Computational Challenges in Cardiovascular Fluid Mechanics

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History

Thomas Young 1773 – 1829

Both a practicing physician and professor of physics

Other early students of blood circulation:

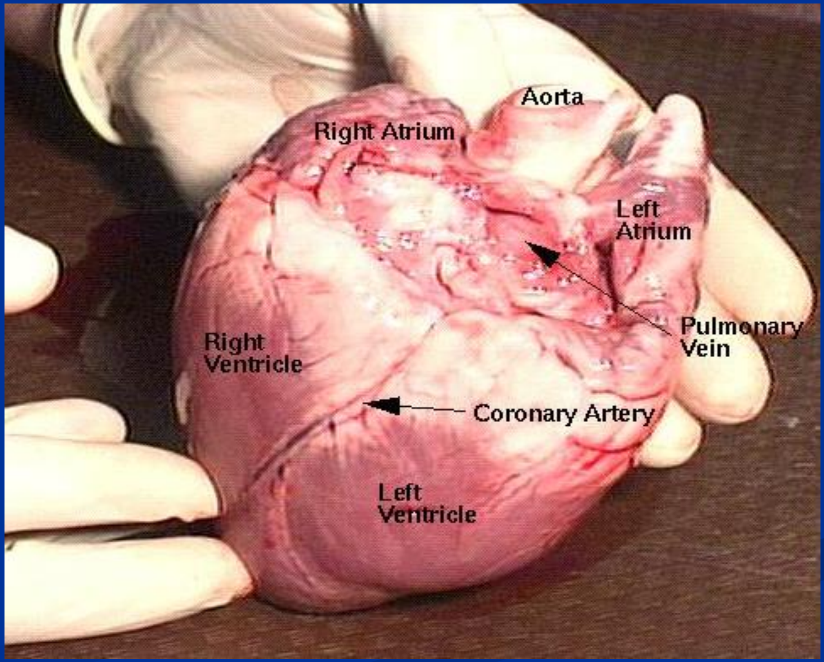
Borelli, Hales, Bernoulli, Euler, Poiseuille, Helmholtz, Fick, …

As science developed, so did specialization and the study of the cardiovascular system became separated from physical science.*

*CG Caro, TJ Pedley, RC Shroter, WA Seed; The Mechanics of Circulation; Oxford University, 1978

The Cardiovascular System

- Three Major Elements – Heart, Blood Vessels, & Blood
  - The Heart - cardiac muscle tissue
  - Pumps blood throughout the body
  - Four chambers
    - Right atrium
    - Right ventricle
    - Left atrium
    - Left ventricle

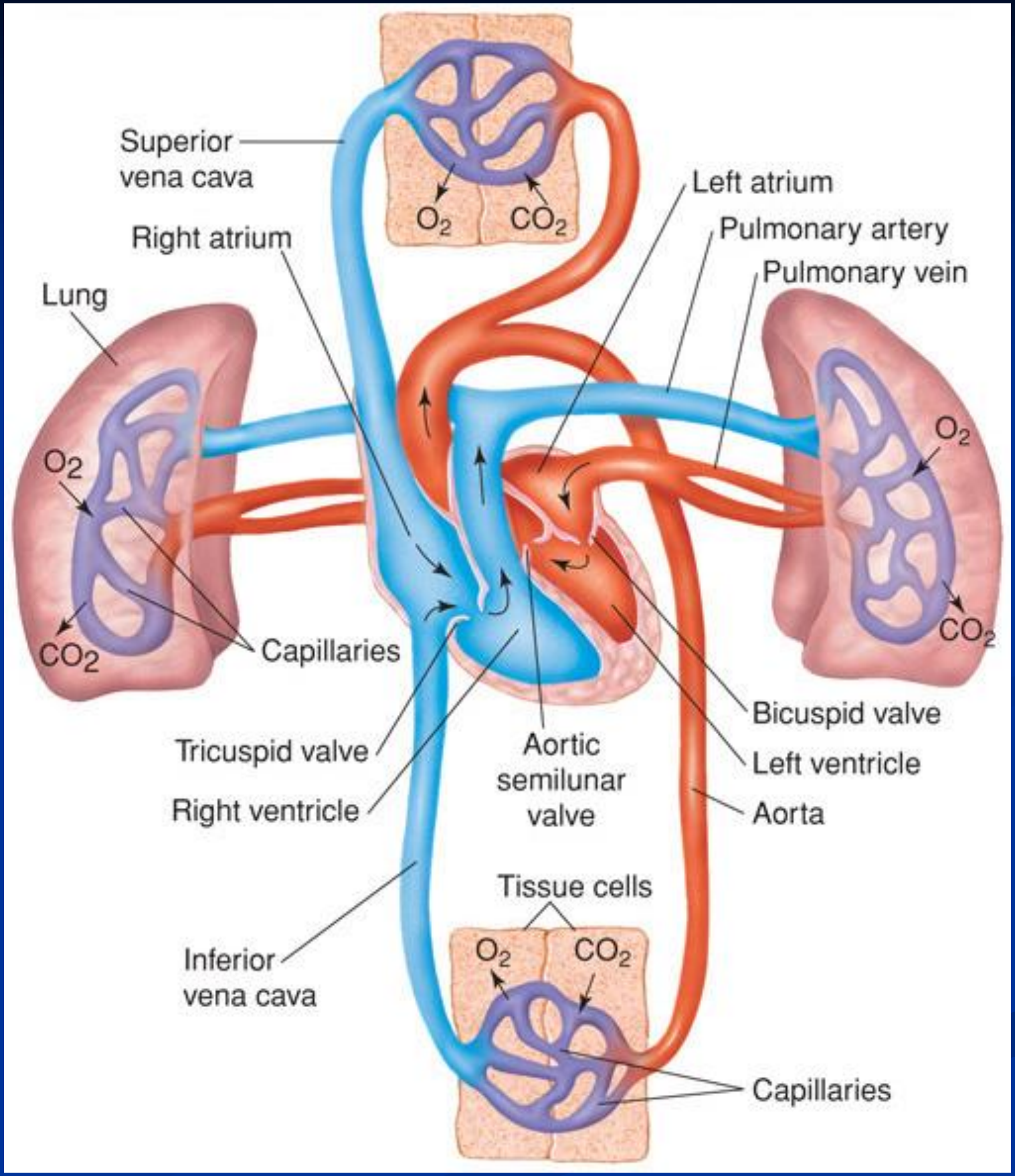


Circulation

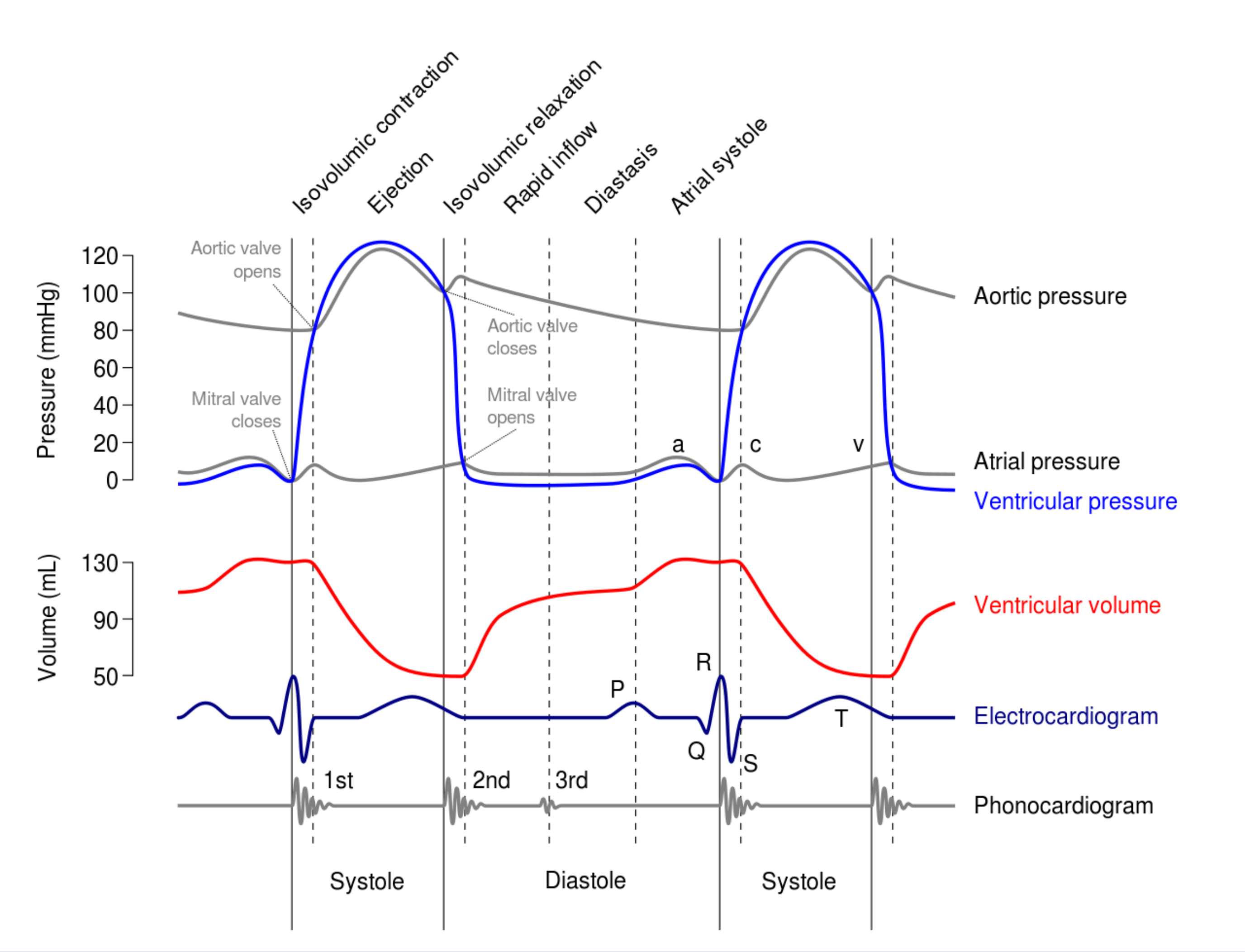
<u>Pulmonary circulation</u>: path of blood from right ventricle through lungs and back to heart

<u>Systemic circulation</u>: path of blood from left ventricle to body and back to heart

<u>Rate</u> of flow through systemic circulation = flow rate through pulmonary circulation



Cardiac Cycle



The Fluid: BLOOD

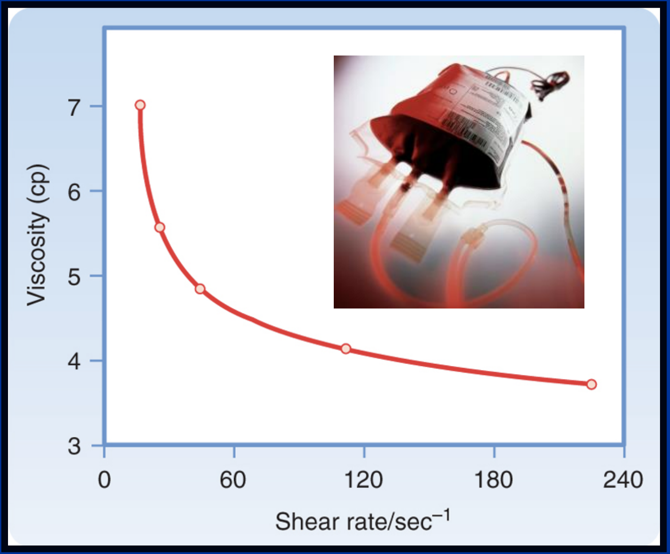
Whole blood ~7% of human body weight:

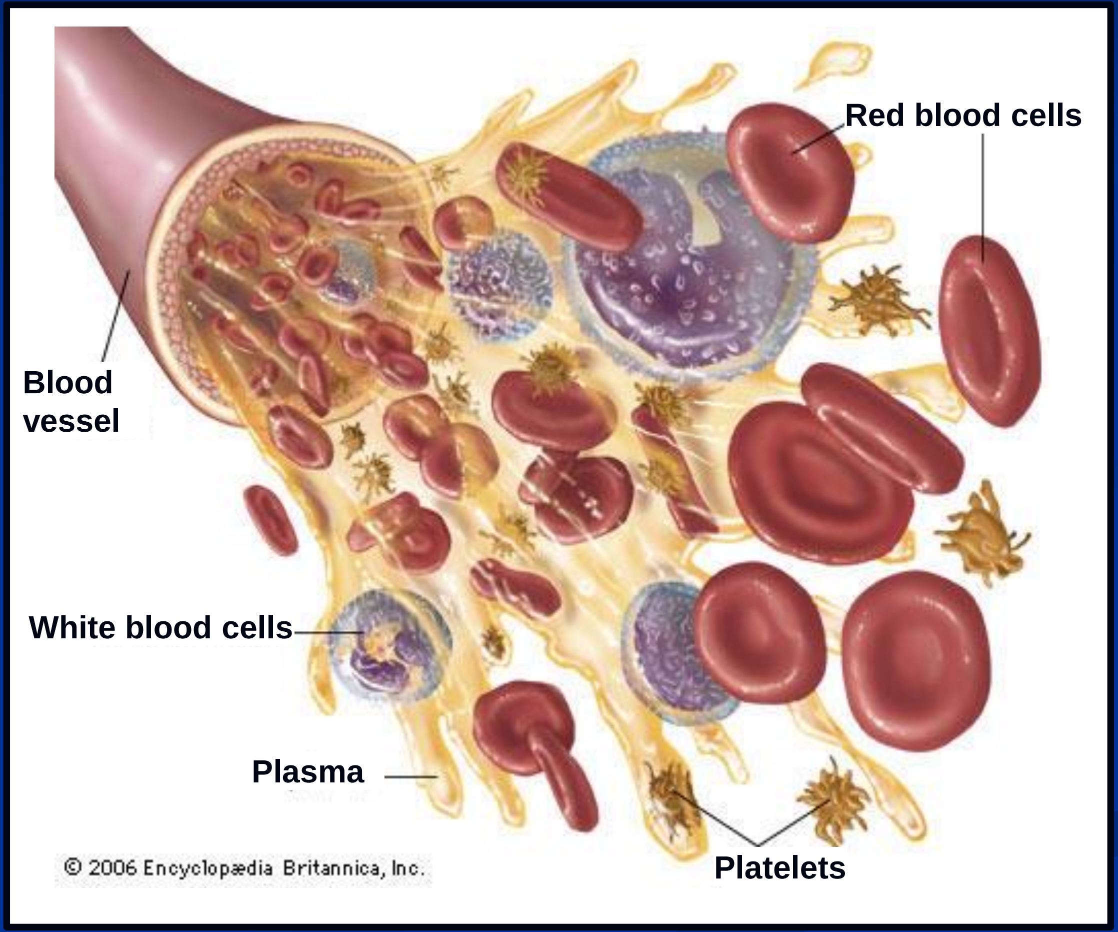
~45% Red blood cells

~2% Platelets

~1% White blood cells

~52% Plasma





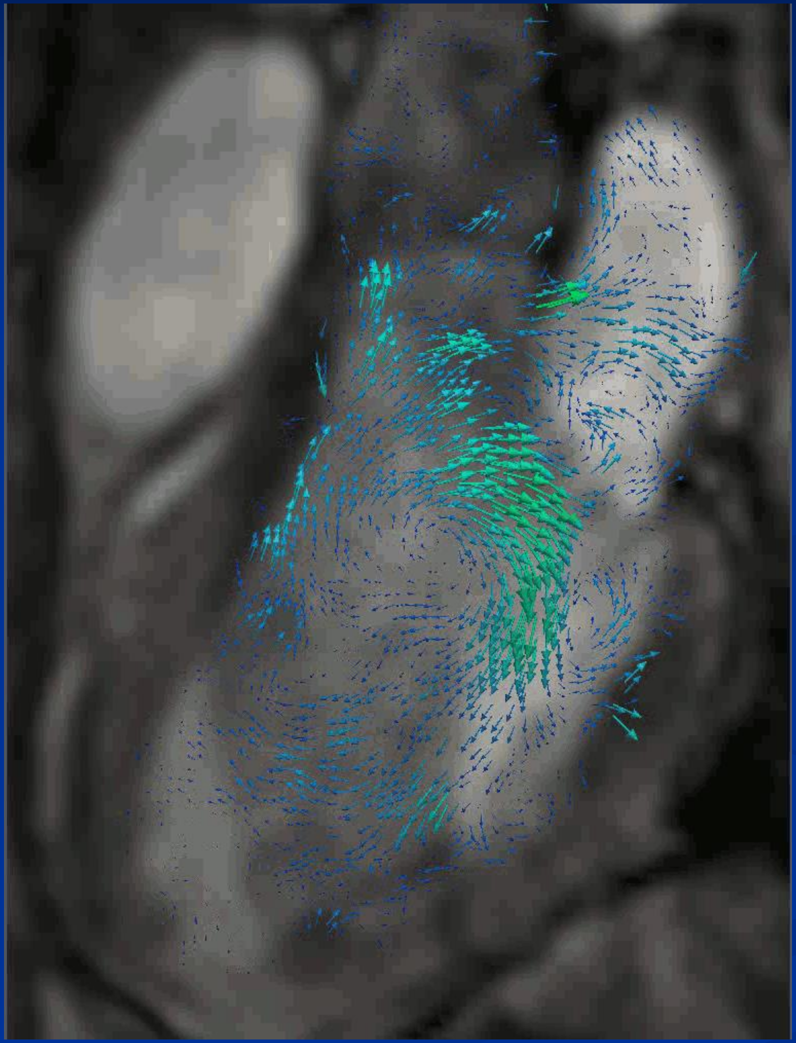
Cardiovascular Flows

- Pulsatile (periodic) flows: heart rate dependent – Womersley #
- Internal (confined; undeveloped) flows
- Moving visco-elastic boundaries (chamber /vessel walls; heart valve leaflets)
- Non- Newtonian (two phase with deformable elements)
- Multi-scale (100 mm to 1 micron)

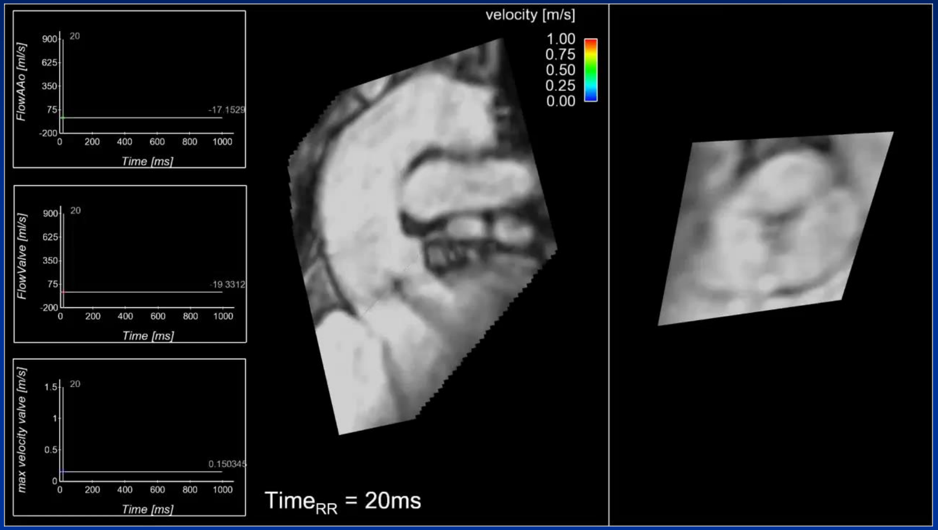
Cardiovascular Flows

- Multi-scale
- Laminar flows: Peak Re~6000 (non-diseased resting states – peak vel ~1.2 m/s; dia ~25mm)
- Transition to low Re turbulent (peak ~ 30,000) flows (exercise and/or diseased states - vel ~5m/s)
- Very low Re flows in capillaries: ~ 0.001 (two phase with deformable elements; vel ~1mm/s; dia 10 micron)

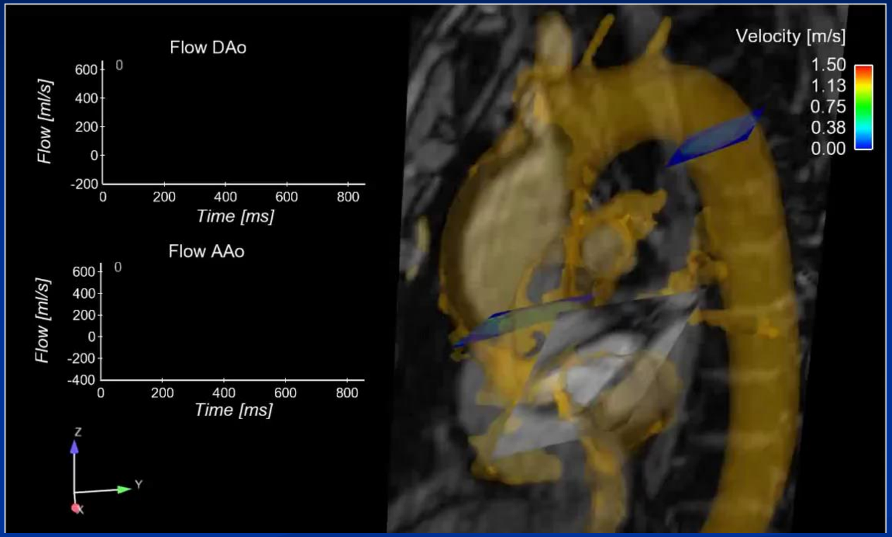
2D PCMR – Healthy Human LV



Identifying Features of BAV



Trileaflet

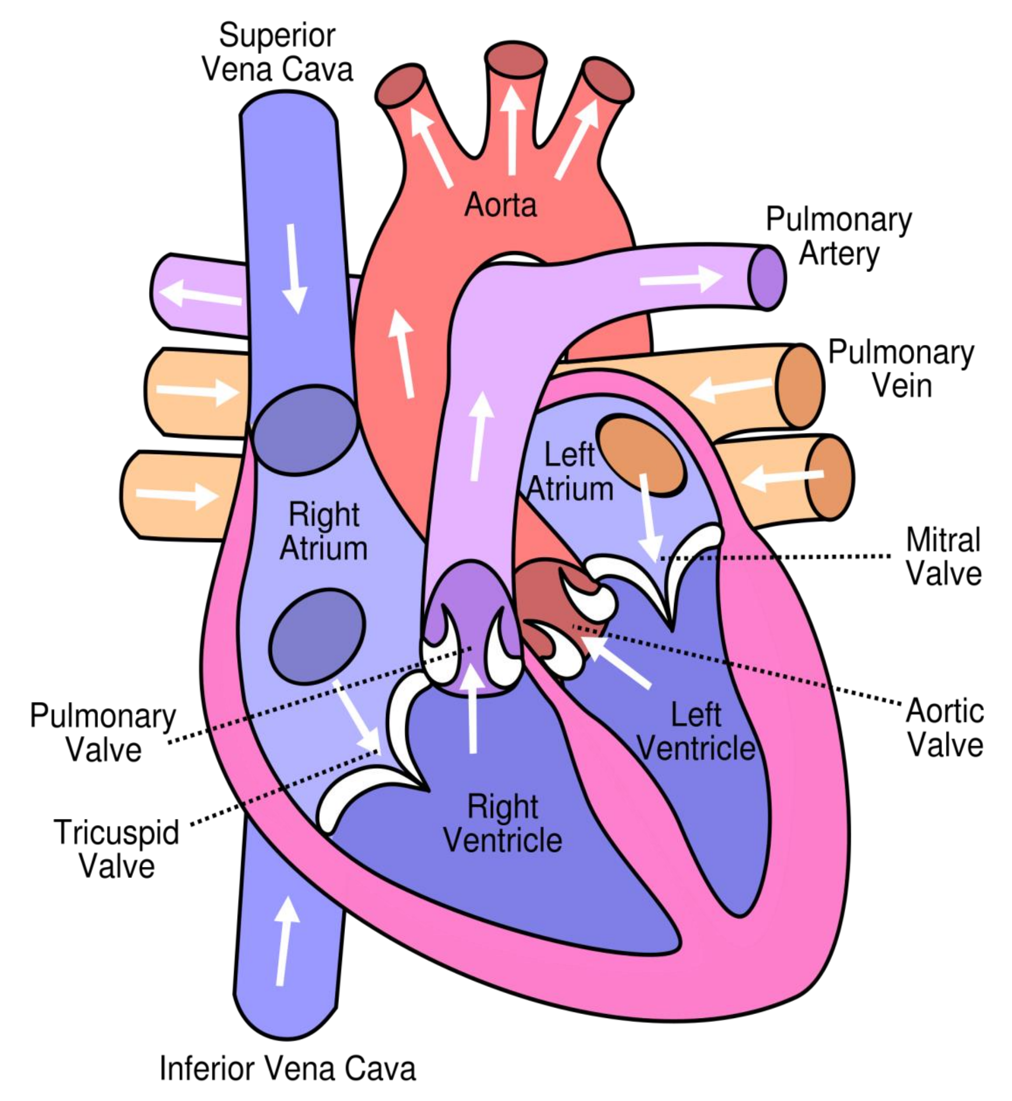


Bileaflet

Courtesy of Northwestern Radiology

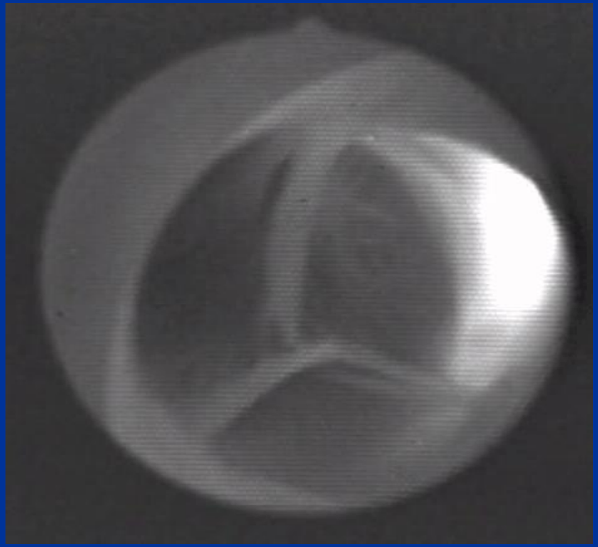
Heart Valves

- Aortic valve
  - Lies between left ventricle and aorta
- Pulmonic valve
  - Lies between the right ventricle and pulmonary artery
- Mitral valve
  - Lies between left atrium and ventricle
- Tricuspid valve
  - Lies between right atrium and ventricle

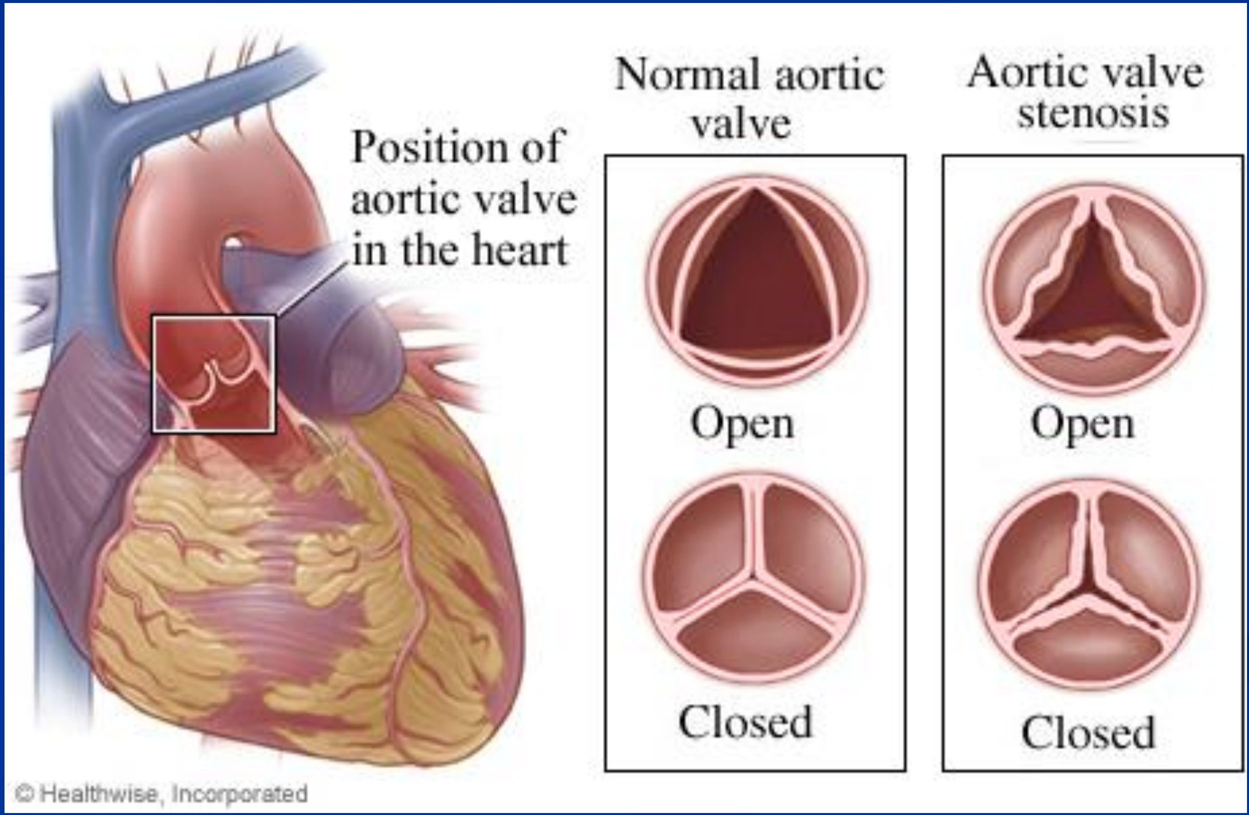


Heart Valves

- Heart valves maintain unidirectional blood flow in the heart
  - Open and close passively due to pressure differential
- Native heart valves may malfunction due to congenital birth defects or disease
  - Valve stenosis (narrowing of valve area) or regurgitation (unwanted backflow through closed valve)



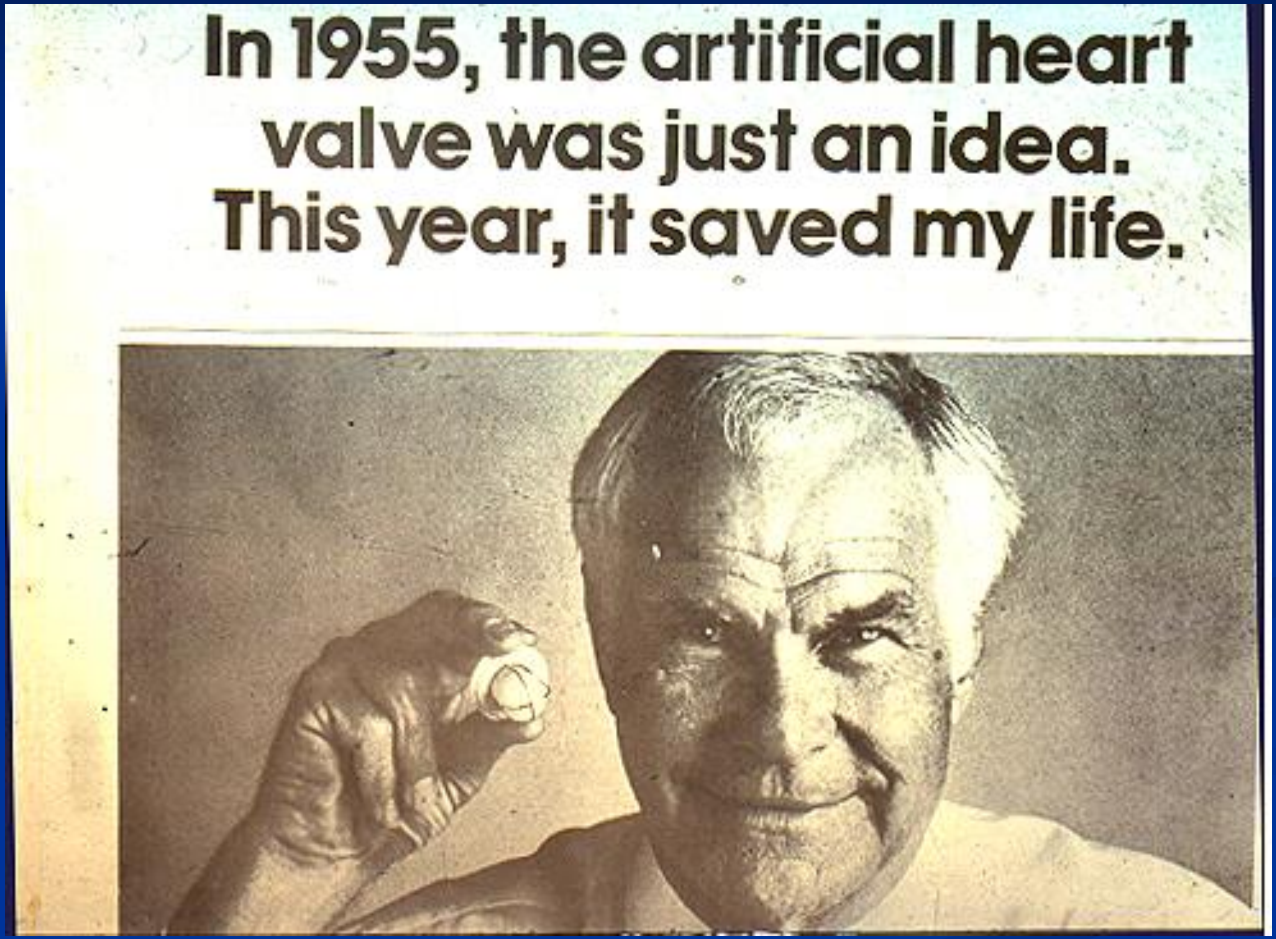
Aortic Valve



Heart Valve Disease

- Heart disease is leading cause of death in developed nations
- In US, 2.5% of population has heart valve diseases
- In developing countries, 2.3% of children have Rheumatic Heart Disease
- 1% of population are born w/bicuspid aortic valves → early calcification of valves

Six Decades of Progress, but….



