COLUMBIA UNIVERSITY
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COLUMBIA ENGINEERING FOR HUMANITY

Cyberinfrastructure for Patient-Specific Modeling of Cardiovascular Disease

Vijay Vedula

Assistant Professor
Mechanical Engineering, Columbia University

SimVascular
SimCardio
www.simvascular.github.io

Stanford University

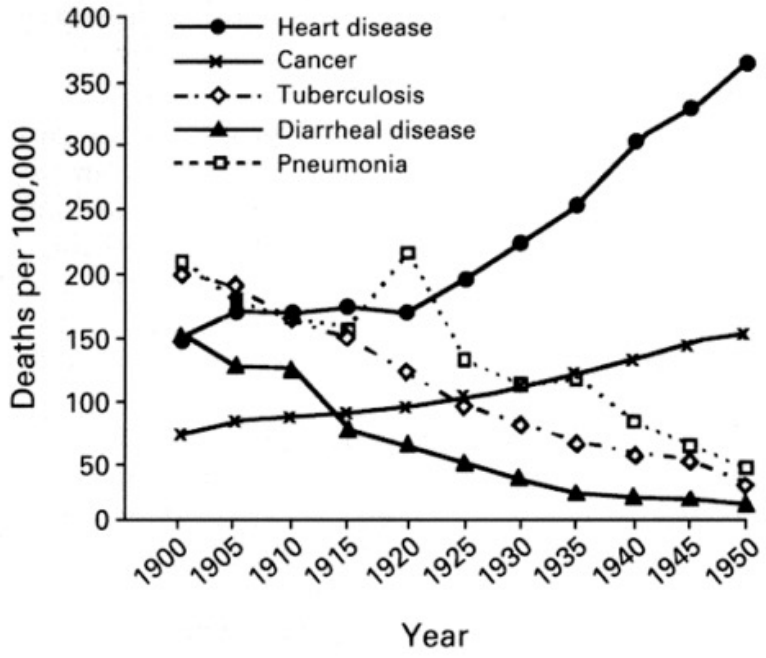
Berkeley
UNIVERSITY OF CALIFORNIA

NSF

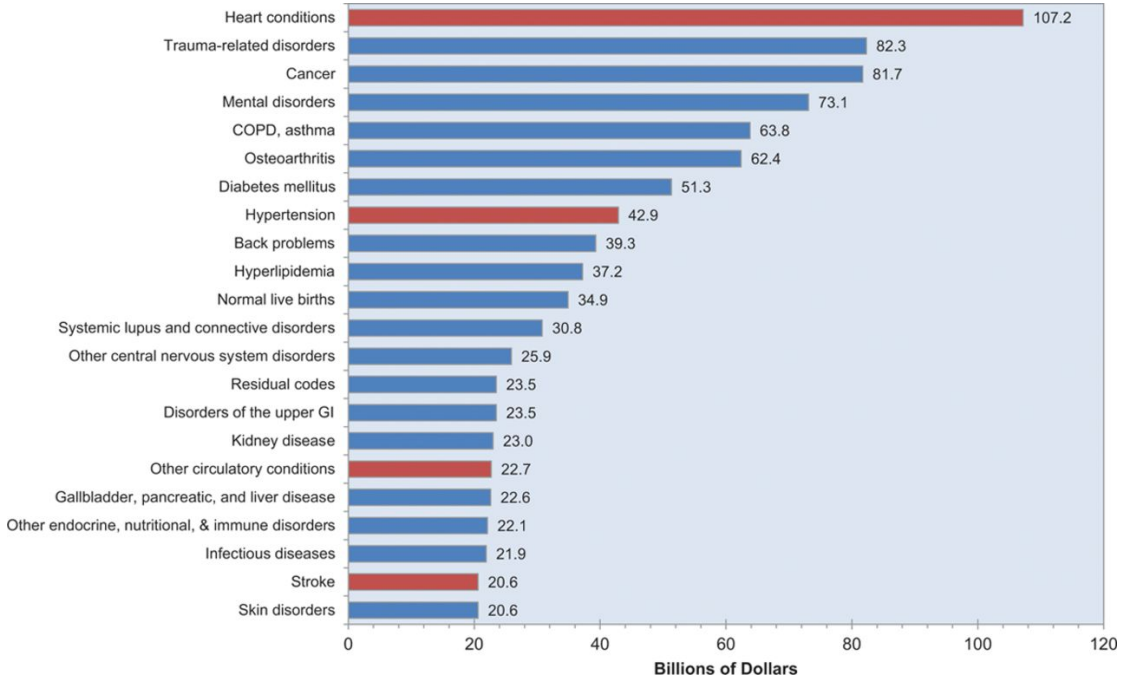
NIH
National Institutes of Health

Motivation

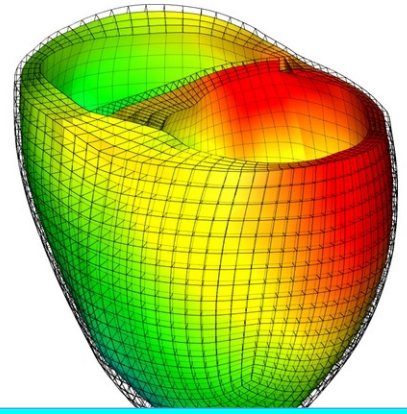
- Cardiovascular disease (CVD) – leading cause of death (1 in 4 in US)
- 1/100 children are born with a congenital heart defect
- High costs (> $500Billion in US)

