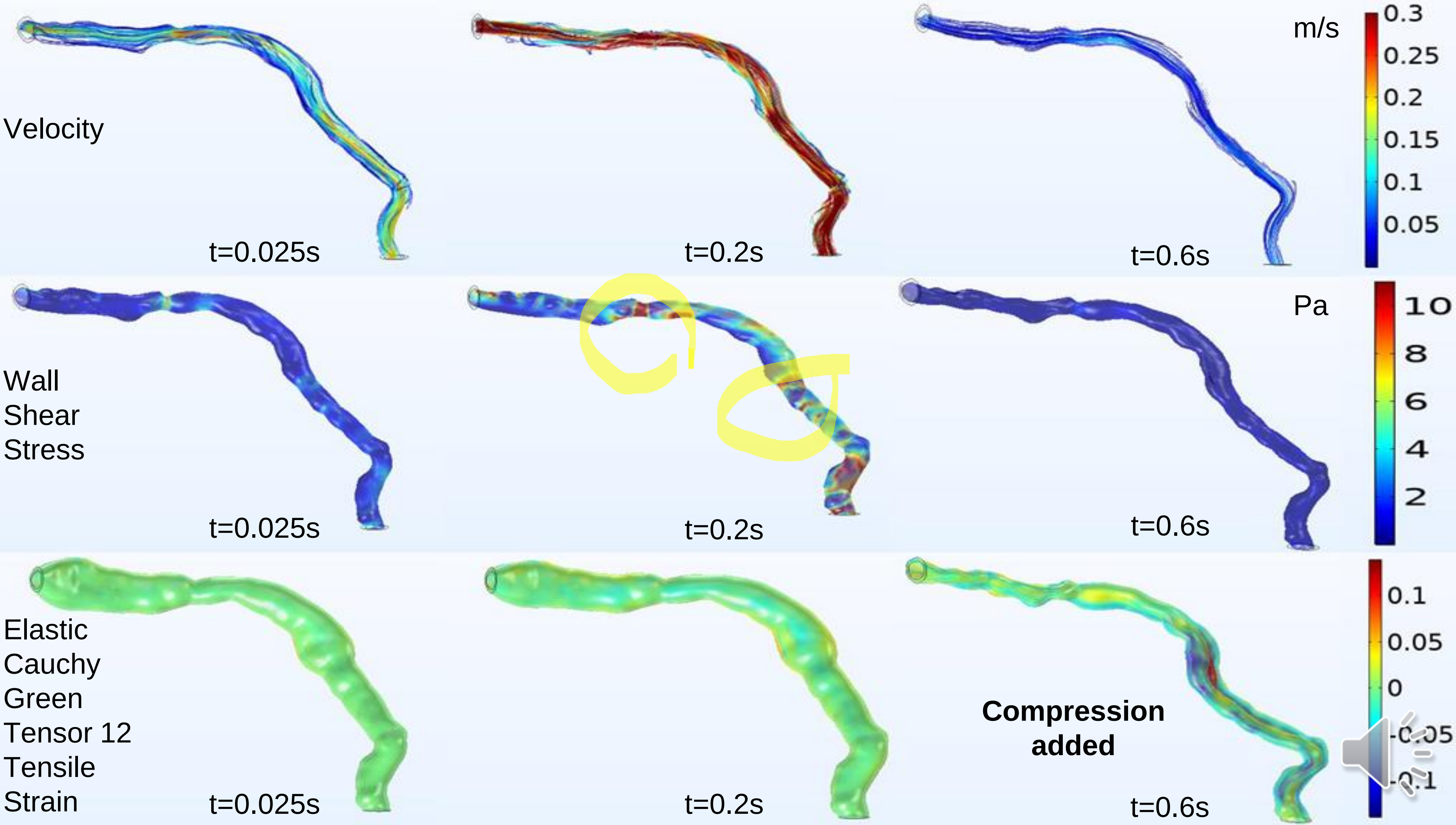
Model 1: Mesoscopic Stenosis Model Results


Velocity
t=0.025s
t=0.2s
t=0.6s
m/s
3
2.5
2
1.5
1
0.5
0
Wall Shear Stress
t=0.025s
t=0.2s
t=0.6s
Pa
60
50
40
30
20
10
0
Elastic Cauchy Green Tensor 12 Tensile Strain
t=0.025s
t=0.2s
t=0.6s
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1

Model 1: Stenosis Model Results Cont.

time (s)	initial velocity (m/s)	Cardiac Squeezing Pressure (kPa)	peak vel (m/s)	avg vel (m/s)	peak WSS (Pa)	average WSS (Pa)	peak tensile strain	average tensile strain
0.025	0.044	0	1.1393	0.07941	82.786	0.8749	0.02841	0.00367
0.2	0.12	0	2.7834	0.23461	328.05	2.6736	0.07046	9.6499E-4
0.6	0.02	1.86	0.5756	0.03173	30.639	0.3422	0.08044	4.6427E-4

Model 2: Macroscopic Normal Model Results



Compression added

Model 2: Normal Model Results Cont.

time (s)	initial velocity (m/s)	phase	Cardiac Squeezing Pressure (kPa)	peak vel (m/s)	avg vel (m/s)	peak WSS (Pa)	average WSS (Pa)	peak tensile strain	average tensile strain
0.025	0.11	Early diastole	0	0.30552	0.096227	11.047	0.91334	0.15848	0.0026173
0.2	0.3	Mid diastole	0	0.76613	0.26878	40.544	2.6236	0.13185	7.68E-04
0.6	0.038	Mid systole	1kPa	0.11924	0.032947	3.3544	0.30594	0.16379	0.0029305

Conclusions

- Successful use of 3D patient-specific geometries to perform FSI modeling in COMSOL on both macro and meso scale
- Using MR material constants from the media layer created reasonable deformations in the arterial wall during normal and stenosis conditions
    - With and without compression
- Higher than expected WSS results in stenosis model
- In normal model, fluid velocity, WSS, and tensile strain are within expected values

Future Directions

- Patient-specific 3D models can be created with patient-specific inlet and outlet pressures serving as BC’s for rigorous validation
- Assessing vulnerability of plaques
- Particle tracing of platelets in the stenosis model
    - High spatial resolution intended to allow for modeling of cellular-level interactions which affect thrombosis.

Thank you!

For additional questions or comments, please contact us at:

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- Dr. Wei Yin: wei.yin@stonybrook.edu

References

[1] Benjamin, Emelia J., et al. "Heart disease and stroke Statistics-2019 update a report from the American Heart Association." Circulation (2019).

[2] CDC Interactive Atlas of Heart Disease and Stroke, deaths 2019, https://nccd.cdc.gov/DHDSPAtlas/?state=County

[3] “File:Coronary arteries.png”, https://commons.wikimedia.org/wiki/File:Coronary_arteries.png

[4] Teng et. al., “The influence of constitutive law choice used to characterise atherosclerotic tissu material properties on computing stress values in human carotid plaques“, JBioMech, 48, pp. 3912-3921, 2015

[5] Zhao, Yingzi, Paul M. Vanhoutte, and Susan WS Leung. "Vascular nitric oxide: Beyond eNOS. Journal of pharmacological sciences 129.2 (2015): 83-94.

[6] Brown, Bolson & Dodge. “Dynamic mechanisms in human coronary stenosis.” *Circulation.* Vol 70 pp 917-922. 1984.