HPC for Simulations in the Human Circulation: Heart Valve Mechanics with potential clinical applications

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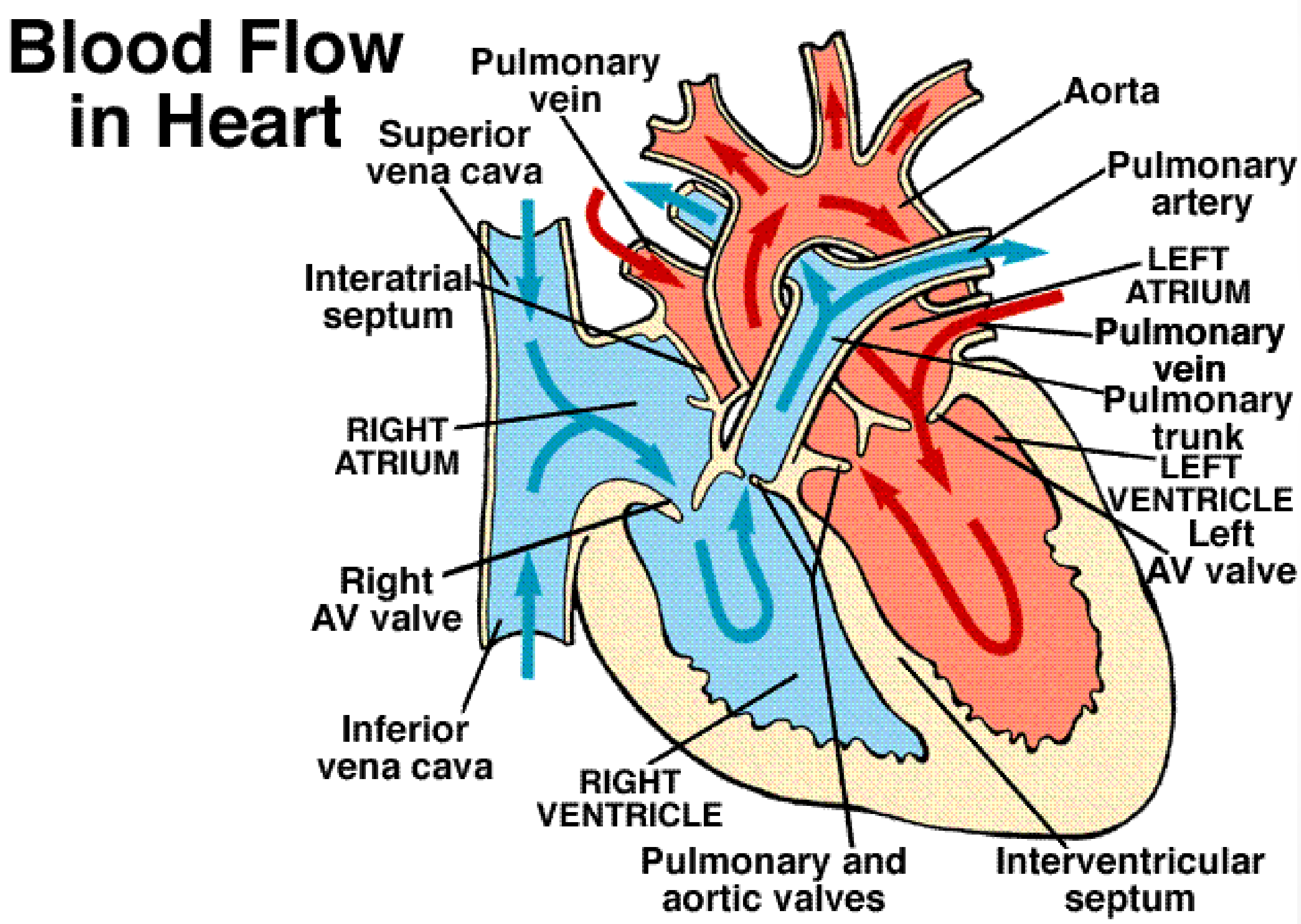
*former graduate students

HUMAN CIRCULATION - Function

- Pumping blood in the body without interruption
  - Transport of oxygen and carbon di oxide
  - Transport of nutrients, hormones
  - Remove waste products from the cells
  - Regulate body fluids and helps prevent dehydration
  - Temperature regulation

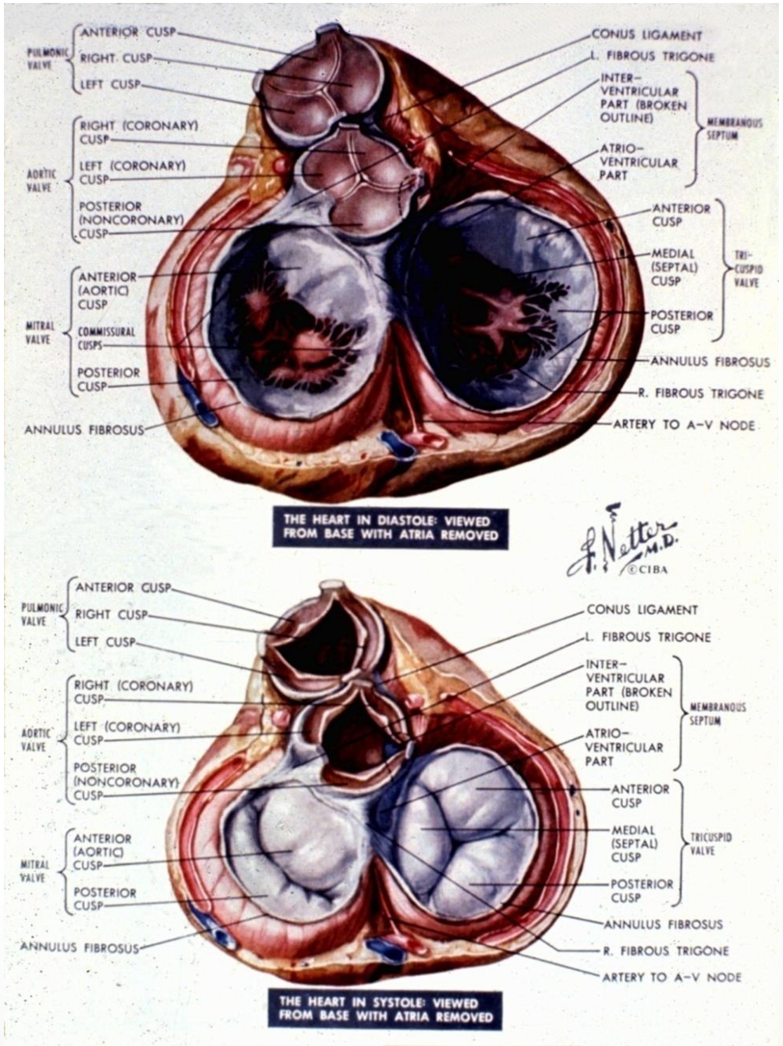
The heart - anatomy



Common cardiovascular diseases

- Atherosclerosis
- Cardiomyopathy
- Congenital heart disease
- Valvular diseases
- Hypertension (Chronic high blood pressure)
- Aneurysms
- Venous thrombosis
- Venous stasis and varicose veins
- Genetic diseases (e.g., Marfan's syndrome)