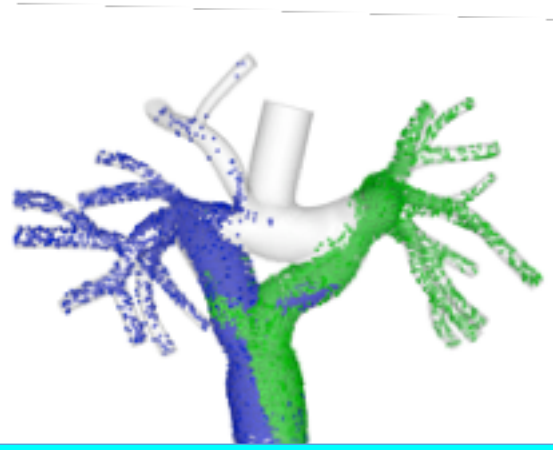


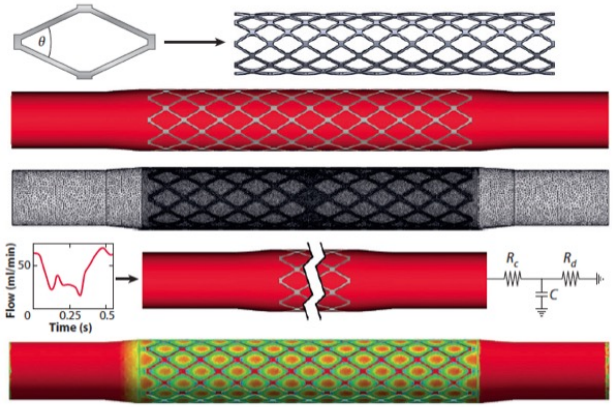
Braunwald, NEJM, 1997

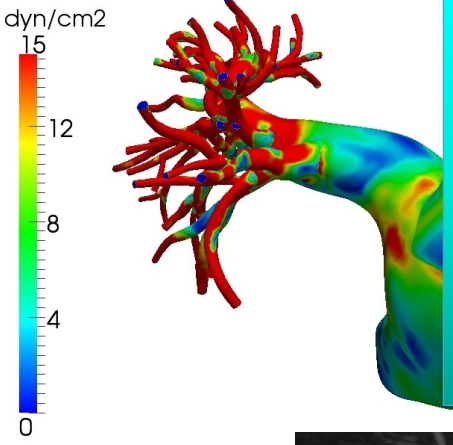


CDC, AHA Statistics Report 2014

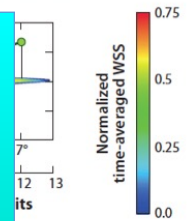


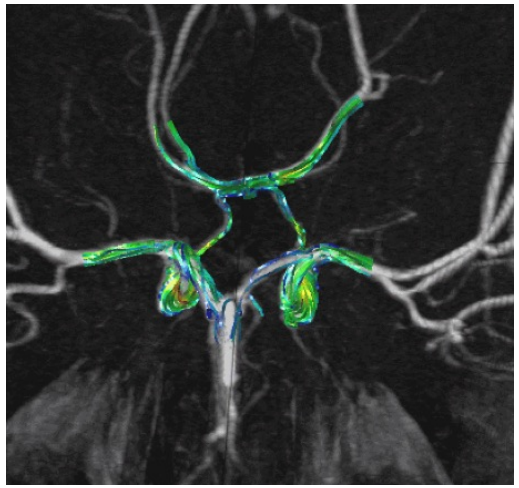


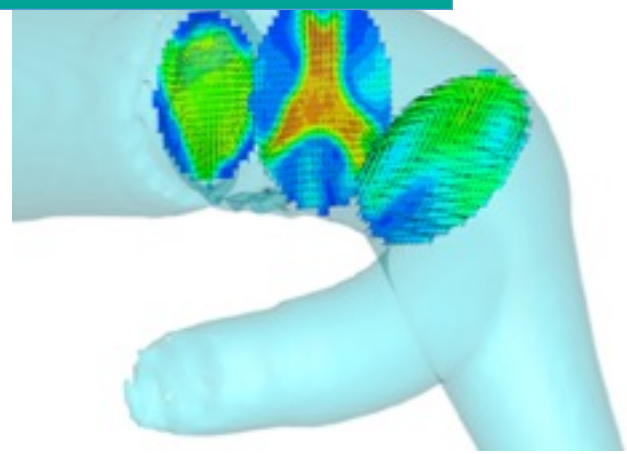




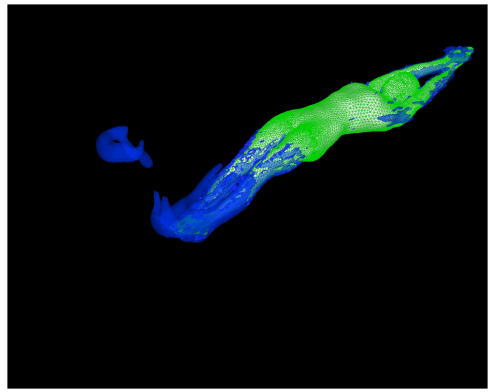
Modeling & Simulation are emerging as critical tools for patient care, treatment planning, and medical device development







©Marsden Research Lab

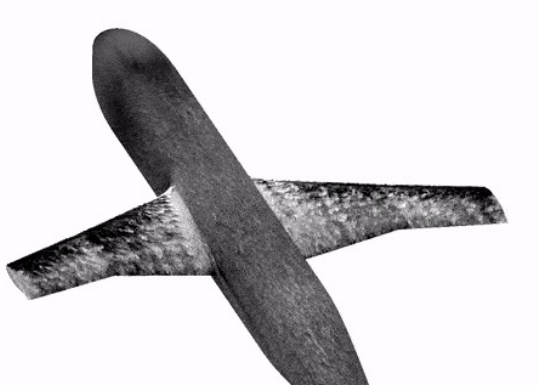


©Mittal, JHU

$$\rho\vec{v}_{,t} + \rho\vec{v}\cdot\nabla\vec{v} = -\nabla p + \nabla\cdot\tau + \vec{f}$$

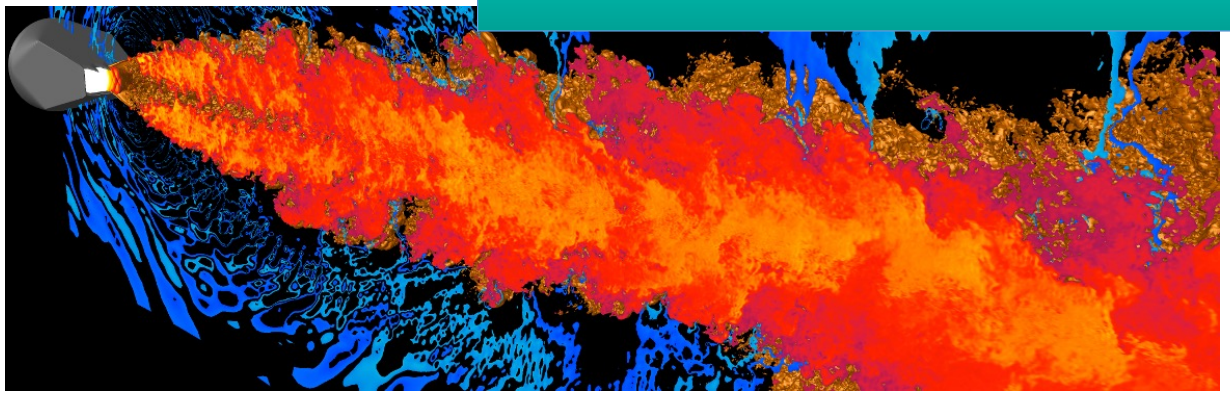
$$\nabla\cdot\vec{v} = 0$$

Navier-Stokes Fluid Mechanics



©Durran, Stanford

We have not leveraged the full potential of predictive computations in clinical medicine



