SimVascular www.simvascular.org

CARDIOVASCULAR MODELING AND SIMULATION IN GRADUATE EDUCATION

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Mechanical and Aerospace Engineering
University of California – San Diego

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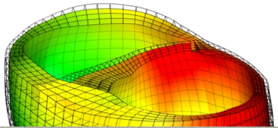
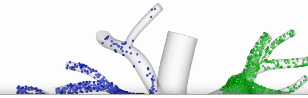
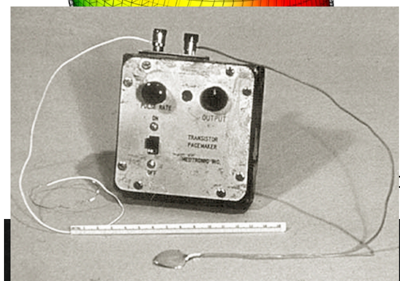
A Common History







Paradigm shifts in cardiovascular medicine have been enabled by new engineering technologies

Simulation has emerged as the next frontier in the partnership

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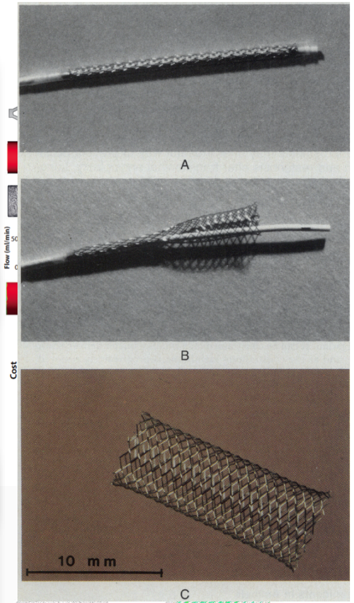
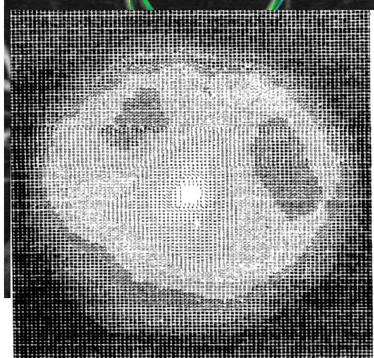
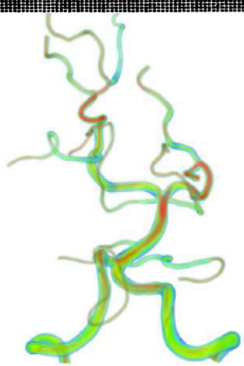
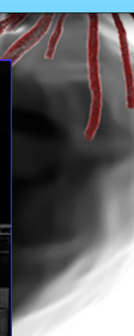
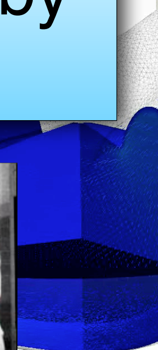
Major advances in engineering technology have been driven by clinical needs