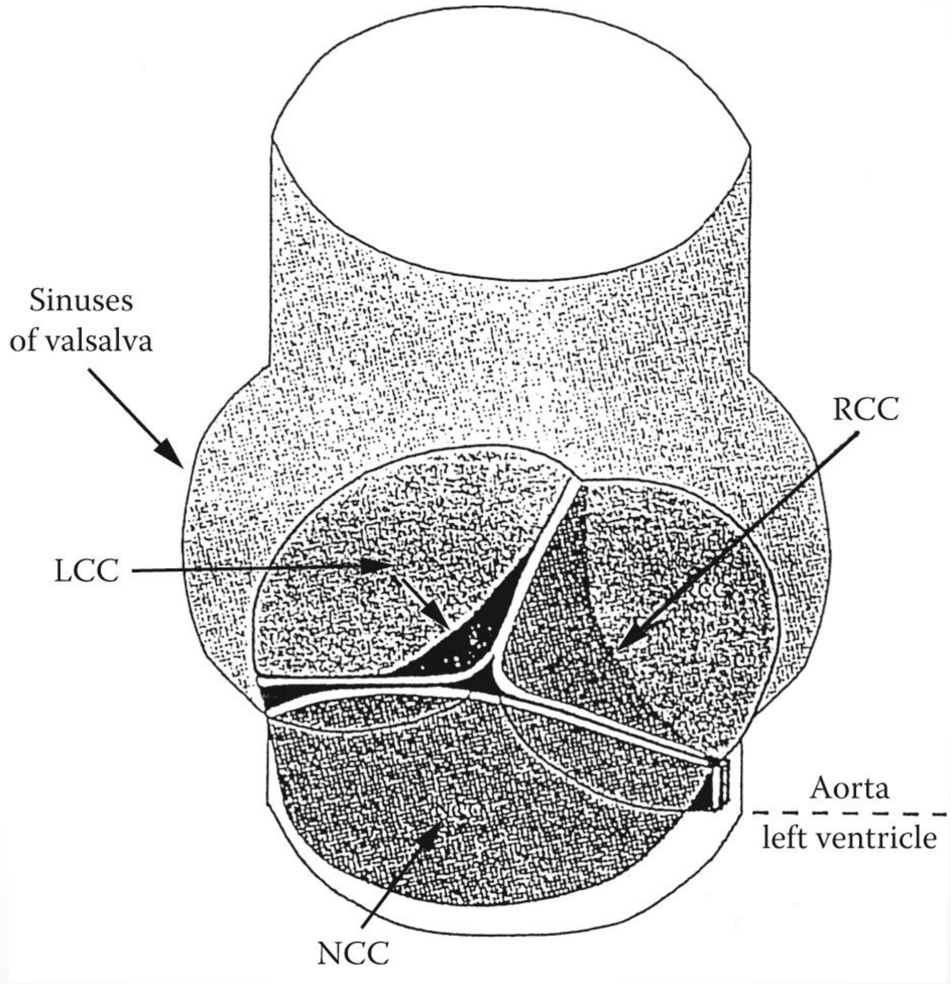
Valve structures (from CIBA volume on Heart)



Valve overview

- Passive structures
- Withstand cyclic loading – at least 1 Hz
- Withstand 3B+ open/close cycles in lifetime
- Ensure unidirectional blood flow
  - Maximize flow rate
  - Minimize resistance

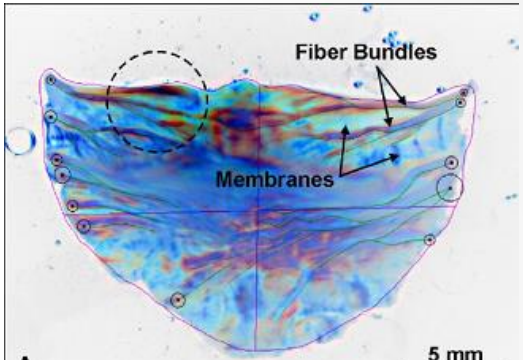
Aortic valve



Leaflet structure and properties

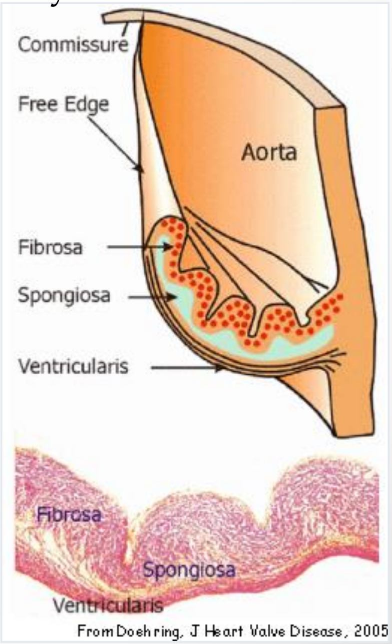
- The leaflets are mostly thin (300-700 μm) passive tissue with elastin and collagen as structural elements and some SMCs
- There are three layers along leaflet thickness:
  - Fibrosa (collagen and some elastin),
  - spongiosa (ground substance) and
  - ventricularis (collagen and some elastin)
- Leaflets are anisotropic – stiffer in circumferential direction