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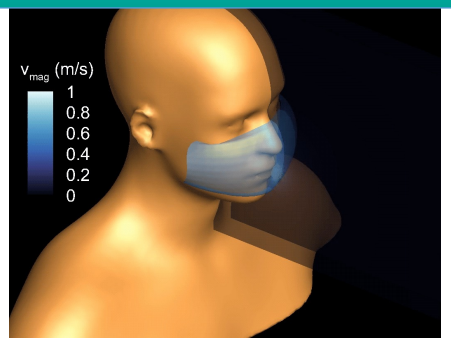

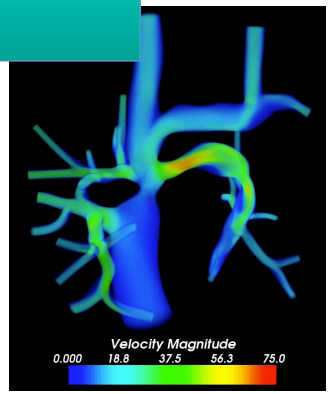

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Personalized Modeling

HeartFlow™

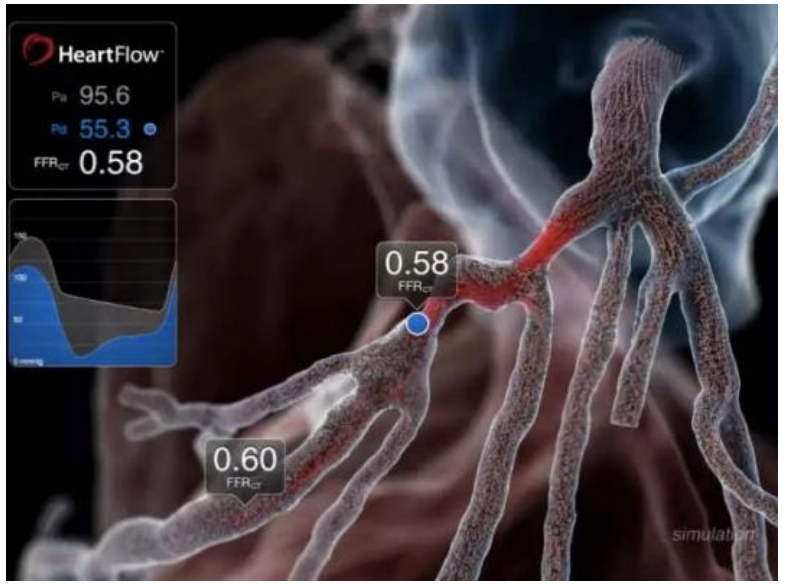
Disease mechanisms
- Invitro experiments

Treatment Planning
- Optimize outcomes
- Device design

Non-invasive
- Imaging
- Complements routine diagnosis

`Predictive' Medicine
- Long-term Prognosis

Personalized Cardiac Modeling

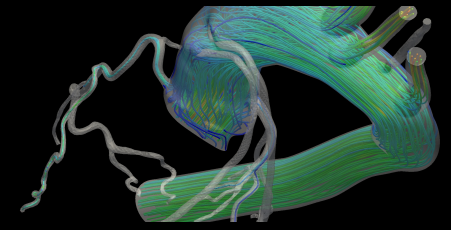


- 61% invasive catheterizations deferred
- 83% reduction in angiograms
- HeartFlow Planner

PLATFORM, Douglas et al., *Eur. Heart J.,* (2015)

Open-Source Software

Sharing tools with the research community



SimVascular

The only fully opensource software package providing a complete pipeline from medical image data segmentation to patient specific blood flow simulation and analysis.

Tweets by @simvascular

SimVascular
@simvascular

New Feb 2021 @simvascular release for Mac, Windows and Linux is out! This includes: 1) Bug fixes, 2) Enhancements to 1D Simulation plugin, 3) Additions to Python API, 4) Rewrite of Colliding Fronts plugin. @MarsdenStanford #OpenSource #cardiovascular simtk.org/frs/?group_id=…

Feb 8, 2021

SimVascular Retweeted

Marsden Lab
@MarsdenStanford

Registration now open for the @simvascular pre-conference software workshop at @SB3Corg. Join us for hands on software training in blood flow simulation and patient specific modeling. Breakouts for experienced and novice users. Sign up here: sb3c.org/sb3c-pre-confe… #SB3C2021

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Alison Marsden
Stanford University