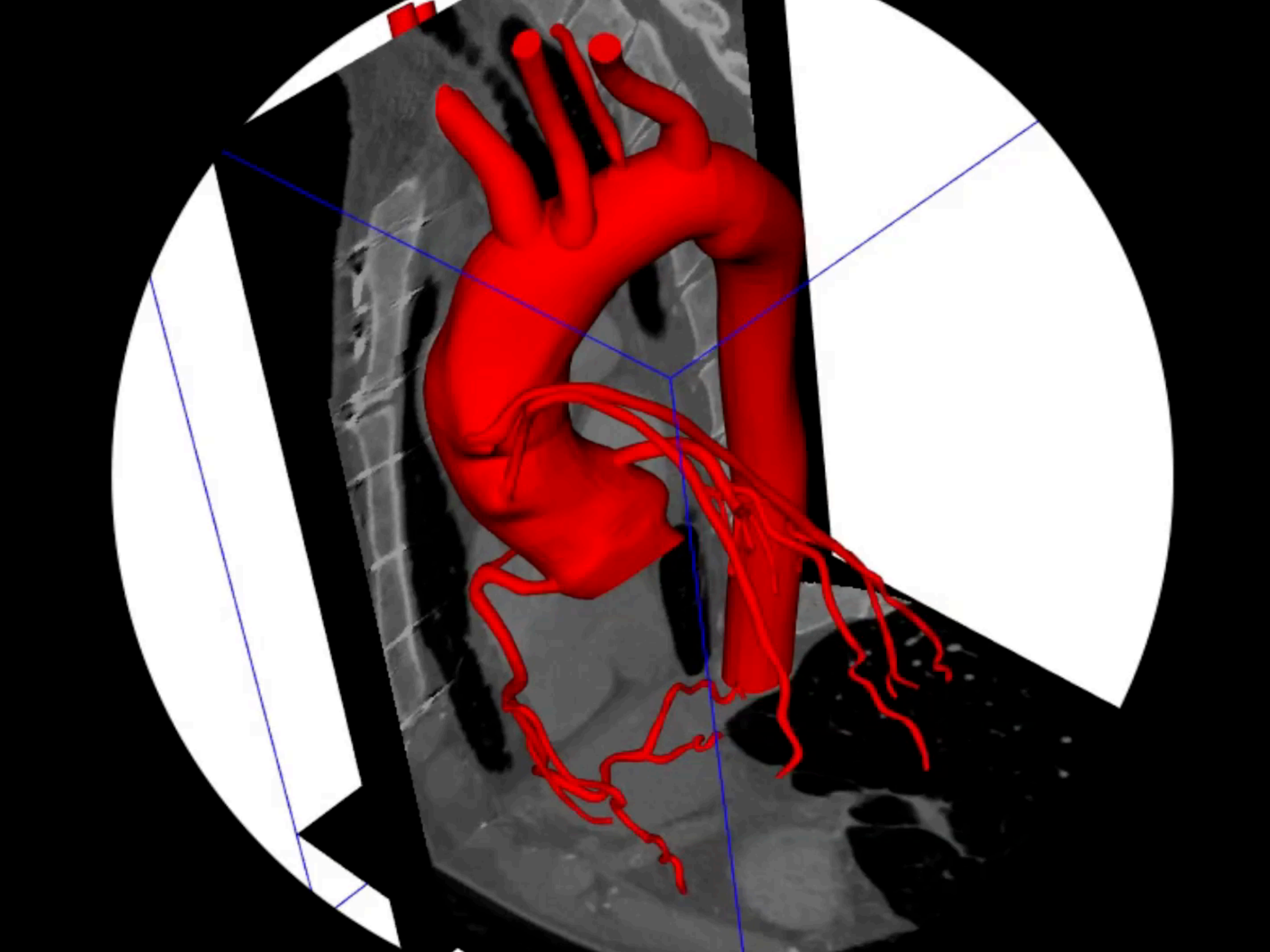












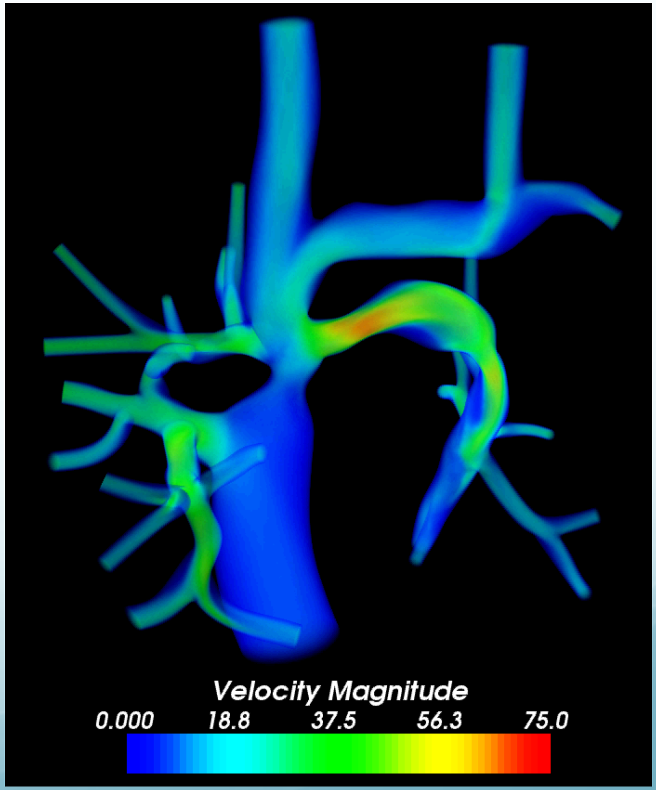
Goal

To incorporate computational fluid dynamics simulations of blood flow into my graduate course MAE 261 "Cardiovascular Fluid Mechanics."

IDI facilitated engagement with ACMS to provide high performance computing resources. This gave students the ability to run large scale CFD simulations.

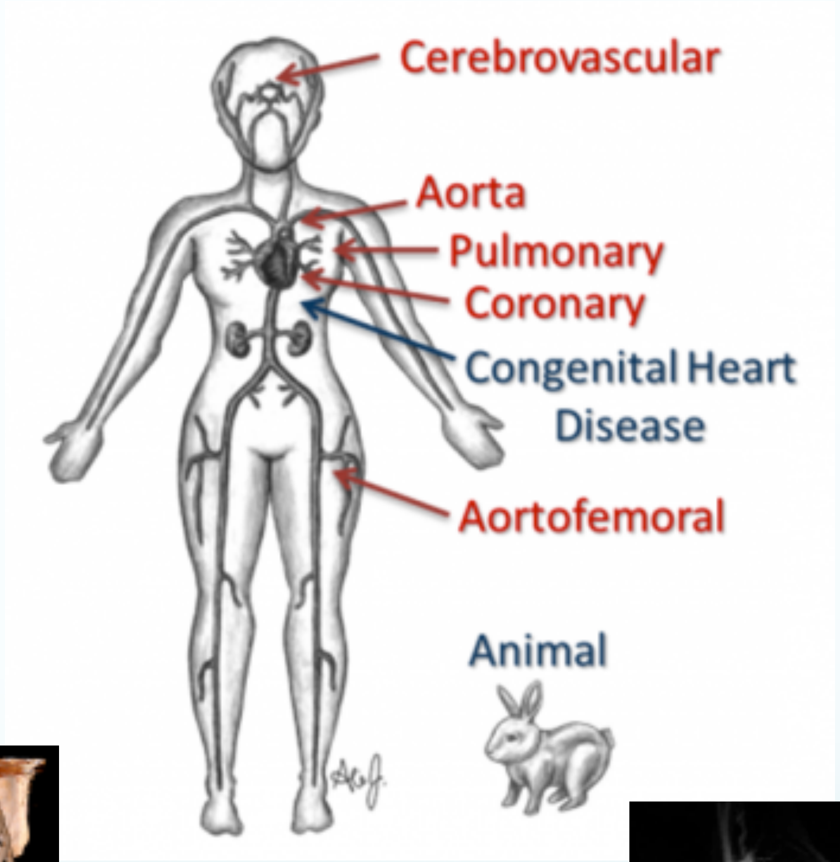
11 students

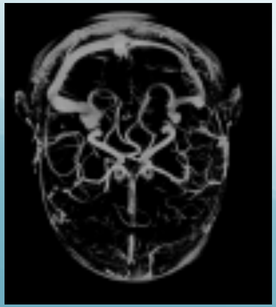
- learn SimVascular
- simulations run on ACMS cluster
- IDI facilitated student exposure to HPC

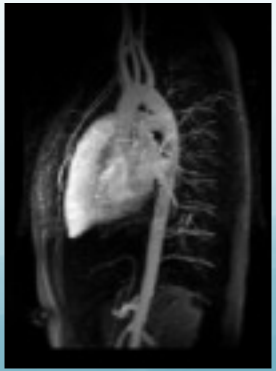


Vascular Model Repository

- Each student built their own unique model
- Image data provided by vascularmodel.com through special arrangement







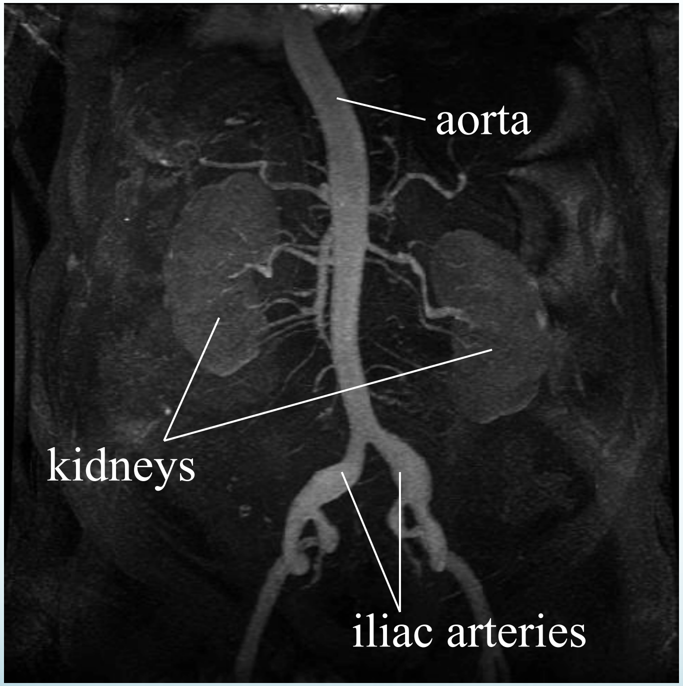
What Students Learned

- Interpreting medical images
- Image segmentation
- Generating high quality meshes
- Impact of boundary conditions
- Running simulations in a cluster environment
- Visualizing and reporting results
- Oral presentation and written report