Collagen fibers in aortic valve



Todd Doehring, J Heart Valve Dis, 2005

Structural layers in aortic valve



Mitral Valve Anatomy

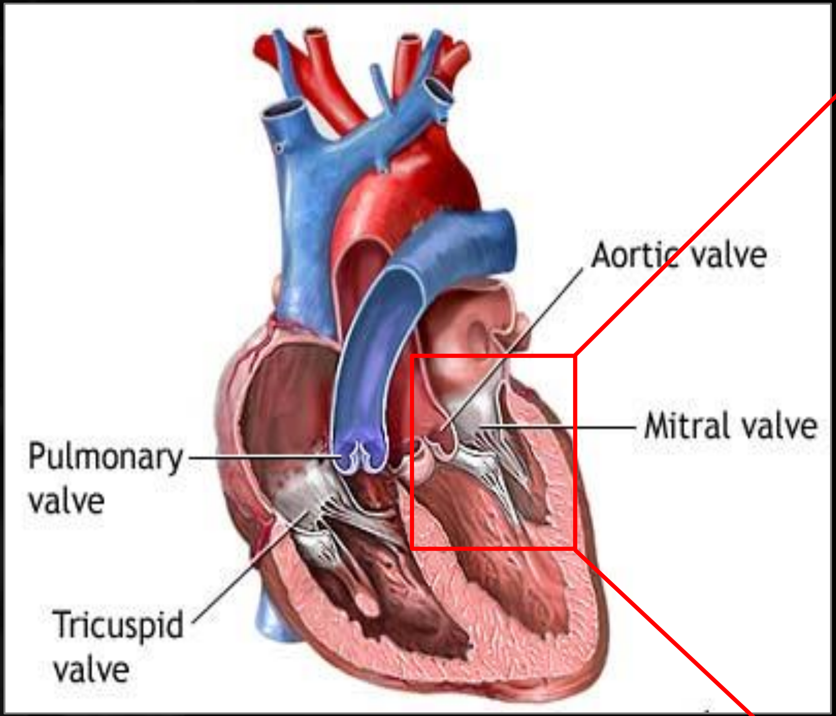


Figure 1. Anatomy of the human heart

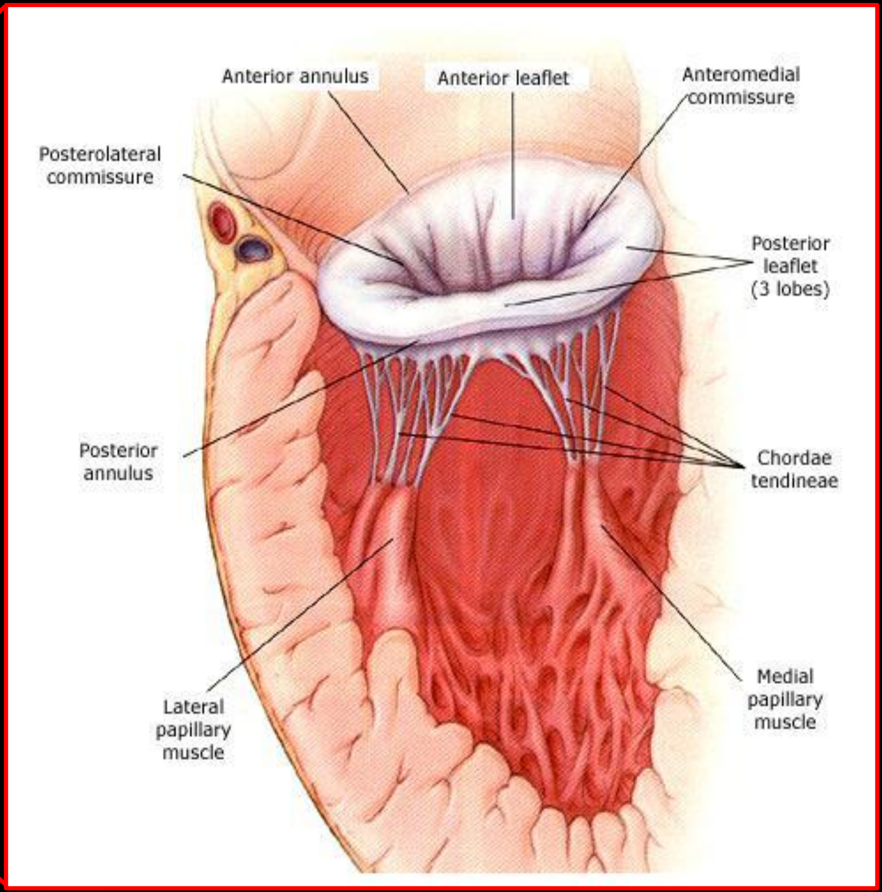


Figure 2. Mitral valve

Fig 1. *http://www.ncbi.nlm.nih.gov/pubmedhealth/PMH0004413*

Fig 2. *http://www.heart-valve-surgery.com/heart-surgery-blog/2008/09/02/mitral-valve-annulus-definition-diagrams-prolapse-calcification-treatment*

Valvular disease overview

- Congenital or acquired
  - Congenital abnormalities
  - Rheumatic fever
  - Degeneration from atherosclerosis
  - Excessive calcification in old age

Valvular stenosis

  - Bacterial infection
  - Enlargement of the heart or aorta

Valvular regurgitation

- 1.5 M individuals in US
  - 20,000 deaths annually (42,000 associated)

Valvular disease states

- Two main classifications of valvular diseases
  - Stenosis
    - narrowing of valve
    - increases pressure drop across valve
  - Incompetence
    - incomplete valve closure
    - increases regurgitation
    - a common cause of heart murmur

Advantages of simulations

- Relatively inexpensive
- No studies on human subjects or in animal models
- Detailed computations can be made in complex geometries
- Once validated, results can be exploited to investigate alterations
- A powerful tool for optimal geometric design of devices before prototyping

Simulation options

- Structural analysis: Assess the deformation and stresses on the valve leaflets and effect of mechanical stresses on valvular disease.
- Computational Fluid Dynamics (CFD): Blood flow analysis to assess alterations in flow patterns and disease development
- Fluid-Structure Interaction (FSI): Combined analysis involving both structures and the flowing blood with detailed interaction at the interface between tissues and blood (Moving boundary specification or FSI analysis).

Requirements for simulations

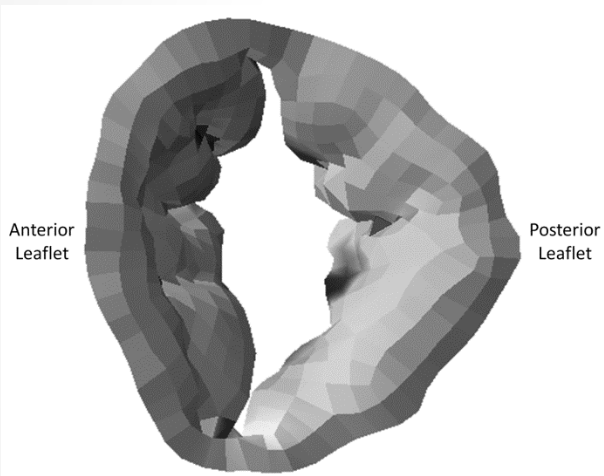
- 3D geometry of interest
  - Various imaging modalities, image processing and 3D reconstruction techniques
  - Patient-specific geometric modeling
- Boundary conditions (inlet, outlet, interface boundary)
- Material specifications (blood and soft tissue)
- Accurate solutions (mesh independence, validation)
- Analysis and interpretation of results (correlations with outcomes)

Imaging modalities

- Ultrasound (3D, trans-esophageal, intravascular)
  - Non-invasive (?) and relatively inexpensive
  - Images are noisy
- CT (contrast infusion and x-ray exposure)
- MRI(time consuming, and expensive)
- Image processing and 3D Reconstruction
  - Managing imaging data
  - Image processing and segmentation
  - Geometric reconstruction
  - Automated mesh generation