Serious Problems and Complications Associated with Prosthetic Heart Valves

Mechanical Valves

- Thrombosis and thromboembolism
- Anticoagulation related hemorrhage
- Red cell damage and hemolysis
- White cell damage
- Tissue overgrowth
- Damage to endothelial lining of vessel walls in the vicinity of the prosthesis
- Leaks caused by failure of valve to close properly
- Infection
- Tearing of sewing sutures

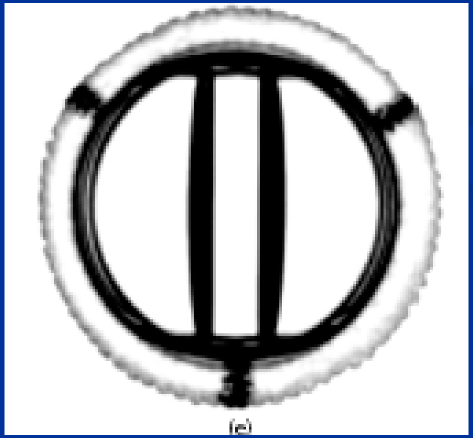
Bioprosthetic Valves

- Calcification of Valve
- Adverse immune reaction
- Structural failure / Wear and tear
- Perivalvular and paravalvular Leakage
- Tisue overgrowth
- Infection
- Tearing of sewing sutures

The Bileaflet Mechanical Valve

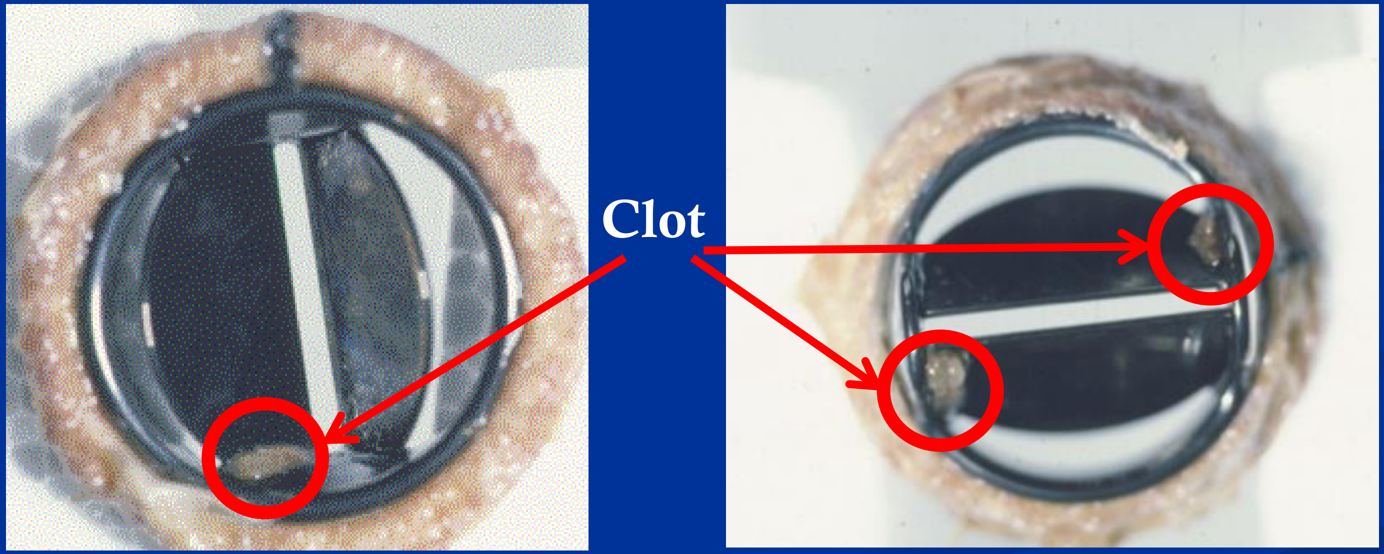
- Trend of implantation:

  55% bioprosthetic valves vs 45% mechanical valves
- The bileaflet mechanical valve design is the valve of choice (>90% of implantation)



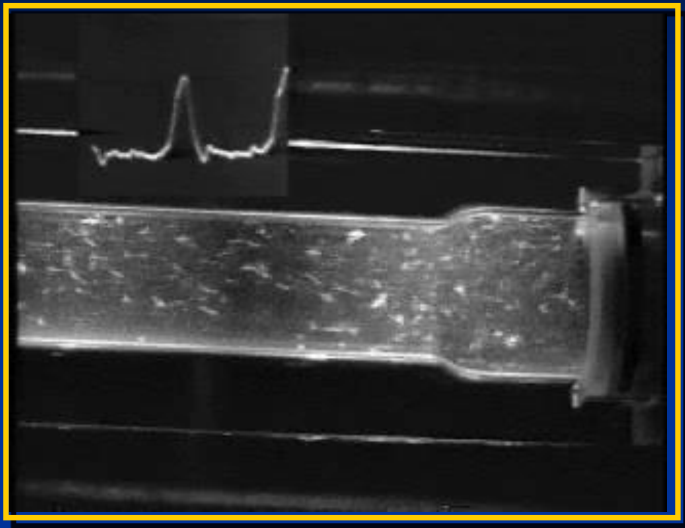
BMHV Complications

- Despite evolution and advantages of BMHVs, complications are known to exist
- Major complications are platelet activation and thromboembolic events
  - Clot formation and detachment
- Clot formation in BMHVs have serious consequences
  - Experiments have shown restriction of normal motion of leaflets due to thrombus[1]
  - Detached emboli may lead to vessel occlusion – resulting in stroke or death

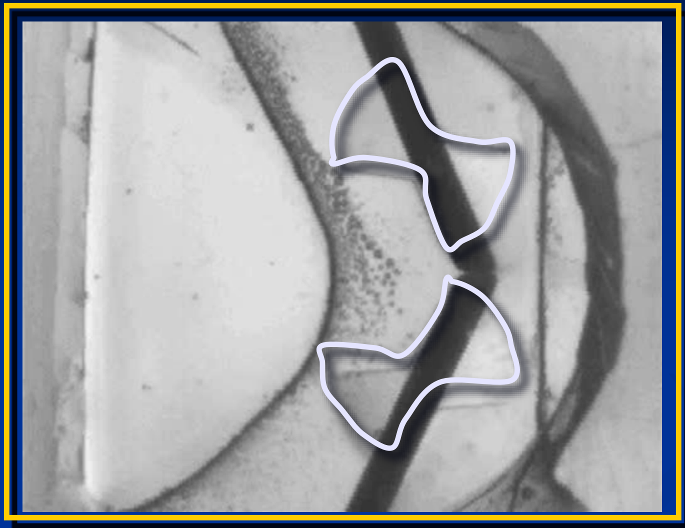


[1] Baumgartner *et al.*, *Circulation*, 1993.

Flow Characteristics through BMHVs



Large scale features



*

Small scale features

- Pulsatile, turbulent flow
- Complicated geometries and flow fields
- Moving objects / Fluid structure interactions

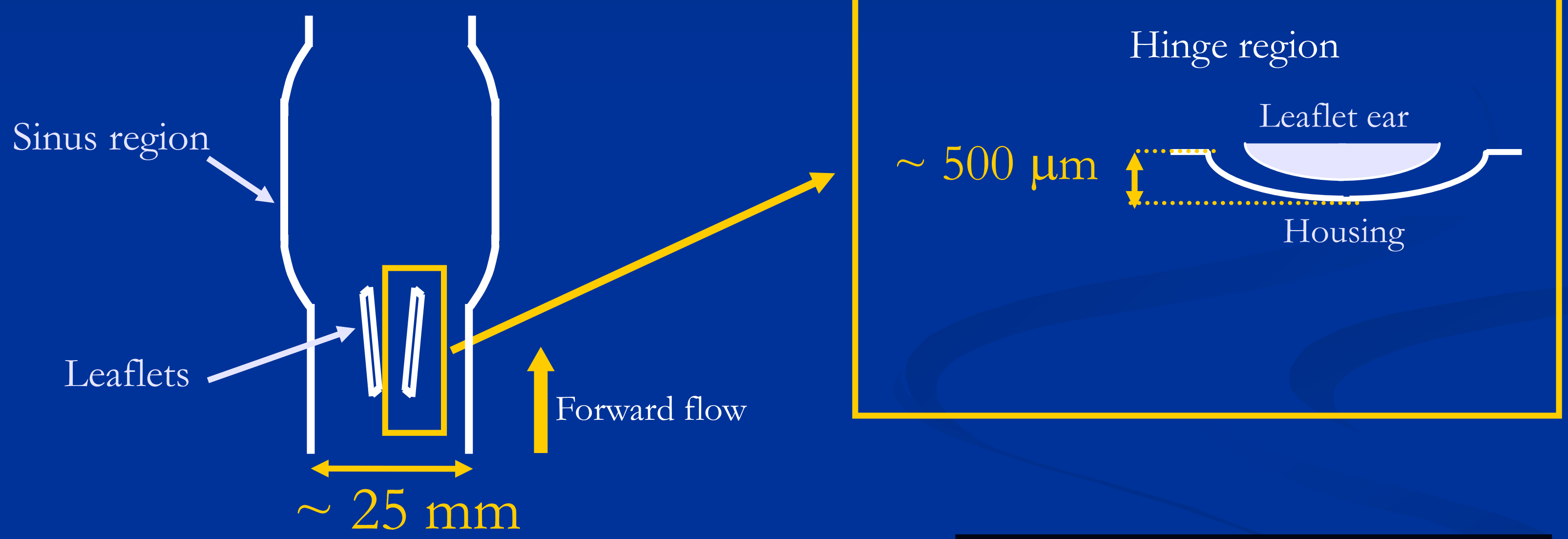
- Flow through narrow gaps
- Complex 3D vortical structures and regurgitation jets

* Courtesy: Medtronic Inc.

Overall Multi-Scale Approach

Numerical Approach

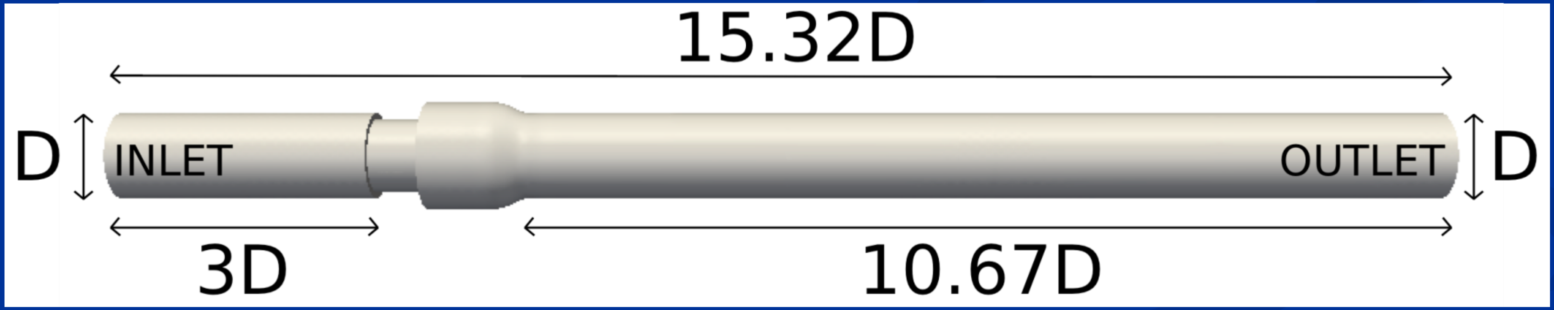
	BULK FLOW	HINGE FLOW
Numerical Approach	Large scale CFD solver	**Micro scale CFD solver**
Experimental Approach	Particle Image Velocimetry	Particle Image Velocimetry/Laser Doppler Velocimetry



Experimental Approach

Single-Phase Flow Validation

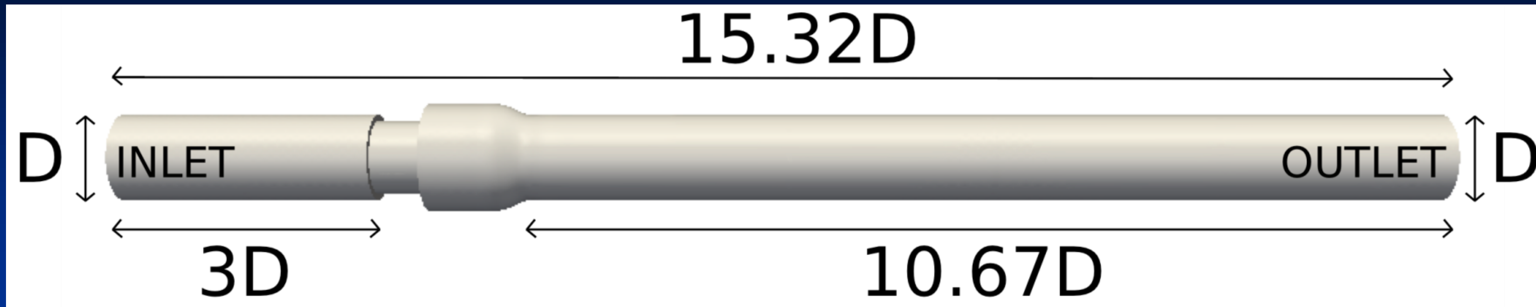
- Model single-phase fluid flow through 23mm St. Jude Medical (SJM) valve
  - In aortic position
- Results compared to experimental Particle Image Velocimetry (PIV) data of flow through an *in vitro* flow loop[1,2]
  - Used blood analog fluid, same kinematic viscosity as whole human blood ($3.5e^{-6}$ m^2/s)
- Compare axial velocity for steady and pulsatile flow valve (mean flow)
  - Re = 750 for laminar regime and Re = 5000 for turbulent regime for steady flow
  - Compare mean flow fields and RMS values for pulsatile flow
- Compare instantaneous vorticity contours for pulsatile flow through valve

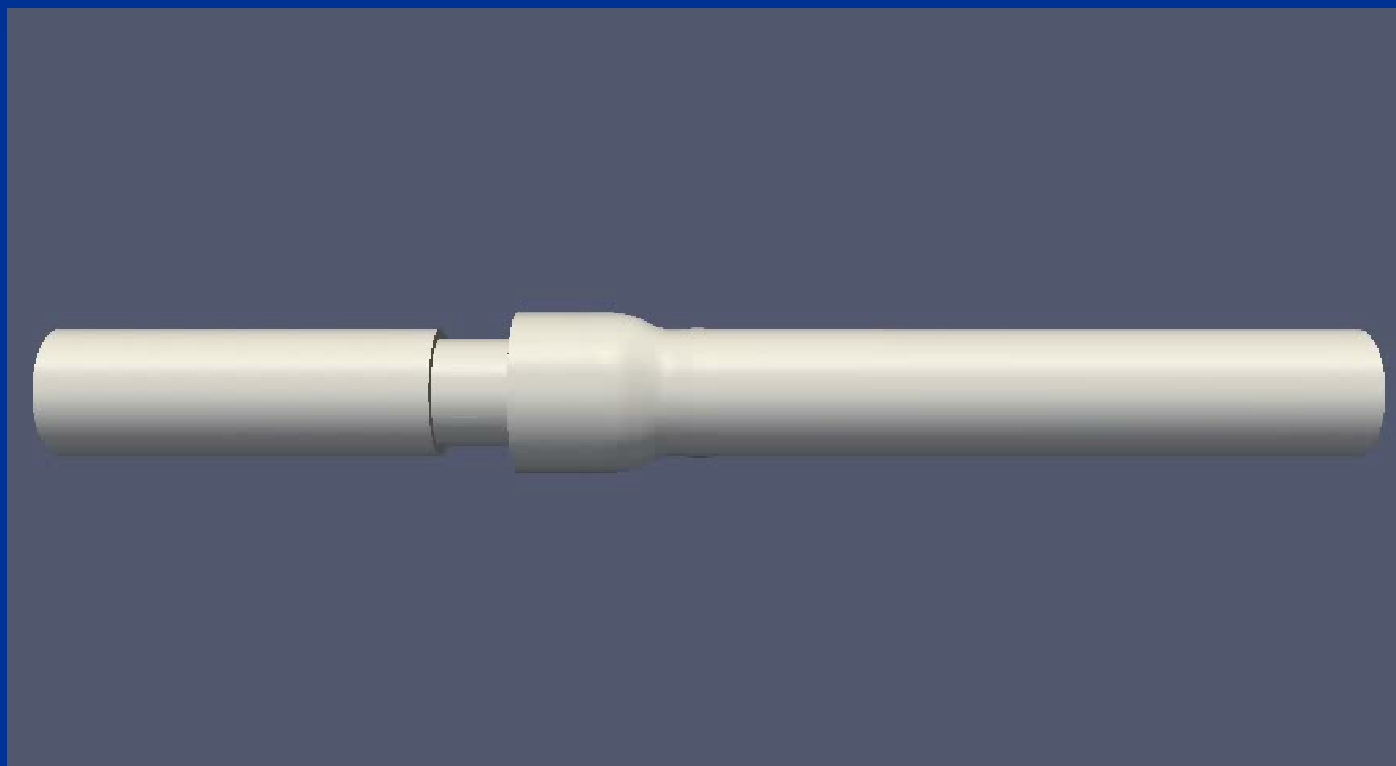


Computational model of experimental *in vitro* flow loop setup

[1]Ge *et al.*, *Journal of Biomechanical Engineering*, **2005**.
[2]Dasi *et al.*, *Physics of Fluids*, **2007**.

SJM Valve Computational Geometry





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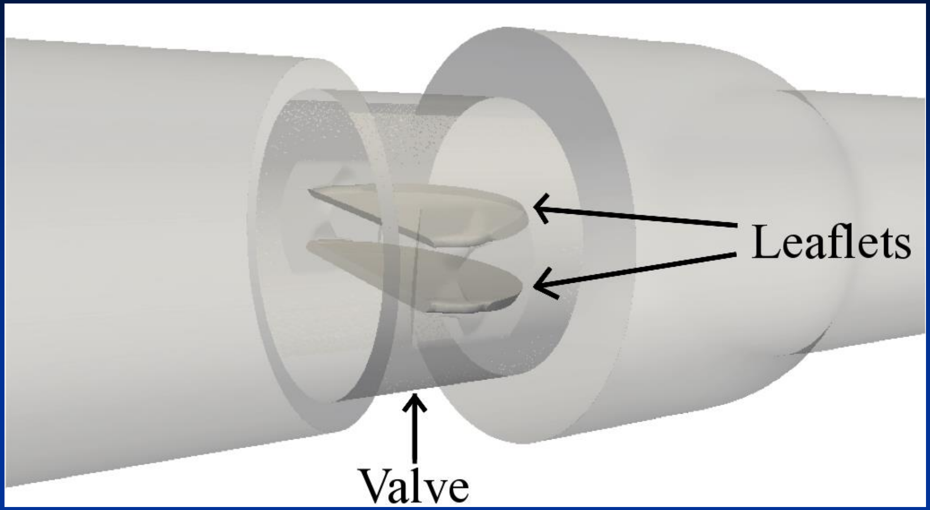
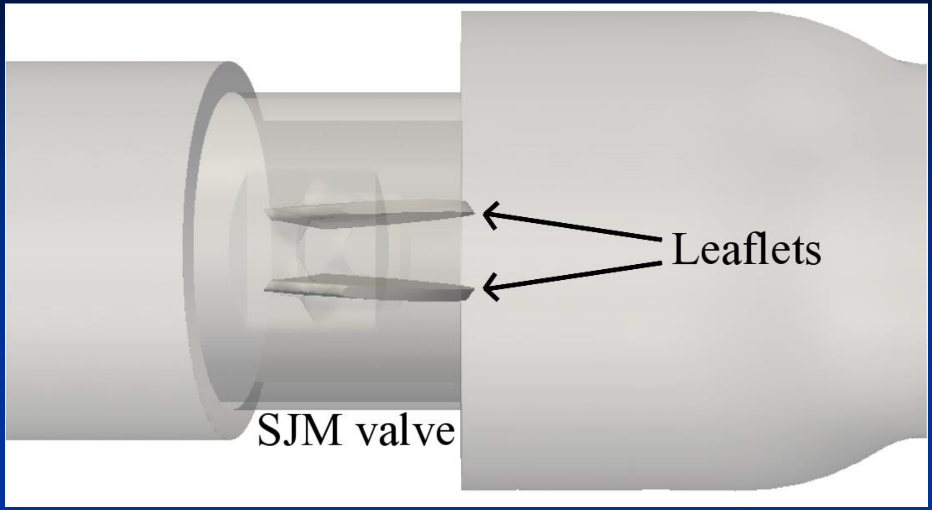
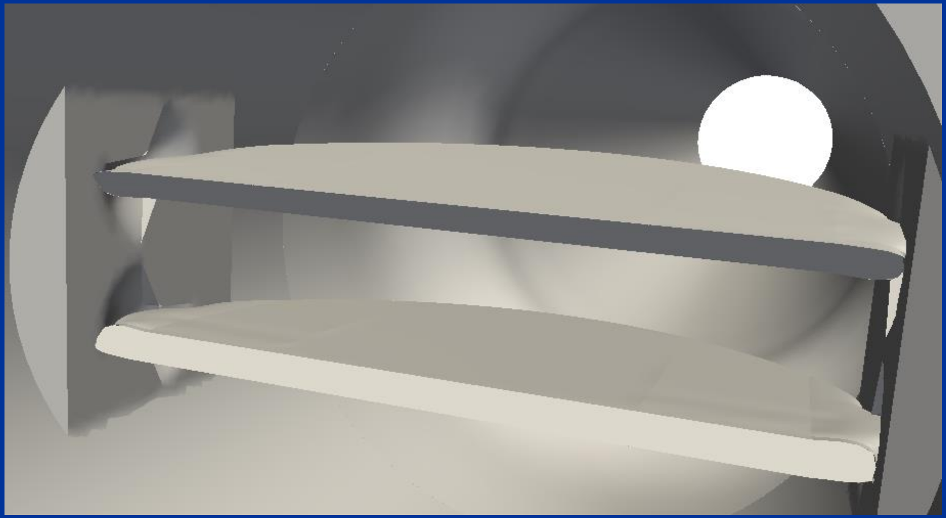
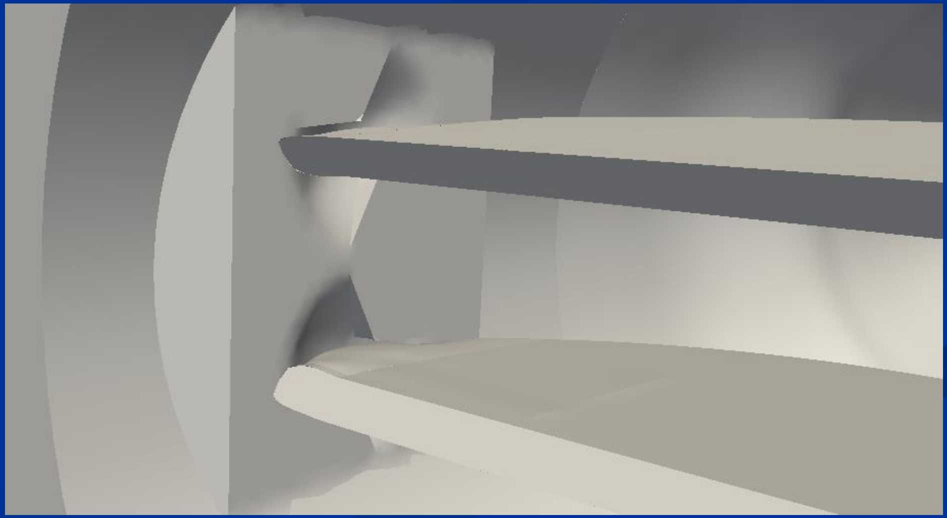
SJM Valve Computational Geometry





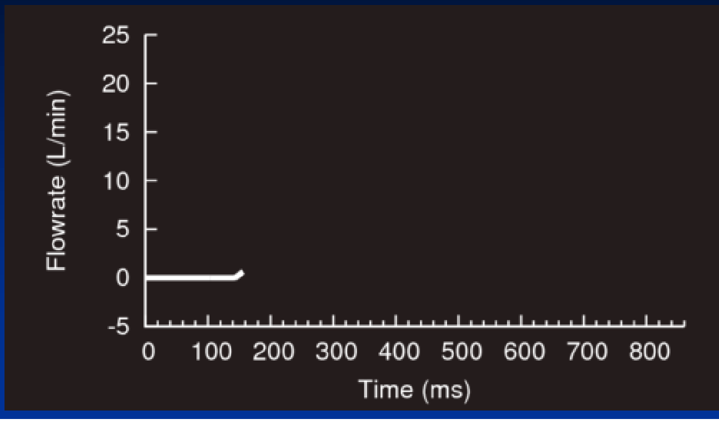
Transparent view of fully open leaflets

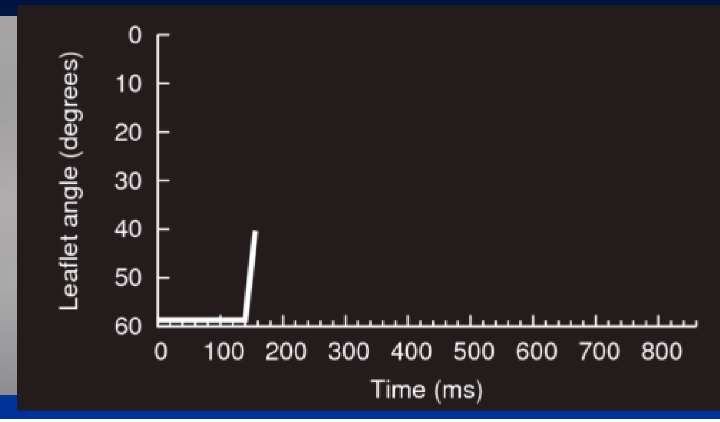




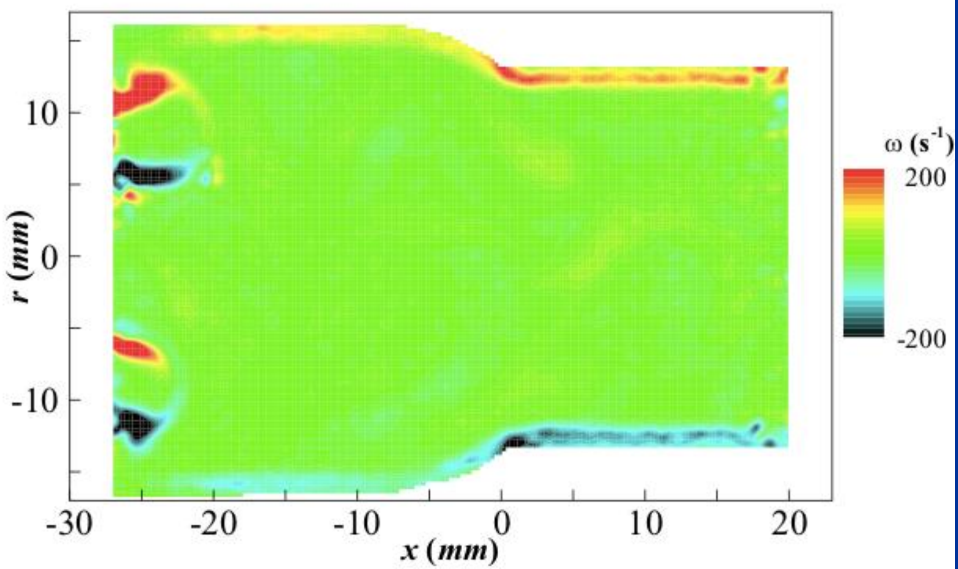
Interior view showing fully open leaflets fitting into butterfly hinge geometries

Comparison with Experimental Data: Leaflet Opening

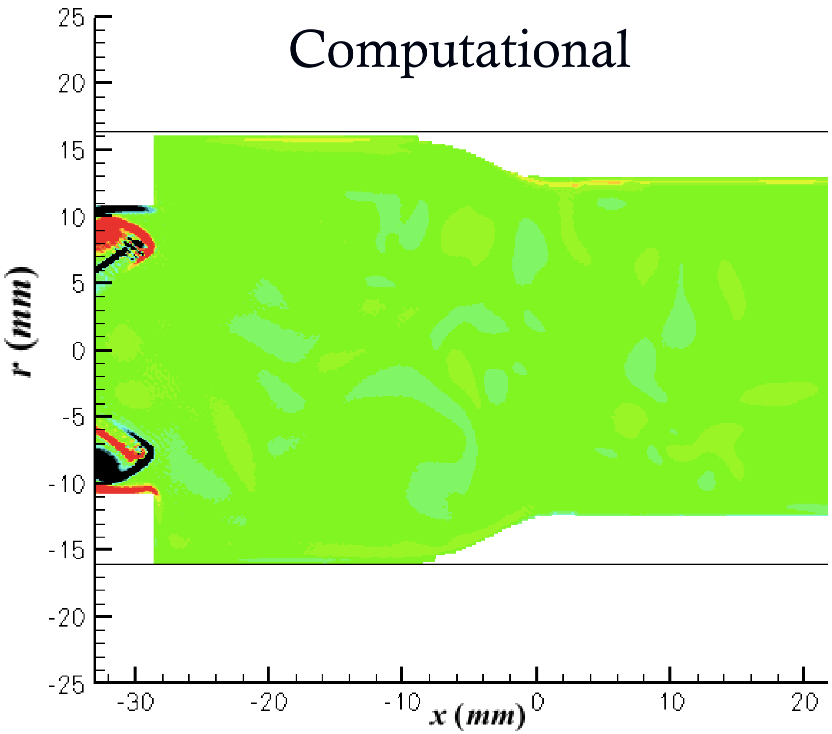




Experimental



Computational



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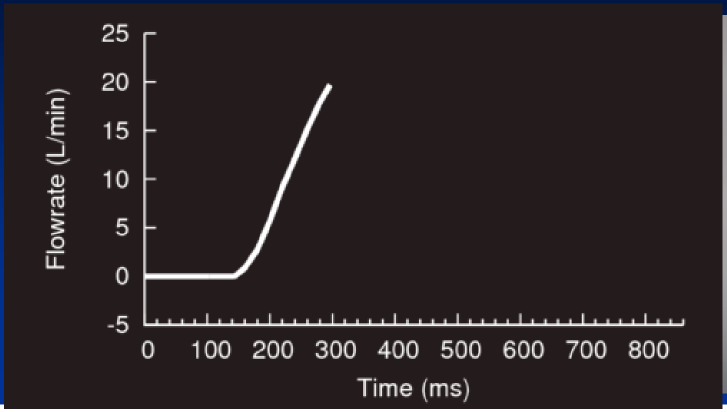
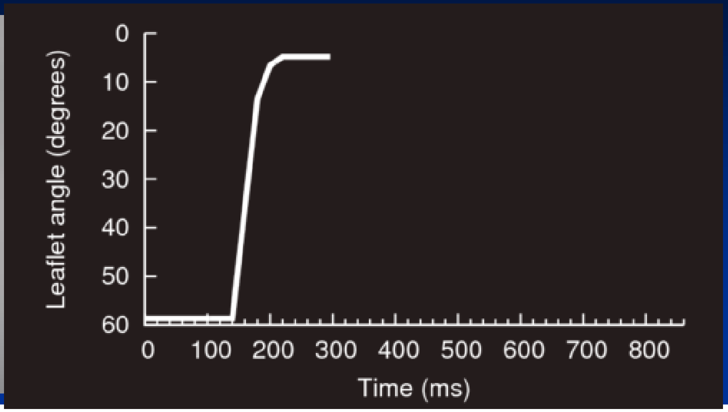
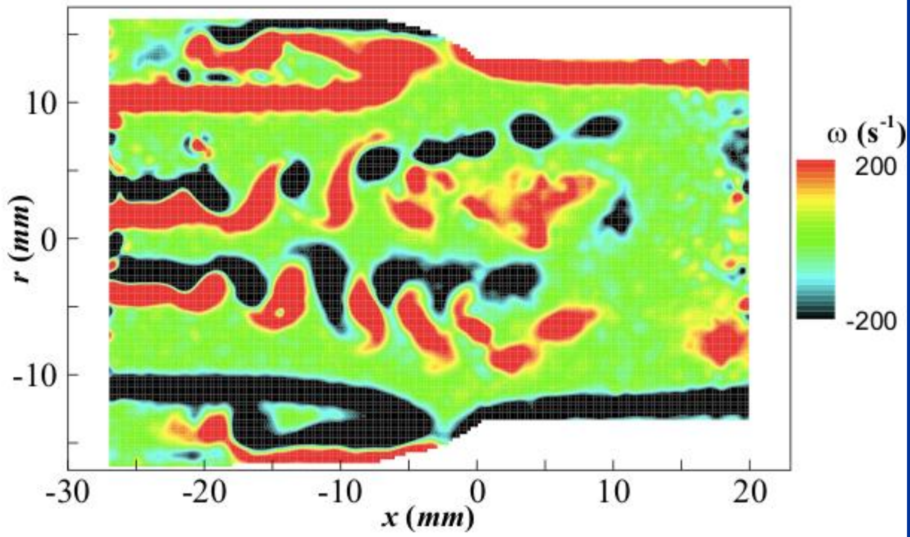
Comparison with Experimental Data: Acceleration