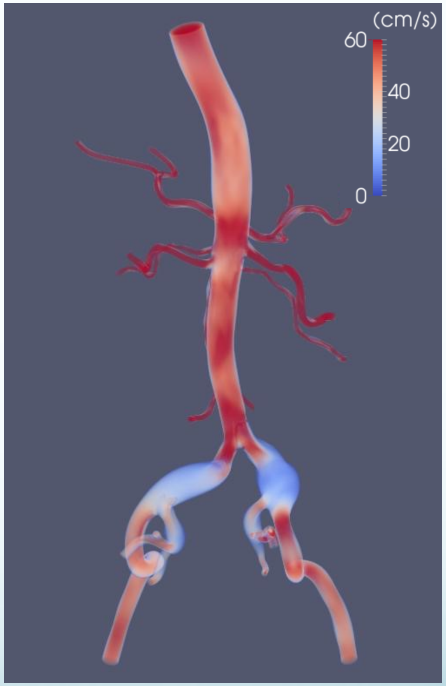
Introduction

SimVascular is an integrated software package that provides a complete pipeline from **medical image data** to **patient specific blood flow simulation.**

Medical Image



Simulation Result



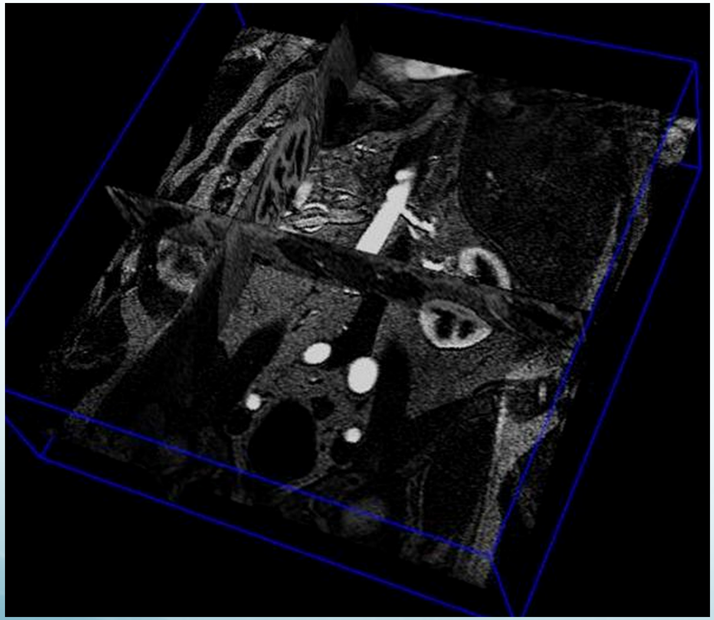
at peak systole

SimVascular Pipeline

Image Handling

Data are loaded from a variety of sources, including **DICOM, VTK and MetaImage** file formats. SimVascular offers a number of tools to view and manipulate the data in 2D/3D space, as slice planes and point clouds, or by volume rendering.

Slice Planes



Point Clouds

Volume Rendering

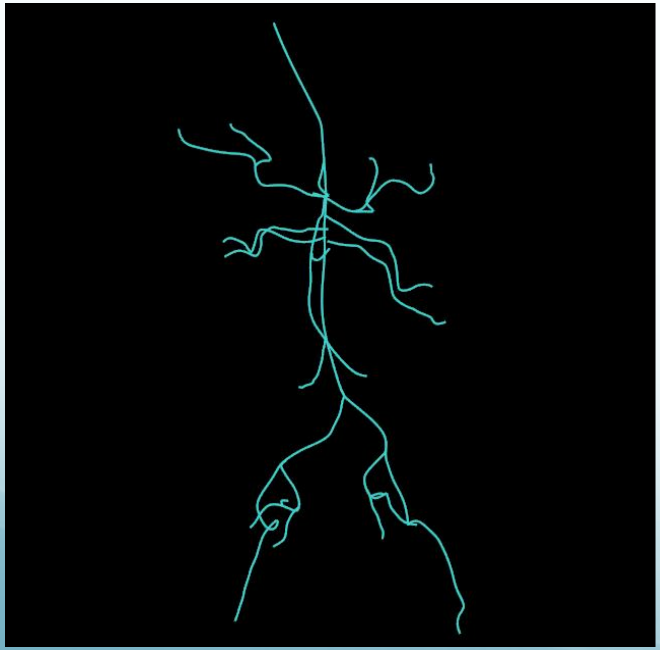
SimVascular www.simvascular.org

SimVascular Pipeline

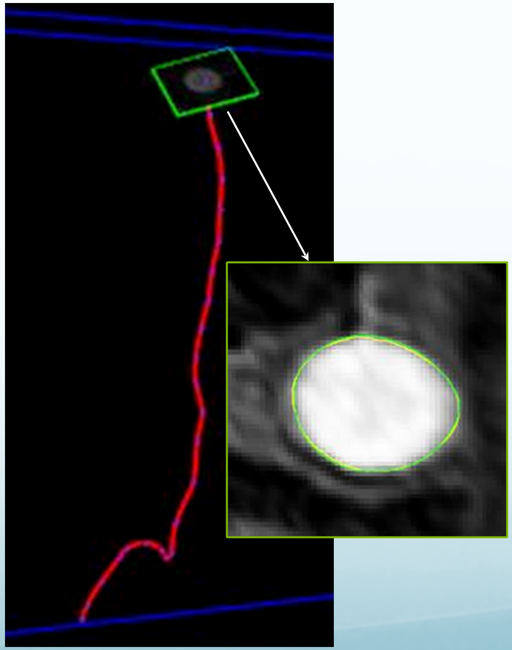
Path Planning and Image Segmentation

Users create vessel paths (centerlines) manually. SimVascular enables creating contours of the vessel lumen along the paths via **specialized segmentation tools** including level set, threshold, analytic fitting, etc. **Batch segmentation** is implemented for automated segmentation of an entire vessel with minimal user intervention.