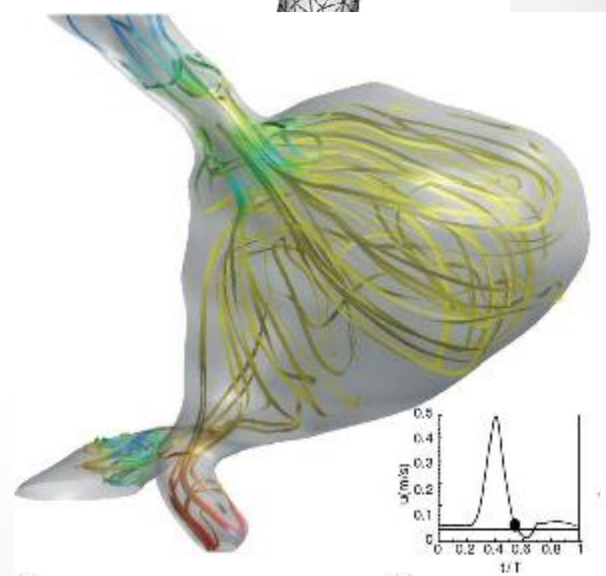
3D geometry

Carotid bifurcation

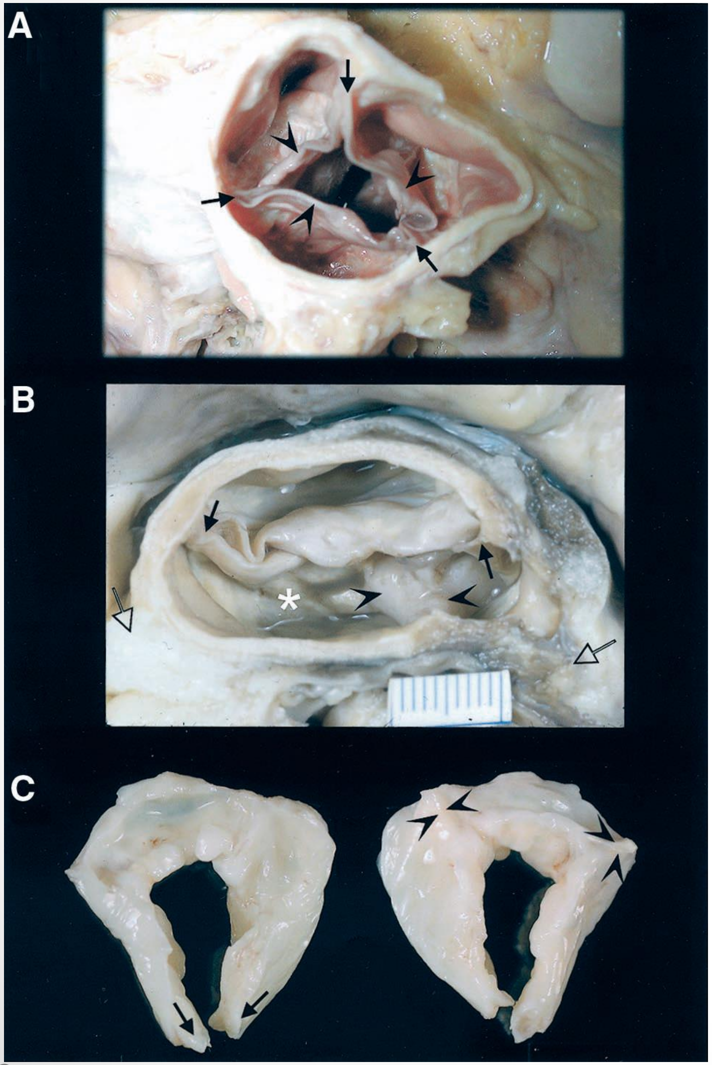


Mitral valve

Abdominal aortic aneurysm



Congenital bicuspid valve



Normal tri-leaflet aortic valve

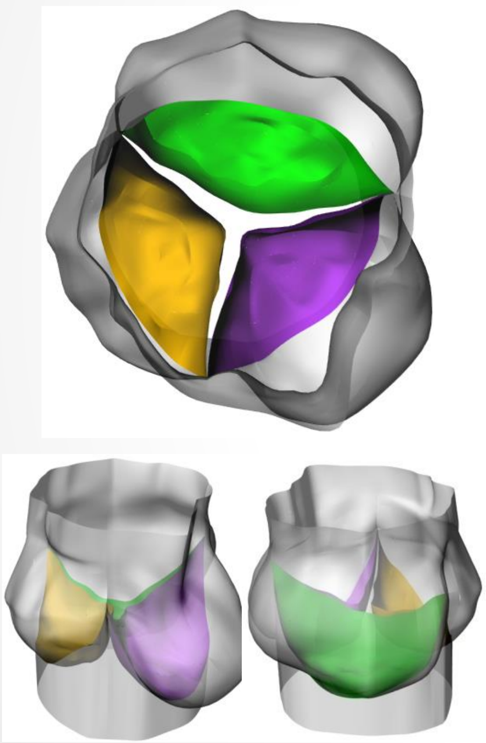
Congenital bicuspid valve with two commissures and a raphe: Cusp thickening due to fibrosis.

Bicuspid valve occurrence in 1-2% of the population. 33% present serious complications.