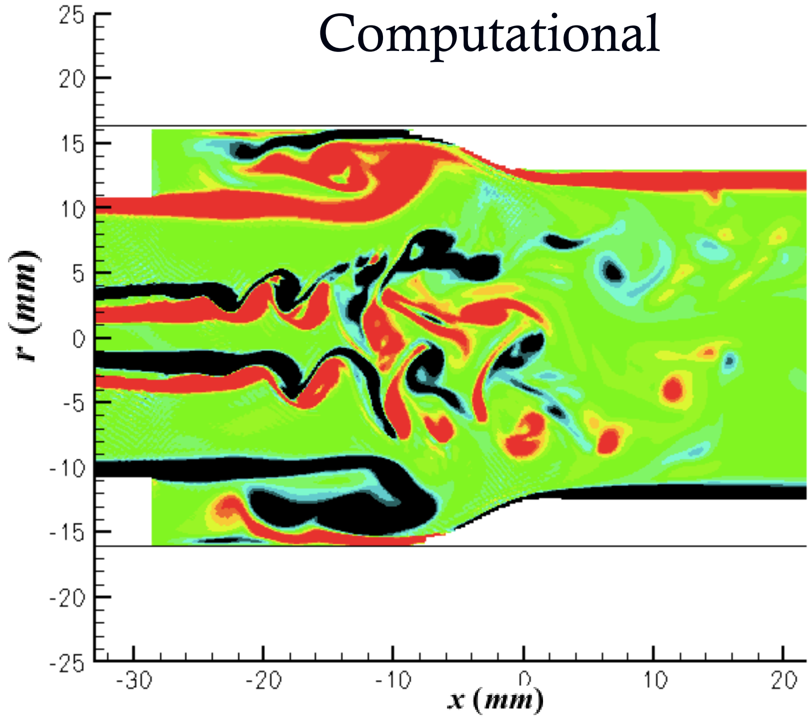




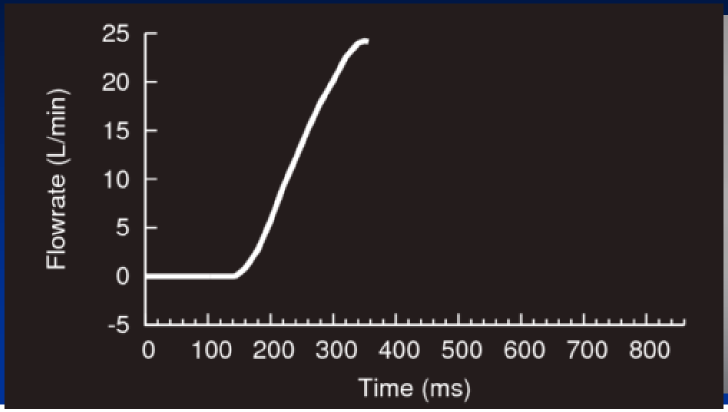
Experimental

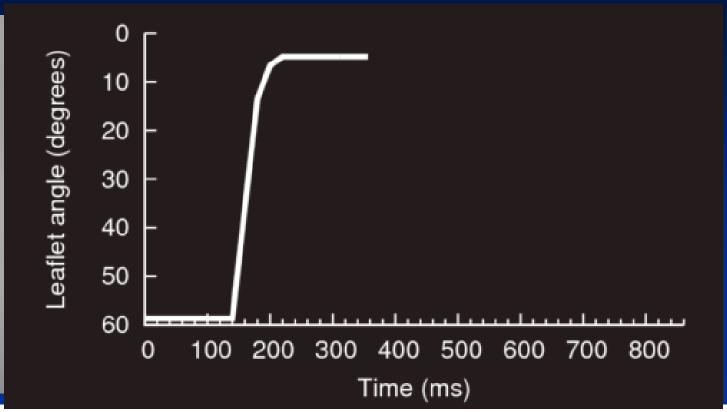


Computational

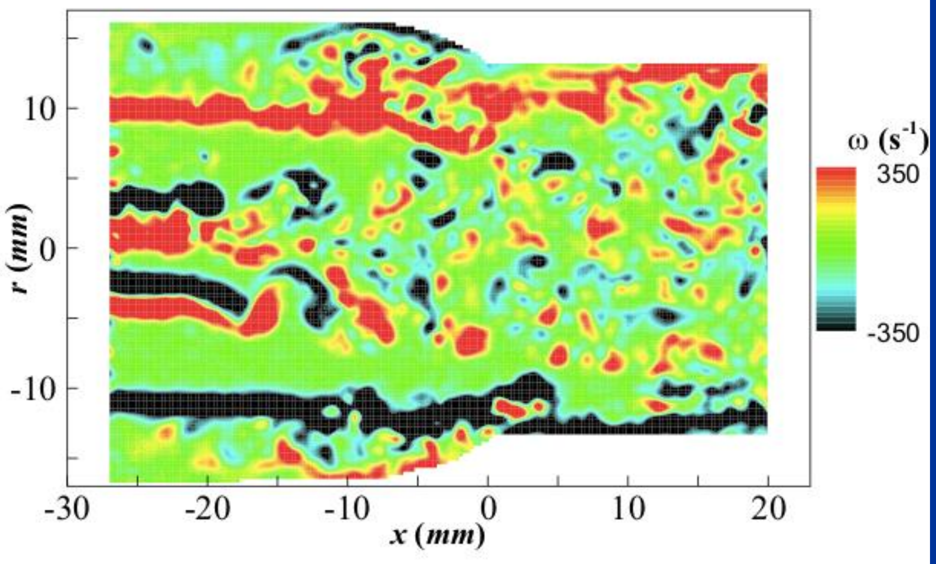


Comparison with Experimental Data: Peak Flow

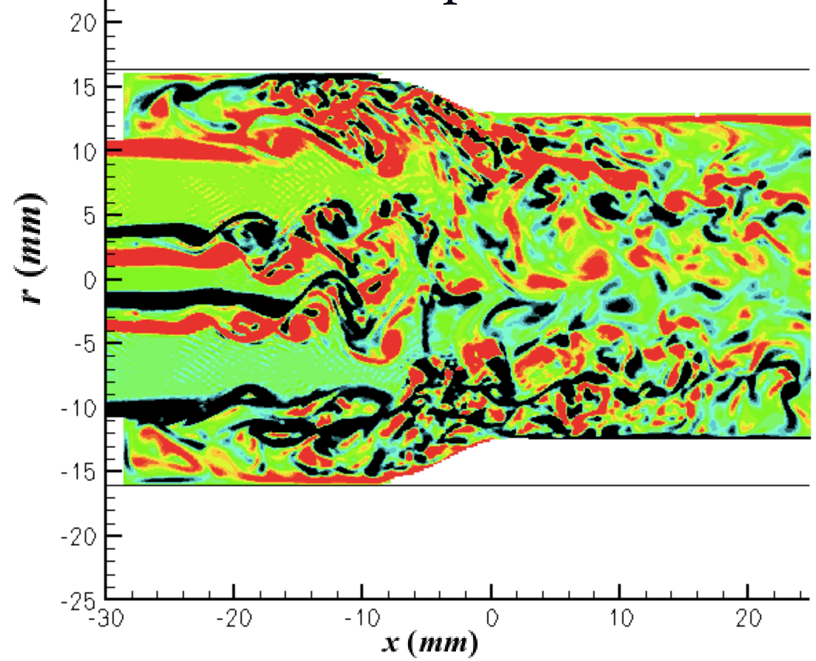




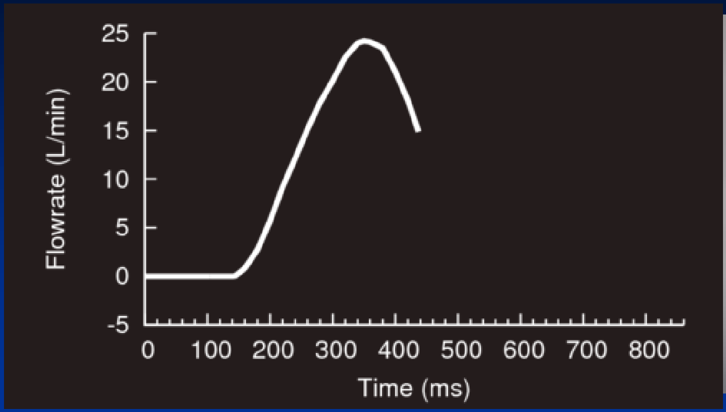
Experimental

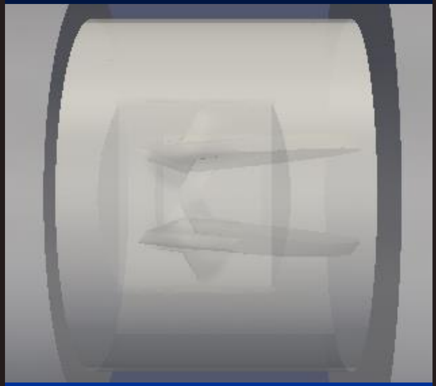


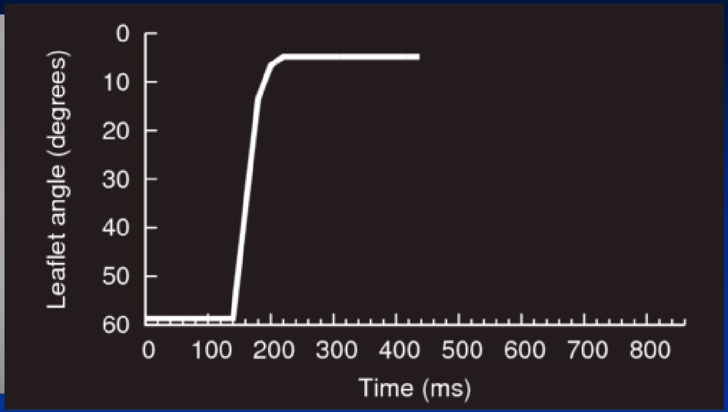
Computational



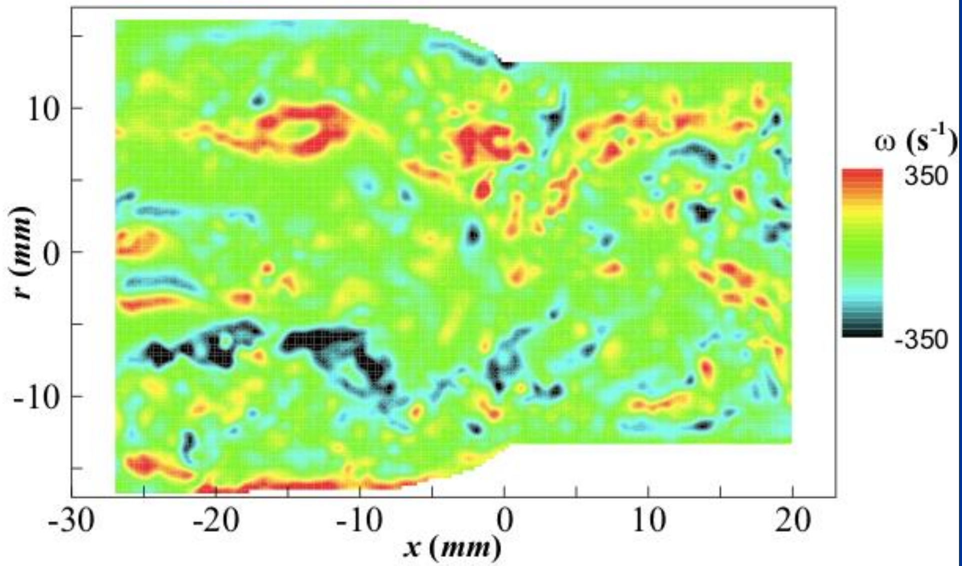
Comparison with Experimental Data: Deceleration



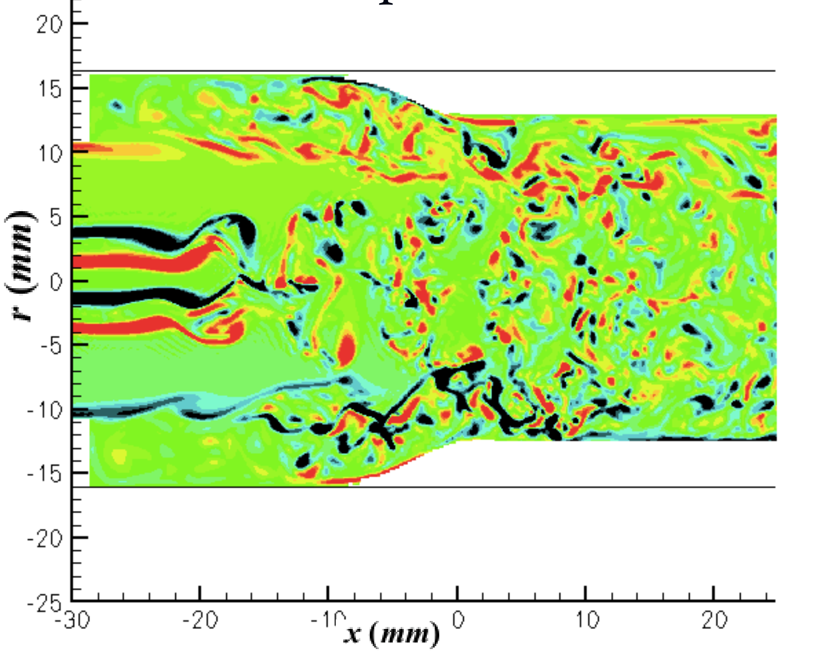




Experimental

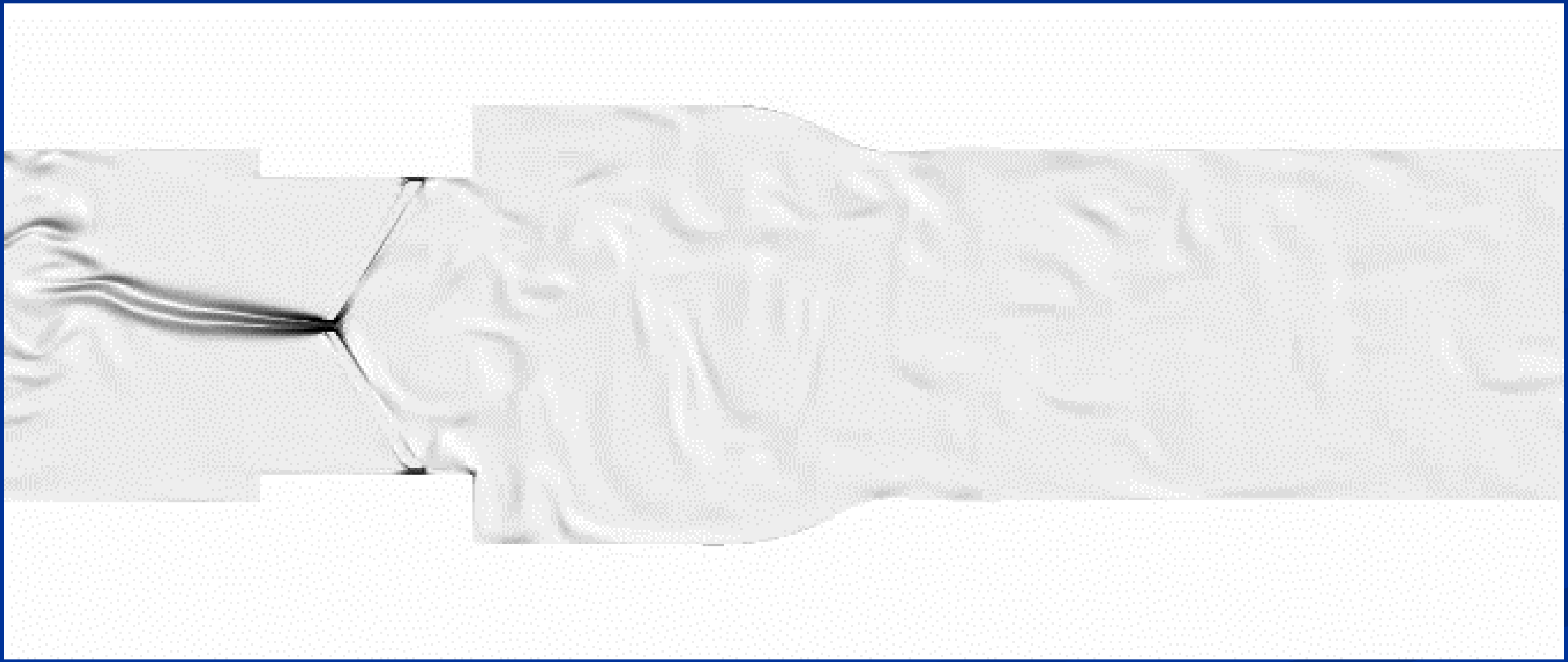


Computational



Single Phase Flow - Vorticity

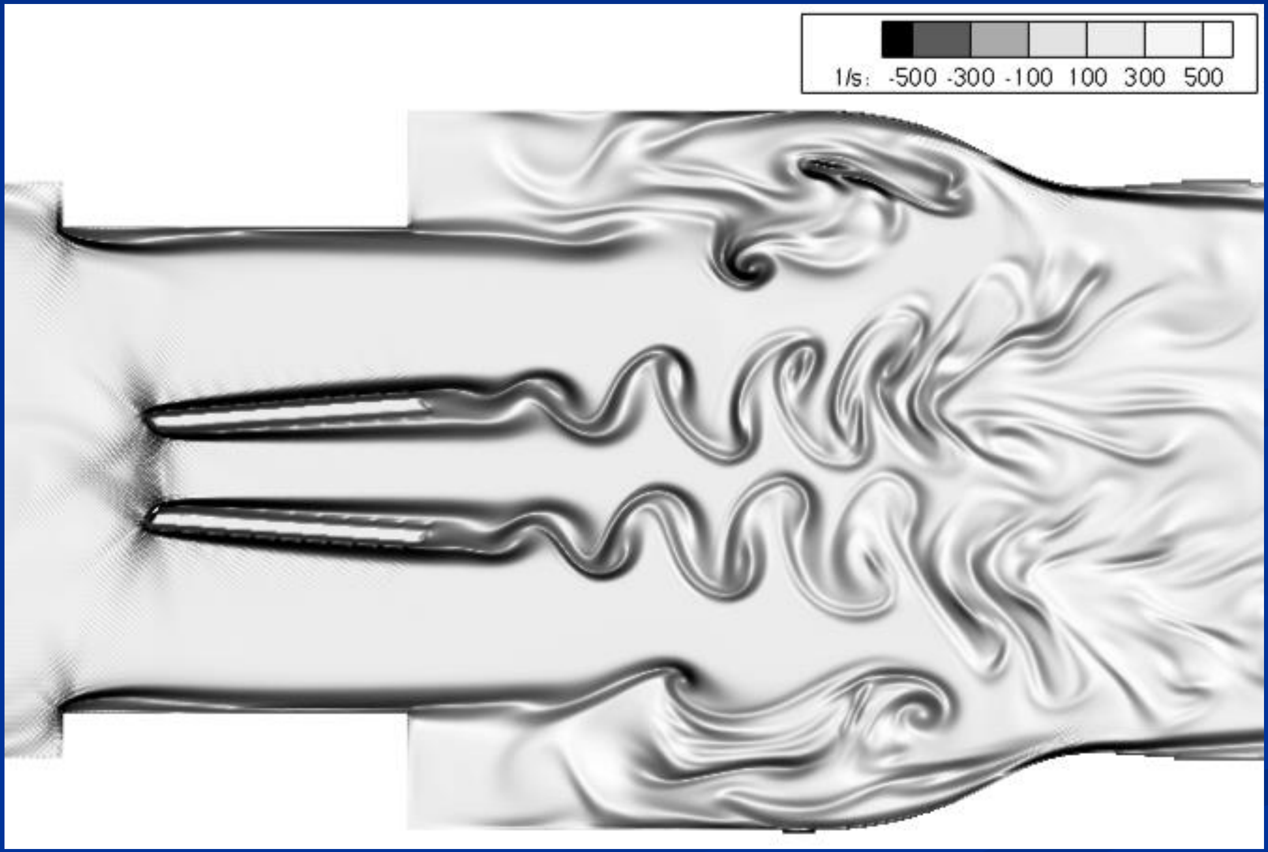
- Demonstration of fine, small-scale flow structures
  - Leaflet wake vortices and sinus recirculation region



Single Phase Flow - Vorticity

Accelerating Flow

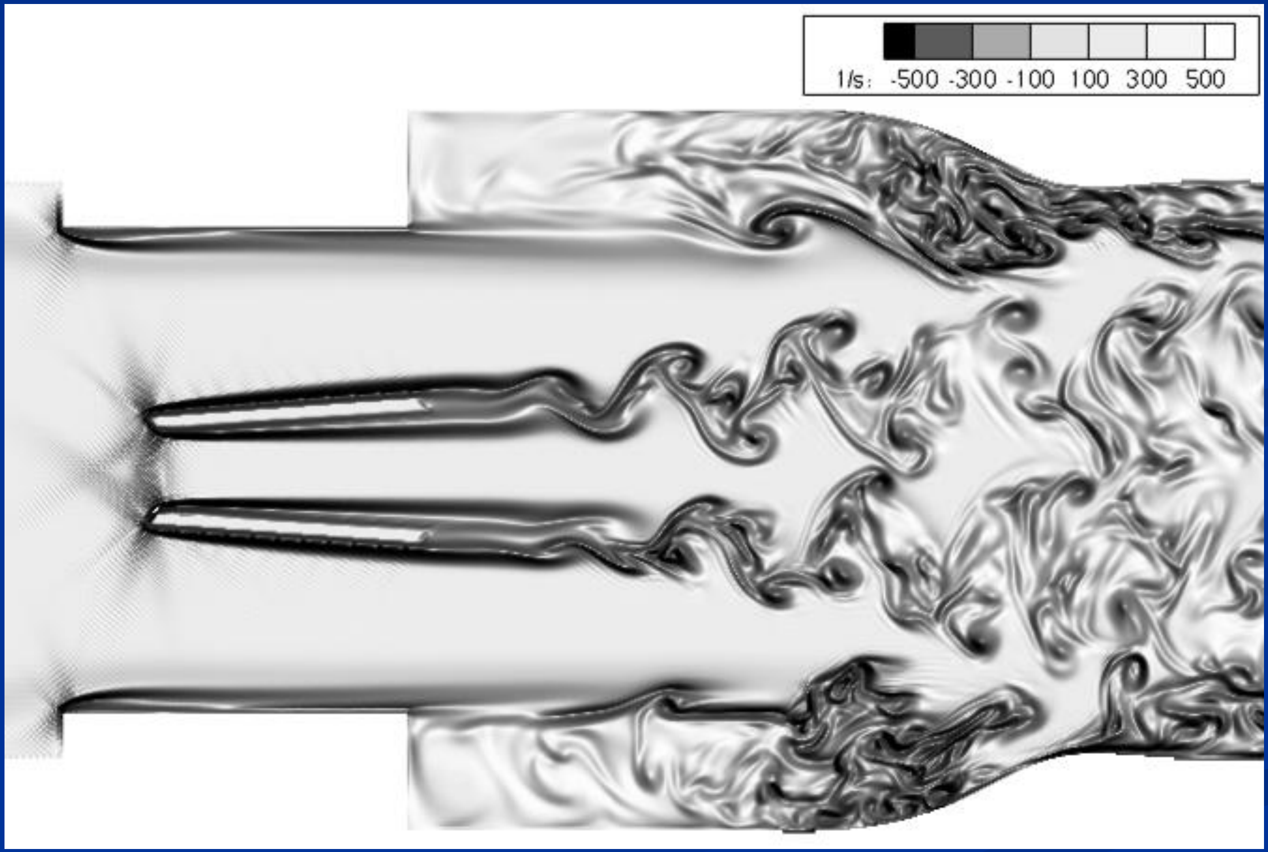
Re = 3500



Single Phase Flow - Vorticity

Peak Flow

Re = 5800



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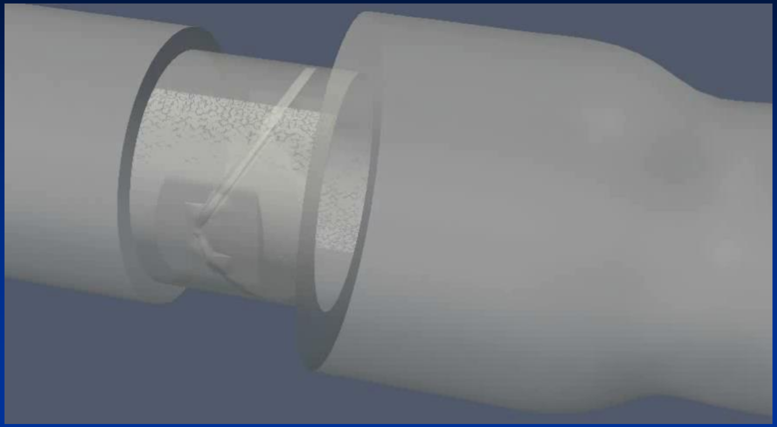
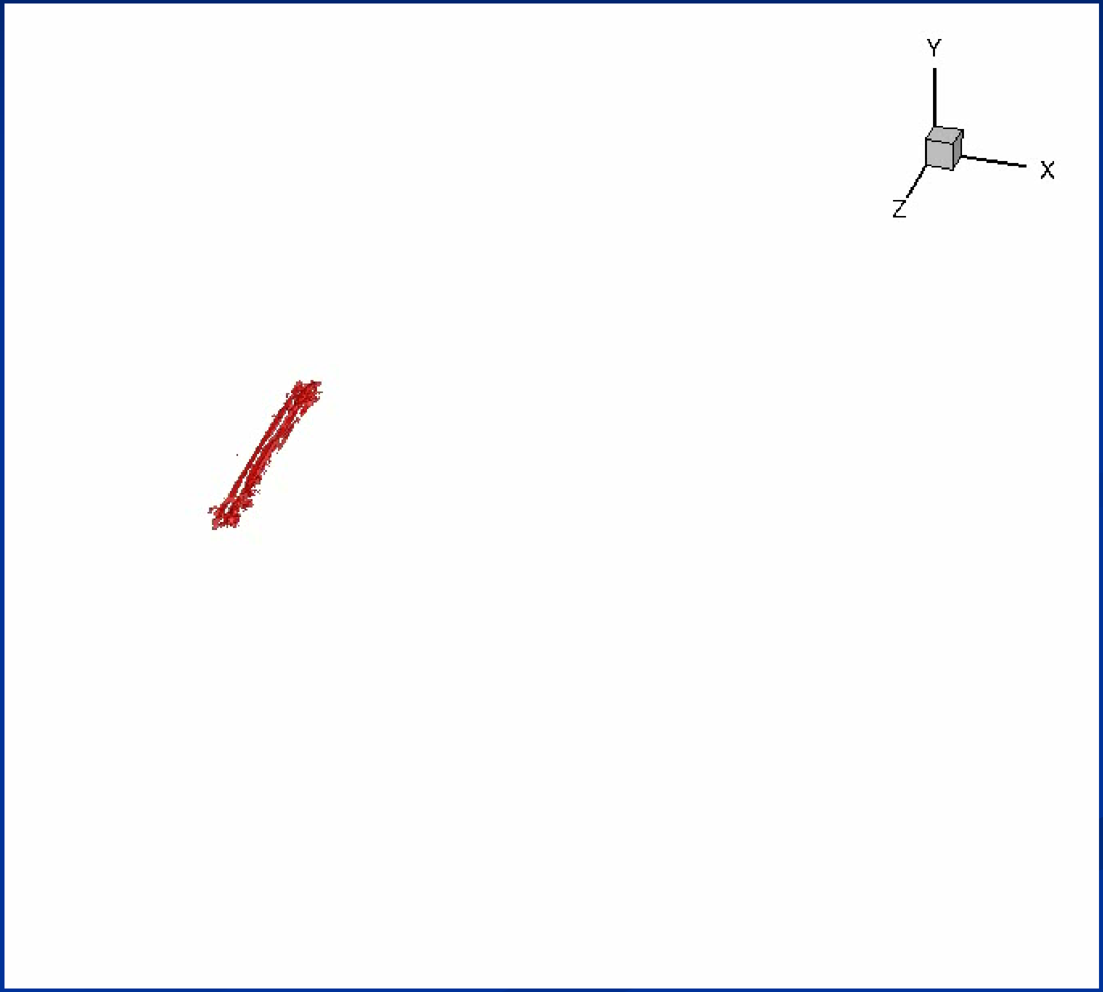
Single Phase Flow - Vorticity

Leaflet Closing

3D Visualization - Vortical Structures





Blood Damage Quantification

Quantifying damage to suspended platelets

- Use of a Blood Damage Index (BDI)
- Linear shear stress – exposure time damage accumulation model
- Previously validated against whole human blood damage experiments[1,2]
  - Validated LBM-EBF numerical method for quantifying platelet damage
  - Selected best BDI model in combination with numerical method
- Can track damage of individual platelets or average across platelets

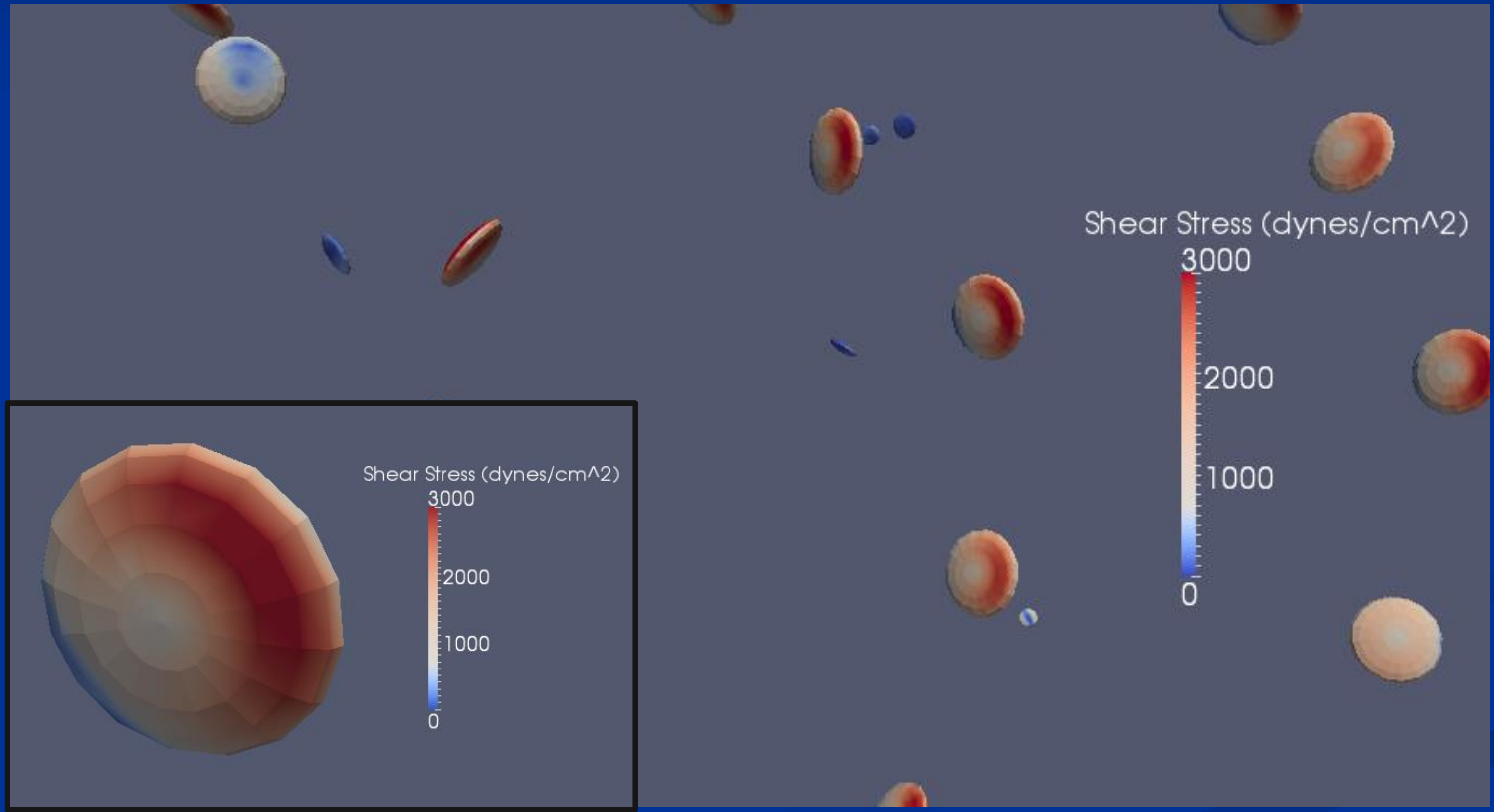
$$BDI = \sum_{t=0}^{t=end} \tau_{max} \cdot \Delta t$$

[1] Fallon, A.M. *et al.* "Procoagulant properties…" *Annals of Biomedical Engineering*, **2008**.

[2] J. Wu, B. Min Yun, *et al.*, "Numerical investigation of the effects of channel…" *Annals of Biomedical Engineering*, **2011.**

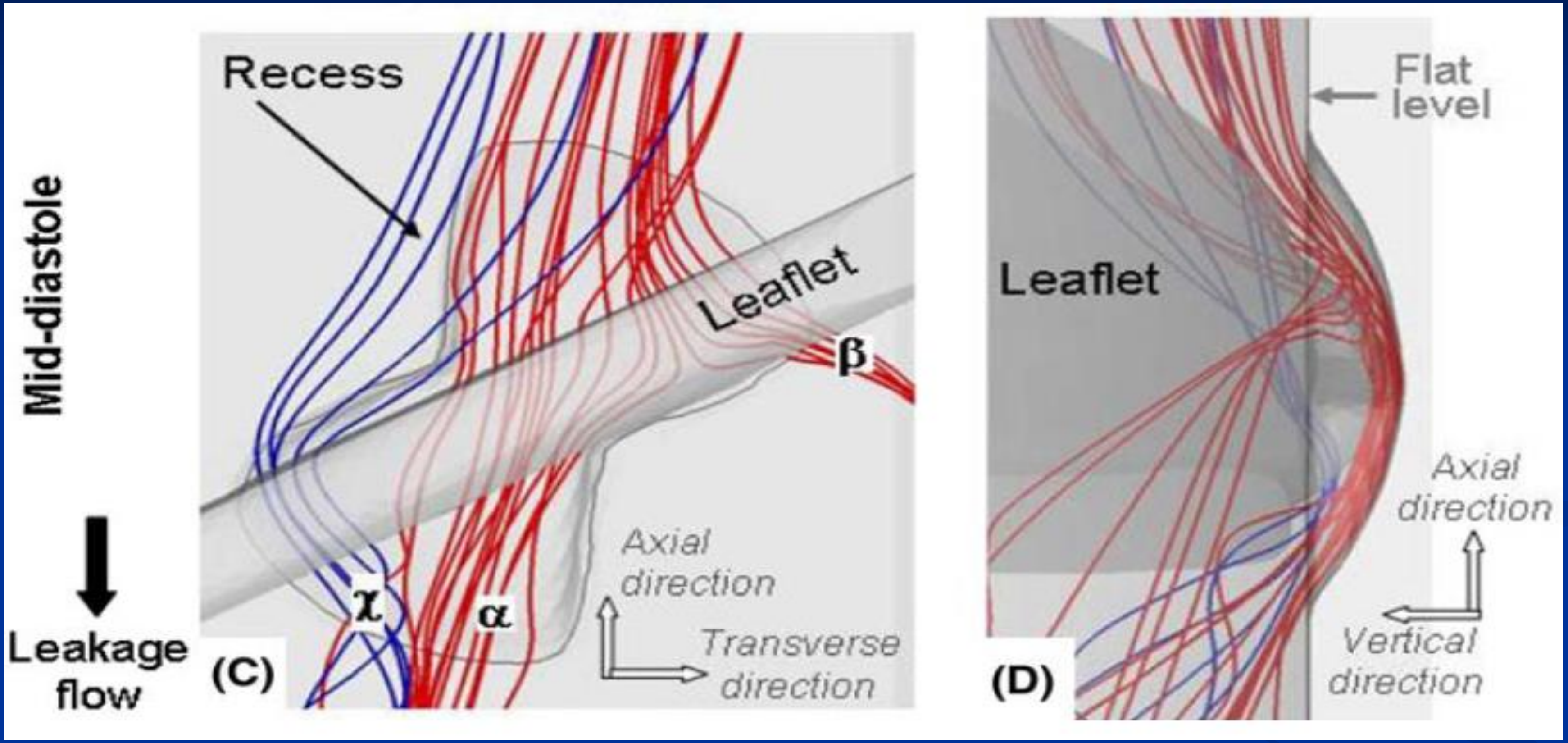
Blood Damage Quantification

$$BDI = \sum_{t=0}^{t=end} \tau_{\max} \cdot \Delta t$$



B. Min Yun *et al.*, "A numerical investigation of blood damage in the hinge area …," *ABME*, **2012**.

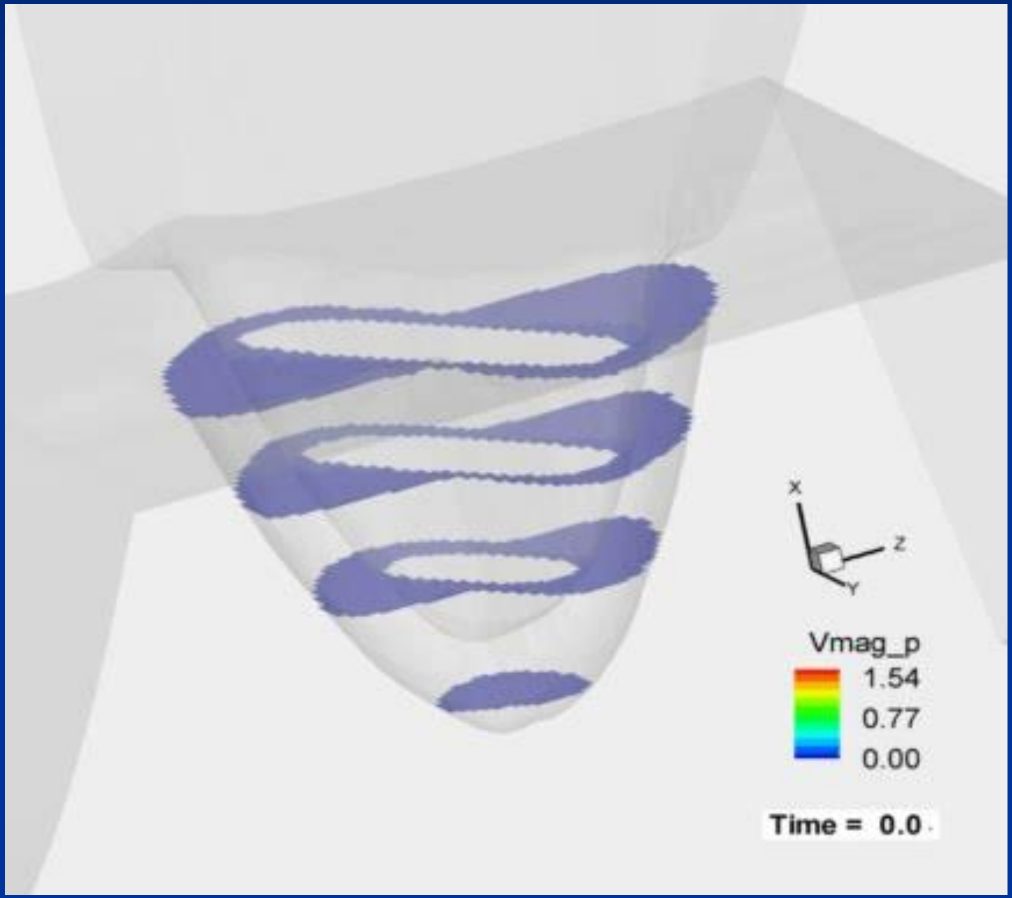
Small-Scale Computational Studies

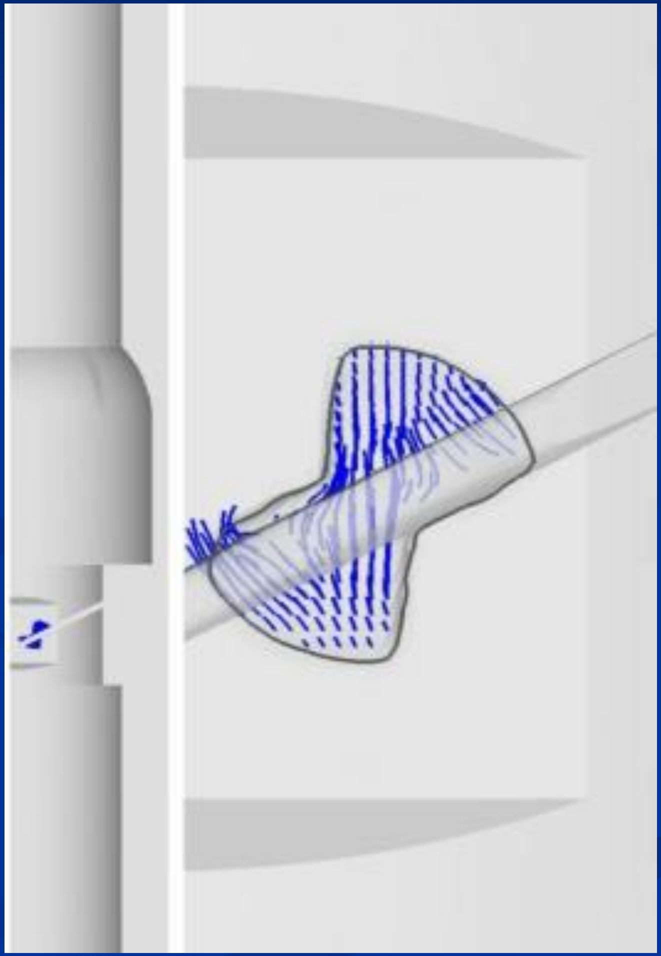


Simon (2010)