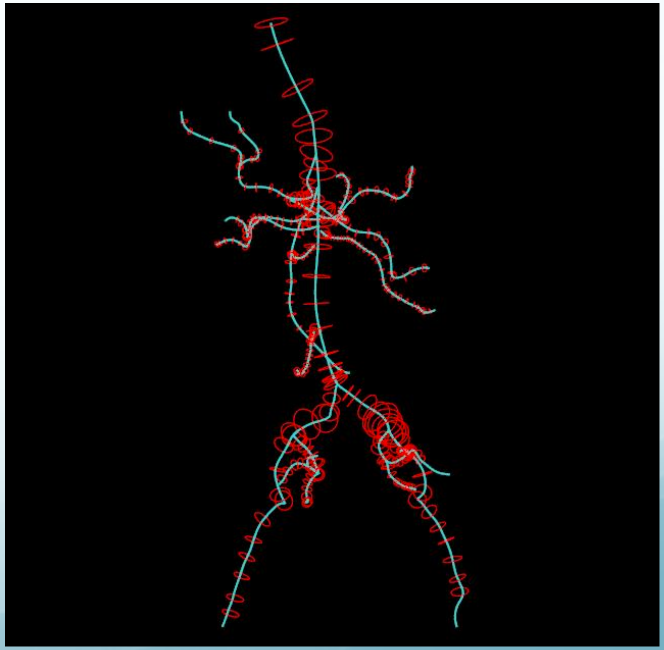
Vessel Paths



Defining a Contour



Segmentation Groups

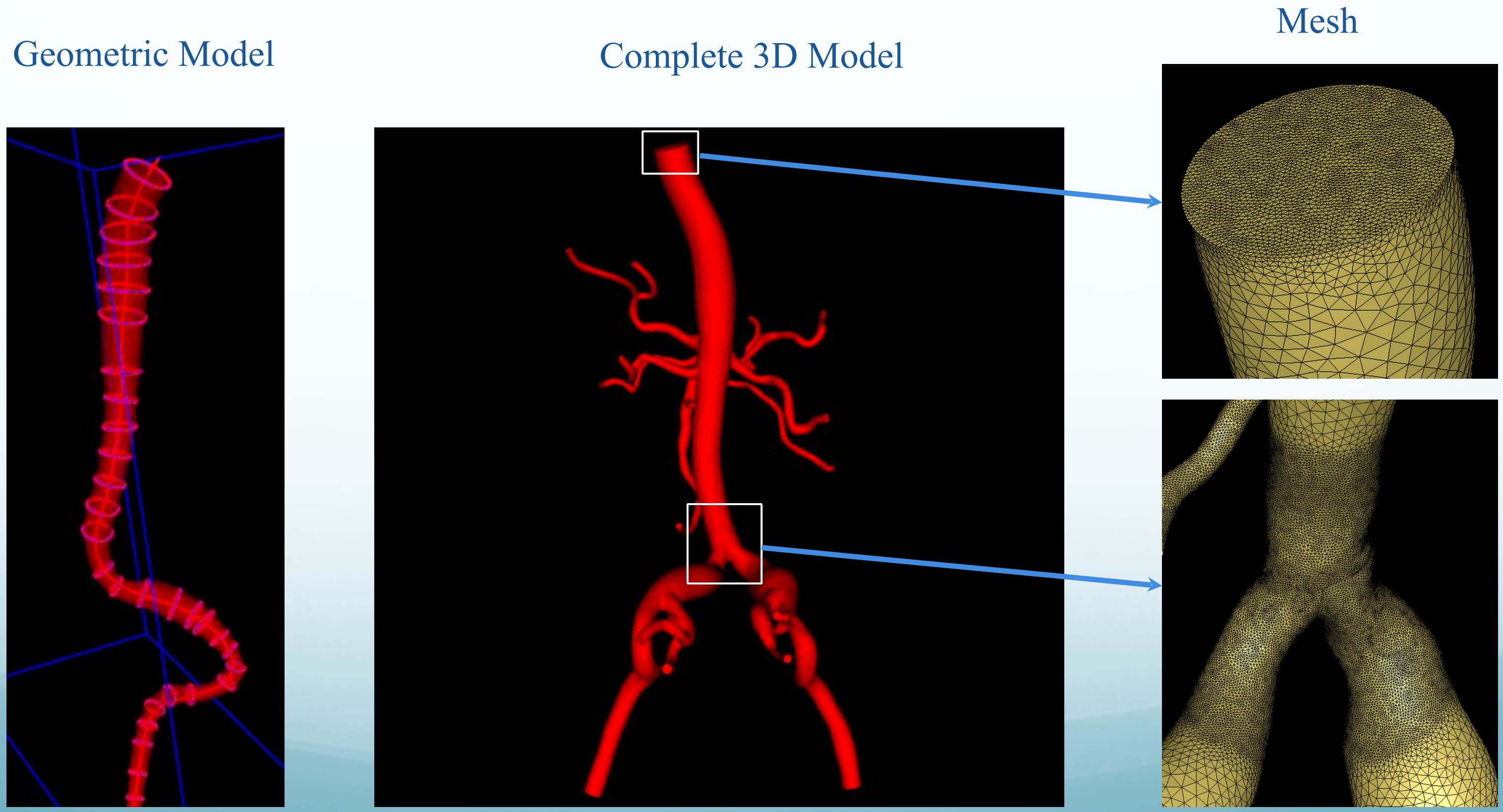


SimVascular Pipeline

Anatomic Modeling and Meshing

SimVascular enables a user to loft 3D geometric models for vessels and union them into a complete 3D model of the vasculature of interest.

It generates an unstructured mesh suitable for computational hemodynamics with **advanced options for local refinement** near selected surfaces, boundary layer meshing, spherical refinement.



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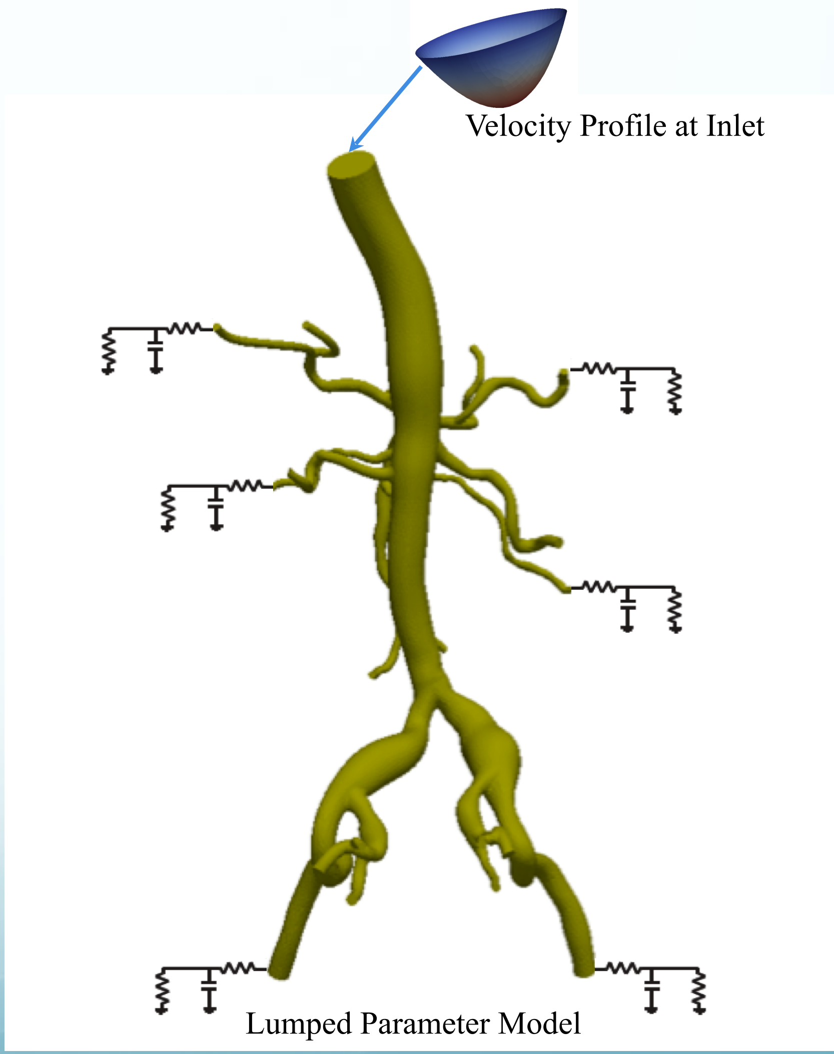
SimVascular Pipeline