Shawn Shadden
UC Berkeley

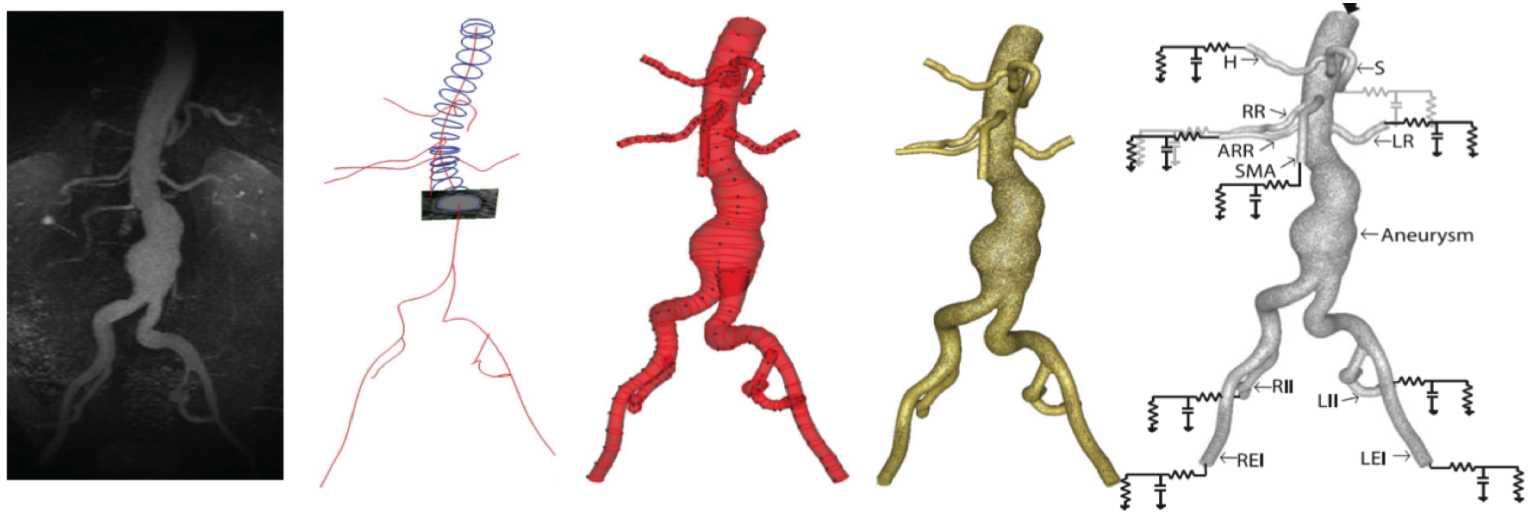
Nathan Wilson
OSMSC

Stanford MEDICINE Berkeley UNIVERSITY OF CALIFORNIA OSMSC NSF SimTK

NSF

SimVascular

Provide a complete pipeline from medical image data to patient-specific blood flow simulation and analysis



- High quality modeling and simulation tool to advance cardiovascular research

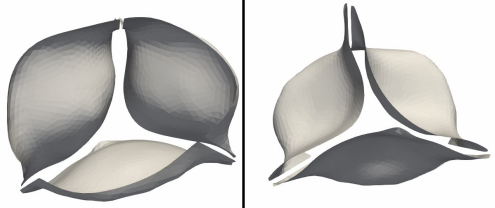
Updegrove et al., Annals Biomed Eng. 2017

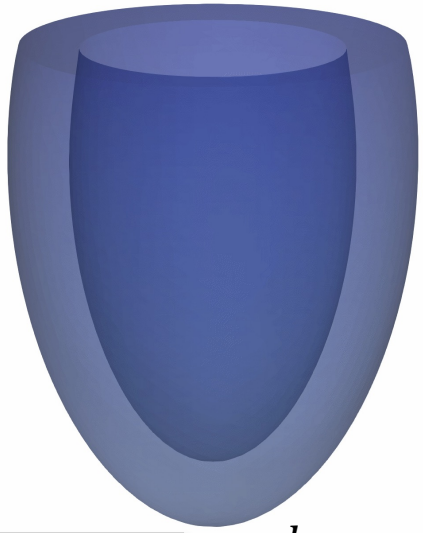
Features:

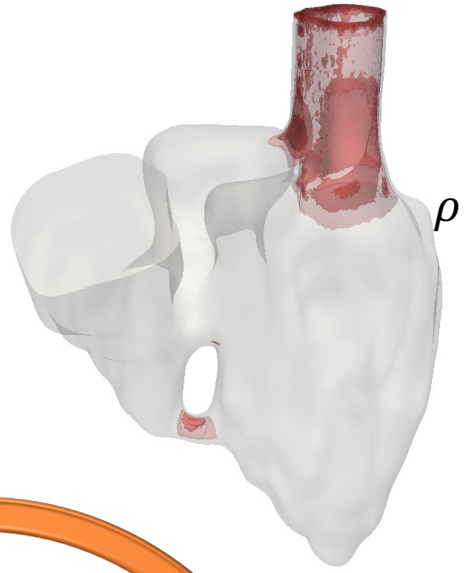
- Fully open sourced and free
- Multiscale modeling, optimization, uncertainty quantification, and FSI
- Online documentation and tutorials
- Medical engineering and education
- Cloud computing on AWS, Online Gateway (XSEDE)

SimCardio: towards whole heart modeling

git@github.com:SimVascular/svFSI.git







Hemo-dynamics

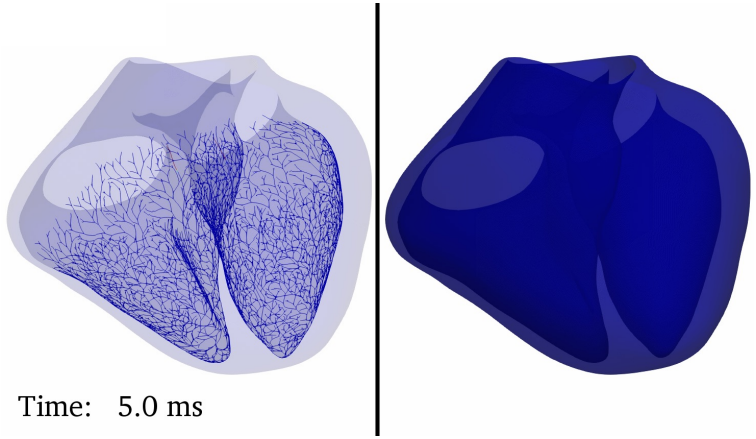
Mechanics

Electro-physiology

Navier-Stokes

$$\rho\left(\left.\frac{\partial \mathbf{u}}{\partial t}\right|_{\hat{x}} + (\mathbf{u}-\hat{\mathbf{u}}).\nabla\mathbf{u} - \mathbf{f}\right) - \nabla.\bar{\bar{\boldsymbol{\sigma}}} = 0$$