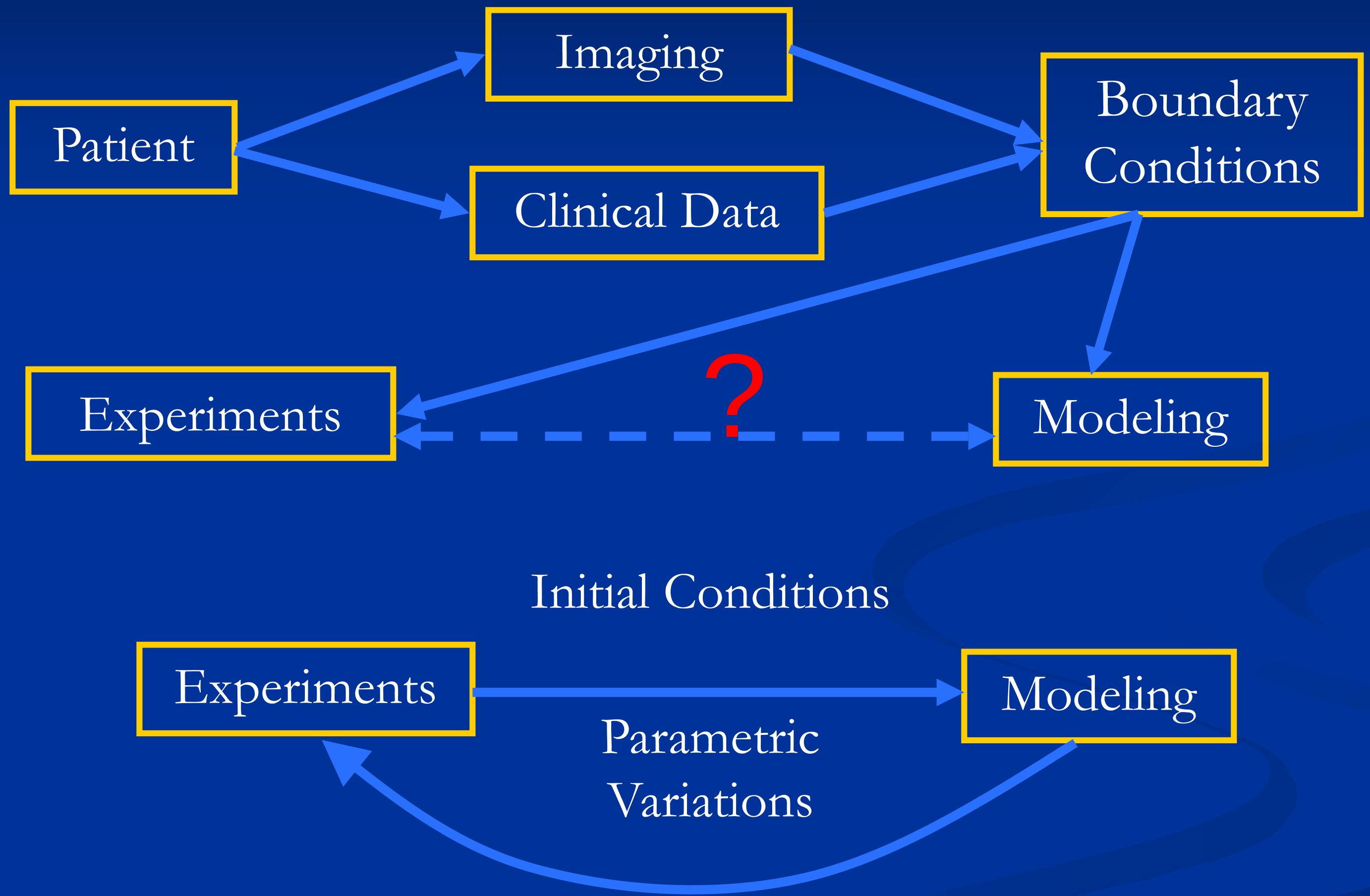
- Simulation of 3-dimensional hinge flow fields
- Pulsatile flow under aortic conditions

Small-Scale Computational Studies





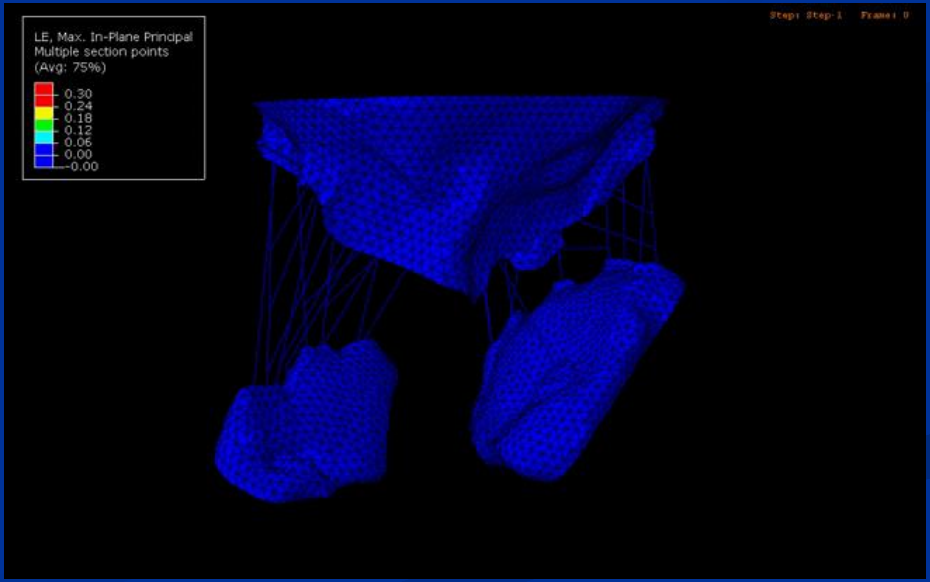
Interfacing Experimental and Computational Approaches to Clinical Translation



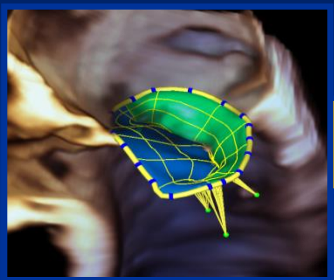
Validation of Model is Critical!

Modeling in Cardiovascular Devices

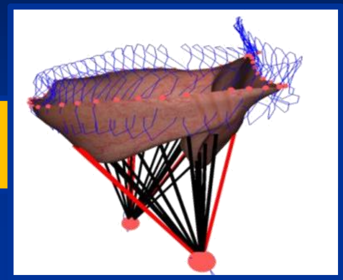
- **High level goals:**
  - Industry – for design performance evaluation, regulatory evaluations
  - Academia/Research – for study of fluid and solid mechanics of devices and blood
- On a finer scale, what matters?
  - Device Performance
    - *Durability*
    - *Fatigue*
    - *Risk evaluation*
  - Hydrodynamics
    - *Shear stress*
    - *Stasis*
    - *Thromboembolic events*
  - Solid mechanics
    - *Strain*
    - *Loading profiles*



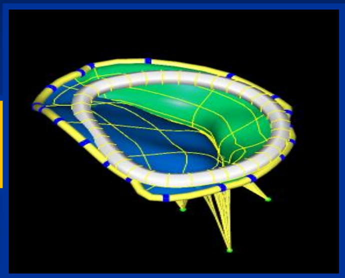
Patient Specific Surgical Planning Models



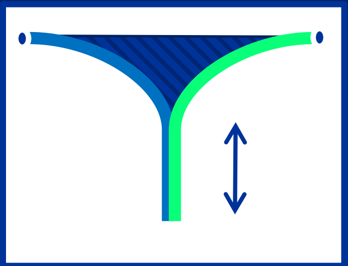
Extract Patient MV Geometry



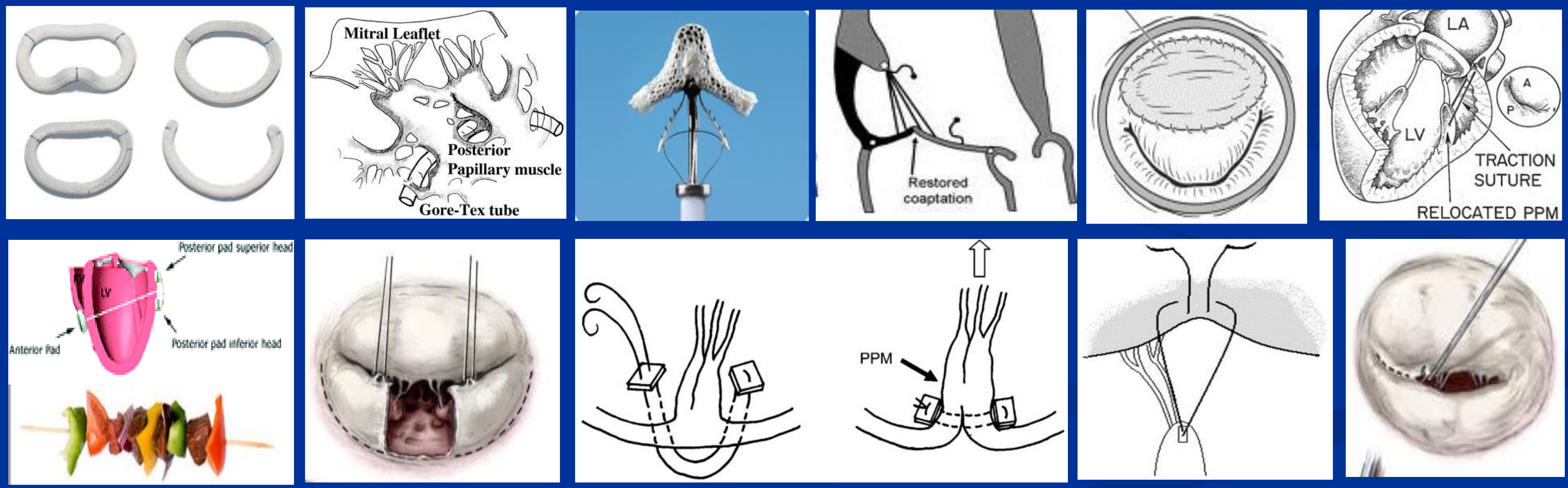
Model Patient MV Dysfunction



Simulate Repair Strategy(s)

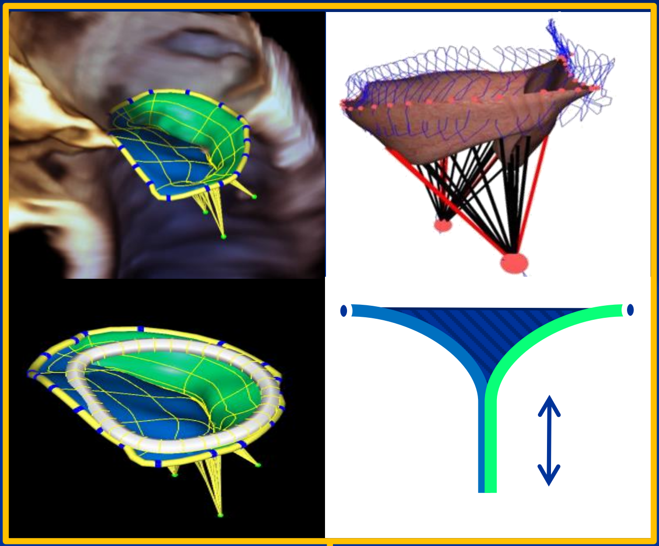


Predict Post-Operative MV Function

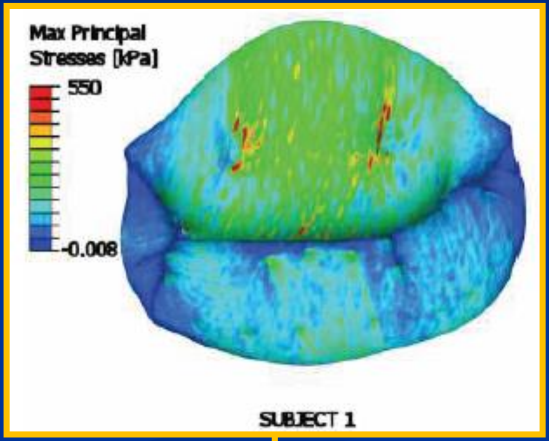


Patient Specific Surgical Planning Models

Predicting Postoperative Function



Predicting Postoperative Tissue Stress



Accuracy is Largely Dependent On

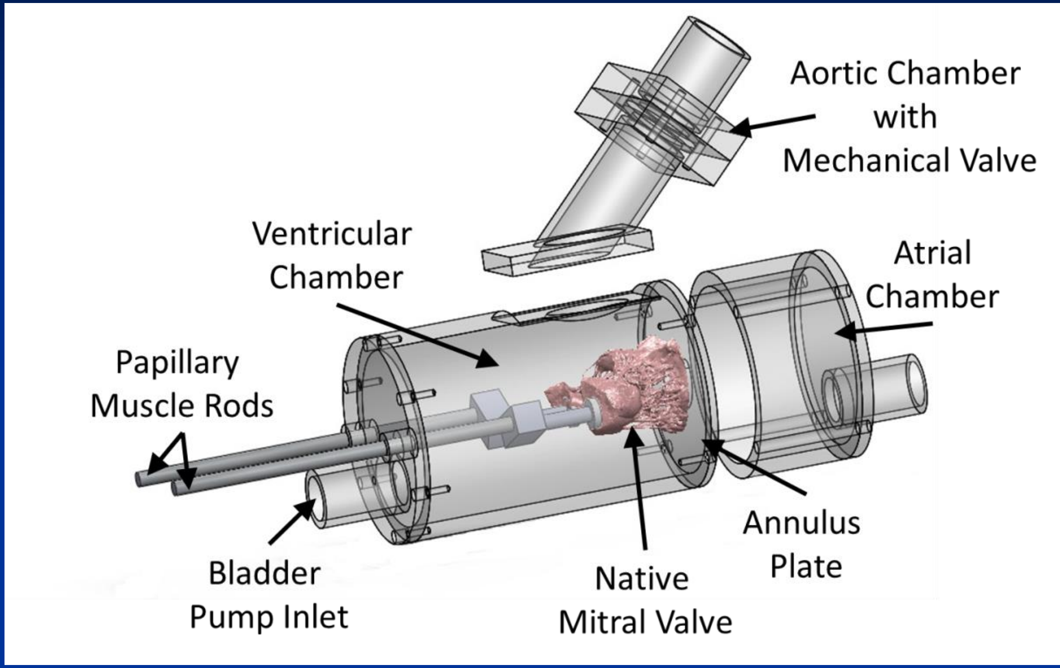
How close these models mimic native mitral valve geometry, function, and mechanics.

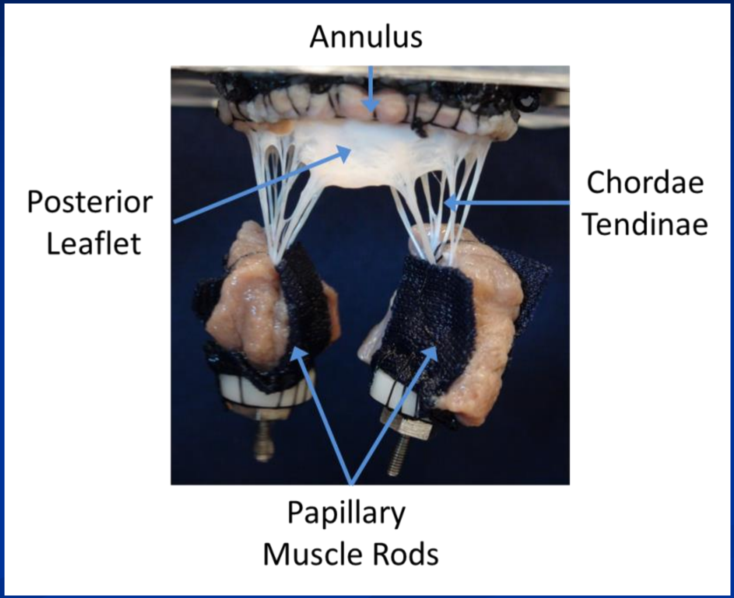
Numerical Simulations of Native MV

- However, without rigorous validation against benchmark data, computational models are of questionable value in their clinical utility

- "…three-dimensional in-vitro flow, deformation and strain data with a native mitral valve are sorely needed." – Einstein et. al, 2010

Novel Modular Left Heart Simulator





- Modular chamber – removable components for various modalities, while maintaining same valve geometry and configuration

Characterization Modalities

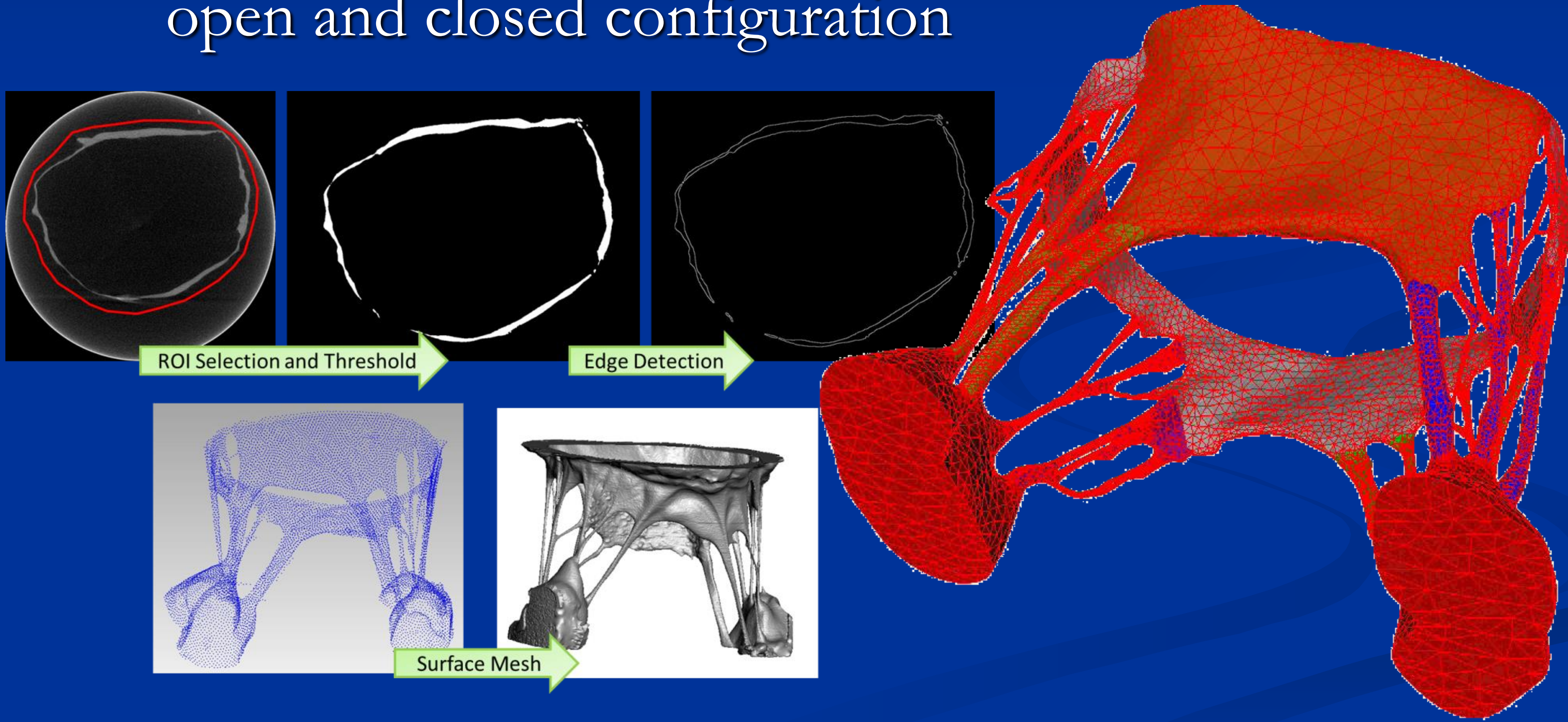
MV Geometry	MV Fluid Mechanics	MV Tissue Mechanics
Micro CT 3D Echo	Hemodynamics Stereoscopic PIV	Leaflet Strain Papillary Muscle Forces

Characterization Modalities

MV Geometry	MV Fluid Mechanics	MV Tissue Mechanics
Micro CT	Hemodynamics	Leaflet Strain
3D Echo	Stereoscopic PIV	Papillary Muscle Forces

Realistic Valvular Anatomy Trough State of the Art Imaging

- Micro-CT imaging provides realistic valvular anatomy, including subvalvular apparatus, up to 21 μm resolution, in open and closed configuration



Valvular Anatomy From Clinical 3D Ultrasound

Acquire 3D echo of MV using a Philips iE33 with X7-2 Probe

⇩

Export echo to Cartesian DICOM and scale to cubic voxels (0.5mm^3)

⇩

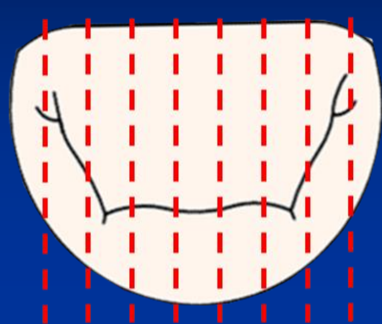
Rotate, crop, and orient Cartesian DICOM

⇩

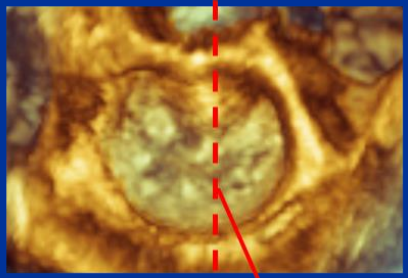
Segment annulus and leaflets using J_0 splines

⇩

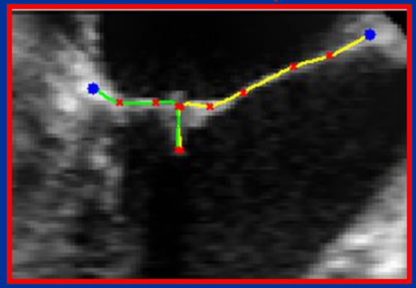
Triangulate segmented data and export as mesh file



Schematic of segmentation planes across the mitral valve

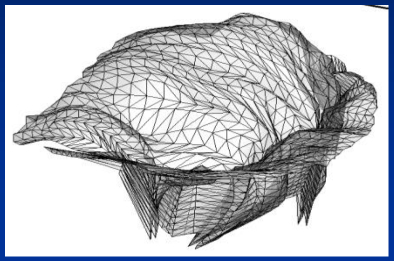


RT3DE image of MV with a segmentation plane shown in red

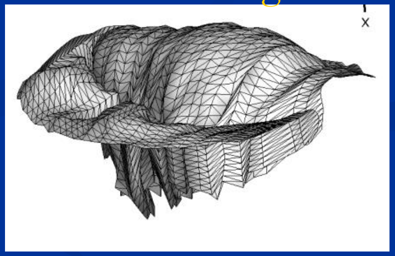


Segmentation plane with anterior (yellow) and posterior (green) leaflets segmented with the user selected points

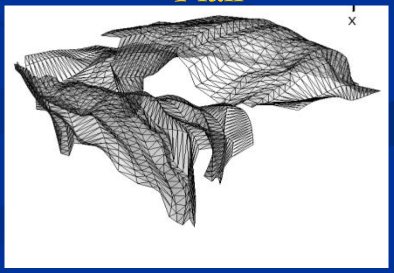
Normal Valve



Anterior Leaflet Bellowing



Anterior Leaflet Flail



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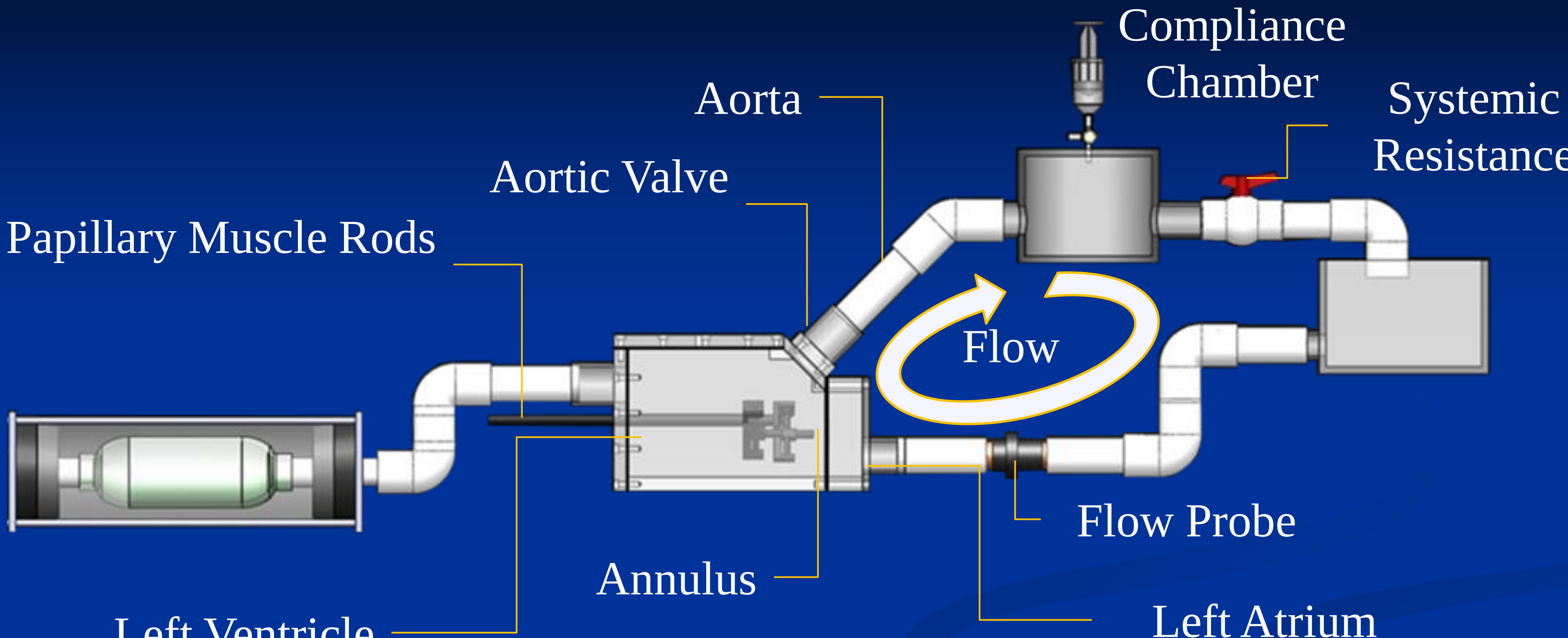
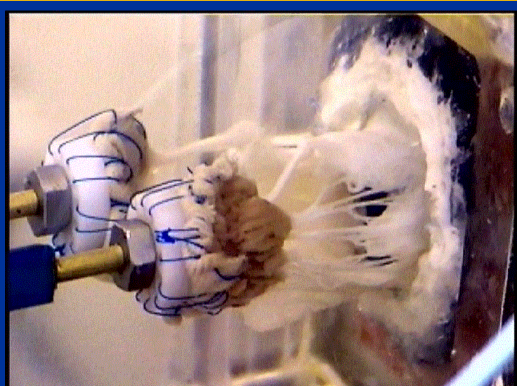
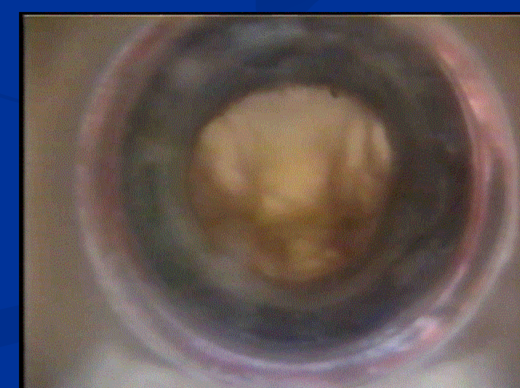
Characterization Modalities

MV Geometry	MV Fluid Mechanics	MV Tissue Mechanics
Micro CT 3D Echo	Hemodynamics Stereoscopic PIV	Leaflet Strain Papillary Muscle Forces

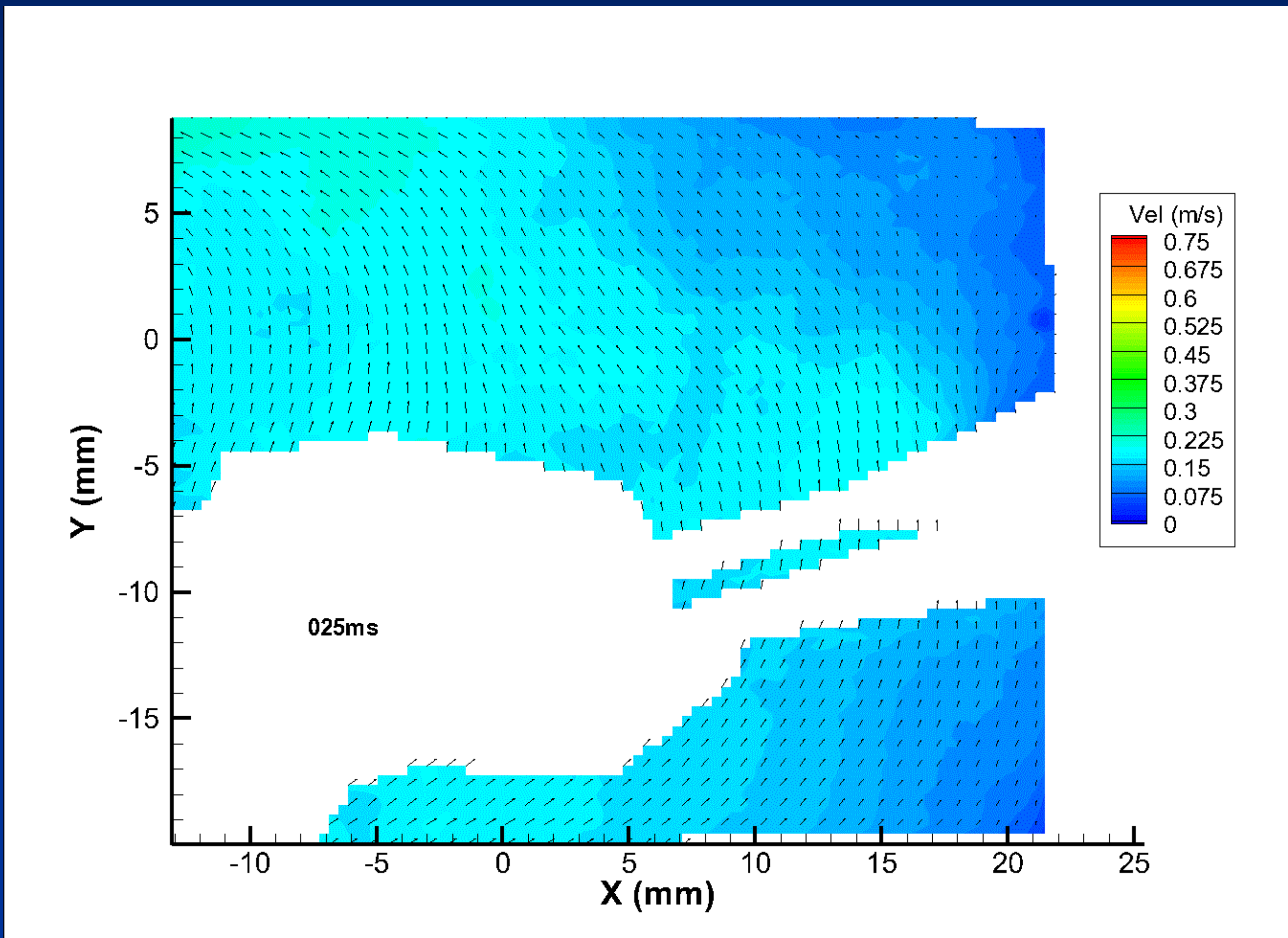
Pulsatile Flow Simulator

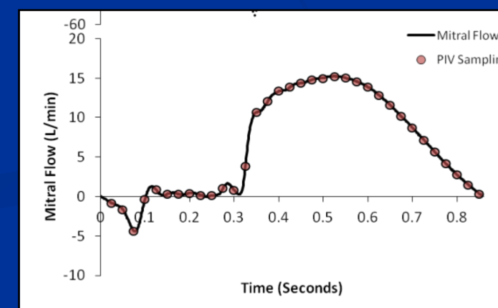




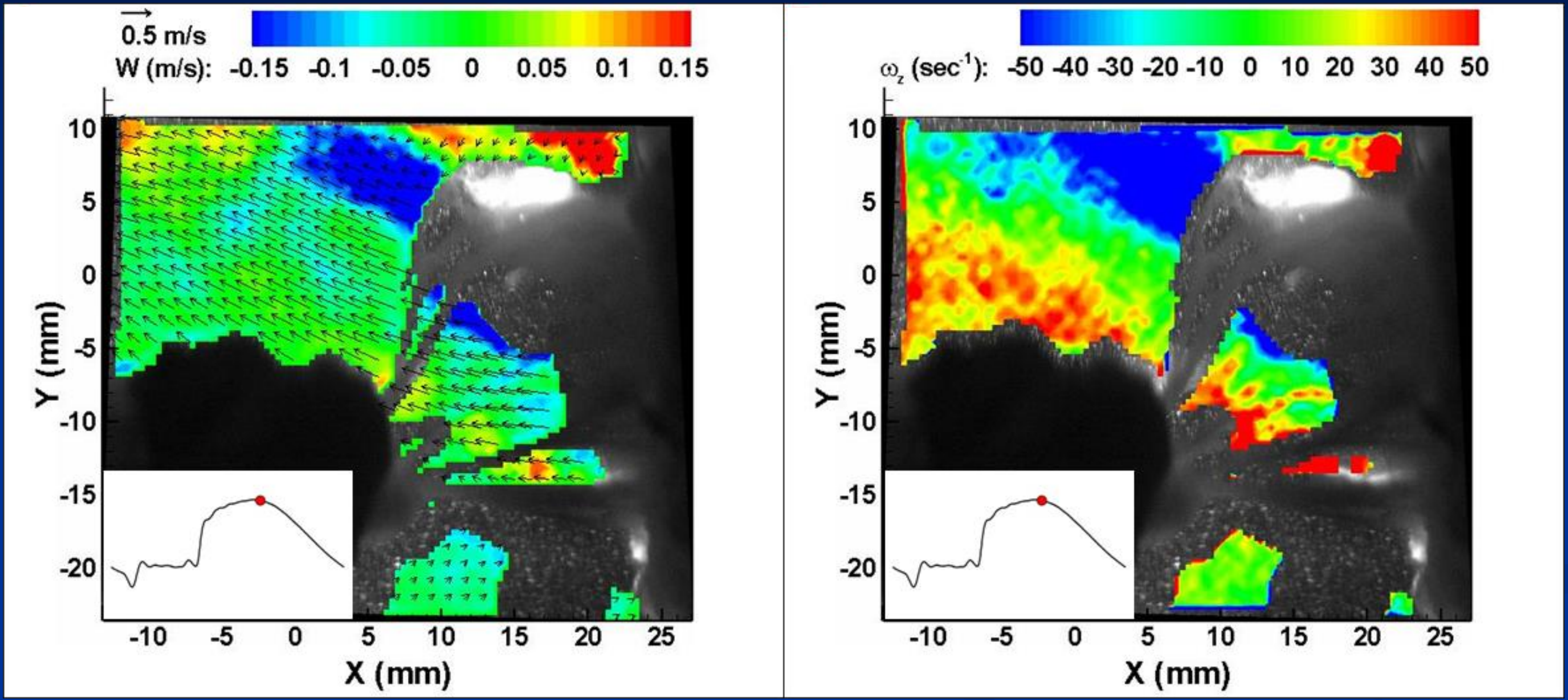


Highly Resolved Flow through the MV





Out-of-plane velocity & vorticity

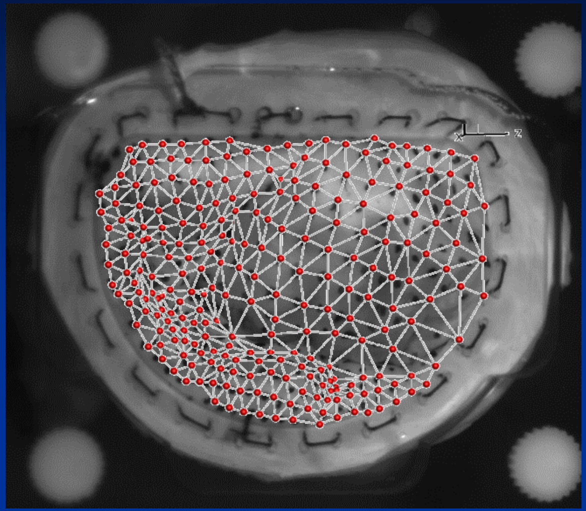


- Very low magnitude of W in the central plane
- Highest vorticity values restricted to edge of diastolic filling jet as expected