Blood Flow Simulation

svPre can define time dependent flow rates or heart models for the inlet(s) and calculate initial wall displacement if vessels are deformable.

svSolver can couple the 3D Navier-Stokes solver to a **lumped parameter network** (LPN), creating multi-scale flow analysis without increasing computational cost.

svPost post-processes results to calculate relevant hemodynamic quantities and export results to VTK visualization files.



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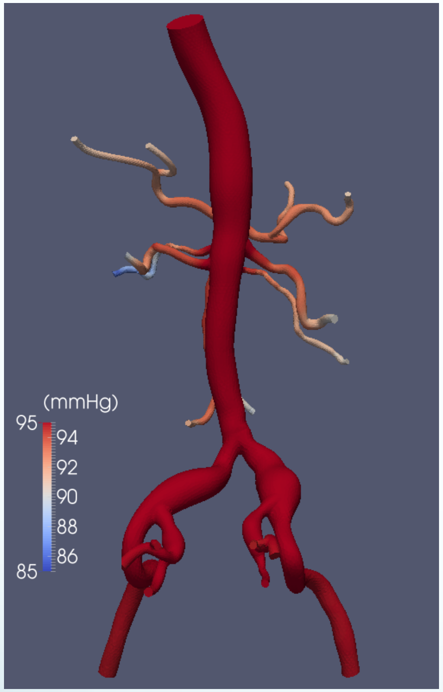
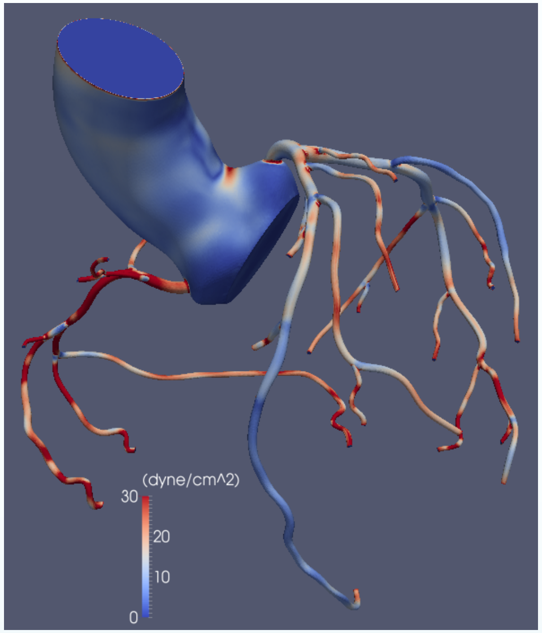
SimVascular Pipeline