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



Cauchy equations

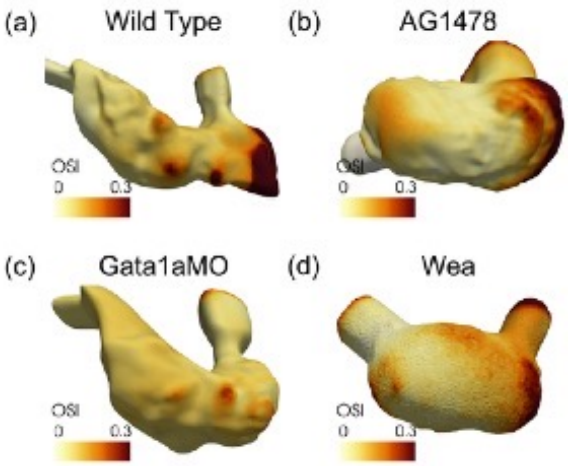
$$\rho\frac{d\mathbf{v}}{dt} = \nabla.\bar{\bar{\boldsymbol{\sigma}}} + \rho\mathbf{b}$$

$$\frac{d\mathbf{u}}{dt} = \mathbf{v}; \qquad \beta_\theta\frac{dp}{dt} + \nabla.\mathbf{v} = 0$$

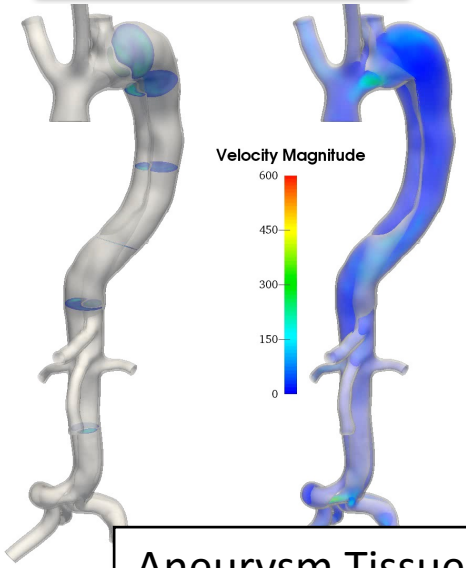
$$C_m\dot{V} = -(I_{ion} + I_{stim}) + \nabla.\mathrm{q}(V)$$

svFSI Applications

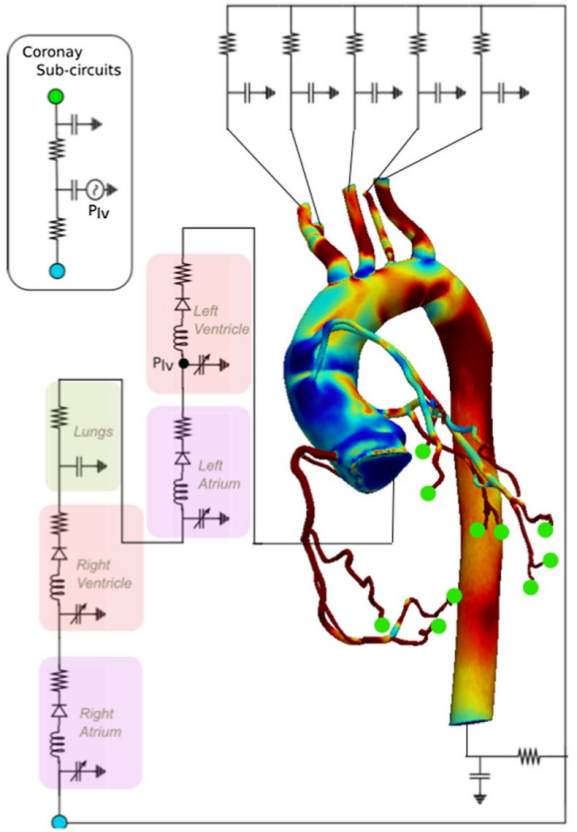
Cardiac Development



Aortic Dissection

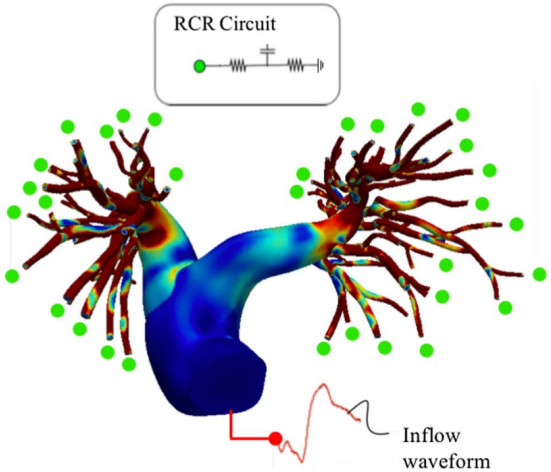


Coronary Artery Disease

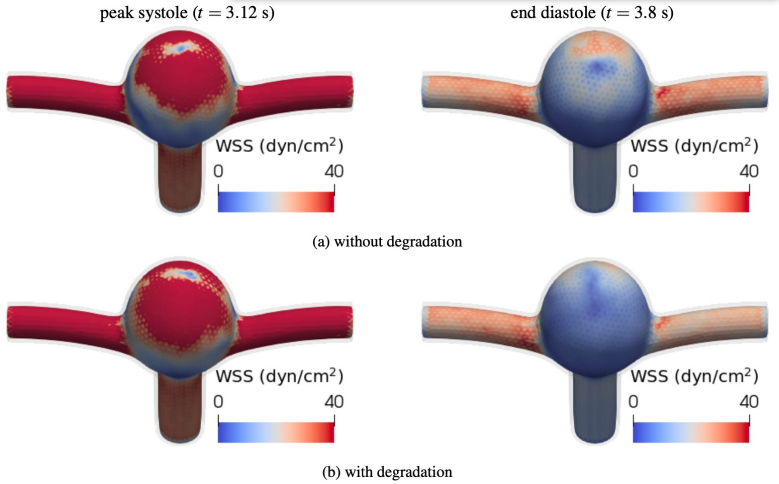


Vedula et al., PLOS Comp Bio
Baeumler et al., BMMB
Seo et al., Comput. Mech.
Liu et al. (in preparation)