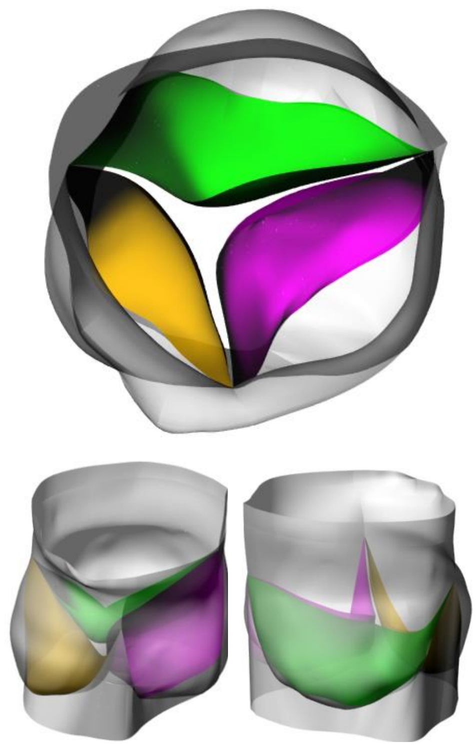
Fedak et al. Circulation, 2002

Patient TAV Models

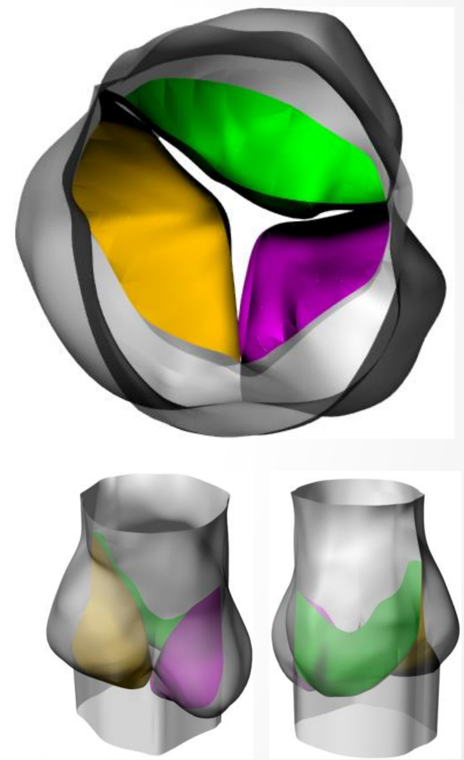
TAV1



TAV2

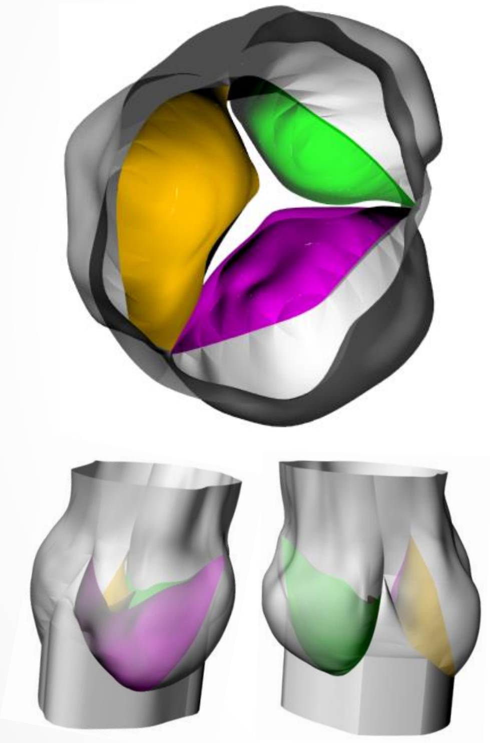


TAV3

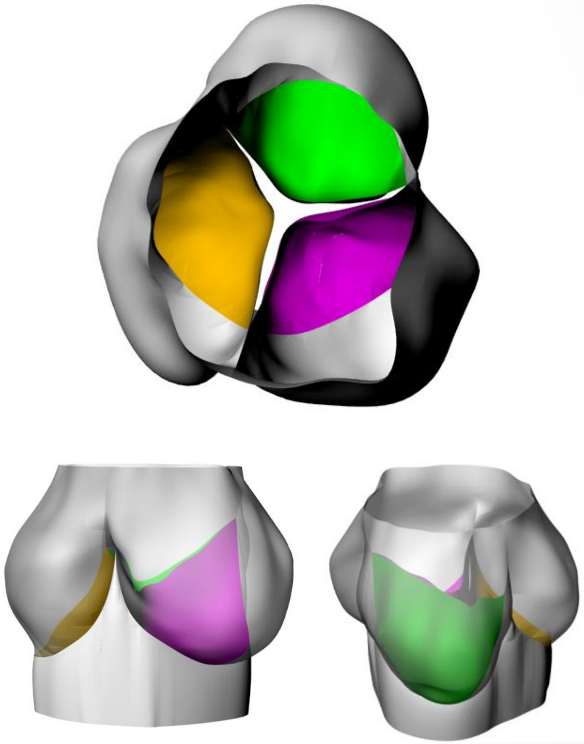


Patient TAV Models

TAV4

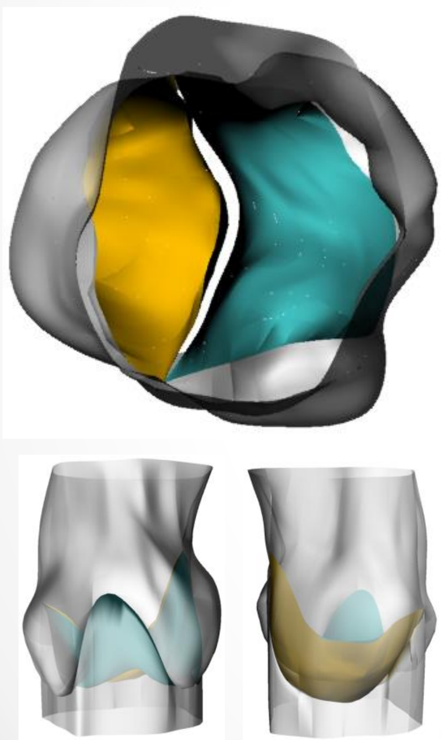


TAV5

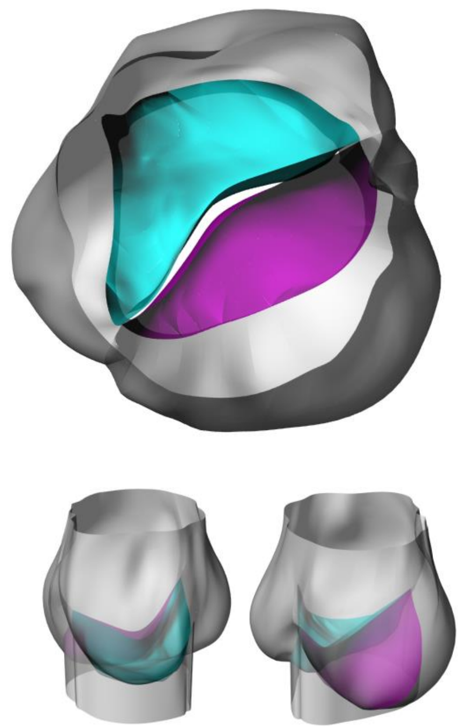


Patient BAV Models

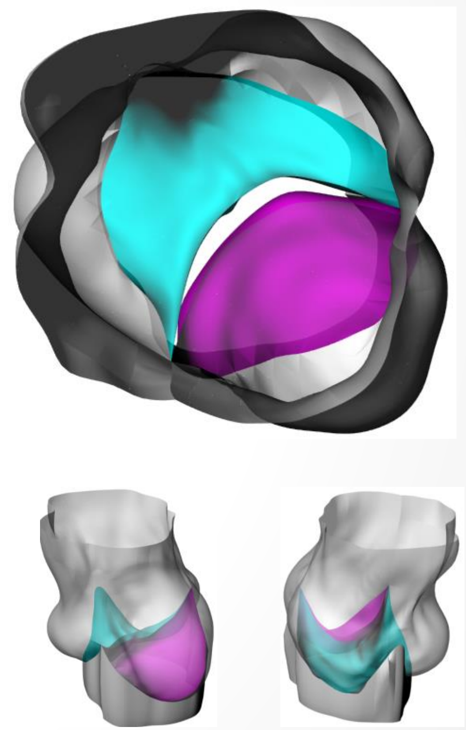