Simulation Results

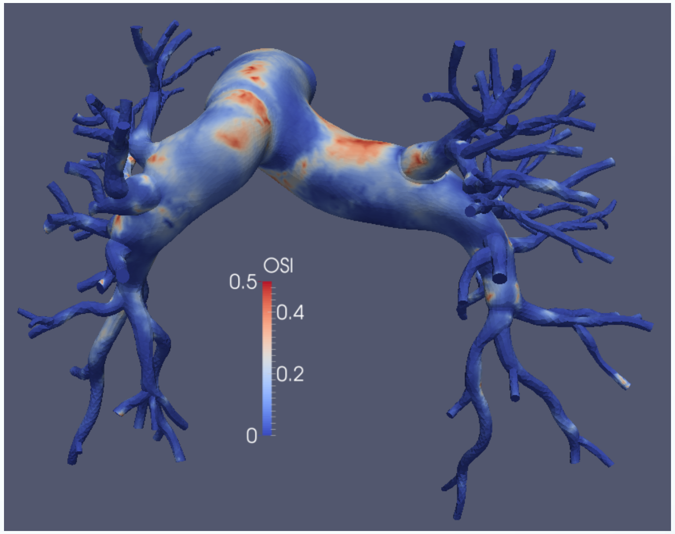
Time-averaged
Blood Pressure



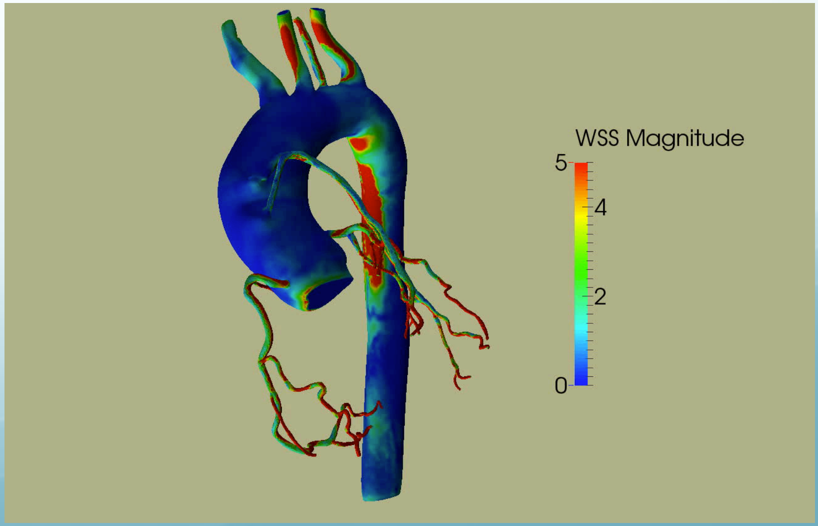
Time-averaged
Wall Shear Stress

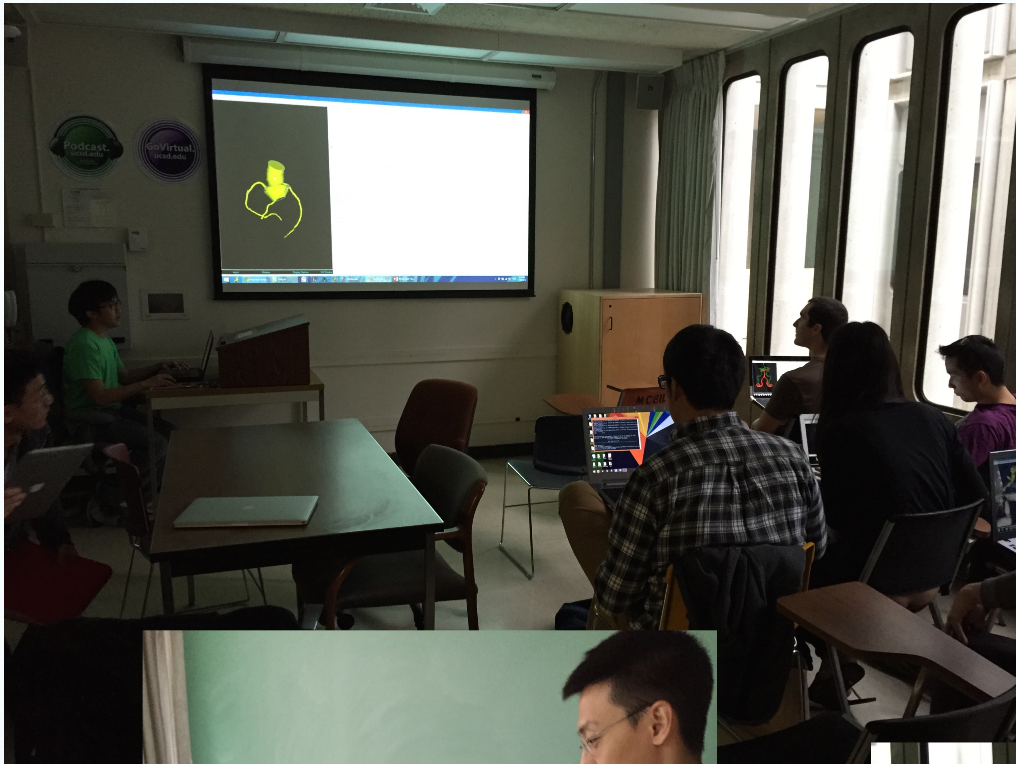


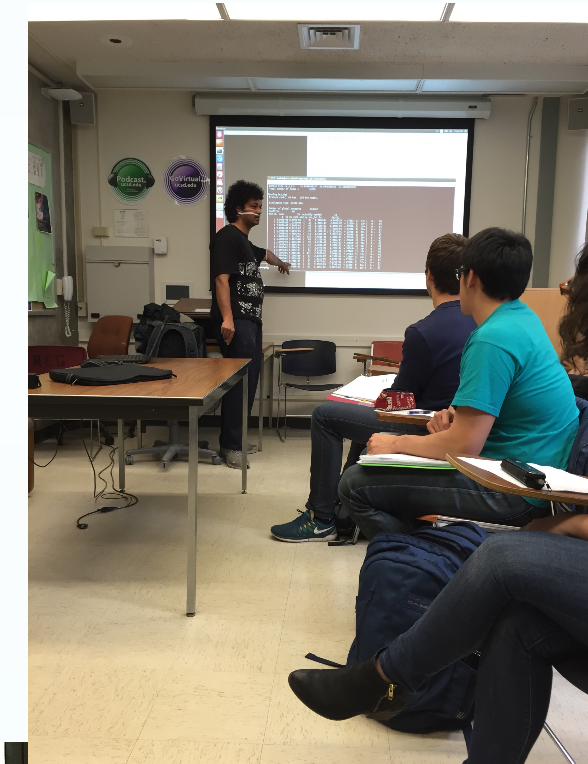
Oscillatory Shear Index



Deformable Wall







MAE 261 Final Project: Simulation of Blood Flow in a Stenosed Coronary Artery Bypass Graft using SimVascular

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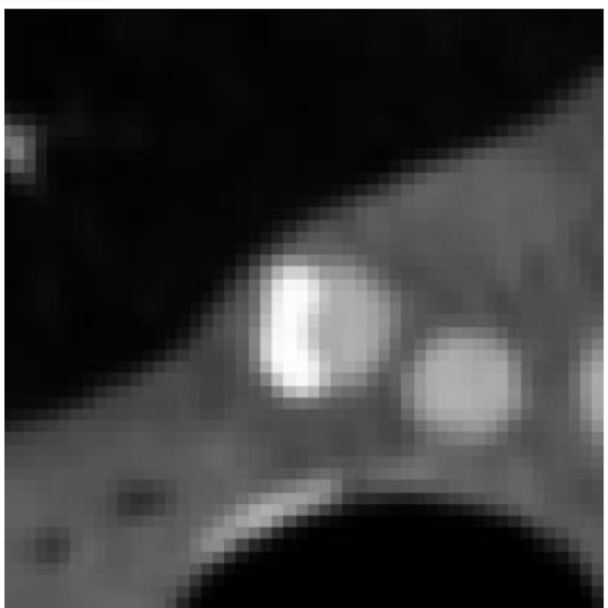
Professor Alison Marsden
MAE 261: Cardiovascular Fluid Mechanics
University of California, San Diego

March 16, 2015

Introduction:

Coronary Artery Bypass Graft (CABG) surgery is the gold standard for treating patients with advanced coronary artery disease. These patients struggle to get enough blood to their heart muscle due to blockages in the coronary arteries, and can lead to myocardial infarction if a coronary artery gets completely blocked. The surgery is performed over 400,000 times in the United States each year. The procedure involves using another blood vessel from the patient's