Pulmonary Hypertension



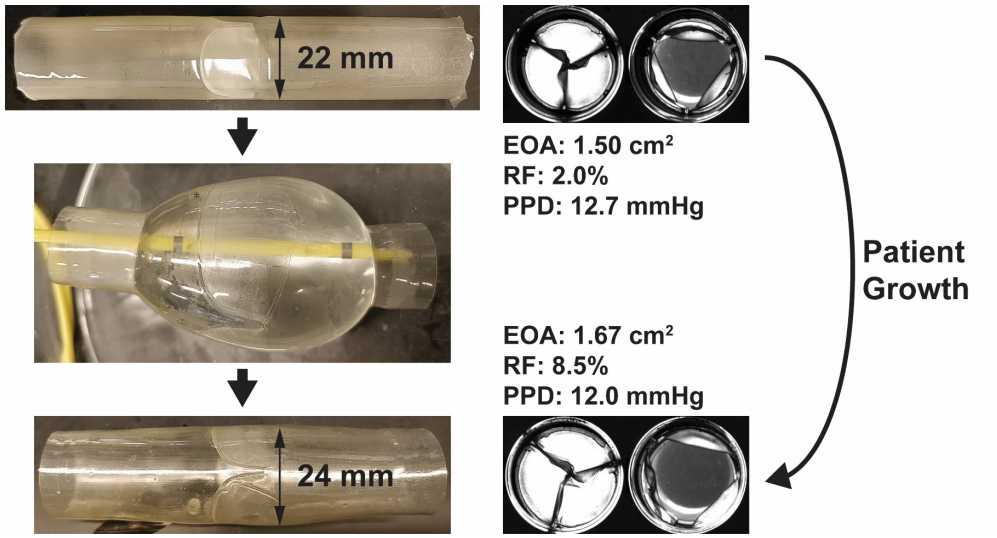
Aneurysm Tissue Damage

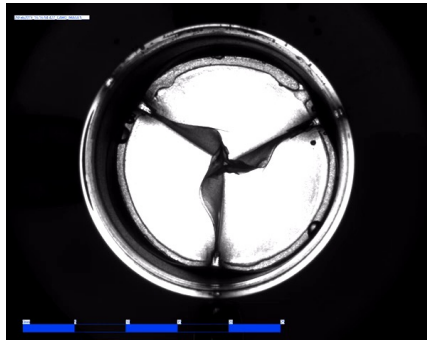


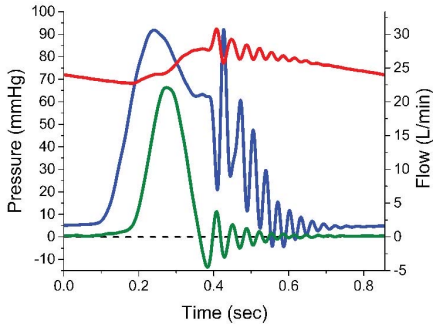
svFSI – Ongoing Developments

Growth-Accommodating Heart Valve

Can pediatric prosthetic valves `grow' in response to somatic growth?







David Kalfa Jeffrey Kysar Haim Waisman

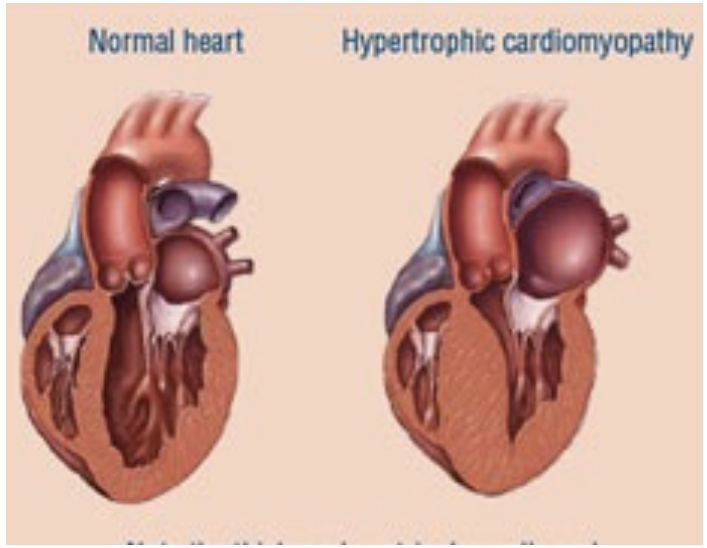
- Expanded polytetrafluoroethylene (ePTFE)
- Material characterization – viscoplastic with damage (Mullins)
- Contact model for valves
- Immersed boundary method with thin shell formulation for thinner valves

svFSI – Ongoing Developments

Hypertrophic Obstructive Cardiomyopathy

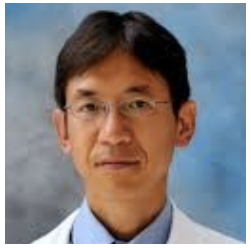
Can modeling be used to plan septal myectomy?

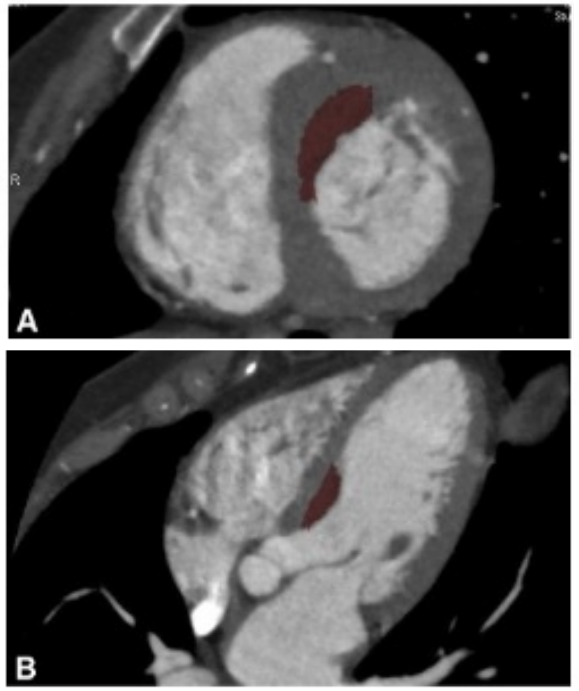
- Thick heart tissue obstructs blood flow into aorta
- Implications for sudden cardiac death



https://inmo.ie/MagazineArticle/PrintArticle/9090

Dr. Hiroo Takayama





Takayama et al. JTCVS 2019

svFSI Features:

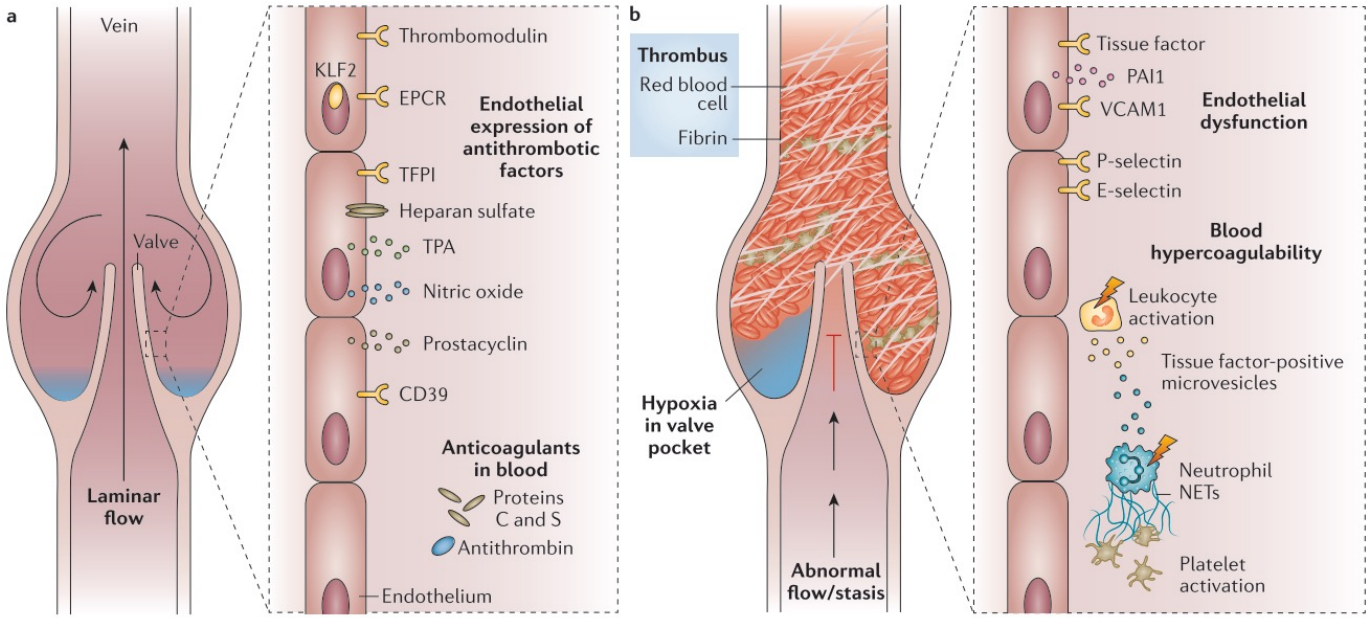
- Multiphysics cardiac model to assess electrical activity, tissue contraction, and blood flow pre- and post-surgery
- Optimization
- Automate model generation using machine learning-based methods

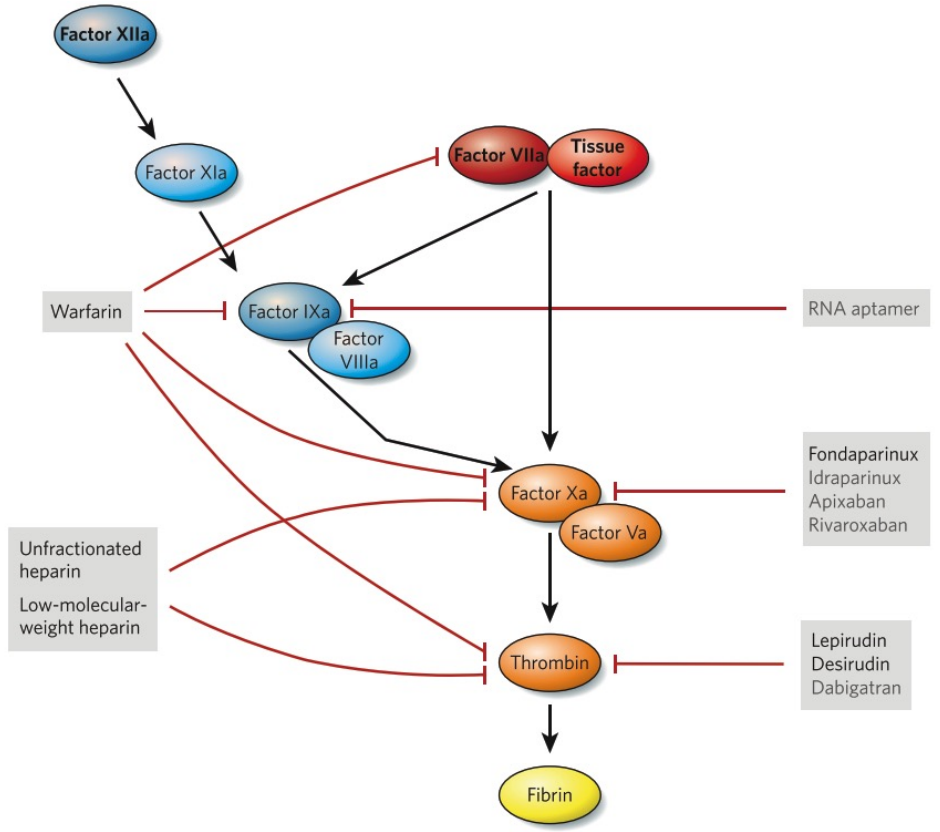
svFSI – Ongoing Developments

Venous Thromboembolism (VTE)

- VTE – third leading cause of cardiovascular related death
- Multifactorial (Virchow's triad)
- Multiscale-multiphysics modeling of VTE (FSI, coagulation cascade specific to venous flow conditions)