Characterization Modalities

MV Geometry	MV Fluid Mechanics	MV Tissue Mechanics
Micro CT 3D Echo	Hemodynamics Stereoscopic PIV	Leaflet Strain Papillary Muscle Forces

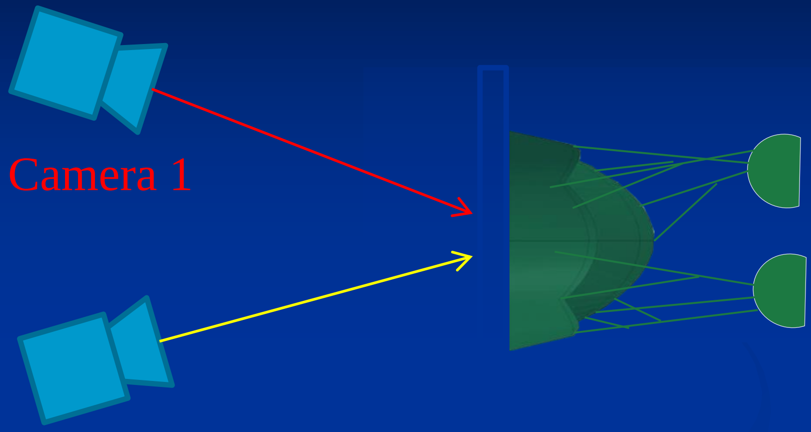
Leaflet Strain



Marker Array 1.5 mm x 1.5 mm

Markers ~0.5 mm in diameter

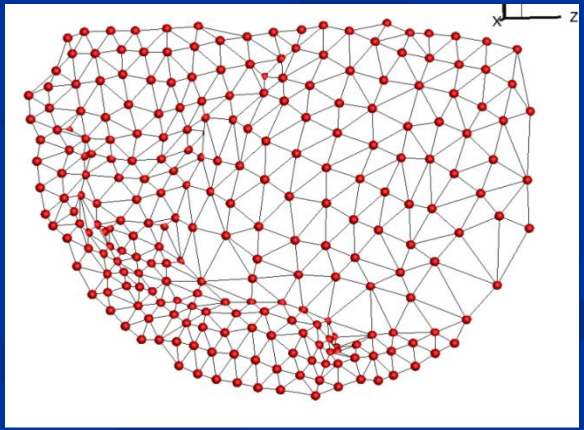
Stereo Photogrammetry



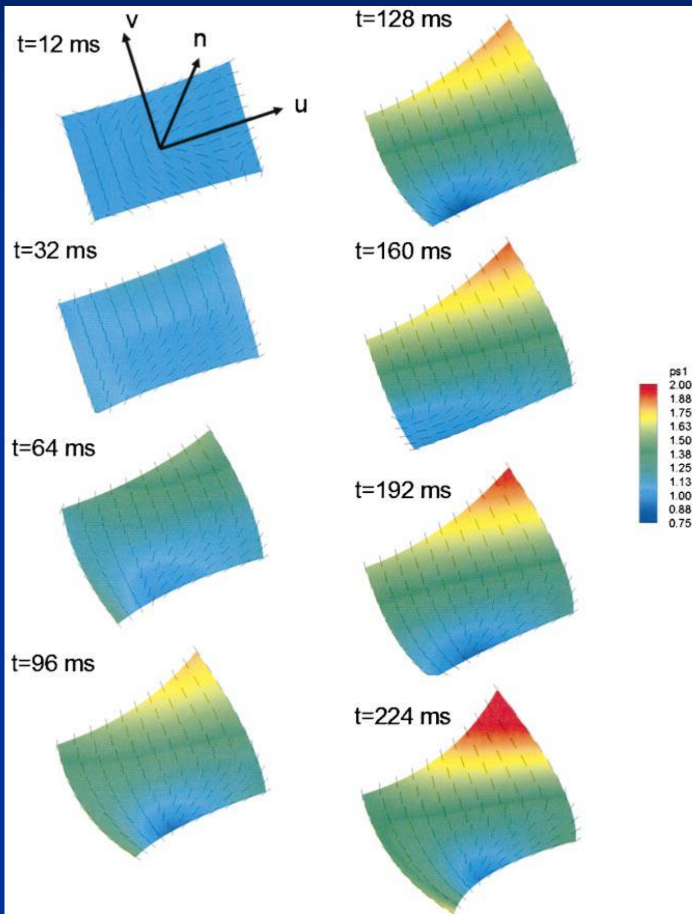
Mitral Valve Mounted in the simulator

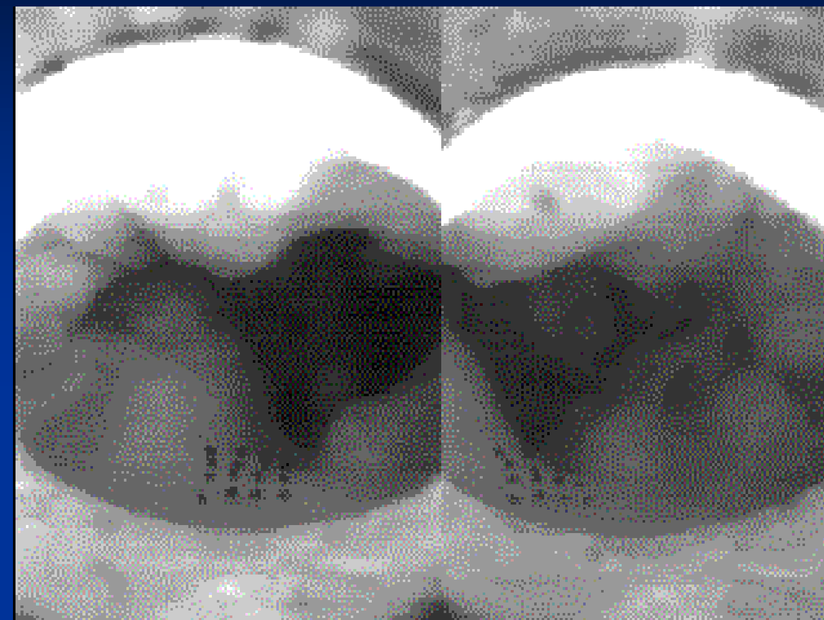
3D marker location accuracy: 65 µm

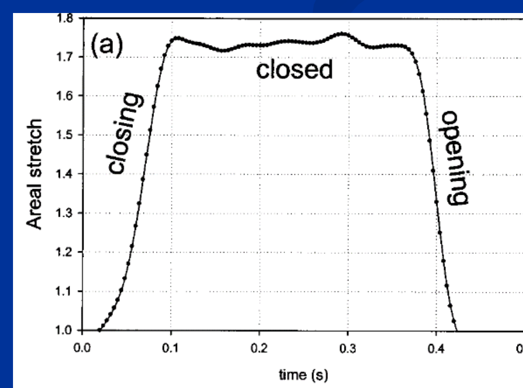
(Based on camera magnification, pixel size, and the calibration)

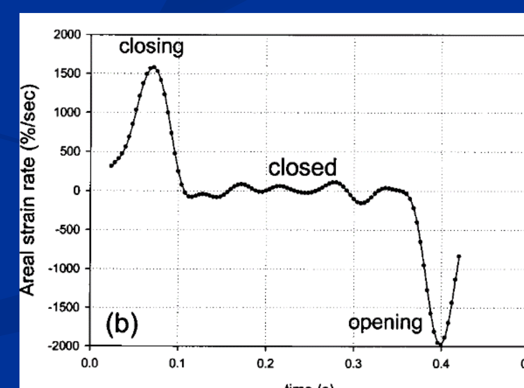


Leaflet Strain



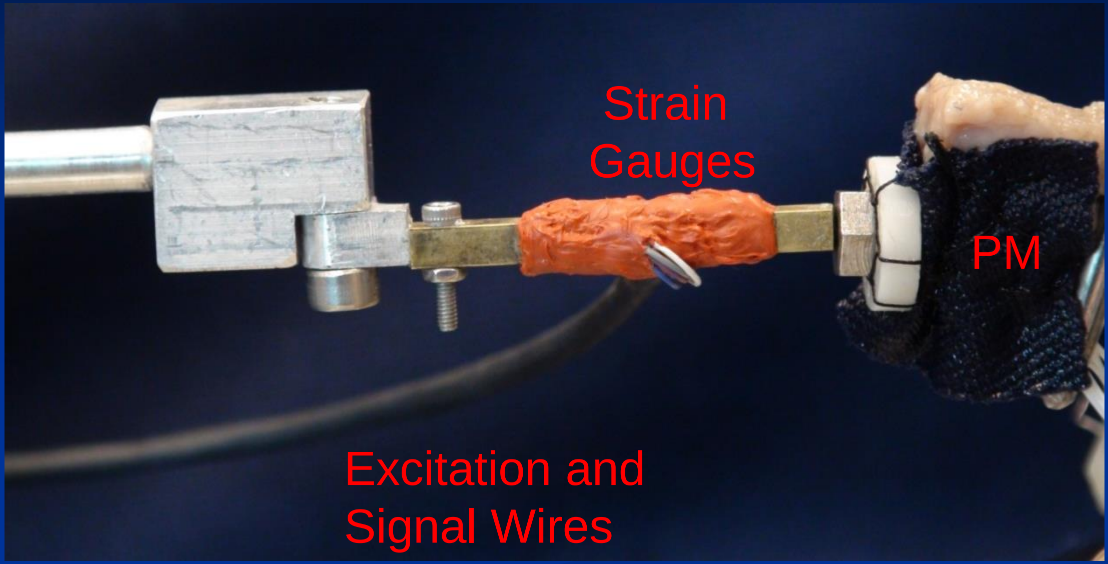


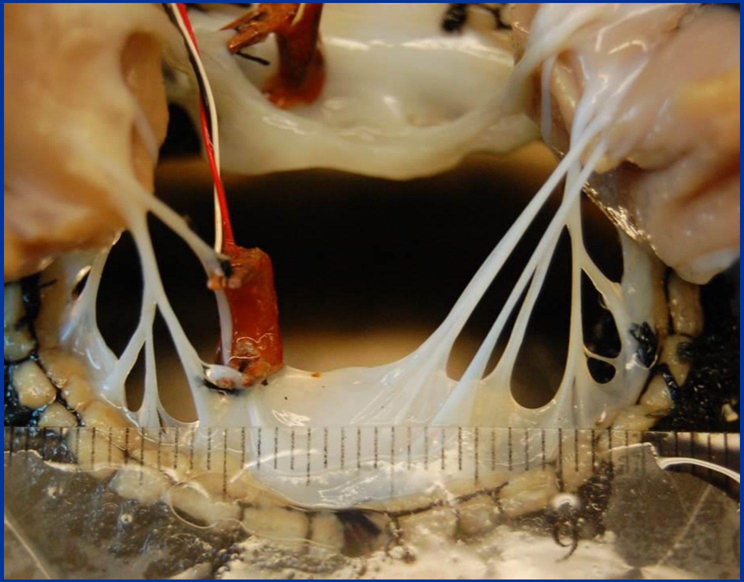




Subvalvular Force Measurements

In-house fabricated strain gauge transducers measure subvalvular forces throughout the cardiac cycle

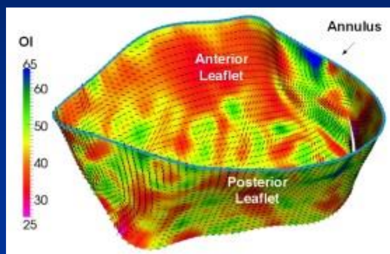




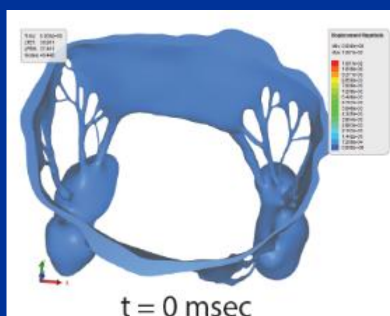
(Top) Papillary muscle force transducers measure axial, and two directions of bending force on each papillary muscle

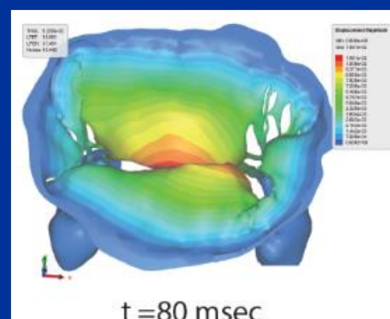
(Left) Miniature chordal force transducers can be applied to the strut, intermediate, and marginal chordae

Current uses in Computational Modeling

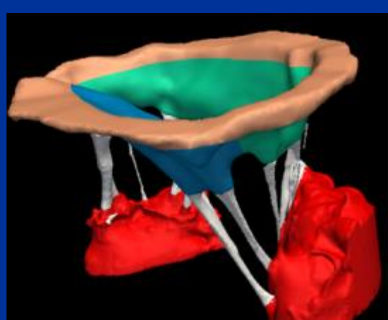


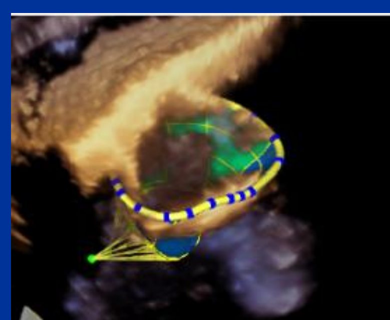
Multi-scale computational model developed at the University of Texas





Fluid-structure interaction model developed at the University of Maine, Pacific Northwest National Labs, and Georgia Tech

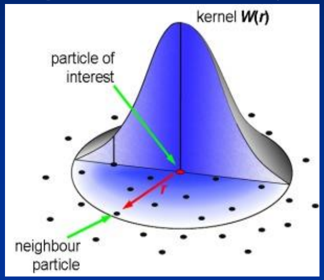


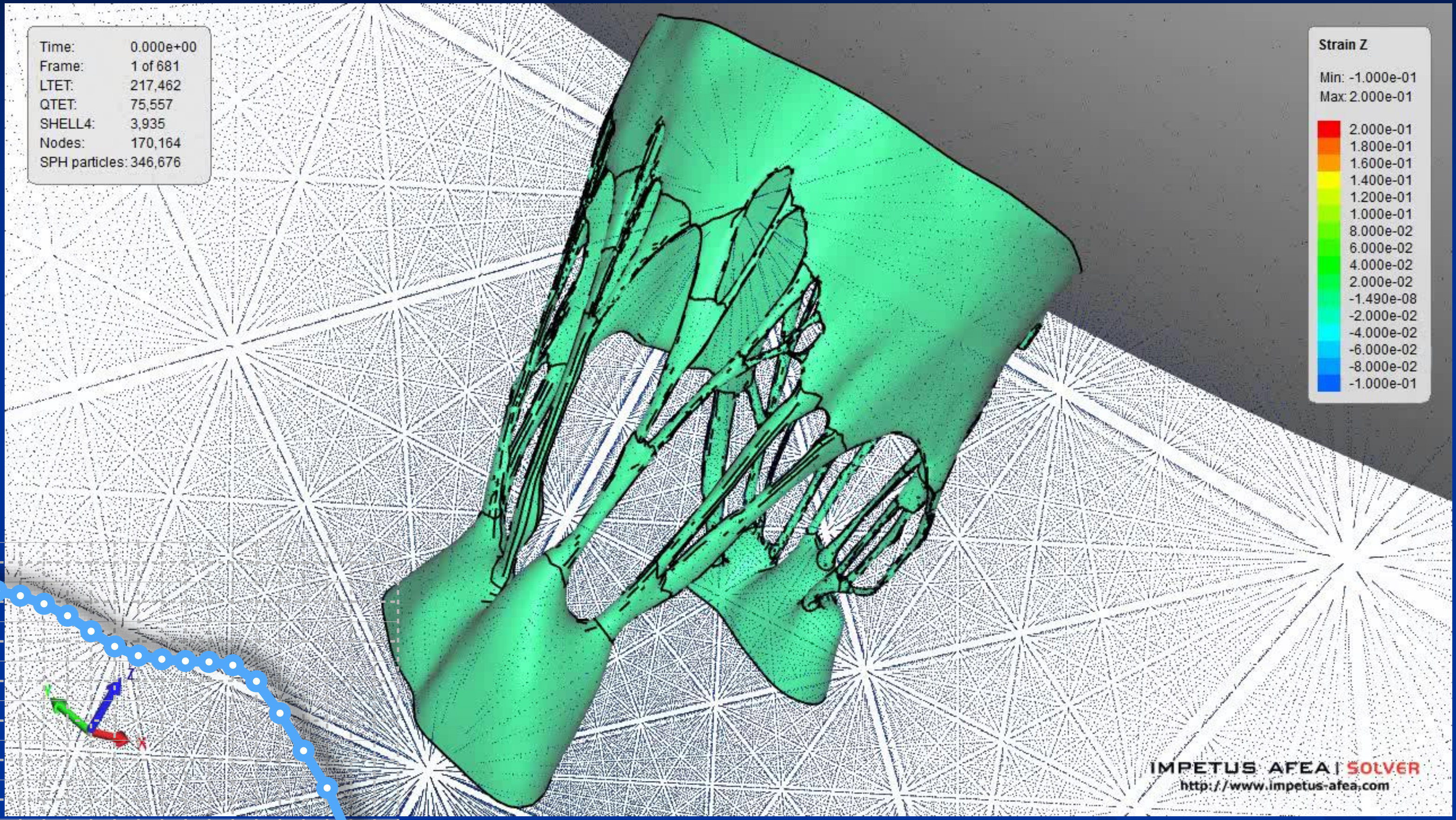


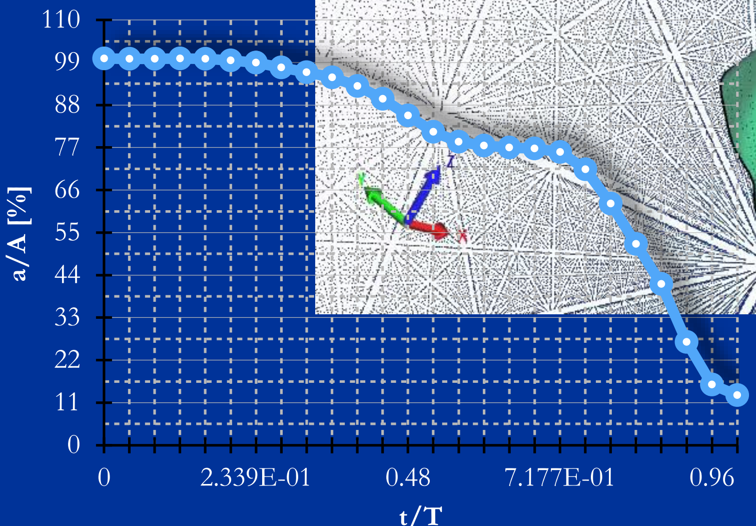
Real-time medical image based model developed at Siemens Healthcare

FSI Analysis - Normal Valve

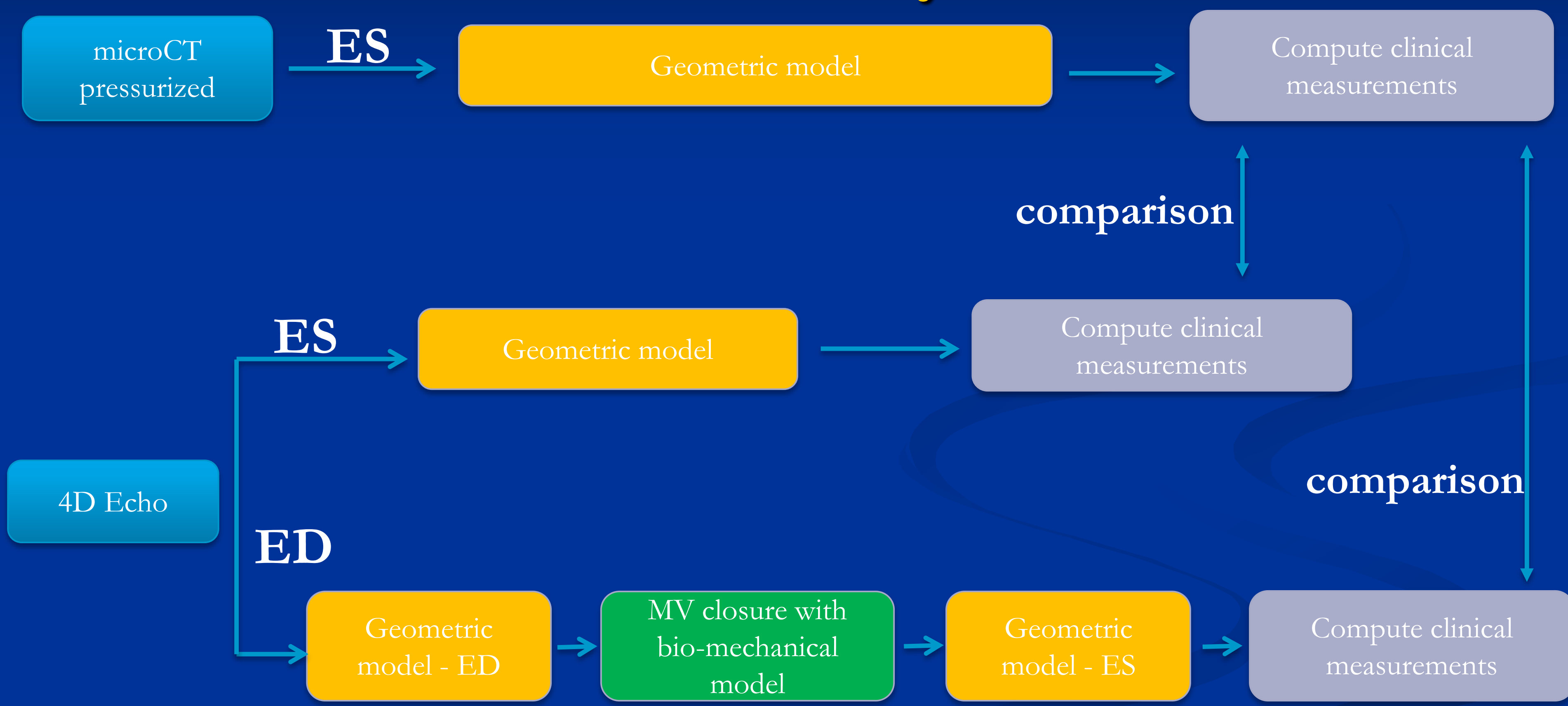
SPH Method







Validation Framework for Computational MV Models to Predict MV Closure Geometry



systole – **ES**, diastole - **ED**

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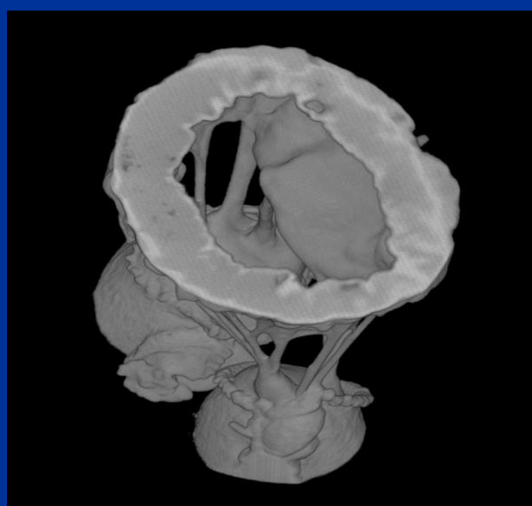
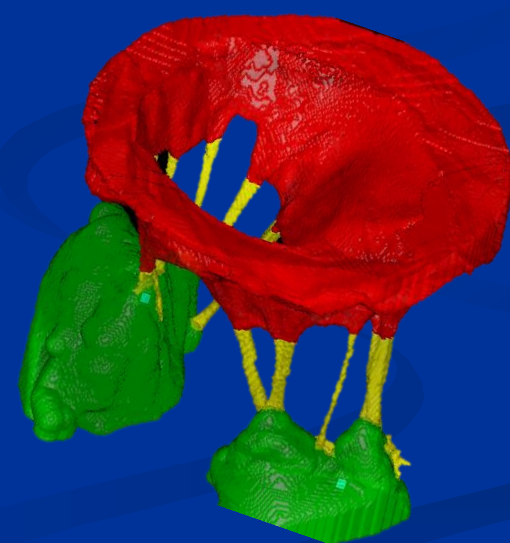
Geometric Model Extraction from microCT

- Developed prototype to process microCT volume received from Georgia Tech group and extract geometric models containing:
  - Anterior and Posterior leaflet meshes (red)
  - Papillary Muscles (green)
  - Mitral Valve Chordae Tree (yellow)

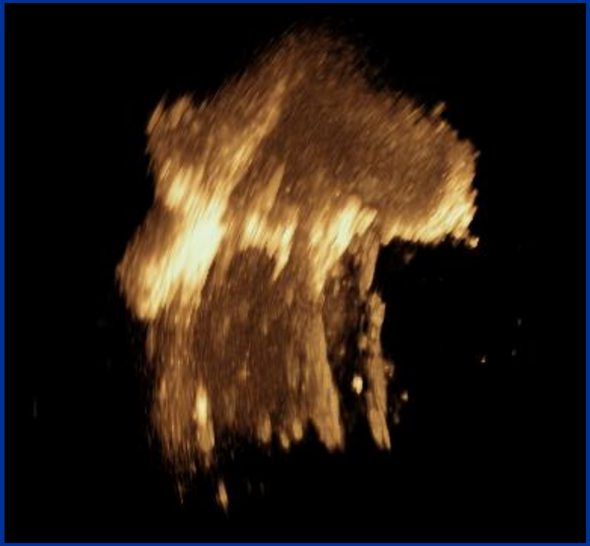


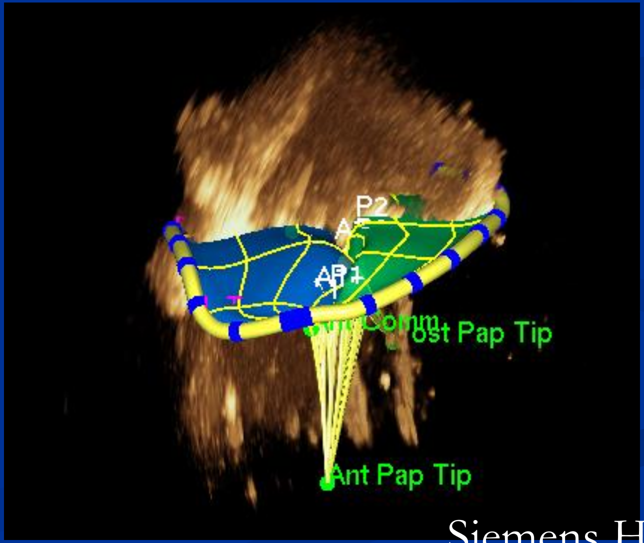


Siemens Healthcare

Geometric Model Extraction from 4D Echo

- Adapted Echo prototype to process ex-vivo 4D Echo data received from Georgia Tech group and extract simplified geometric models containing:
  - Anterior (blue) and Posterior (green) leaflet meshes
  - Papillary Muscles Tips (green points)





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Bio-mechanical Modeling of MV Physiology

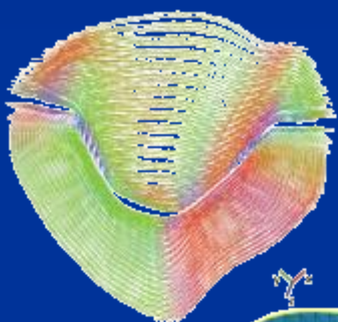
Mass

Rayleigh damping

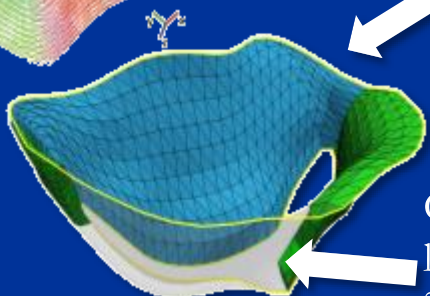
Displacement

Pressure

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{C}\dot{\mathbf{U}} + \mathbf{K}\mathbf{U} = \mathbf{F}_c + \mathbf{F}_p$$



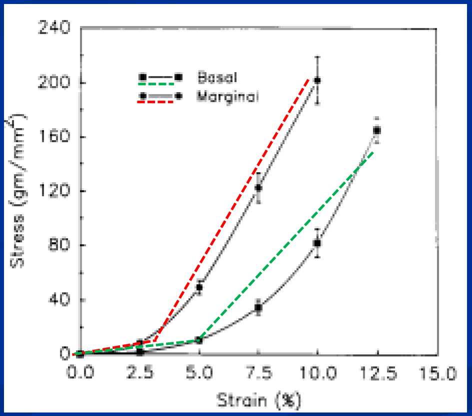
Leaflets: anisotropic linear elastic



Co-rotational tetrahedral FEM to cope with large deformations and rotations (Nesme et al., 2005)

Chordae: piecewise linear tensile springs

(Kunzelman et al., 1990)



T. Mansi et al., Medical Image Analysis, 2012

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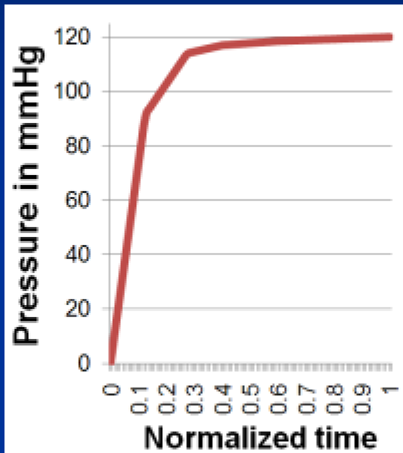
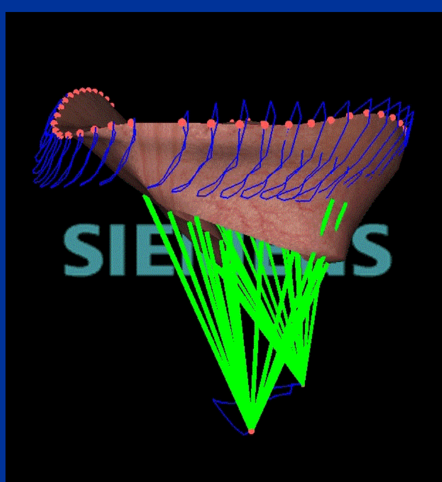
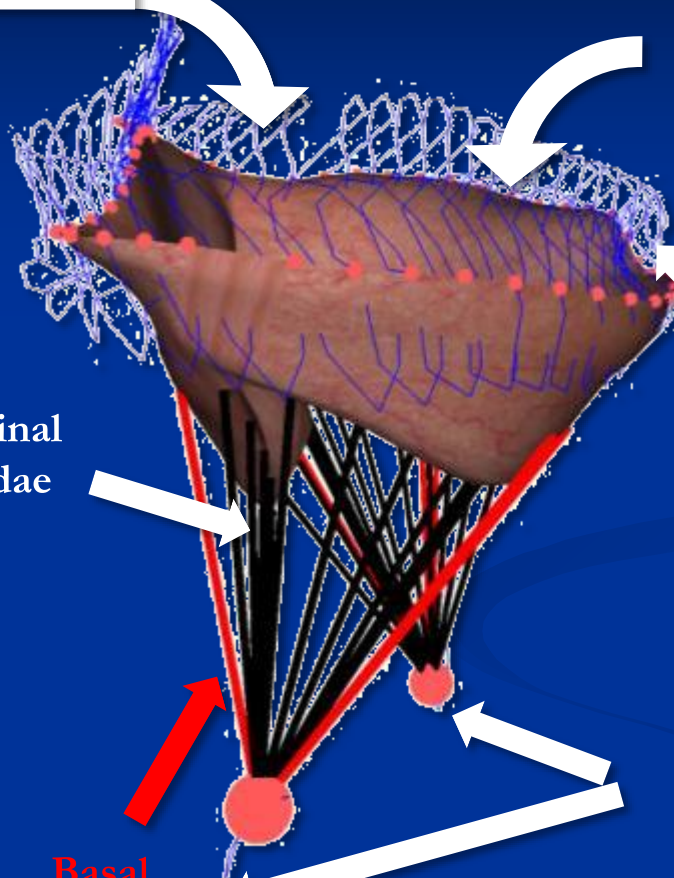
Boundary Conditions

Pressure: generic profile (from 0 to 120 mmHg)
(Prot et al., 2009)





Collisions and frictions: Handled automatically using collision springs

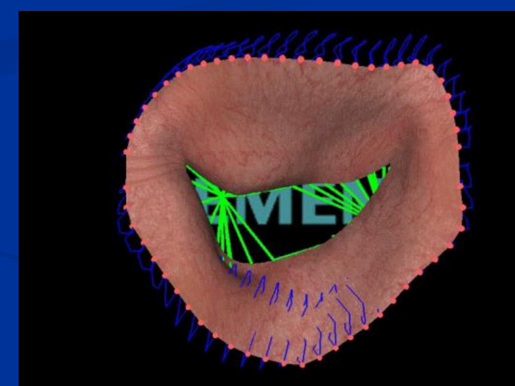


Marginal chordae

Basal chordae

Mitral annulus: Fixed in this experiment

Papillary tips: Fixed in this experiment



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Clinical Measurements for Quantitative Evaluation

- **Selected Clinical measurements relevant for short term post-mv surgery repair:**
- Coaptation Area
- Coaptation Length
- **As we use a parametric model, additional measurements can be easily added**
- Leaflet Tenting Height

Tenting Area, and Tenting Volume

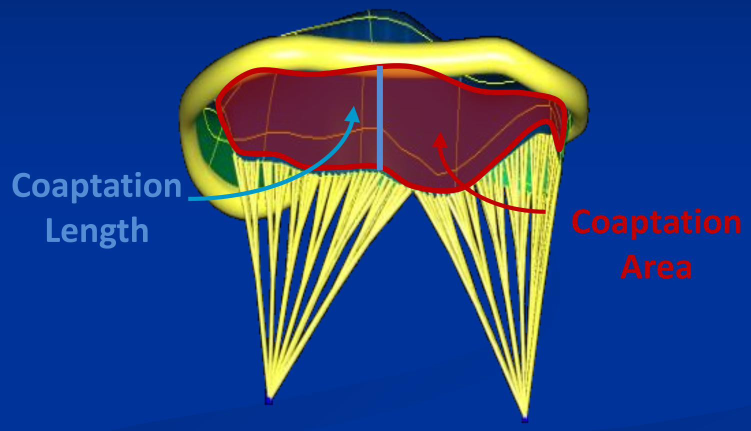
Annular-Height-to-Commissural-Width Ratio (Saddle Geometry)

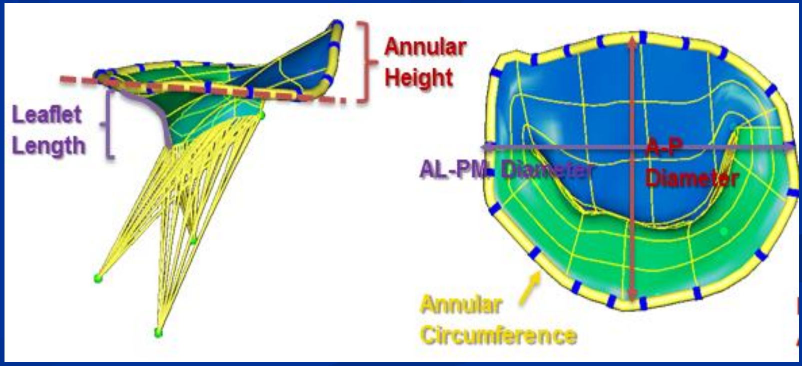
Mitral Annular Area

Circumference

Septal-Lateral Diameter

Transverse Diameter





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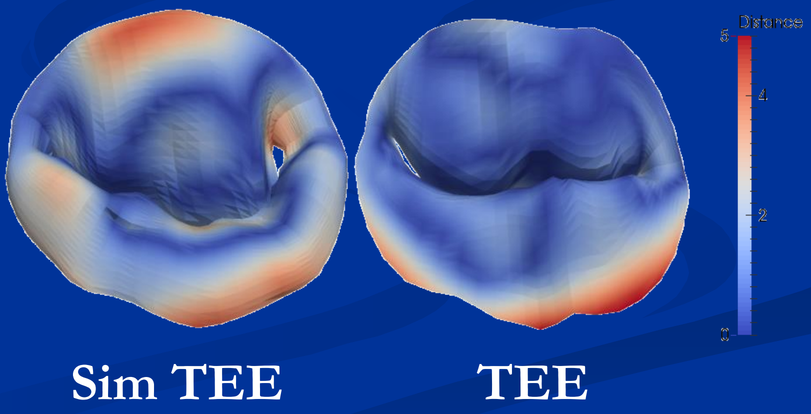
Quantitative evaluation

- Evaluation of mitral valve closure geometry from TEE, microCT (µCT) and simulated closure from TEE (Sim TEE) on 3 data sets.
- Promising correlation between biomechanically-closed TEE MV and microCT ground truth
- Abstract submitted to BMES (04-23-2014)

	Coaptation Length [mm]			Coaptation Area [mm^2]		
	TEE	µCT	Sim TEE	TEE	µCT	Sim TEE
Data Set 1	2.62	2.41	2.71	41.2	46.10	45.80
Data Set 2	2.00	1.92	2.05	50.07	48.23	51.42
Data Set 3	2.25	2.12	2.32	56.17	53.17	58.07



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Summary

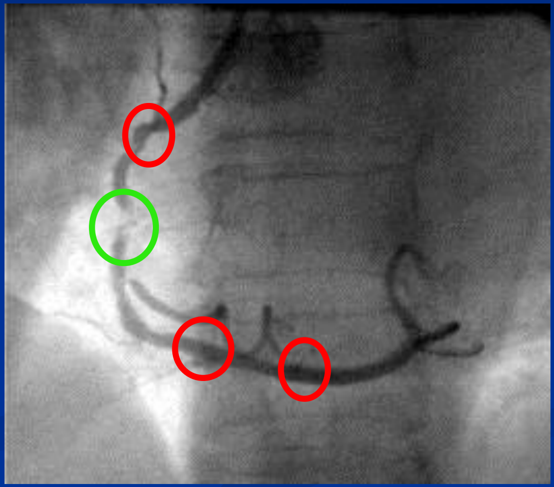
- Computational MV models need high fidelity boundary conditions & validation:
  - High fidelity MV anatomy obtained through state of the art imaging (μCT, 3D Ultrasound, High speed stereo photogrammetry)
  - Hemodynamic boundary conditions are captured using direct flow and pressure instrumentation
  - Force measurements on MV verify CFD model and adjust material properties models
  - Complex flow fields can be captured through Stereoscopic Particle Image Velocimetry for model validation

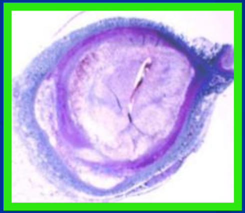
ENGINEERING APPROACH TO CLINICAL PROBLEM

Develop methodology to quantify in vivo patient specific hemodynamic environment from clinical imaging data that achieves the following:

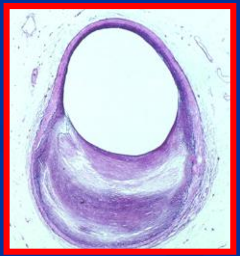
- accurately models physiologic environment
- technically sound (i.e., robust, validated)
- provides clinically useful information
- adaptable to numerous clinical pathologies (disease state, anatomic location)
- *reasonable* time requirements

Detection of Vulnerable Plaques





stenotic plaque



potential TCFA

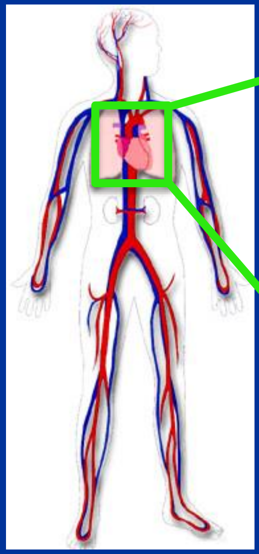
Courtesy of P. Stone,, TCT 2011

Clinical Questions

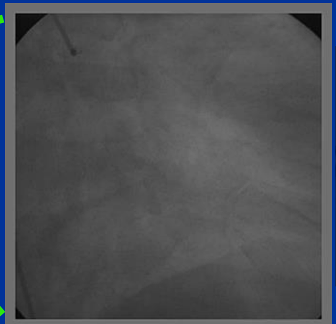
1. Following presentation of coronary disease, can we predict plaque evolution?
2. What is the role, if any, of hemodynamics in cardiac allograft vasculopathy?