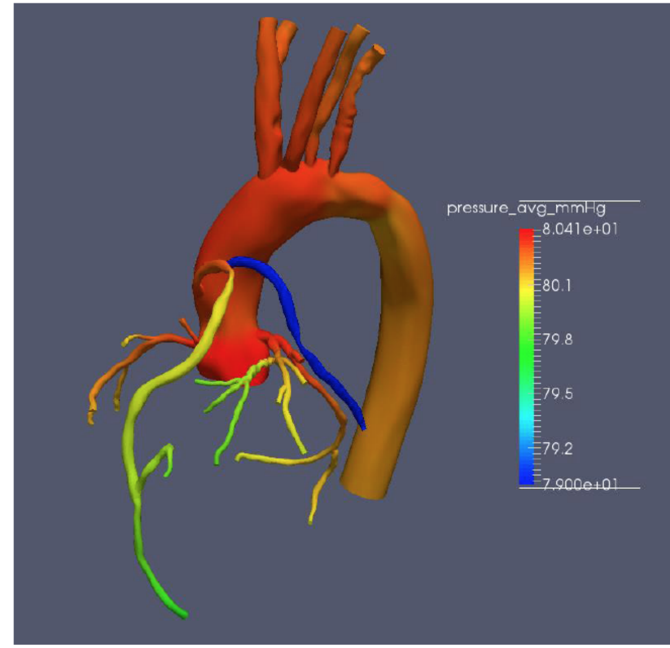


Figure 8: Pressure Distribution

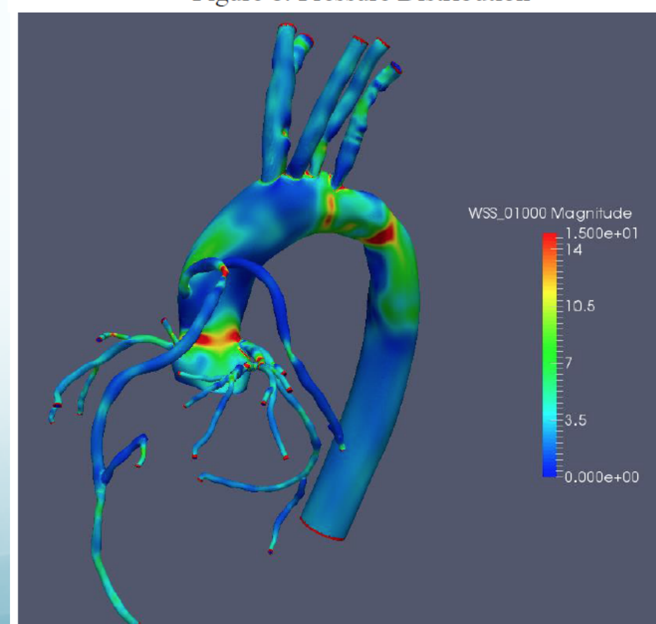
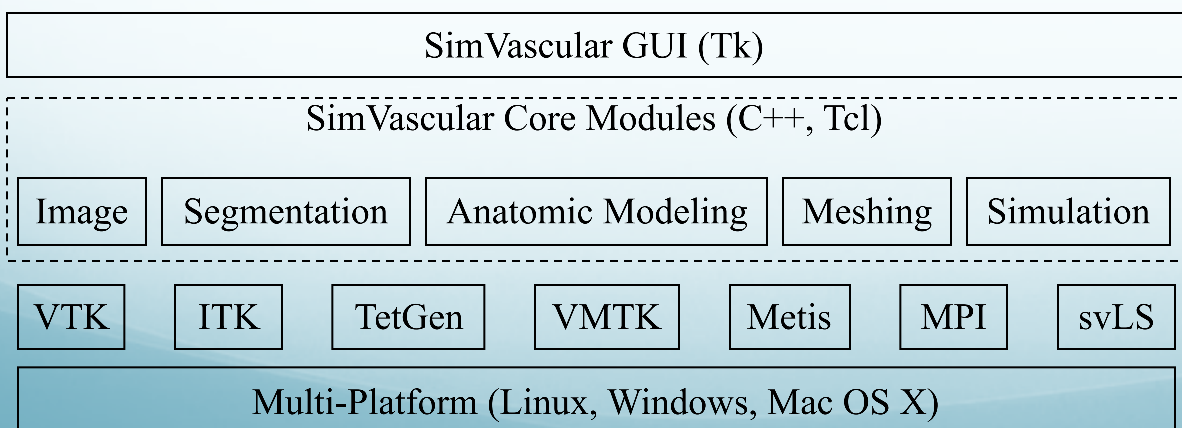


Figure 9: Wall Shear Stress Distribution

Advances of SimVascular 2.0

- Using CMake, it simplifies the compilation process and supports users across all major platforms:
- Fully open source by integrating open source alternatives, although continuing to support select commercial components.
- A fully integrated test suite has also been developed with continuous testing and nightly binary creation.
- An improved documentation website (www.simvascular.org) has been launched. It includes software guides and clinical case study examples.

Software Architecture of SimVascular 2.0



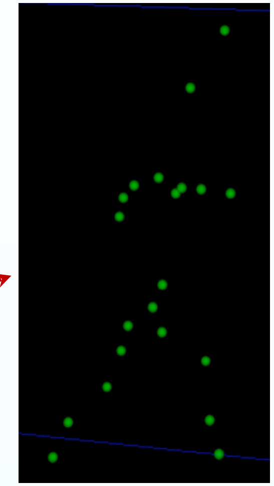
Open Source Alternatives

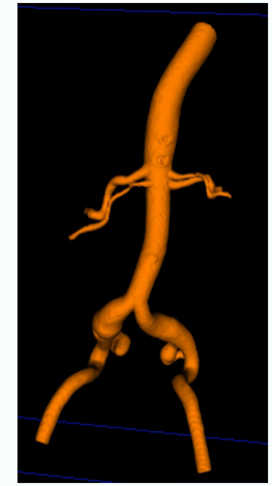
	Commercial	Open Source
Anatomic Modeling	*Parasolid*	*VTK*
Meshing	*MeshSim*	*TetGen*
Linear	*LesLib*	*svLS*

Advances of SimVascular 2.0

Image Segmentation

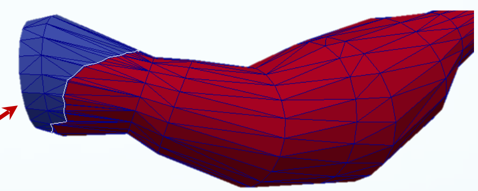
- More efficient algorithms to perform 2D image-based segmentation
- Can define 3-D segmentation for regions of interest

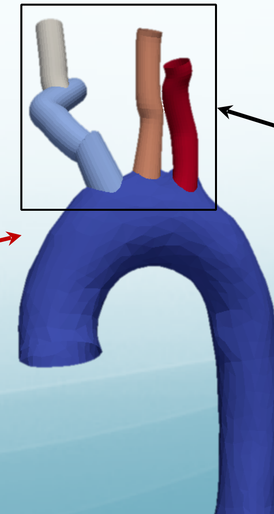




Anatomic Modeling

- Newly developed Boolean operation for discrete triangulated surfaces create the unified flow domain.
- This allows the capability to combine 2D and 3D image segmentation.





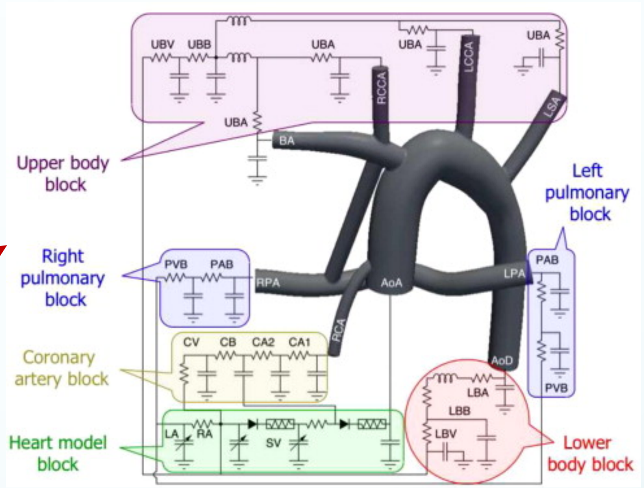
Advances of SimVascular 2.0

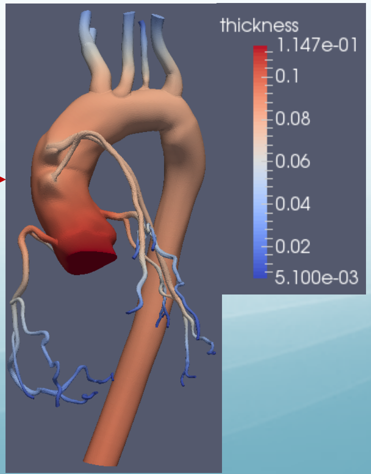
Meshing

Open source specialized meshing techniques for vascular structures with automated tools for complex geometries using Tetrahedral Mesh Generation (TetGen) and the Vascular Modeling Toolkit (VMTK).