Keefe Manning, PennState

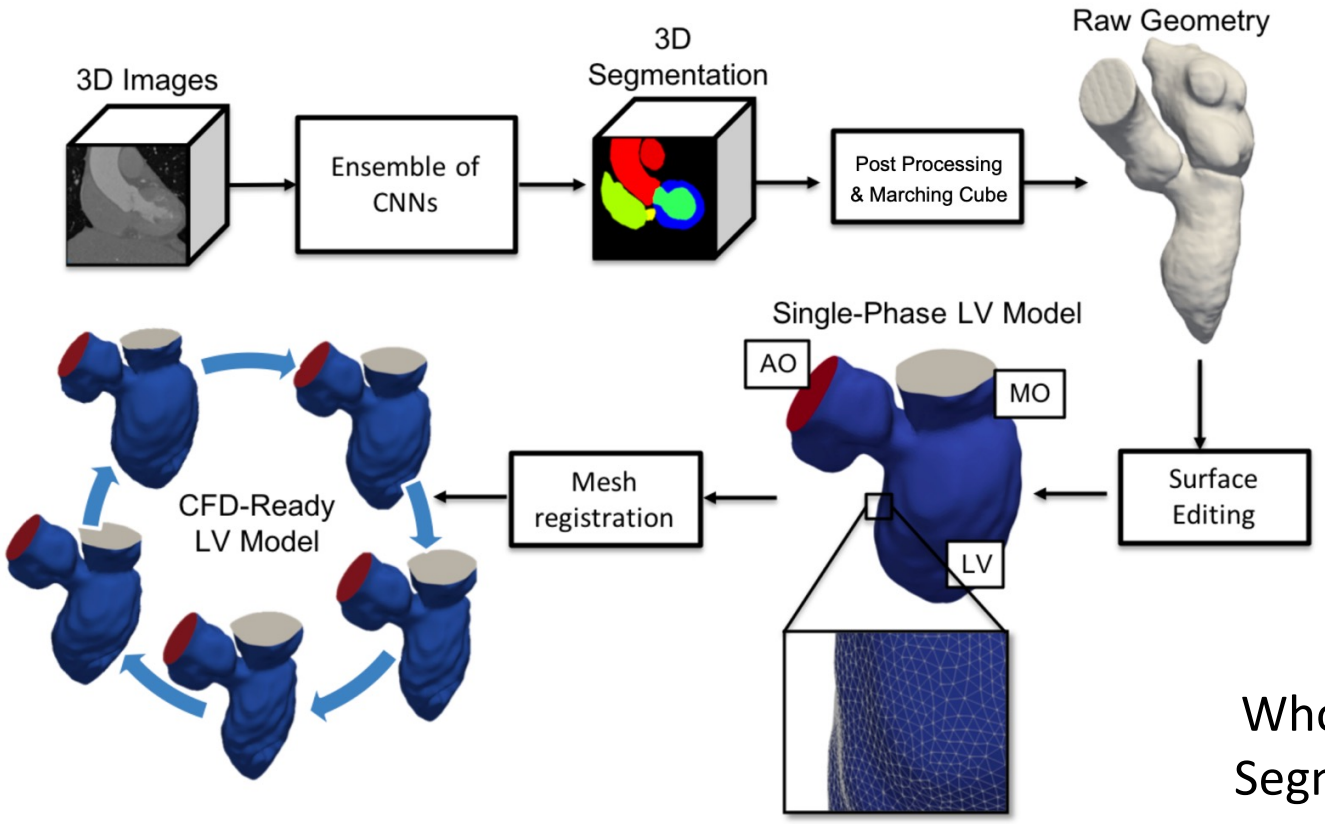




Wolberg et al., Nat. Rev. Dis. Prim., 2015

Ongoing Developments

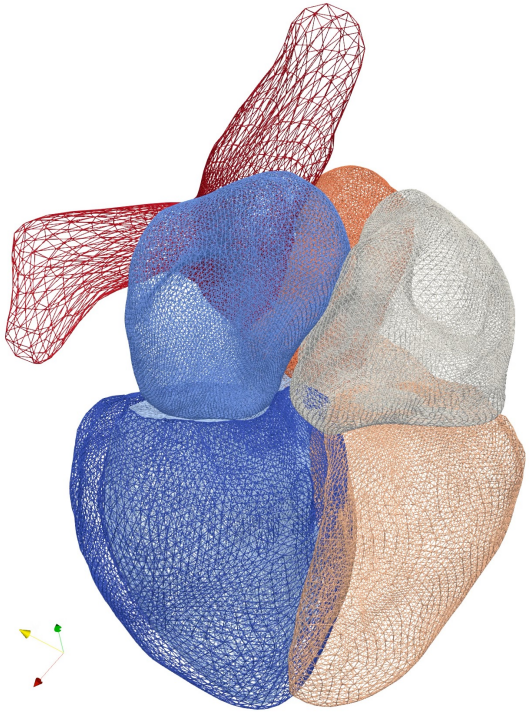
Automatic Cardiac Segmentation and Model Creation



Shawn Shadden

Fanwei Kong

Whole Heart Segmentation



- Deep-learning based segmentation, geometry processing, and image registration
- Python-based framework

Closing Thoughts

- Simulations have a greater role to play in clinical applications (disease mechanisms, risk stratification, treatment planning, and device design)
- Open-source software being increasingly used for cardiovascular research and education
- Research thrusts – automated workflow (AI/ML, DD), uncertainty quantification, multiphysics-multiscale modeling, reduced-order and multi-fidelity modeling

Acknowledgments

Alison Marsden

Shawn Shadden, Berkeley

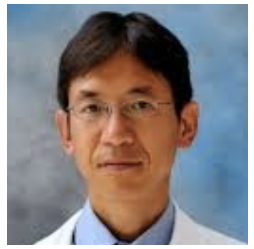
Ellen Kuhl

Jeff Kysar

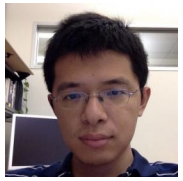
Haim Waisman

David Kalfa

Jamie Harrington



Hiroo Takayama



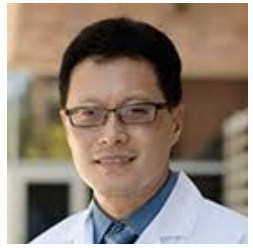
Ju Liu

Oguz, T.

Chi Zhu, Berkeley

Francisco Sahli

Ian Chen
Cardiologist
Stanford, VA Palo Alto



Tzung Hsiai, UCLA

Juhyun Lee, UTA

Funding

NIH National Institutes of Health

NSF

Stanford Children's Health

Computing

XSEDE
Extreme Science and Engineering Discovery Environment

Cardiac Biomechanics Modeling <vv2316@columbia.edu>