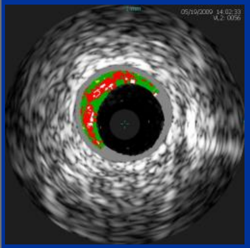
Lucas H. Timmins, Ph.D., et al.

Overview of GT/Emory Computational Methods

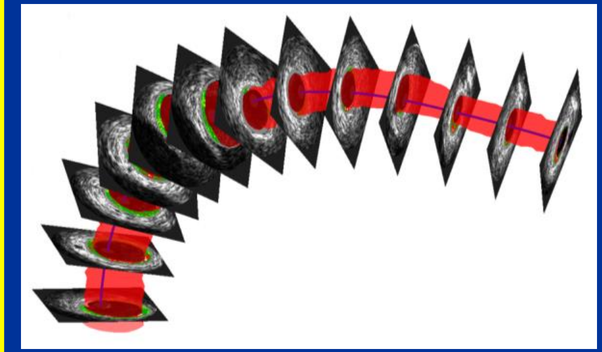


Clinical Data





Geometry Reconstruction



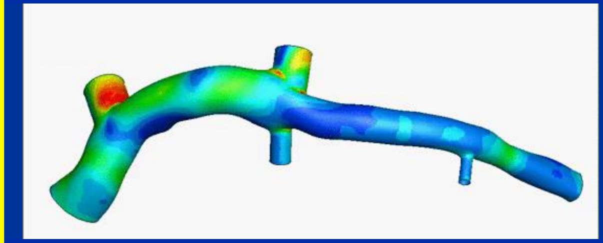
boundary conditions, numerical methods

Verify calculations

Lucas H. Timmins, Ph.D., et al.

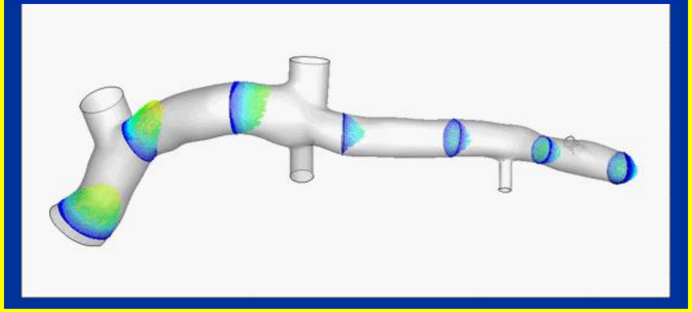
Hemodynamic Parameters

(e.g., WSS, oscillations, gradients)



Calculate Flow-field

(i.e., reproduce flow environment)

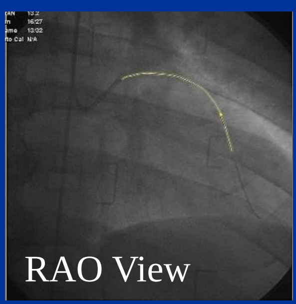


3D Geometry Reconstruction

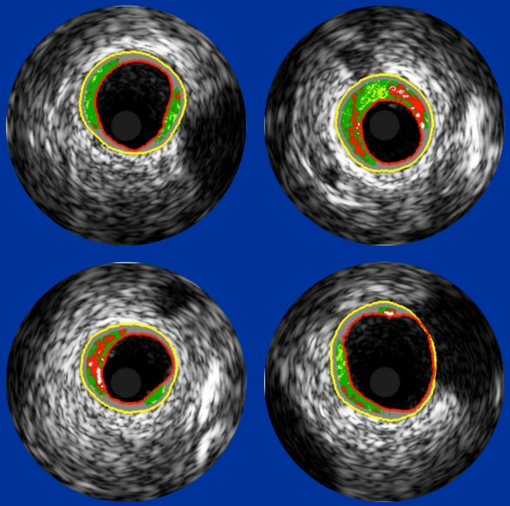
Utilized combination of ANGiography and intravascular UltraSound (ANGUS)

- 3D space of IVUS catheter determined from <u>biplane</u> data
- lumen borders are segments from VH-IVUS images
- images stacked perpendicular to wire, apply global rotation
- branches extended perpendicular from main vessel

Laban et al., *Comp. in Cardiol*, 1995
Krams et al., *ATVB*, 1997

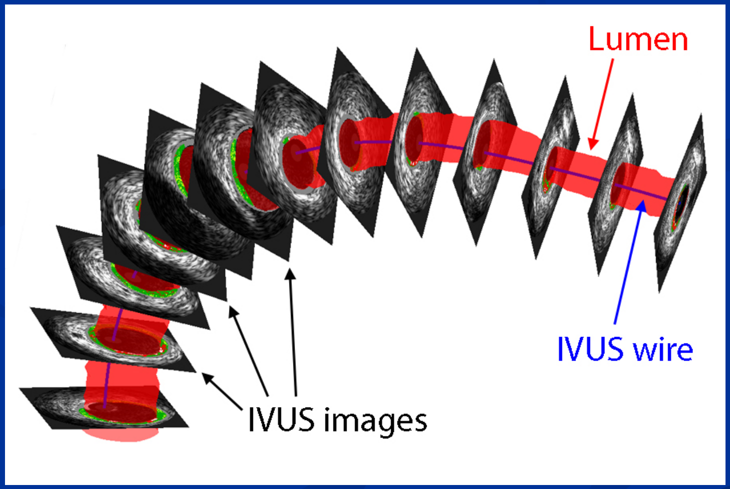


+



~ 120 per patient

=



* can also utilize OCT images

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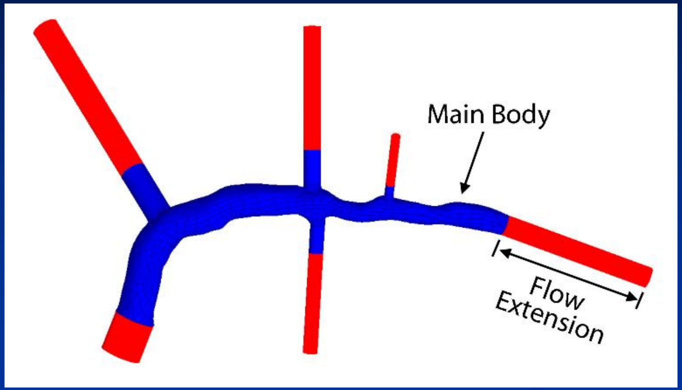
COMPUTATIONAL FLUID DYNAMICS (CFD) TECHNIQUES

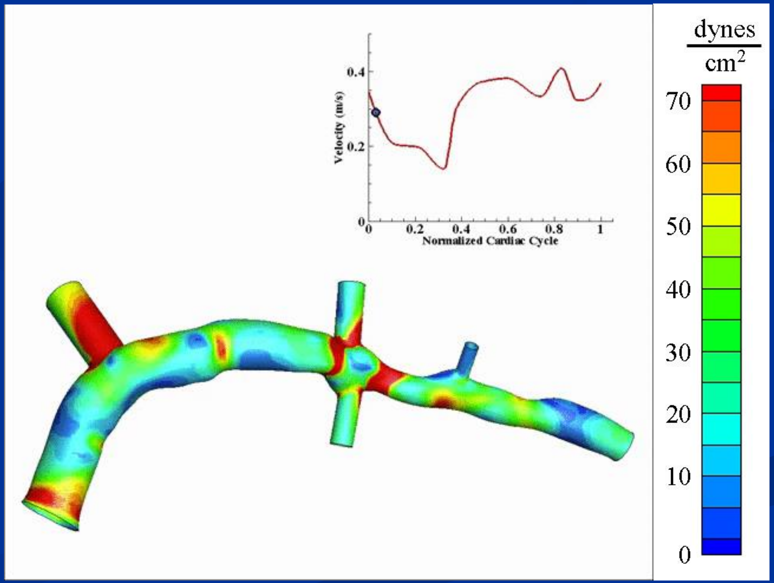
Flow extensions are added
- inlet: smooth transition into domain
- outlet: fully developed flow



Geometry discretized with boundary layer to resolve near-wall flow patterns

Boundary Conditions
- inlet: pulsatile (blunt) velocity waveform
- outlet: pressure-free (traction-free)
- wall: no-slip (i.e., $\vec{v} = 0$), rigid

Newtonian fluid ($\rho = 1060\ kg/m^3,\ \mu = 3.5\ cP$)



Post-process (node) data to quantify WSS vectors
- temporally average magnitudes; yield time-averaged WSS

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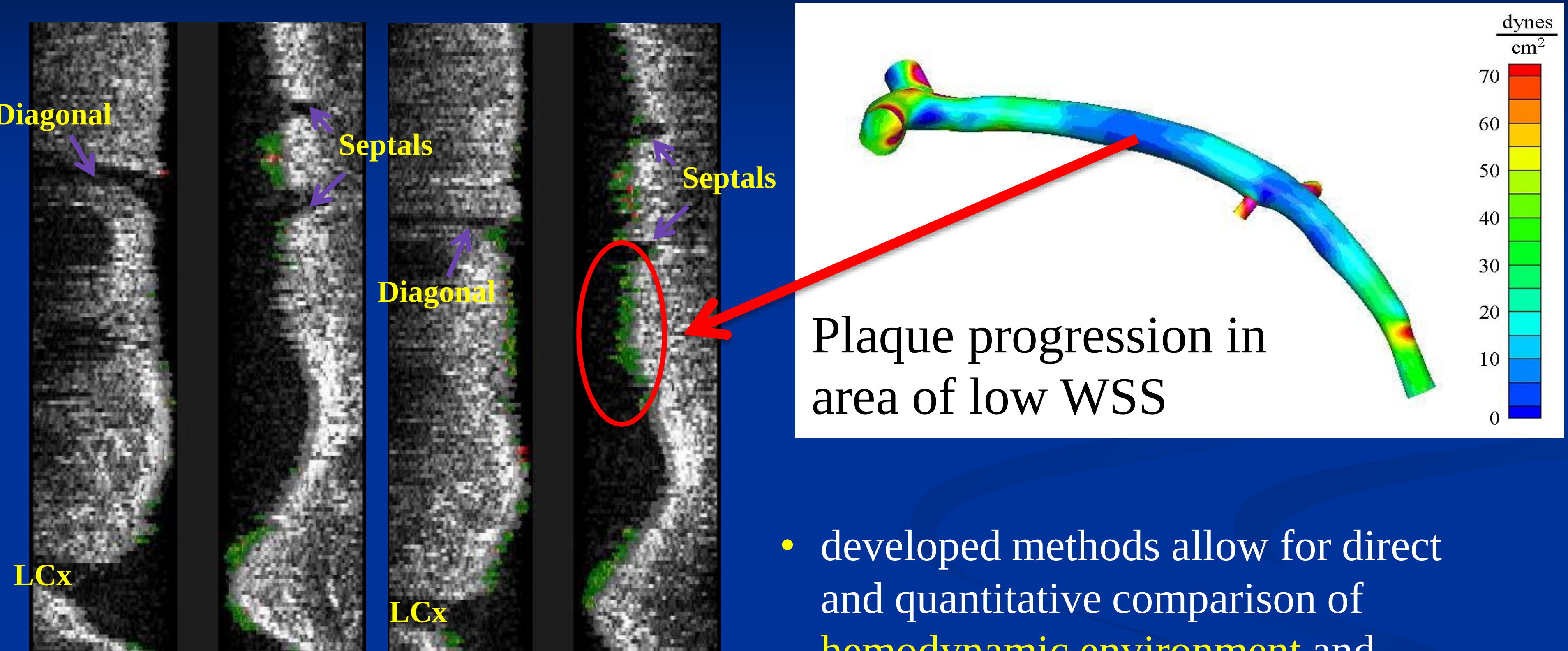
Representative Association of Baseline WSS and Plaque Progression



Baseline Pullback

Follow-up Pullback
(6 months later)

- developed methods allow for direct and quantitative comparison of hemodynamic environment and clinically measured coronary artery disease progression

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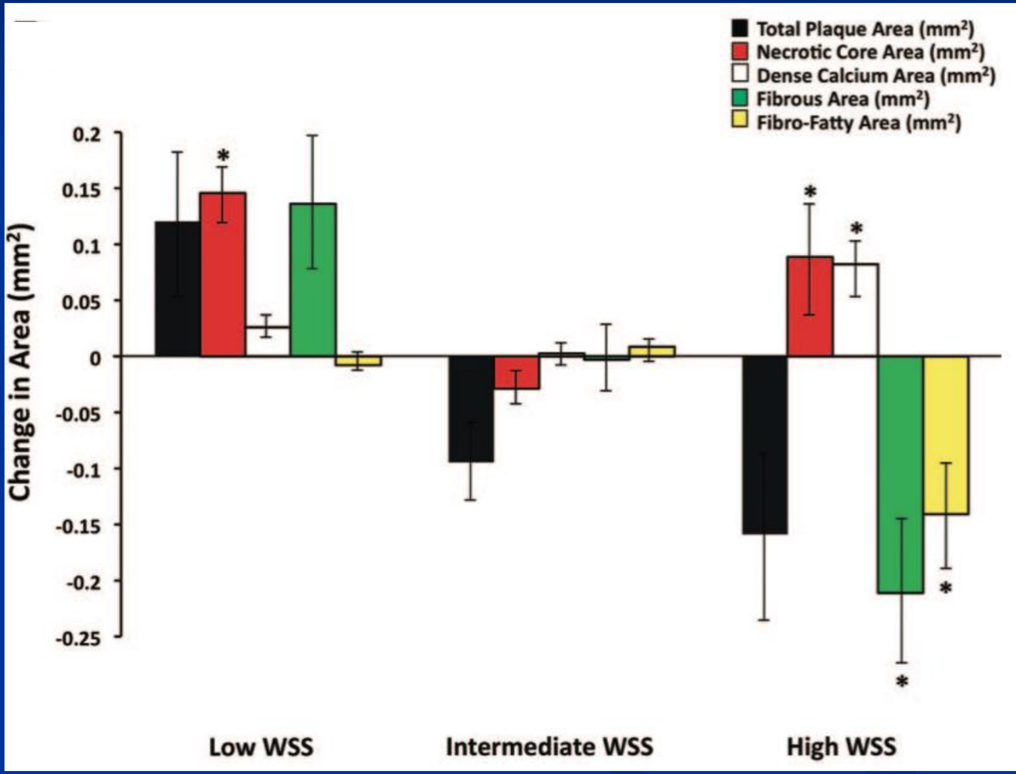
Association of Wall Shear Stress and Change in Plaque Composition Over 6 Months

Examined association between wall shear stress and plaque progression in 20 patients

- Low WSS: plaque progression
- Intermediate WSS: plaque regression
- High WSS: progression to vulnerable plaque (significant increase necrotic core tissue)

Utilized computational fluid mechanics as clinical marker to identify variations in coronary artery disease progression



Samady, Eshtehardi, McDaniel, Suo, Dhawan, Timmins, Quyyumi, Giddens, *Circulation*, 2011

Lucas H. Timmins, Ph.D., et al.

Translational Impact

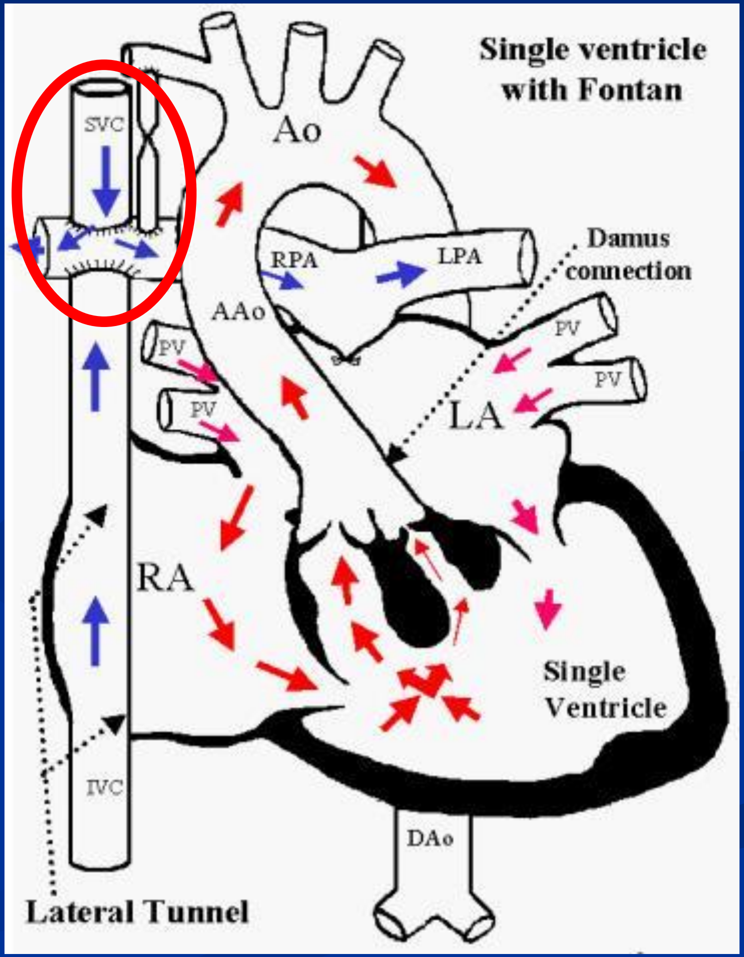
From Bench to Bassinet

Image-Based Surgical Planning

- A novel means to pre-operatively evaluate blood flow characteristics
- Allow the possibility to tailor the surgery to the patient-specific scenarios
- Here, we present our experiences of surgery planning of single ventricle heart defect palliations

Total Cavopulmonary Connection

- The Total Cavopulmonary Connection (TCPC) is a modification of the original Fontan surgical repair
- TCPC results in single ventricle driving flow
- Control of power loss may be critical
- Requires tool for clinical assessment of TCPC performance

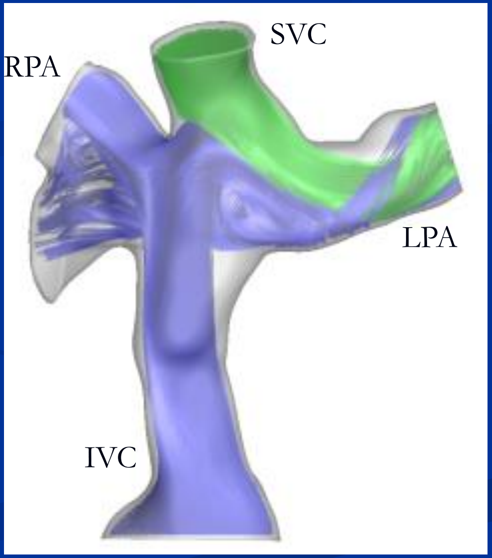


Complications

- Limited Exercise Capacity
- Pulmonary arteriovenous malformations (PAVMs)
- Progressive Cyanosis from shunting
- Thromboembolism
- Arrhythmias
- GI System Disorders
  - Protein Losing Enteropathy
  - Feeding Disorders
  - Liver Failure

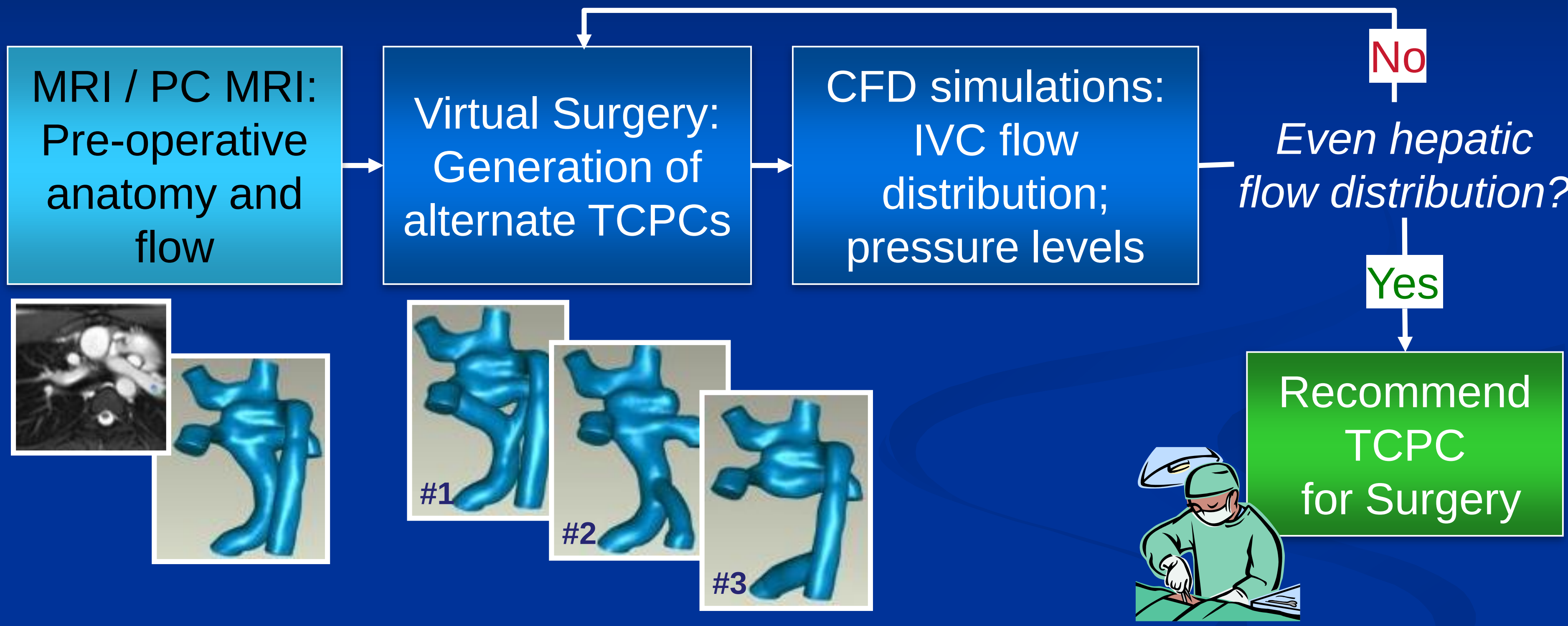
Complex TCPC Hemodynamics

- Relevant to some of these long-term complications
- Requires tool for clinical assessment of TCPC performance
- Parameters of interest:
  - central venous pressure
  - power loss across the connection
  - balanced flow to the lungs

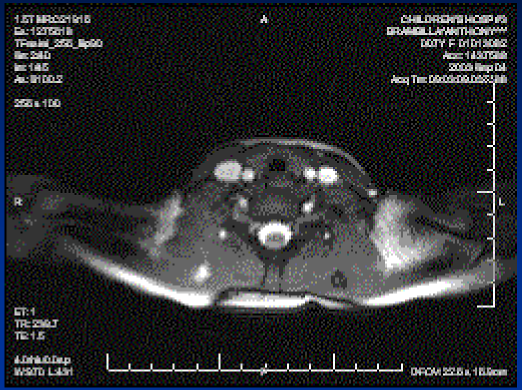


Surgical Planning of TCPC: Methodology

Methodology Overview



Methodology – 3D reconstruction from MRI



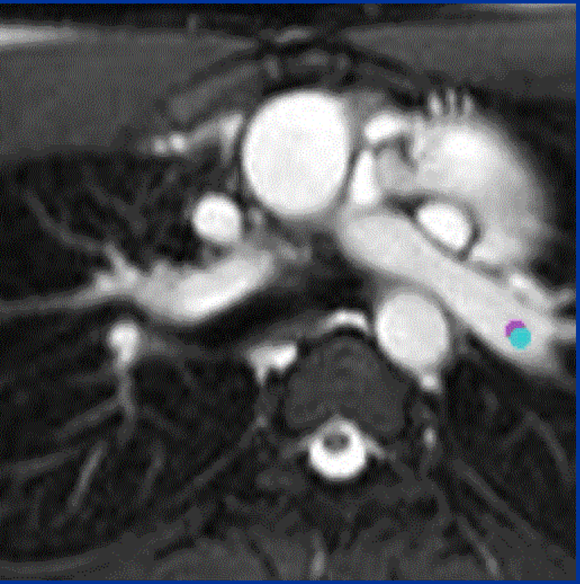
Patient MRI

Anonymization & interpolation

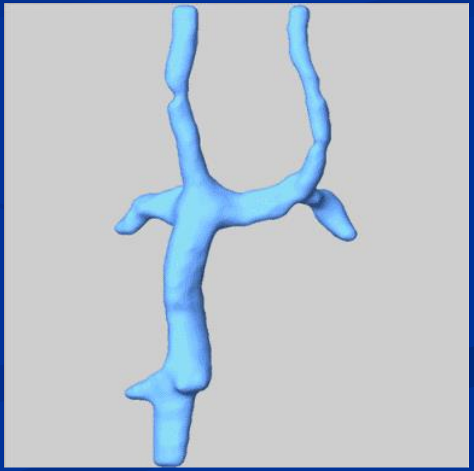
Stack of interpolated images

Segmentation

Bouncing Ball algorithm



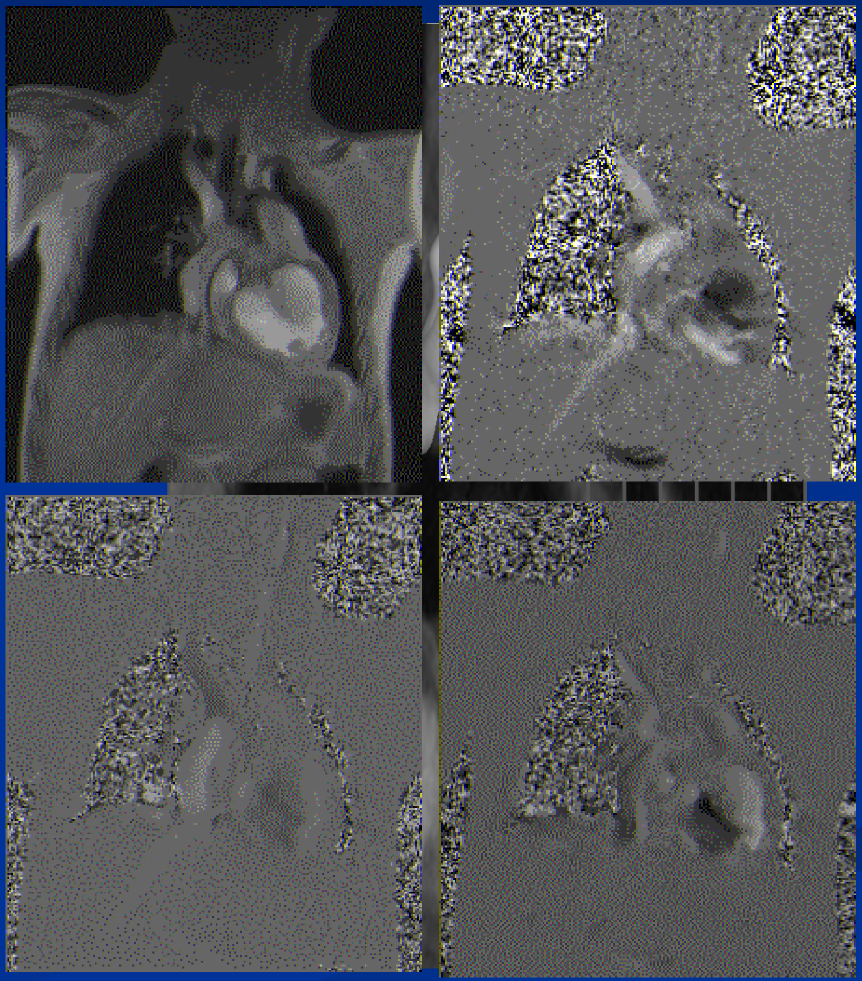
3D Reconstruction



In Vivo Flow Fields – PC MRI

[Sundareswaran KS, J Magn Reson. Imaging, 2009]

- Sequence: BFFE (PC MRI)
- Direction: Coronal
- N = 5-7
- Slice Thickness: ~6 mm
- TR/TE = 42/3.1 – 69/4.8
- Pixel Size ~=1 x 1 mm^2
- Matrix Size: 256 x 256
- Directions: 3 (AP, FH, RL)
- VENC: 80 (FH), 80 (RL), 40 (AP)



3D PC-MRI Velocity Reconstruction Methodology

Patient MRI *(DICOM Images)*

Segmentation

SNAKE segmentation

Semi-automatic Noise Removal

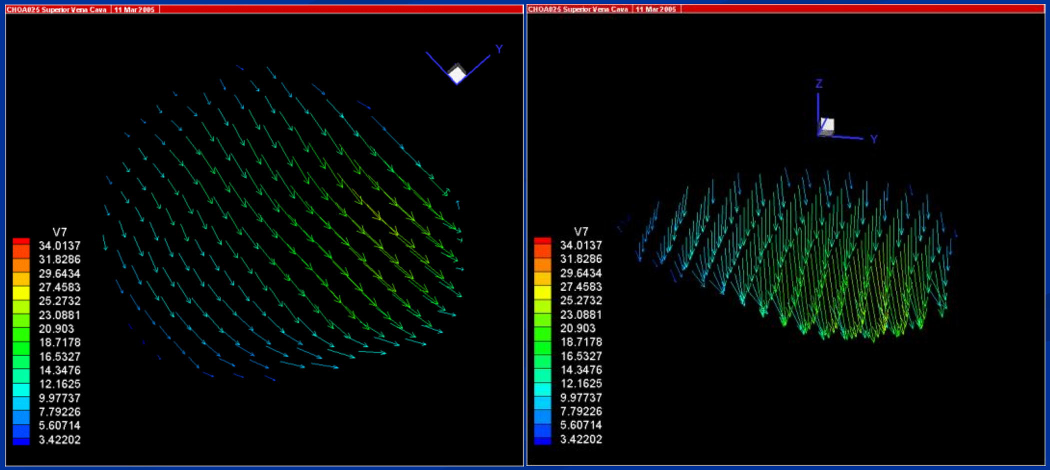
Based on Fuzzy Logic

<u>Functional Analysis</u>
Regional Flow Parameters
Vessel Area change
Pulsatility, etc.