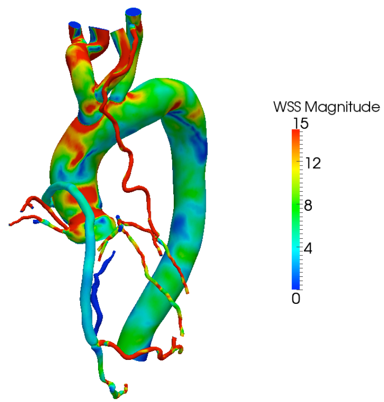
Simulation

- Back-flow stabilization
- Multi-scale coupling for closed loop boundary conditions
- Fluid structure interaction (FSI) for deformable vessel walls using the coupled momentum method (CMM)
- Variable wall properties (thickness, elastic modulus)

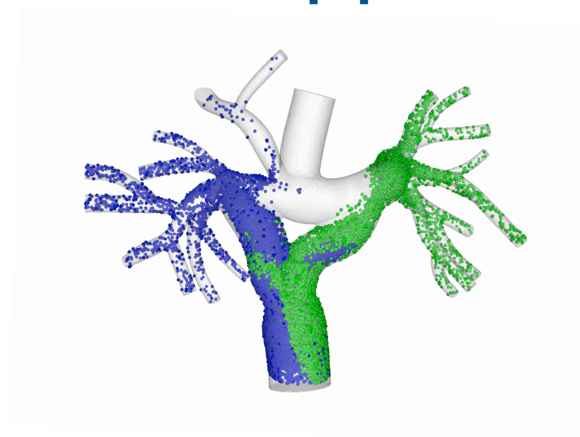




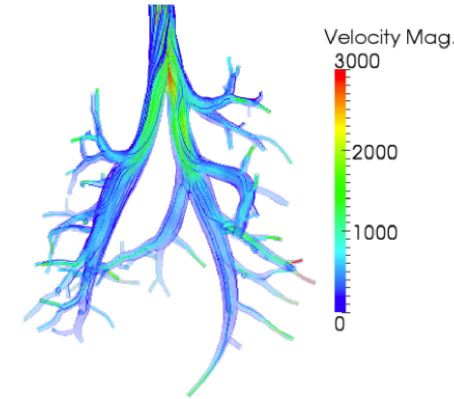
Clinical Applications



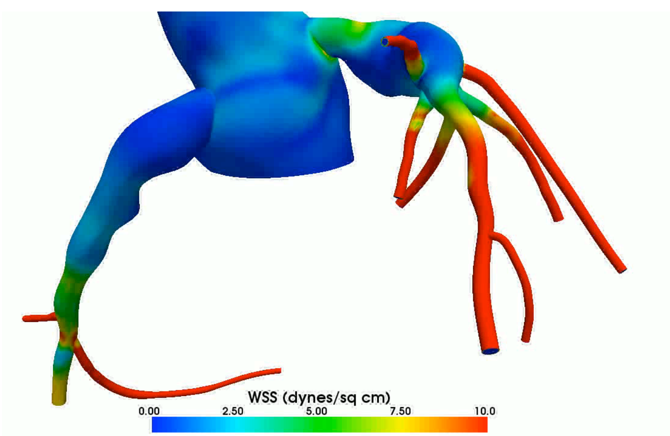
Coronary Artery Bypass Grafts



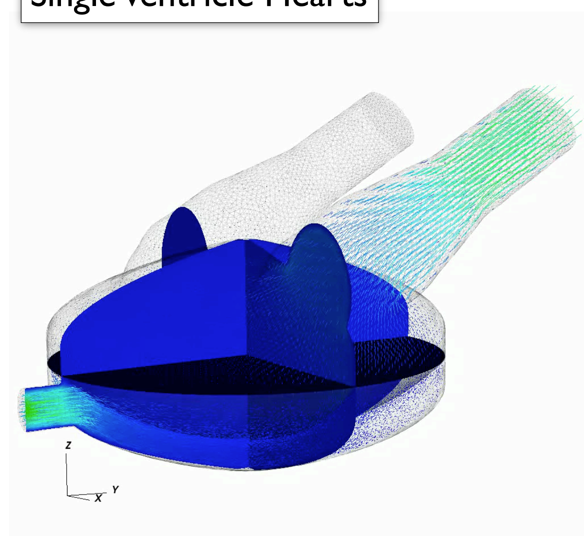
Single Ventricle Hearts



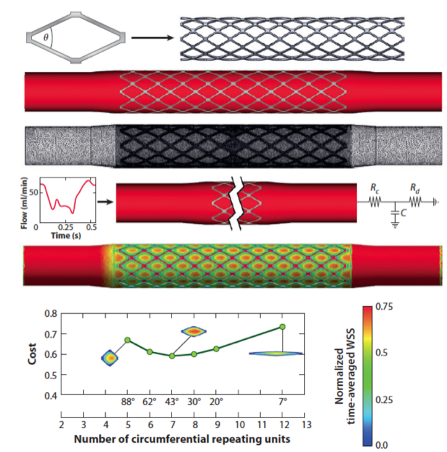
Respiratory Fluid Mechanics



Kawasaki Disease



Ventricular Assist Devices



Stent Optimization

Future Work

- Improving workflow and user experience with the development of a new graphical user interface (GUI) based on modern cross-platform toolkits.
- Enhancing anatomic model construction including new 3D image segmentation and machine learning methods.
- Additional modularity of the software to enable users to add their own plugins and modules (including commercial components) to extend SimVascular's functionality.
- The integration of an optimization module to enable users to automate device design and perform virtual surgical planning.
- **Continued use in graduate education as a mechanism for exposing students to HPC and computational fluid dynamics.**
- **Education for medical students.**

SimVascular www.simvascular.org

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Collaboration:

UCSD Jacobs: Dr. Alison L. Marsden's Lab
Cardiovascular Biomechanics Computation

Berkeley University of California: Dr. Shawn C. Shadden's Lab
Theoretical and computational methods to quantify complex fluid flow

OSMSC: Open Source Medical Software Corporation
Dr. Nathan M. Wilson

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SimVascular

Thank you!

Welcome to visit www.simvascular.org