BAV1



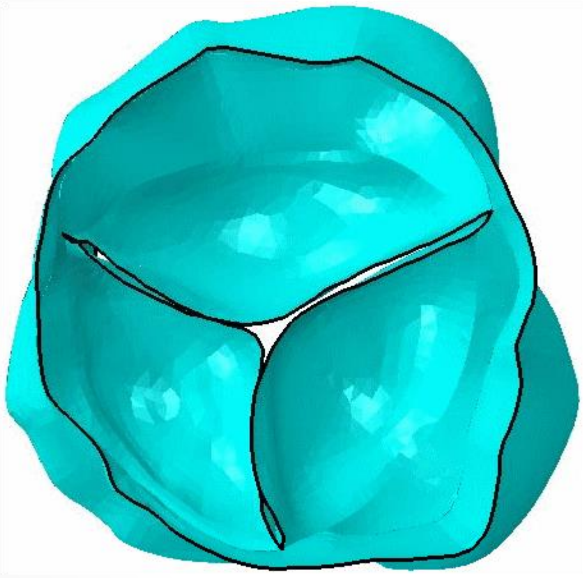
BAV2



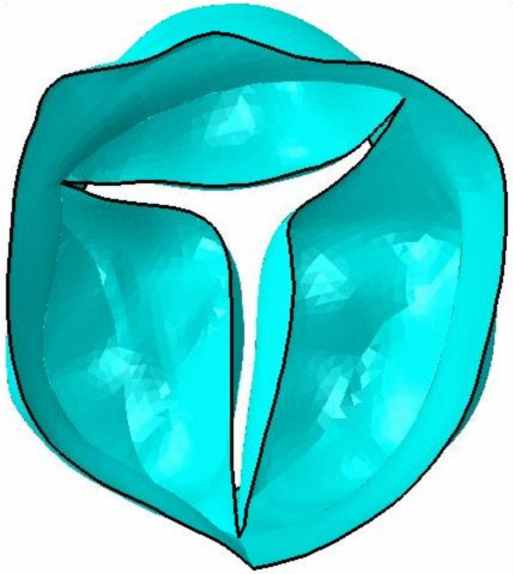
BAV3



Valve Motion

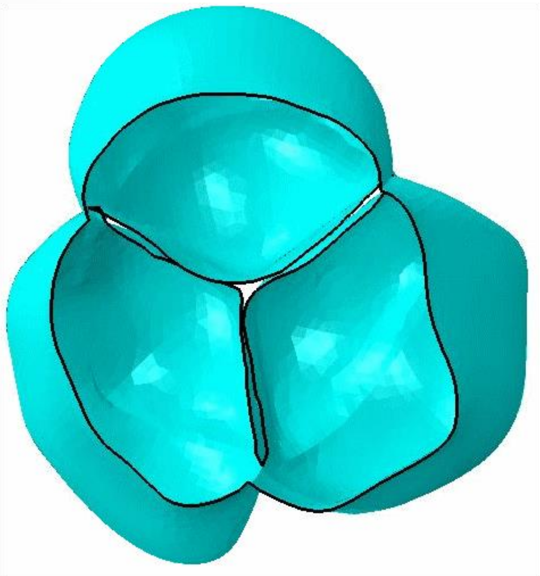


TAV
1

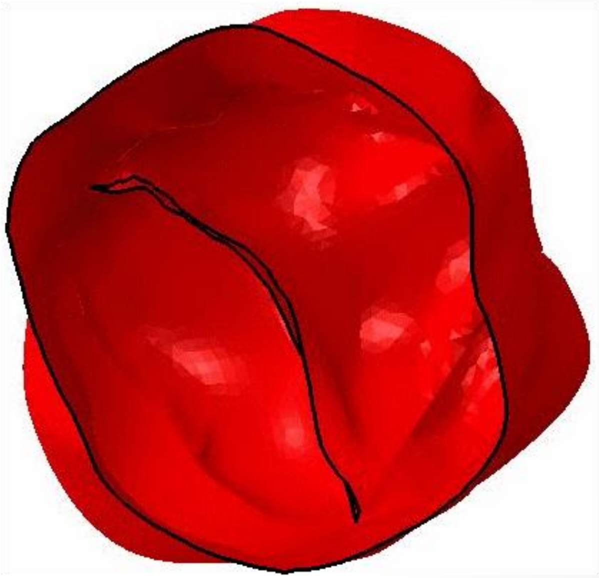


TAV
2

Valve Motion

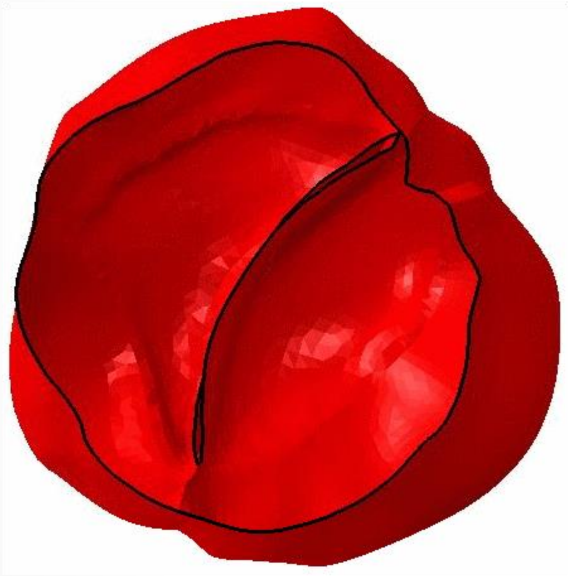


TAV
5

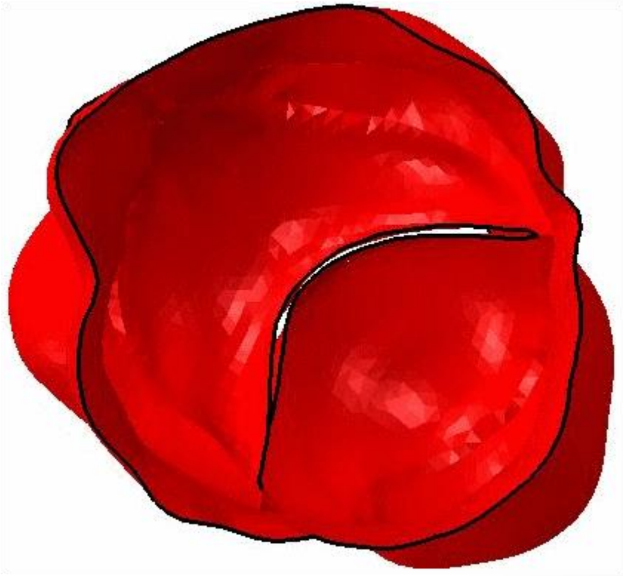


BAV
1

Valve Motion

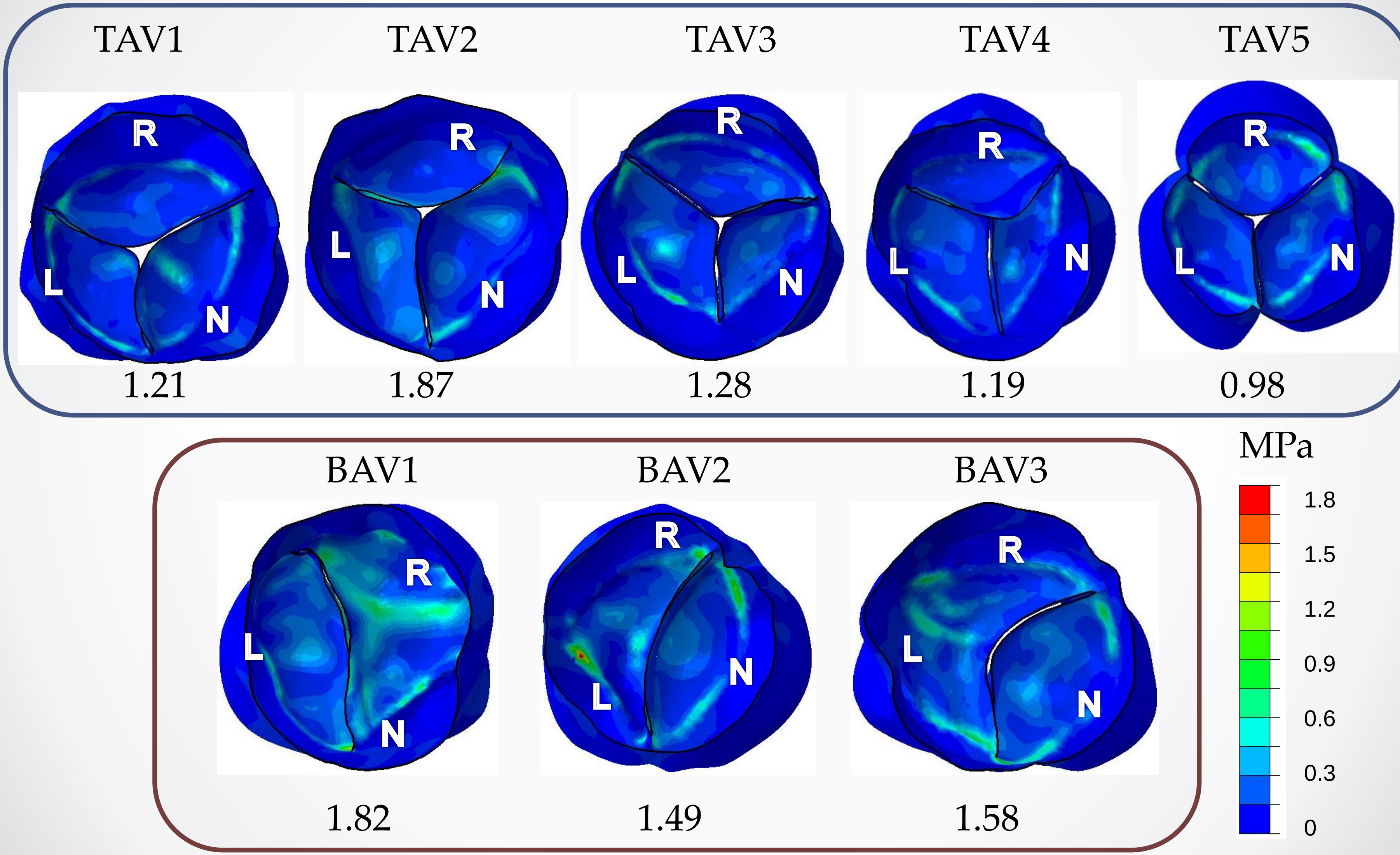


BAV
2