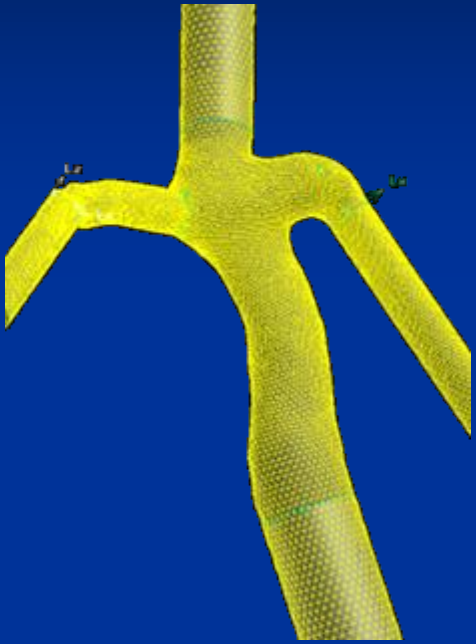
Boundary Conditions for Unsteady CFD Simulations

~20 Cardiac Phases

SVC - Flow Vectors



Computational Fluid Dynamics (CFD)



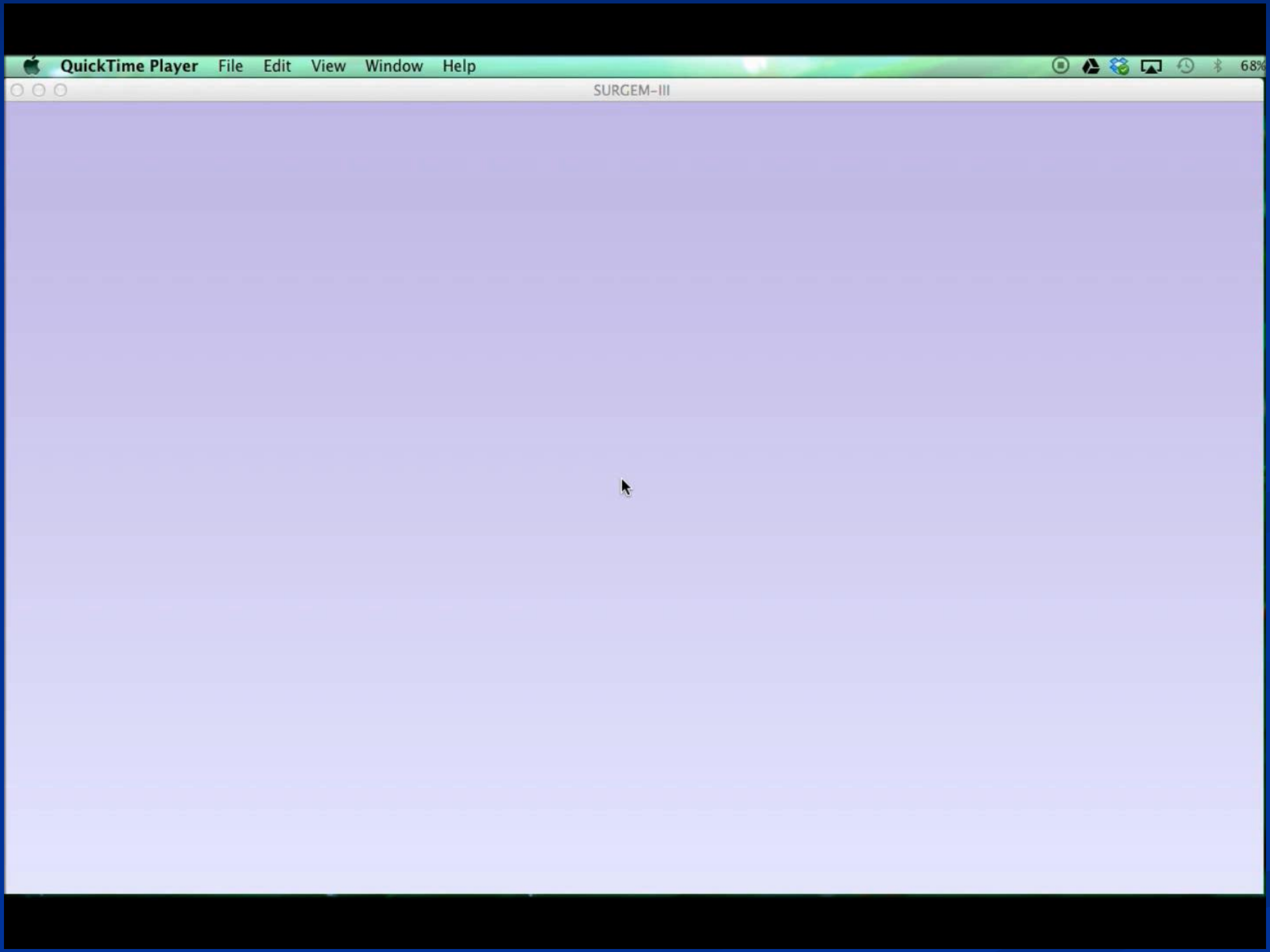
- Method for numerically solving the Navier-Stokes equations of fluid motion for a given model
- Widely used in studying cardiovascular flows by using patient-specific vascular models for the fluid domain → requires input from medical imaging
- CFD yields better spatio-temporal resolution than currently possible with medical imaging
  - But patient-specific modeling is dependent on high fidelity imaging to ensure proper *boundary conditions* on the numerical simulations.

Surgical Planning: Preliminary Designs and What-if Scenarios?

Develop a framework for the surgeon to:

- Envision different scenarios before going into the operating room
- Quantitatively evaluate flow for each of these scenarios
- Estimate the power losses for each scenario
- Optimize the flow distribution to both lungs

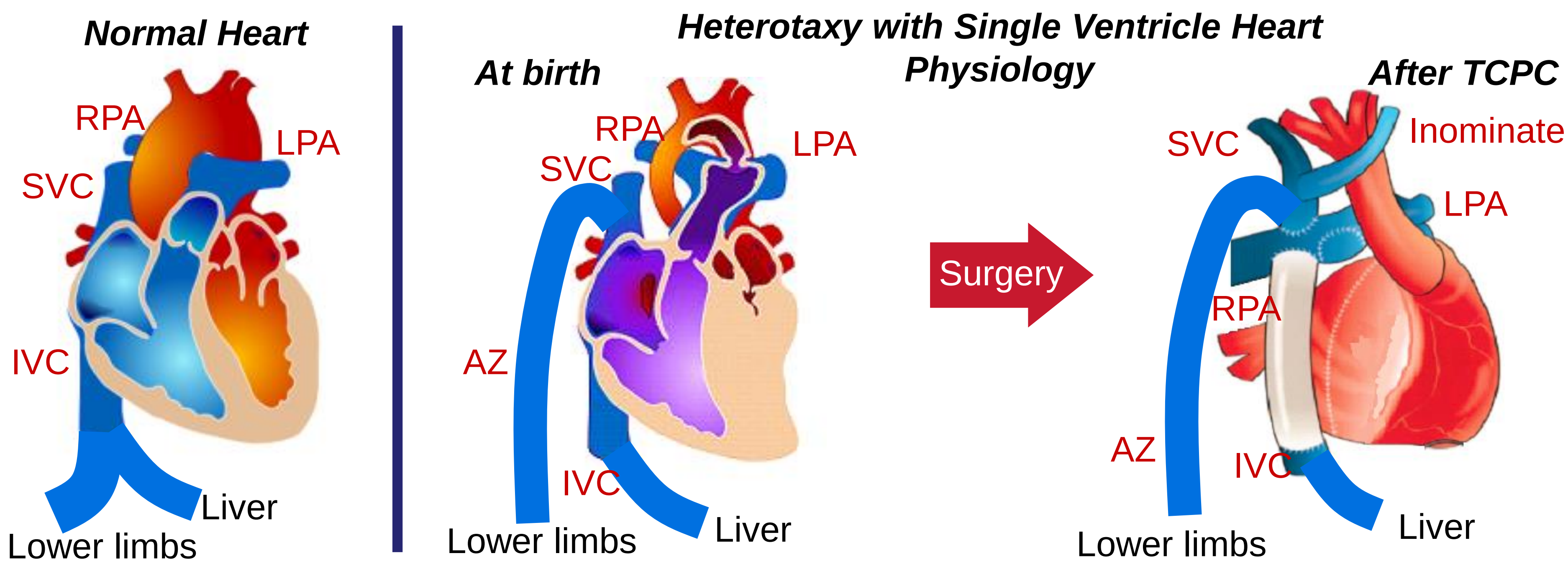
Virtual Surgery Environment



CASE 1:
Correcting Failing Fontans

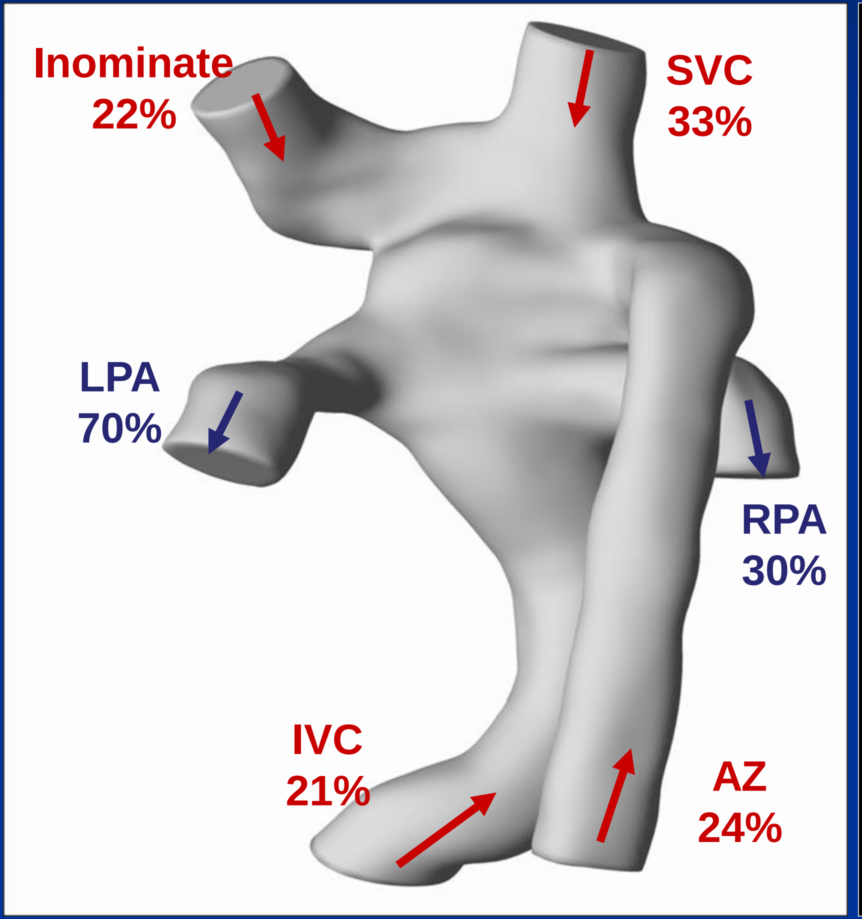
2007: Failing Fontan patient presented to CHOP with

- 4 yr. old; Heterotaxy syndrome; Functionally-single ventricle
- Arterio-venous malformations (AVMs) in the left lung.

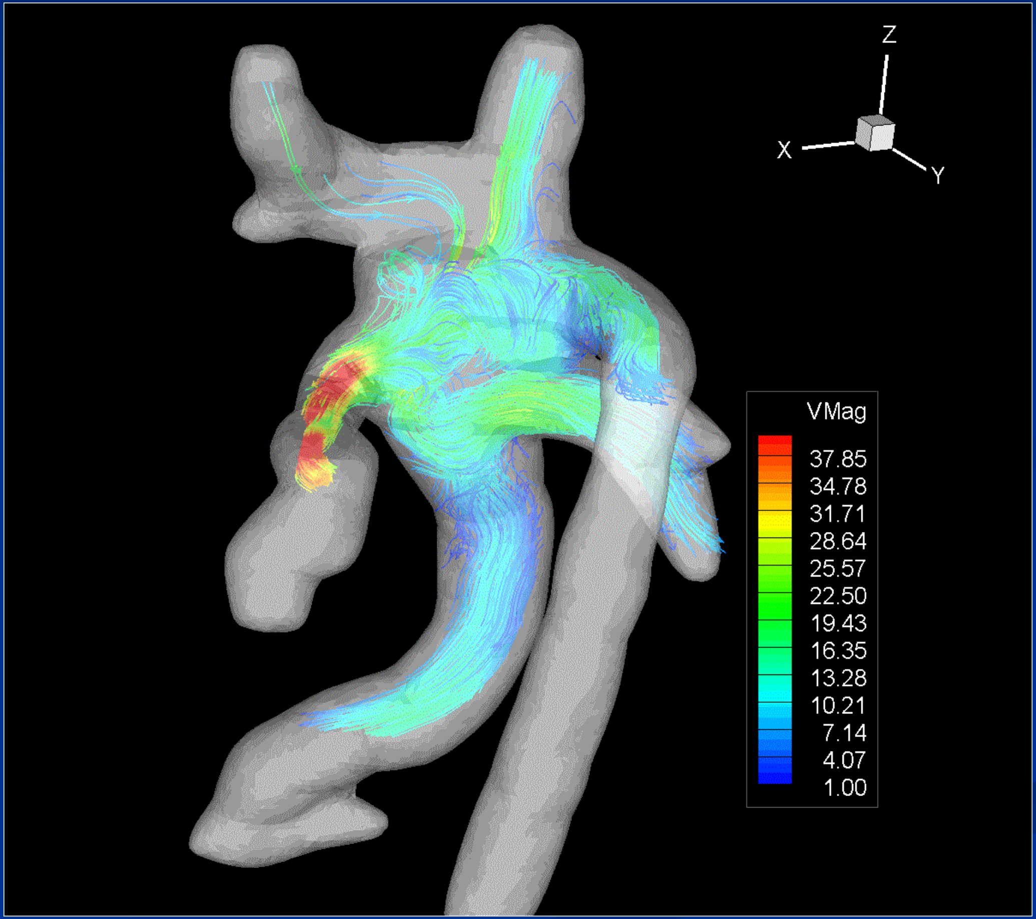


Patient's Anatomy and Flow

TCPC anatomy (from MRI)

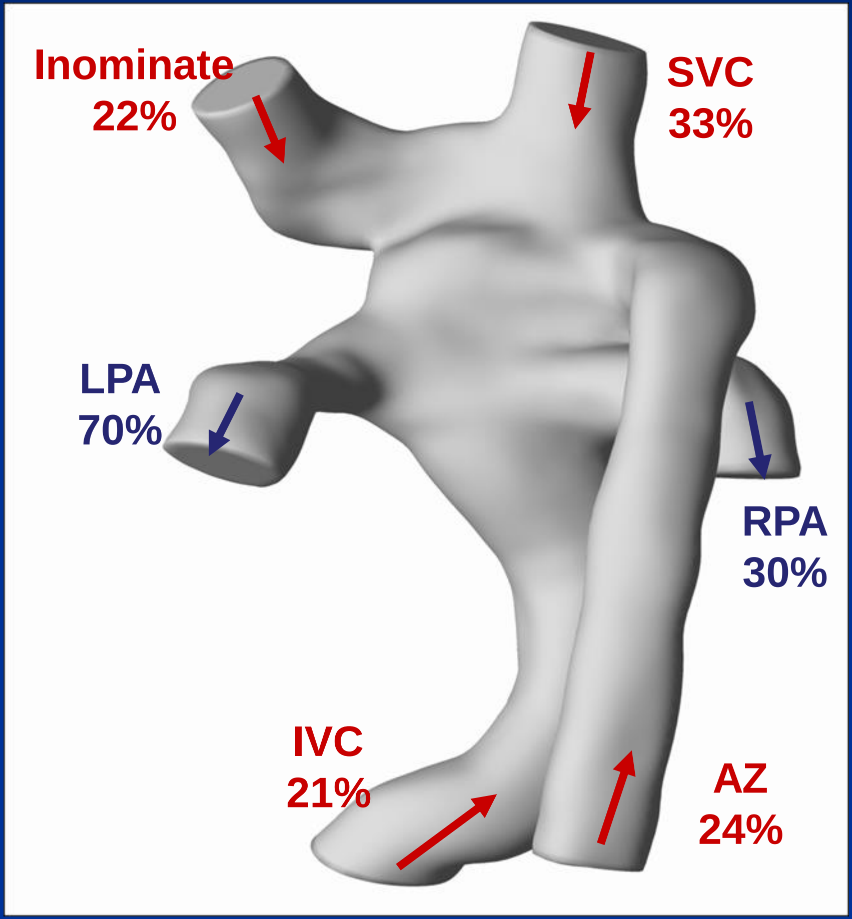


3D PCMRI flow field

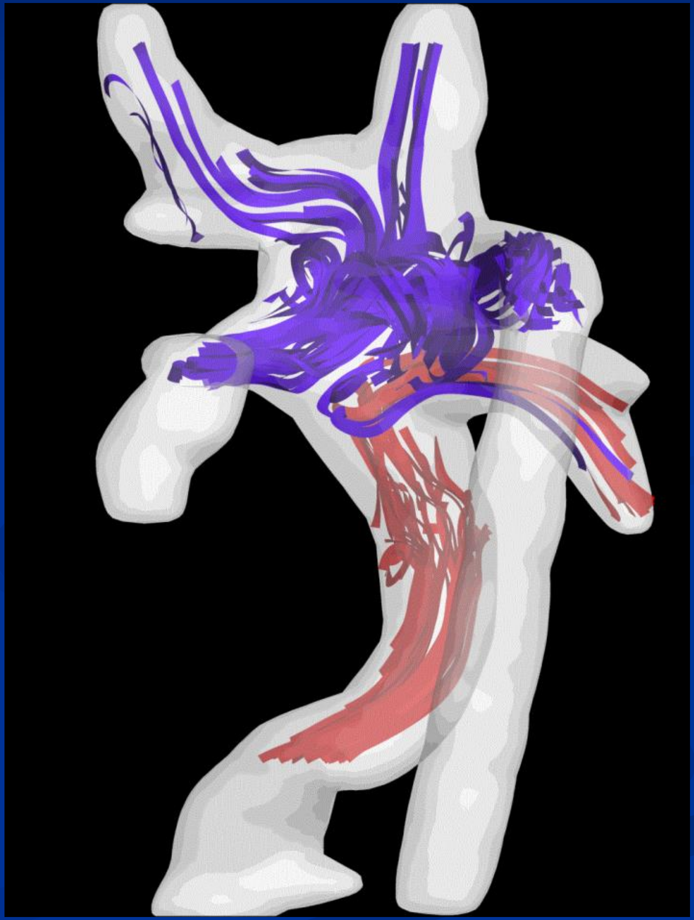


Patient's Anatomy and Flow

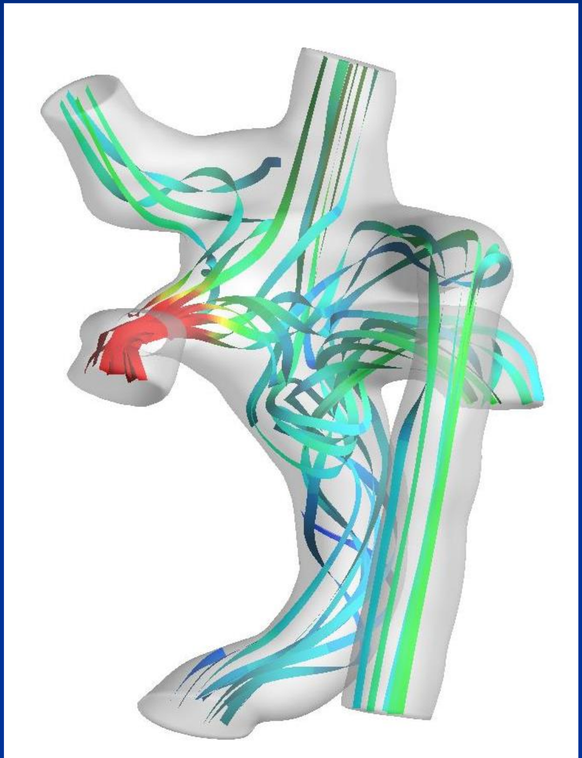
TCPC anatomy (from MRI)



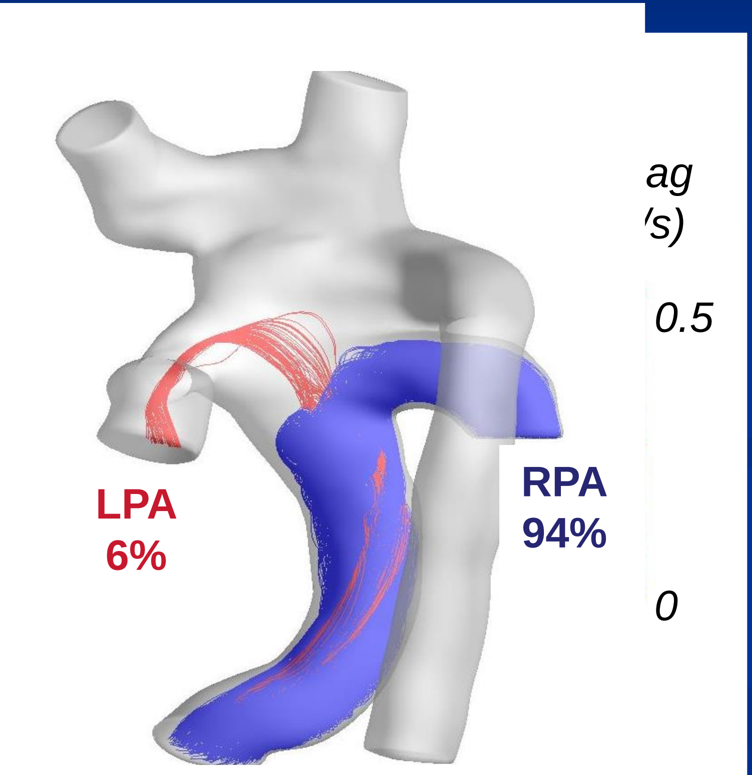
3D PCMRI flow field



Simulations of Pre-Operative Anatomy



CFD

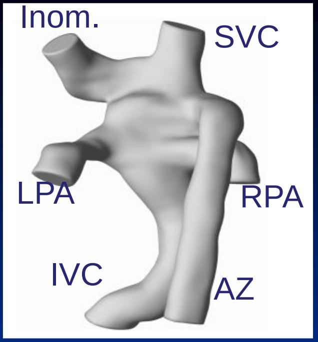


Hepatic flow distribution

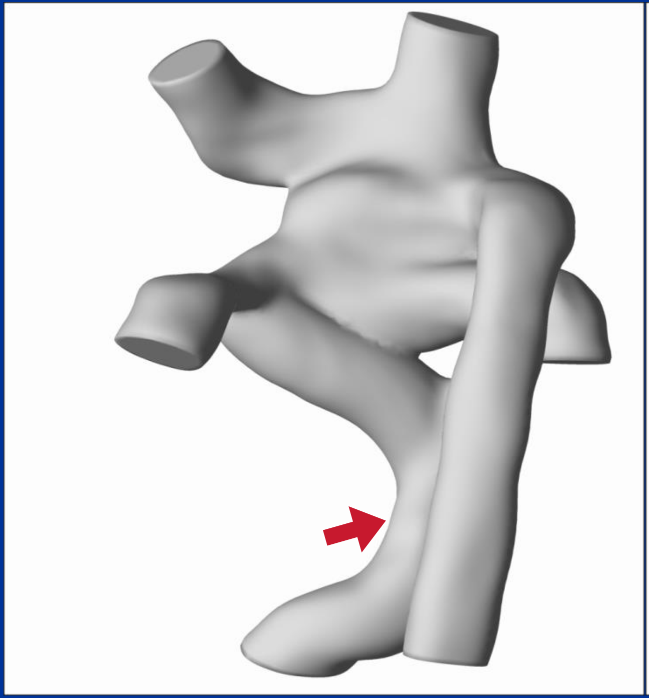
Objective

- ***To plan the re-operation, using image-based computational fluid dynamics (CFD), that will best distribute hepatic factors to the right and left lungs in order to reverse the AVMs***
  - Assess pre-operative hemodynamics to better understand problem
  - Investigate alternate TCPC designs and identify the one that best distributes hepatic blood flow

Investigated Options

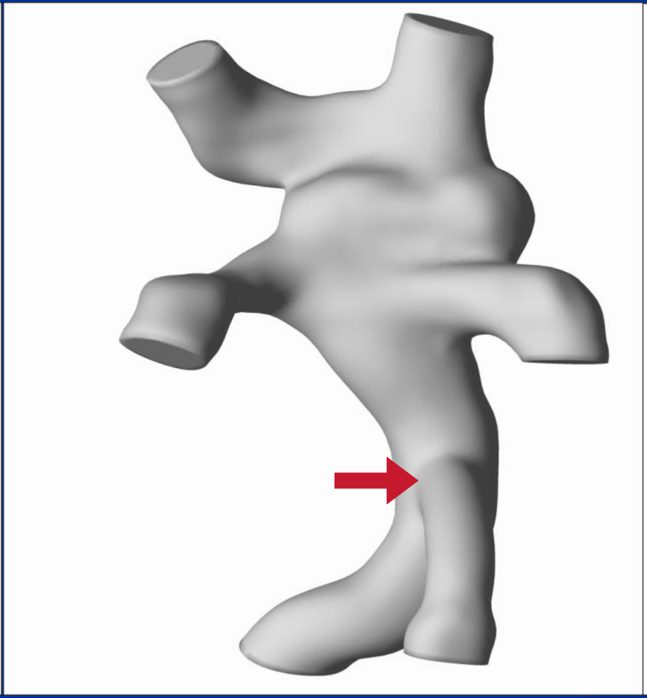


Option 1



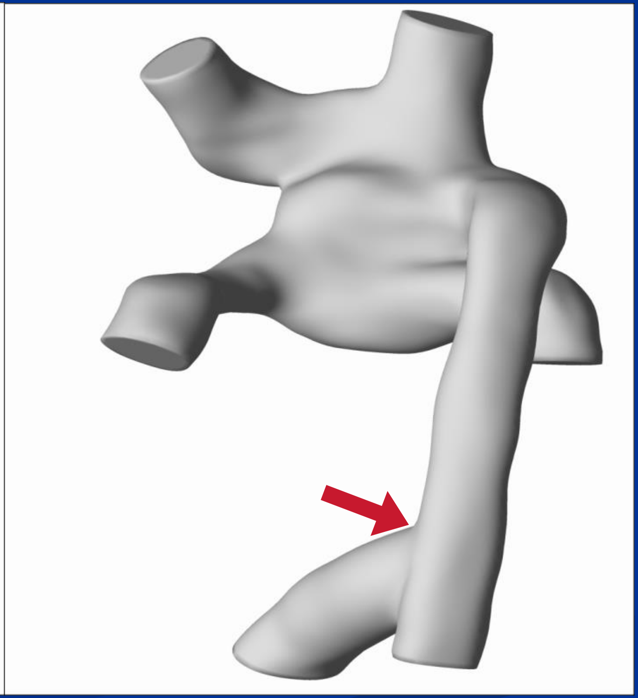
Split IVC in 2 branches

Option 2



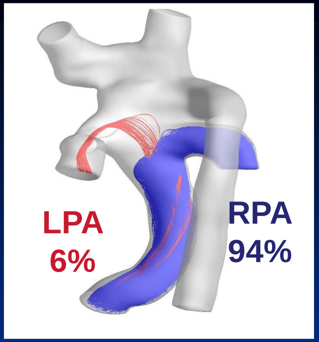
Connect AZ to IVC

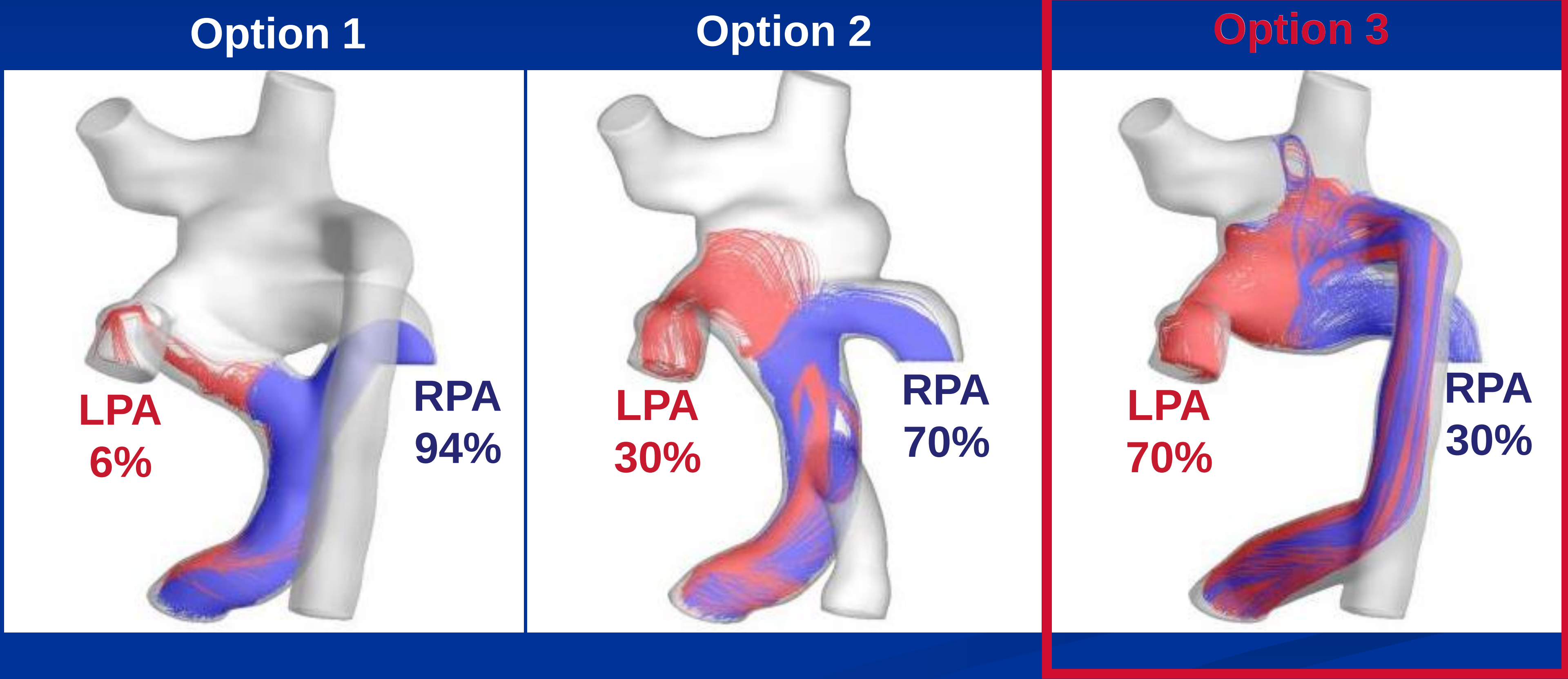
Option 3



Connect IVC to AZ

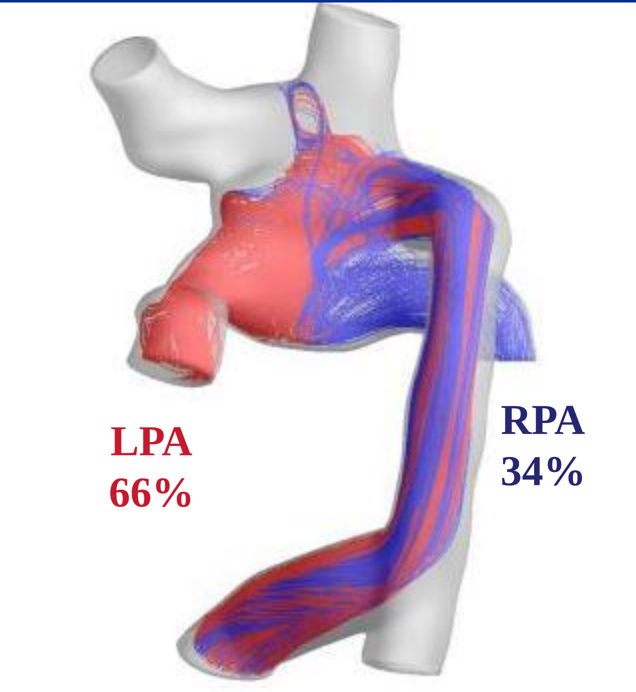
Performance of Investigated Options



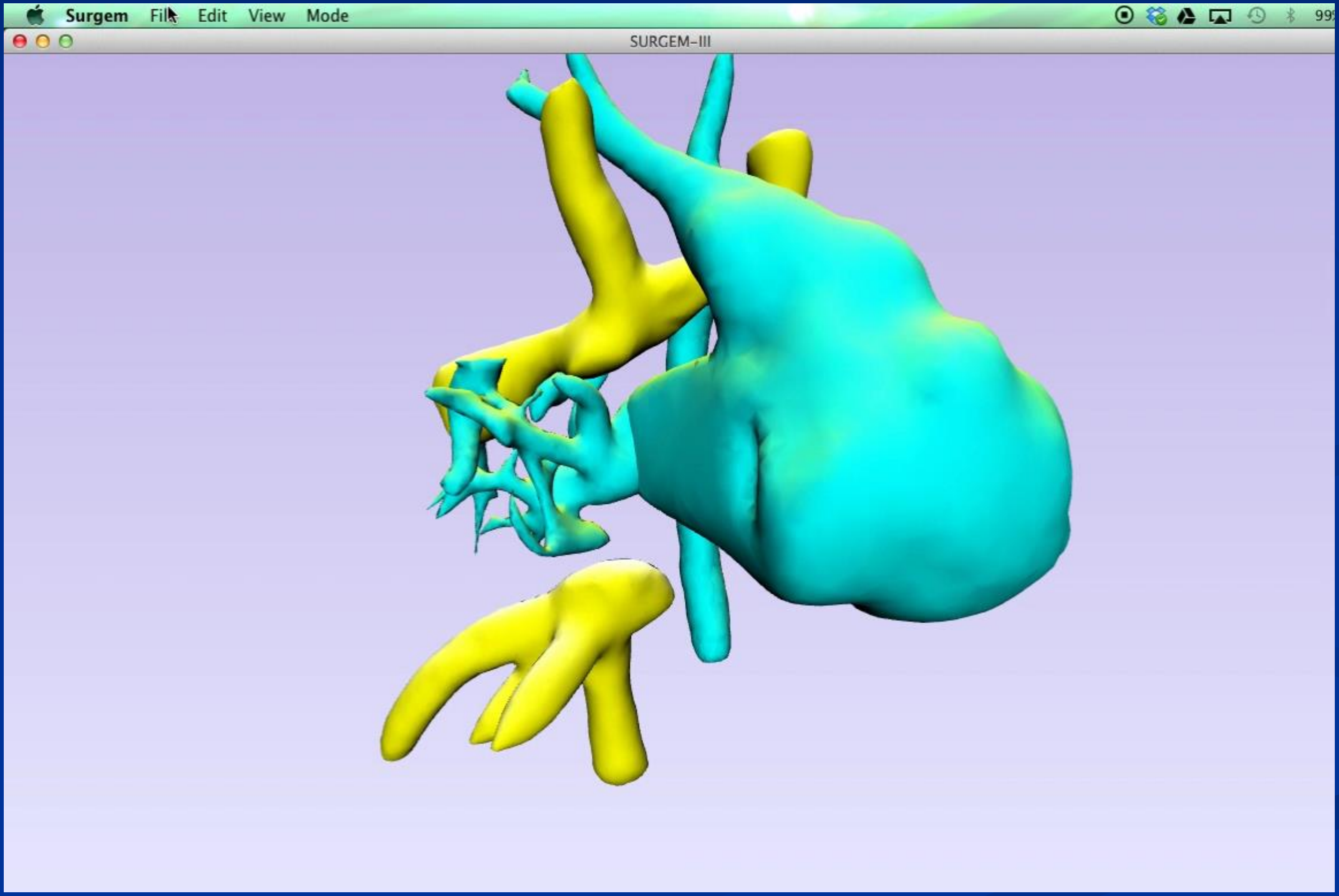


Surgery and Clinical Follow-up

- Surgery performed in February 2008
- Five month follow-up:
  - 94% Oxygenation saturation levels (vs. high 60's pre-operatively)
  - Significantly better clinically



Surgical Planning of the Y-graft



Translational Test Bed:

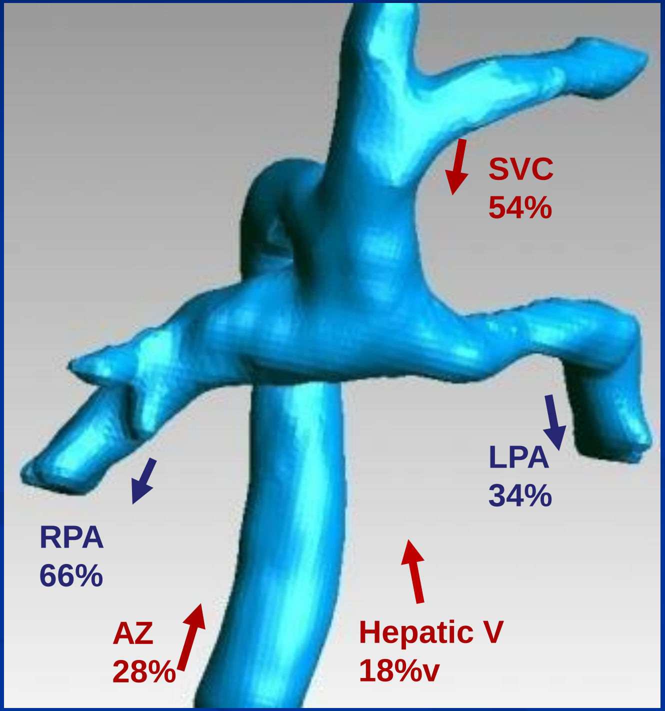
Y-graft application

Comparison to post-operative state

CASE 2:
Planning Initial Fontan Procedure

- 2 yr. old patient
- HLHS and interrupted IVC
- AVMs in right lung

Kawashima anatomy

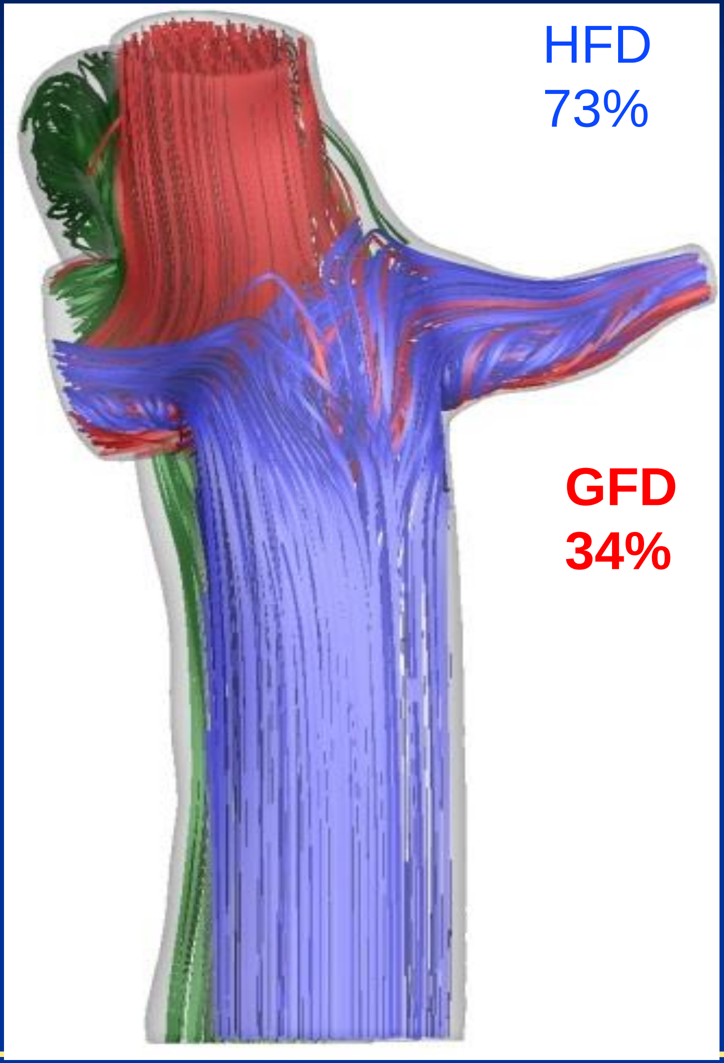


CHOP_M9

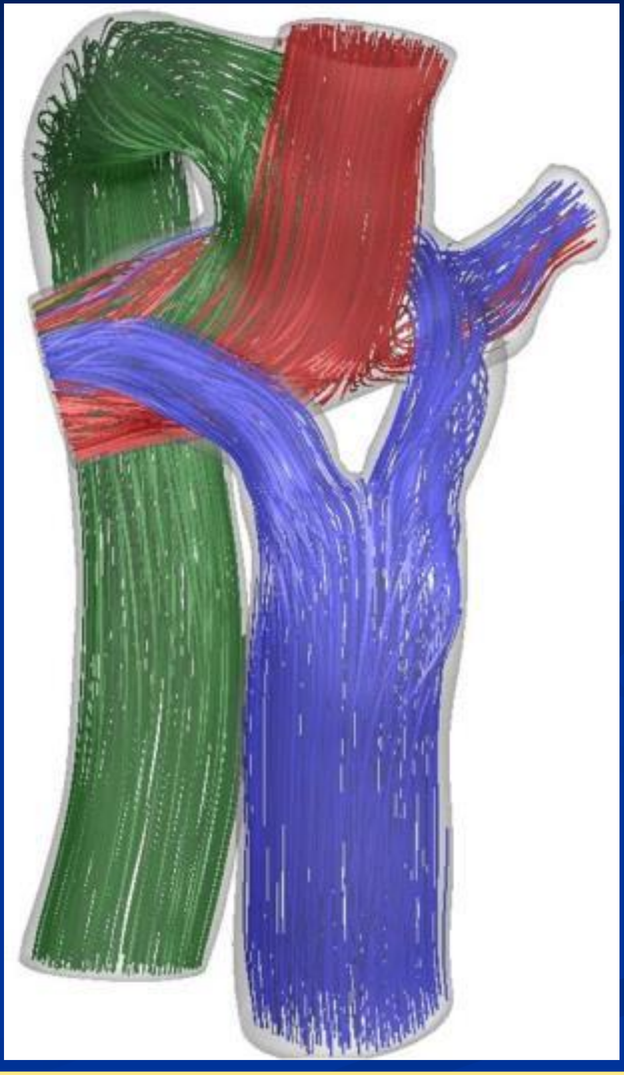
Design Hepatic Baffle to Avoid Poor Flow Distribution Scenarios

Graft Bifurcation to Reduce Sensitivity

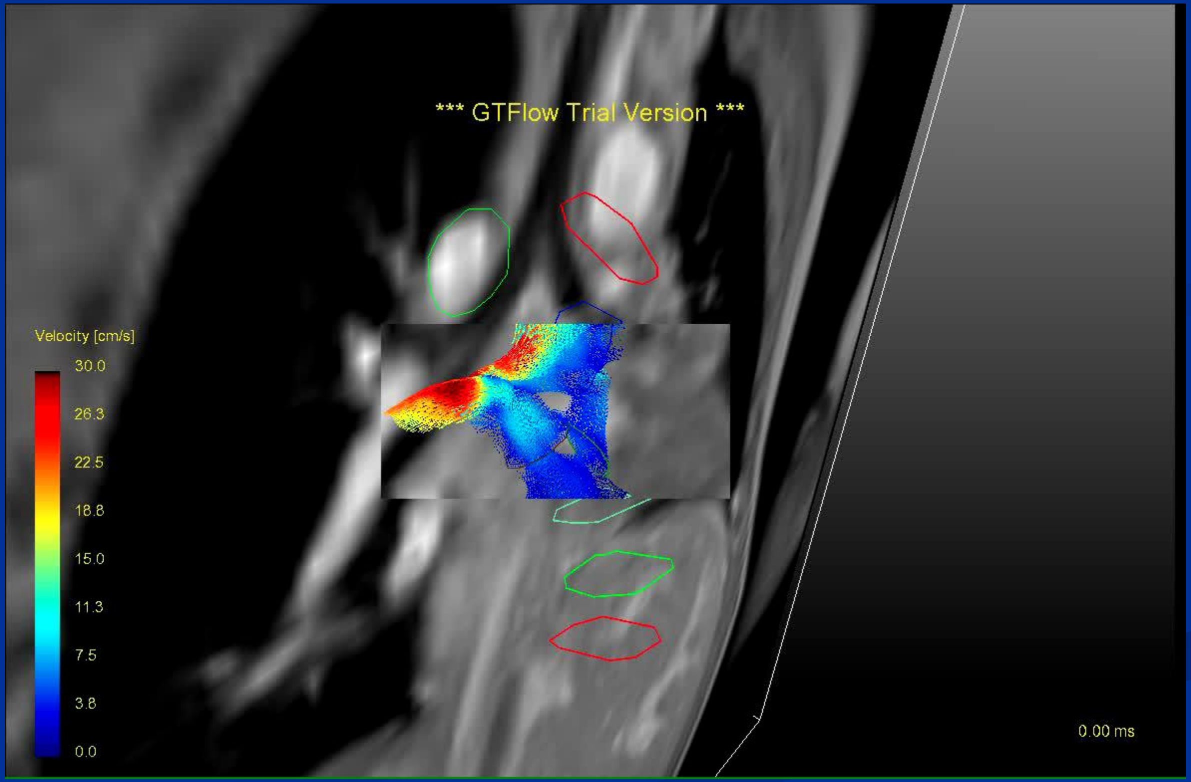
'Traditional Extracardiac'



Y-graft



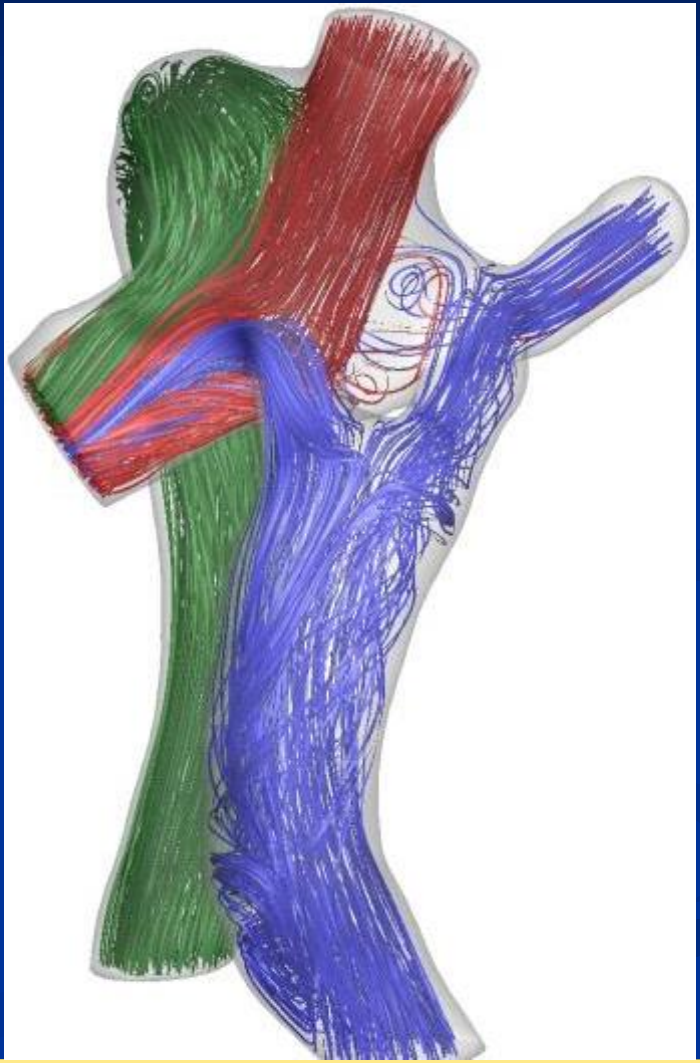
Surgical Implementation



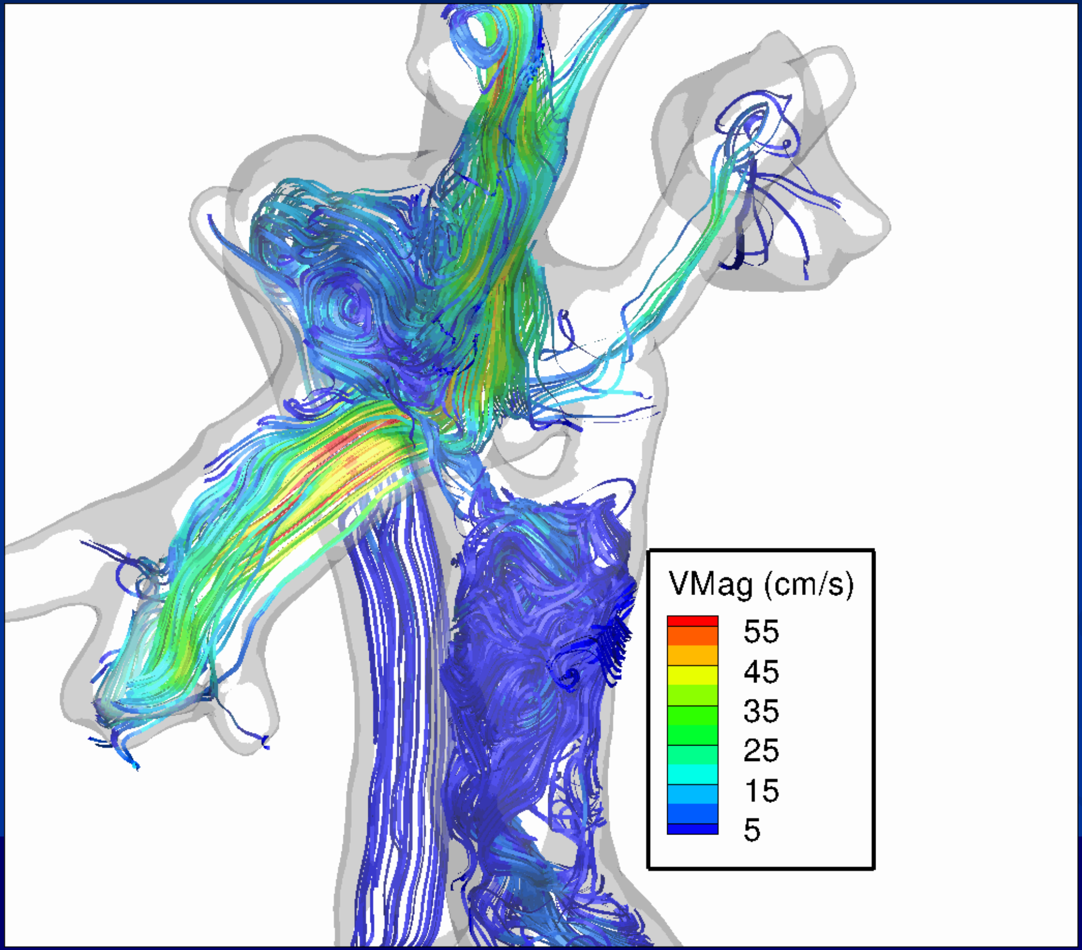
Comparison to Post-Operative Results

Pre-operative model

Post-operative results

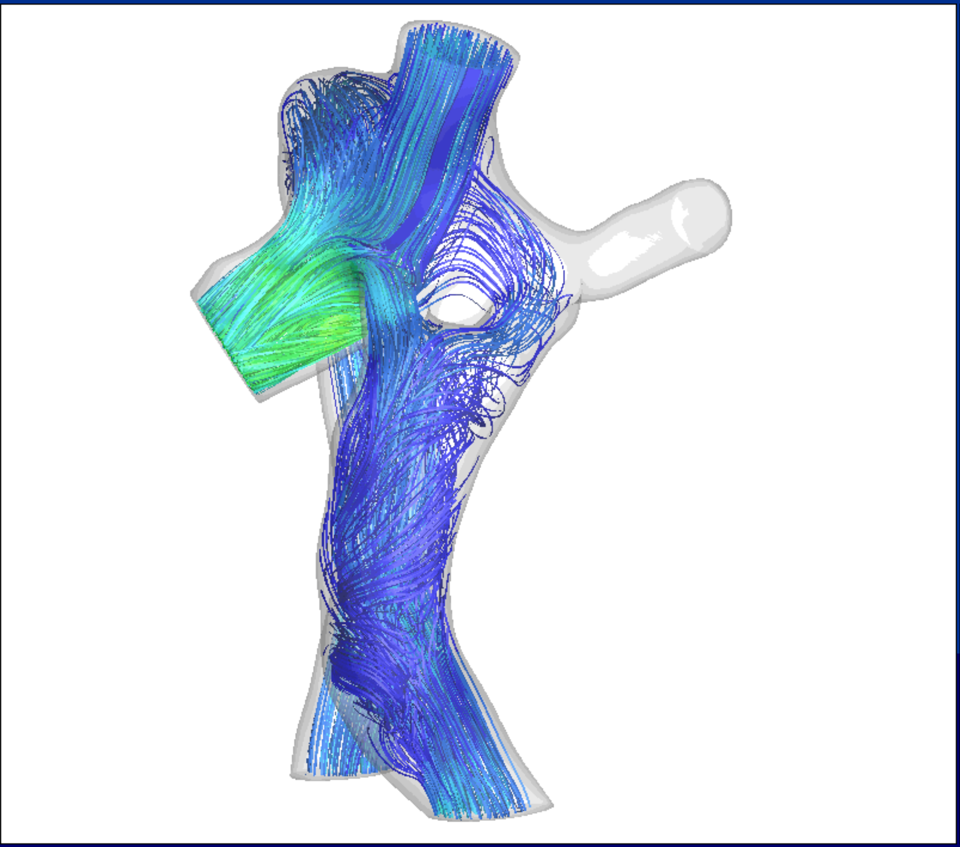


Post-Operative Hemodynamic Outcome

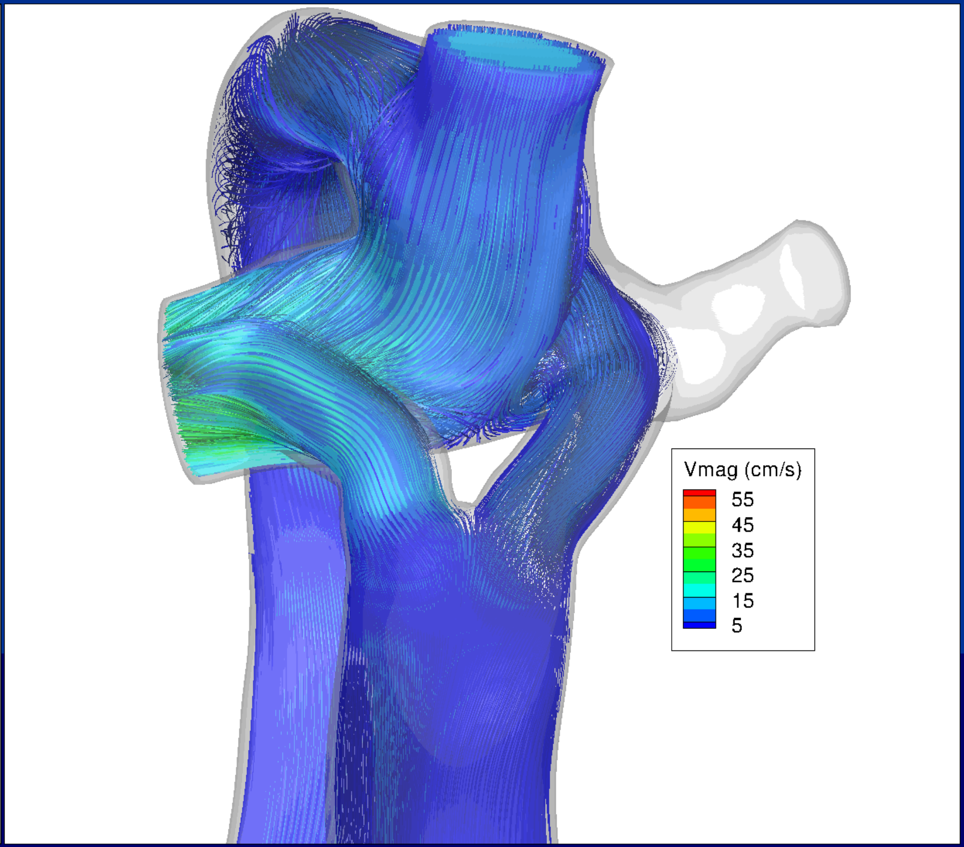


Post-Operative Hemodynamic Outcome

Post-op Anatomy



Virtual model



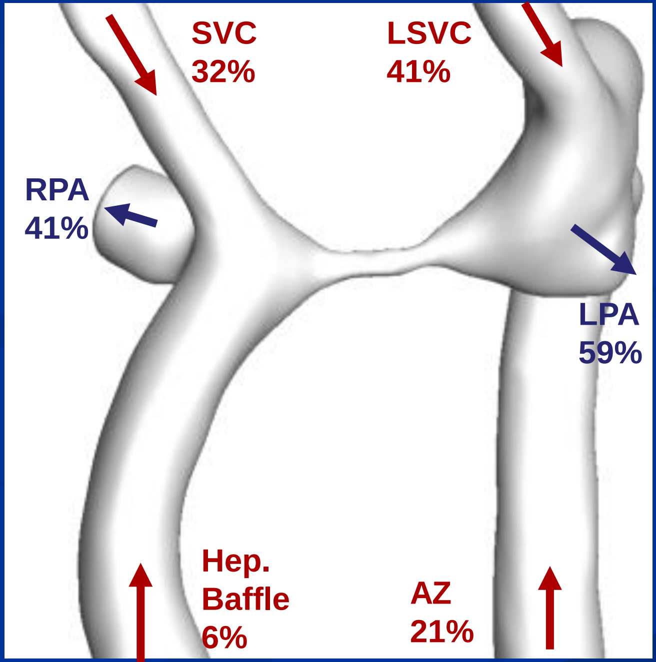
Application to Diagnosis and Risk Assessment

Patients with interrupted IVC and Azygous continuation

CASE 3:
Clinical Case Report

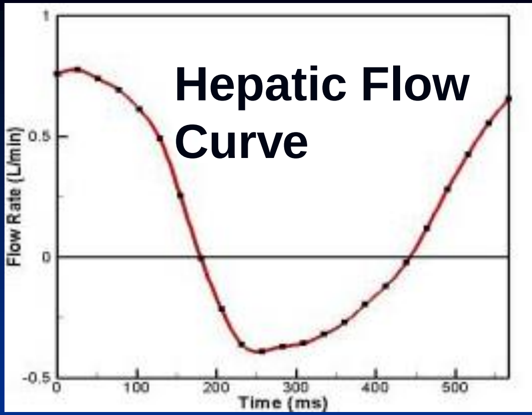
- Nov. 2009:
  - 6 yr. old male with heterotaxy syndrome, unbalanced AV canal to the RV, VSD, hypoplastic LV, and an interrupted IVC with azygous continuation
  - Had undergone TCPC completion in Summer 2009, coming for a follow-up scan
  - Assess risk of PAVM development

TCPC anatomy
And time-averaged flow distribution



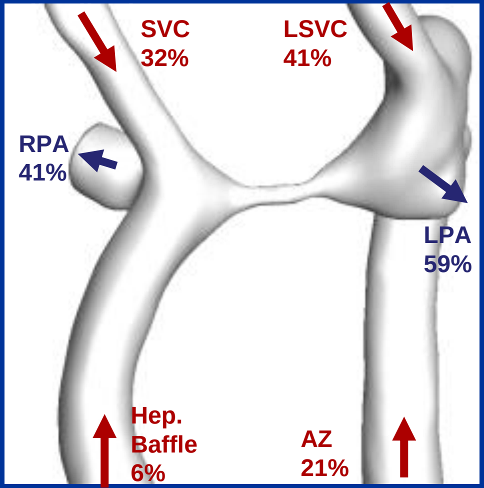
Cardiac Output: 2.8 L/min

In Vivo PC MRI

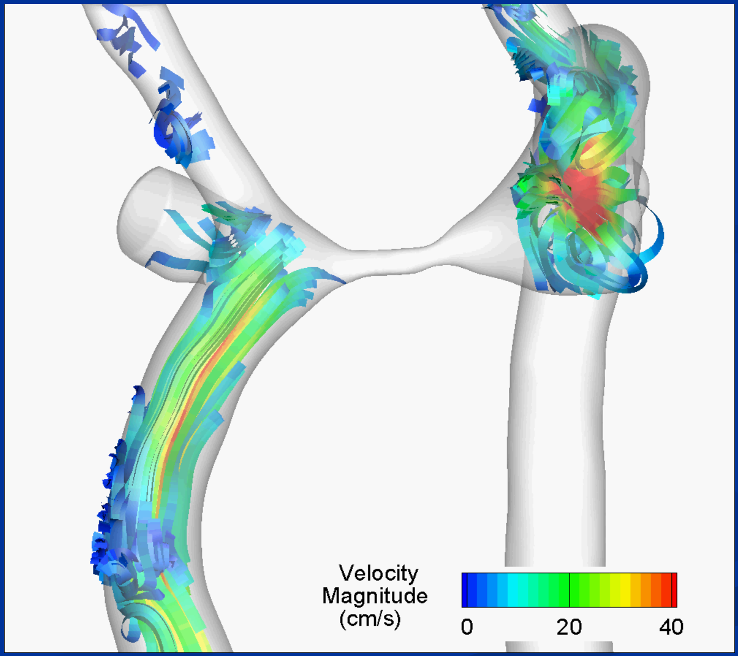


- Important flow reversal in the hepatics
- Data loss in the SVCs and connection areas due to the limited number of PC MRI slices and high flow disturbances

TCPC anatomy
And time-averaged flow

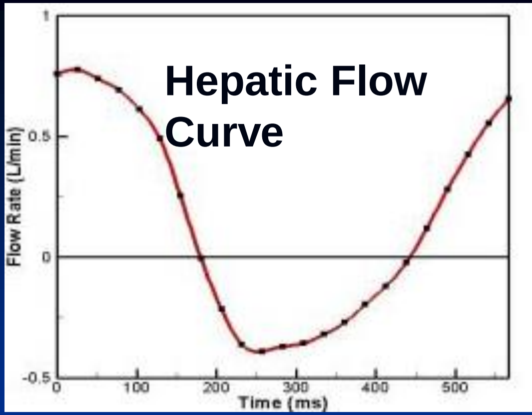


Cardiac Output: 2.8 L/min

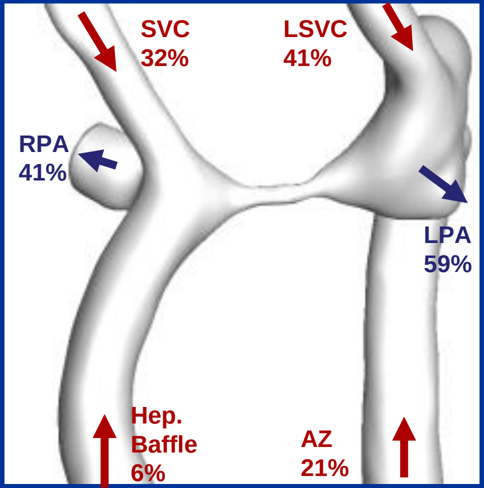


In Vivo PC MRI

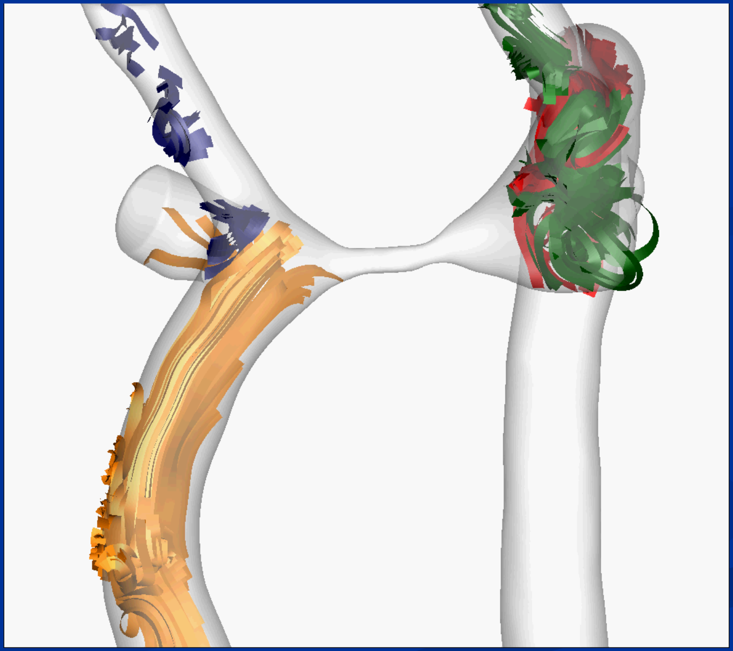
- Important flow reversal in the hepatics
- Data loss in the SVCs and connection areas due to significant de-phasing from flow disturbances and intense mixing



TCPC anatomy
And time-averaged flow



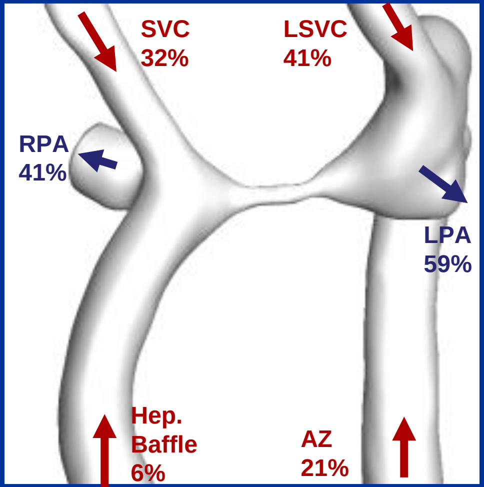
Cardiac Output: 2.8 L/min



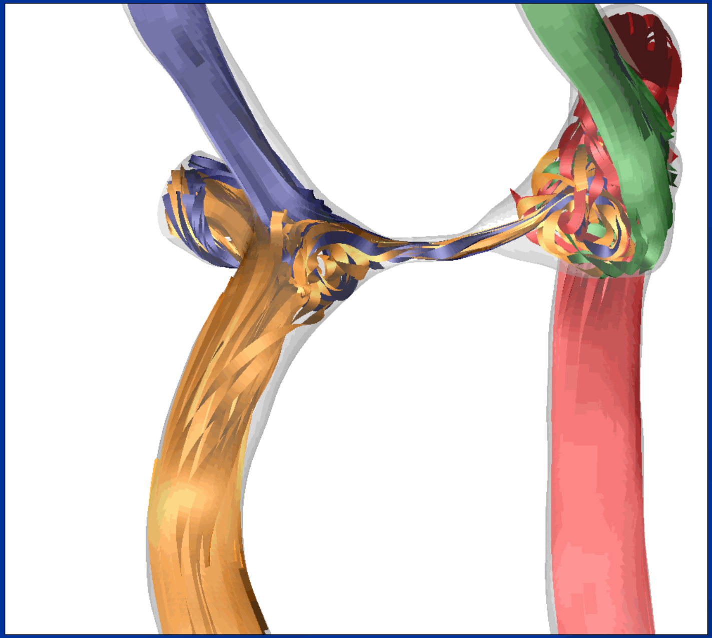
Pulsatile CFD Simulations for Detailed In Vivo Hemodynamics

- **Hepatic streamtraces almost exclusively go to the RPA, apart from a few instances at the peak of the hepatic flow curve**

TCPC anatomy
And time-averaged flow



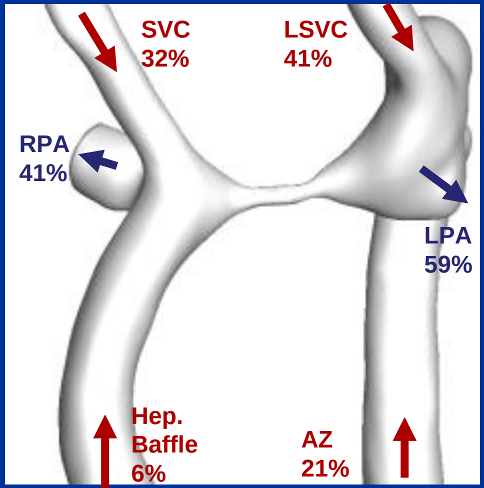
Cardiac Output: 2.8 L/min



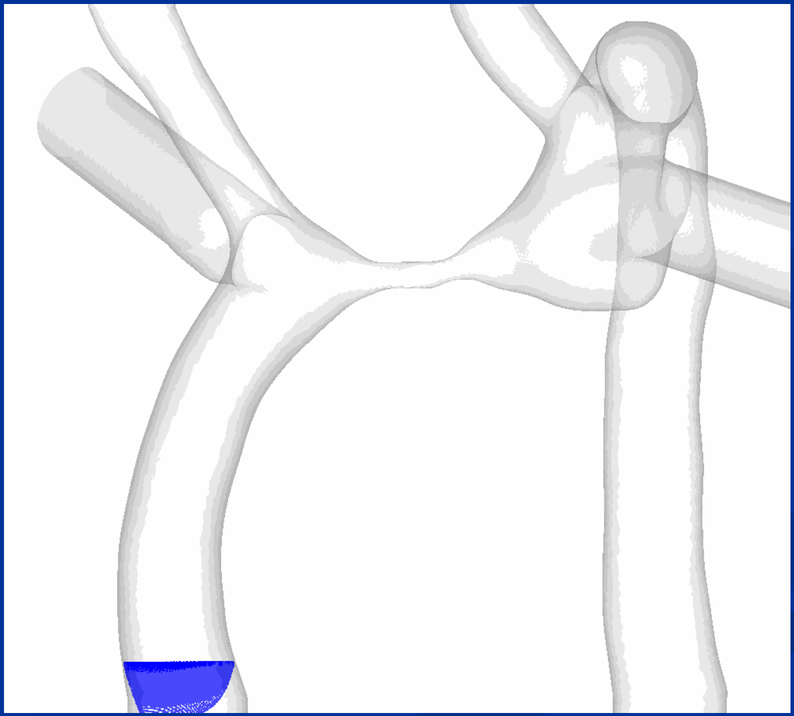
Distribution of the Hepatic Nutrients

- Hepatic nutrients are seeded towards the hepatic inlet and typically take 1.5 cardiac cycle to reach the RPA
- No hepatic particles succeeded to reach the LPA
- <u>This patient might develop left-sided PAVMs</u>

TCPC anatomy
And time-averaged flow distribution



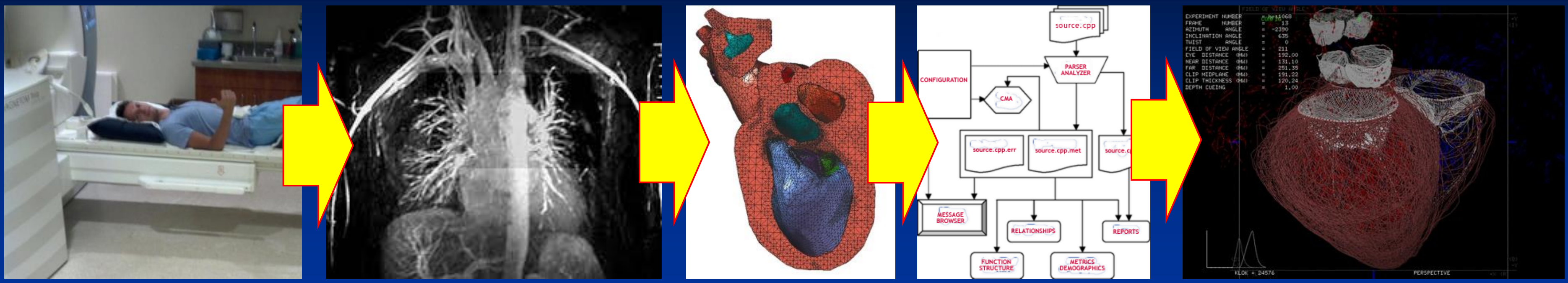
Cardiac Output: 2.8 L/min



Summary

- Magnetic Resonance Imaging provides:
  - patient-specific anatomy: computational geometry
  - flow reconstruction: boundary conditions.
- Virtual surgical environment assists in:
  - parametrically investigating various patient-specific surgical options
  - designing pre-operatively the best surgical connection on a patient-specific basis
- Cutting-edge computational fluid dynamic model assesses
  - hepatic flow distribution
  - power loss
  - baffle pressure drop

Future Challenges



Scan | Image Processing | Mesh | Numerical Method | Post-process

- Improve image processing to gain more realistic geometries more efficiently
- Improve efficiency and quality of mesh generation
- Obtain realistic boundary conditions and material properties
- Develop more efficient and more reliable numerical methods (eg: fully coupled FSI with moving boundaries)
- Develop more user-friendly and automated post-processing tools

Acknowledgements

- Dr. Cyrus Aidun, Georgia Tech
- Dr. Fotis Sotiropulos, Univ. of MN
- Dr. Jarek Rossignac, Georgia Tech
- Siemens Healthcare
- Clinical collaborators at CHOP & CHOA
- National Heart, Lung, and Blood Institute (NHLBI)
- American Heart Association


The CFM Lab