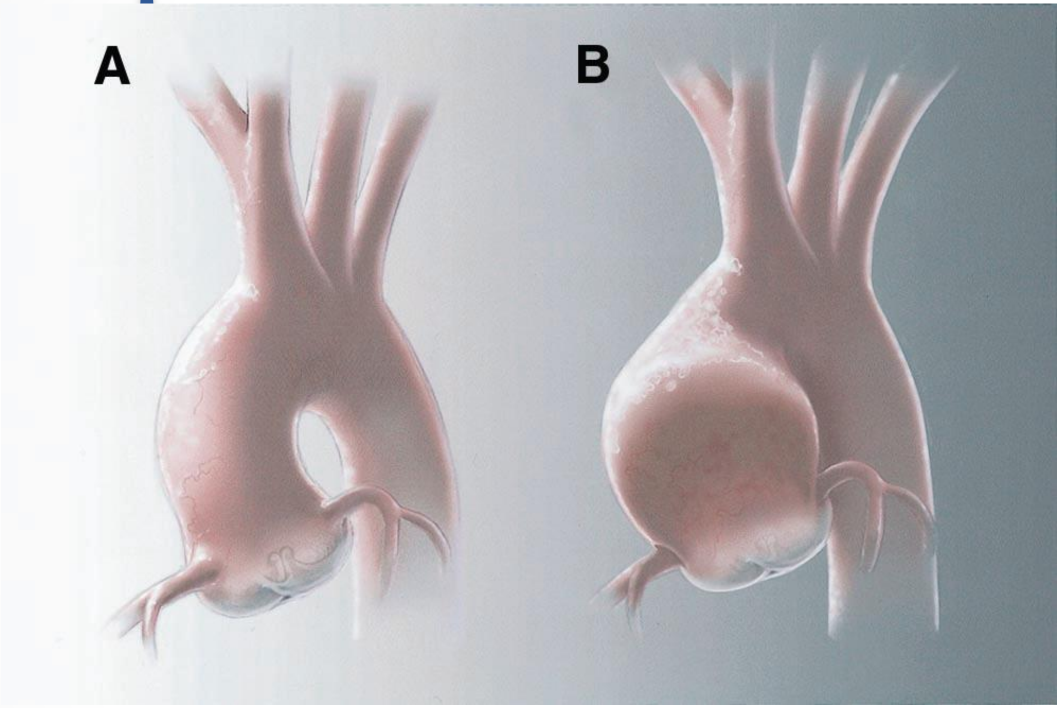
BAV
3

In-Plane Principal Stress Contours At Full Closure:

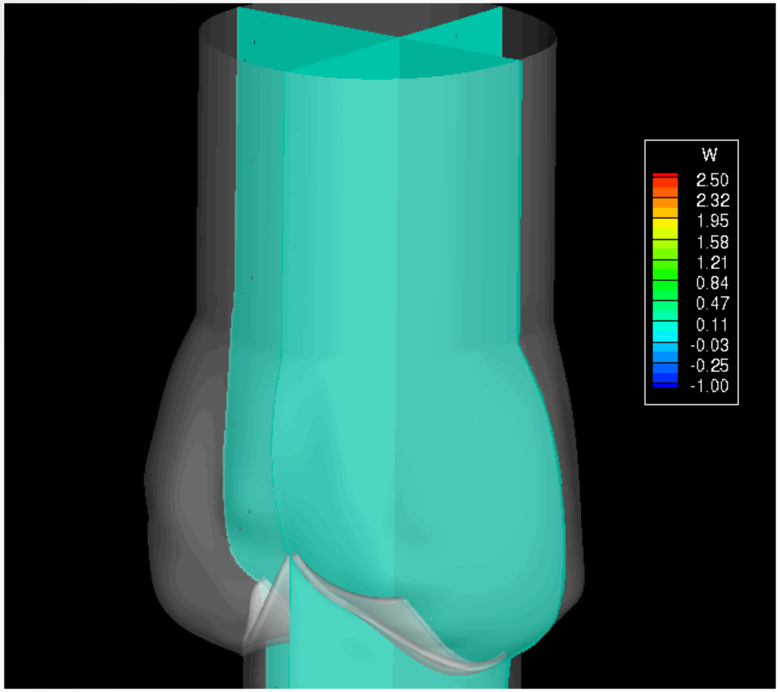


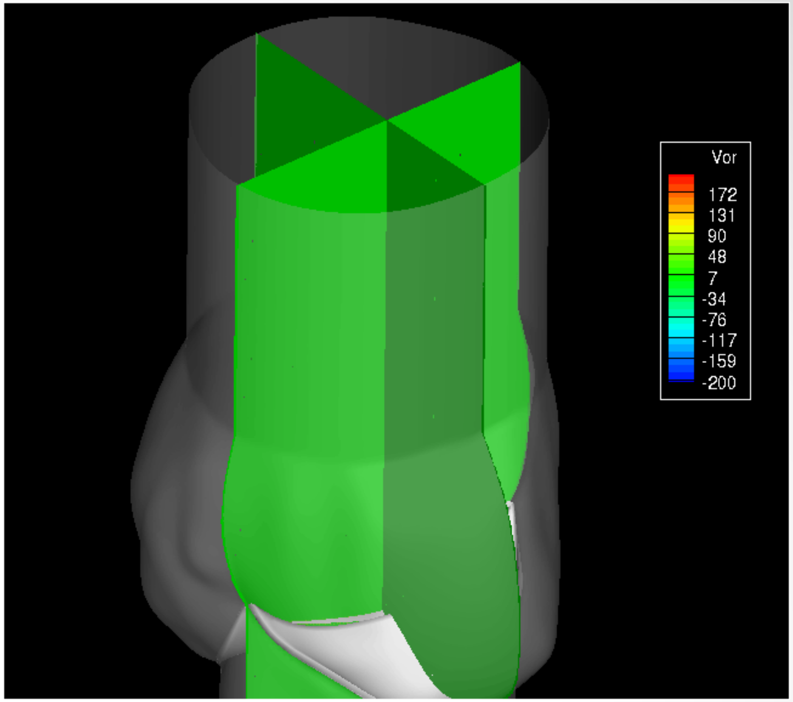
99th Percentile

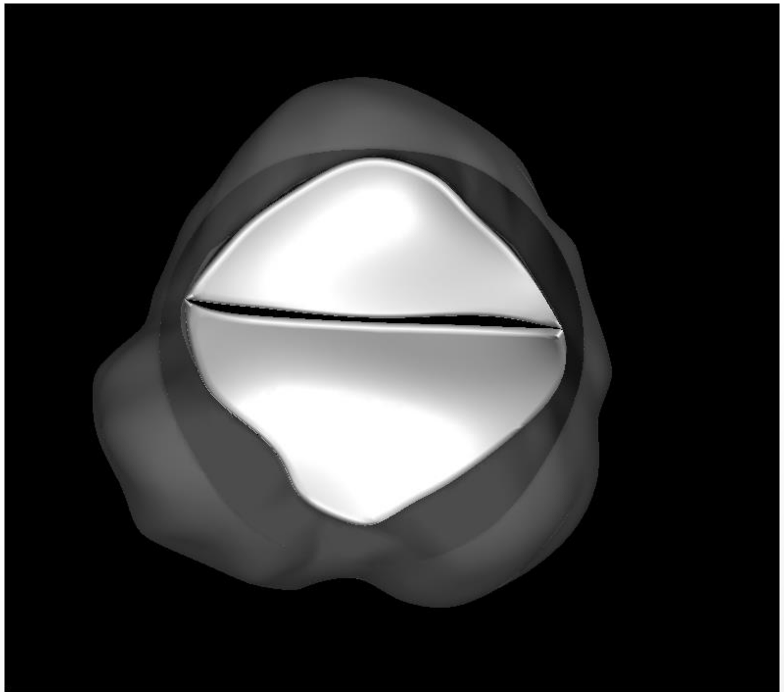
Comparison of aortic root



A: Normal aortic root; B: Dilated aortic root, characteristics of patients With bicuspid aortic valve. Fedak et al., Circulation 2002.


W
2.50
2.32
1.95
1.58
1.21
0.84
0.47
0.11
-0.03
-0.25
-1.00

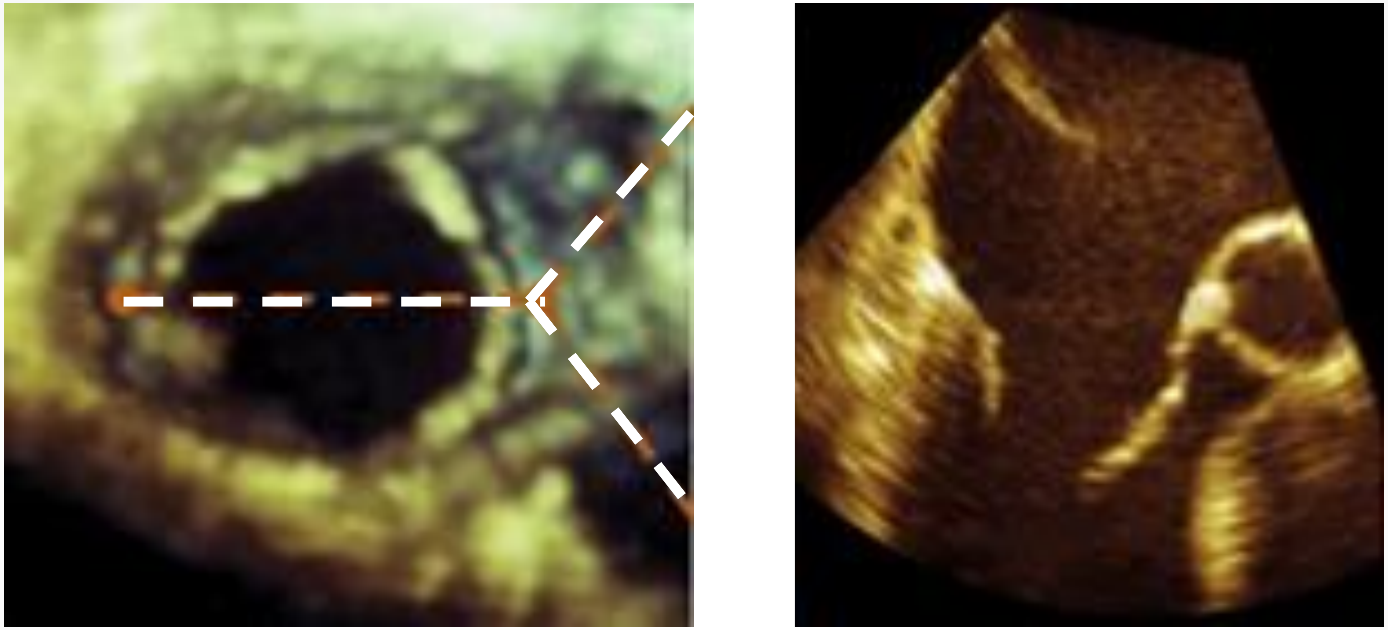

Vor
172
131
90
48
7
-34
-76
-117
-159
-200



FSI simulation of Mitral Valve Function

- Images obtained using TEE and 3D reconstruction of MV Geometry (U. Texas Medical Center at Houston)
- FSI Analysis algorithm development and analysis (University of Iowa)
- Complete FSI for the valve leaflets
- Moving boundary to simulate the ventricular chamber expansion

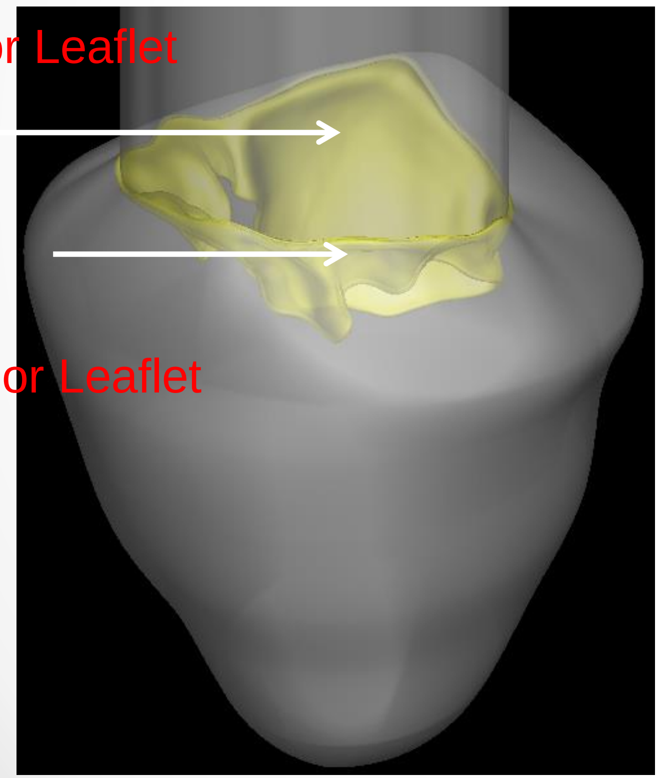
3D-TEE to obtain Patient Specific Geometry

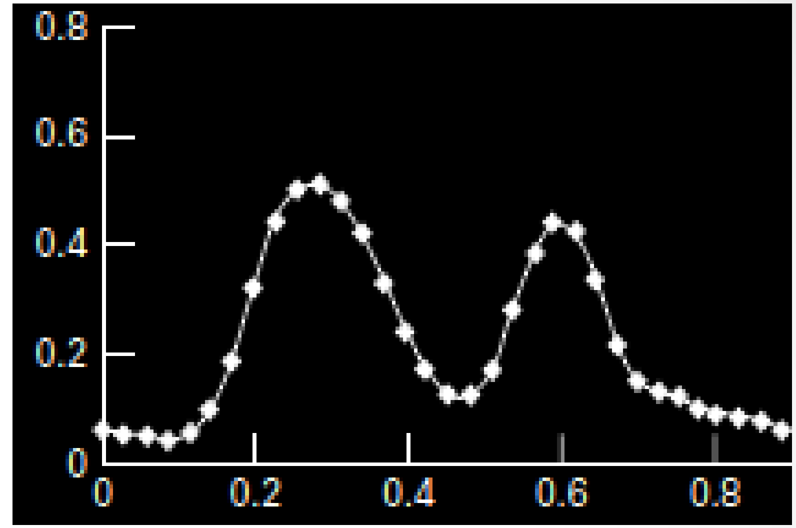


3D-TEE: 3D transesophageal echocardiography

Rim et al., J Biomech. 2013

Physiological boundary conditions at the atrial inlet





Magn Reson 2008

Fyrenius et al. *Heart* (2001): 448-455

Additional details: FSI Governing Equations

Fluid

Conservation of mass:

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

Conservation of momentum:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{\mathrm{Re}} \nabla^2 \mathbf{u}$$

Structure:

$$\rho_s \ddot{\mathbf{x}} - Div\boldsymbol{\sigma}_s = \mathbf{b}$$

Interface

Kinematic compatibility:

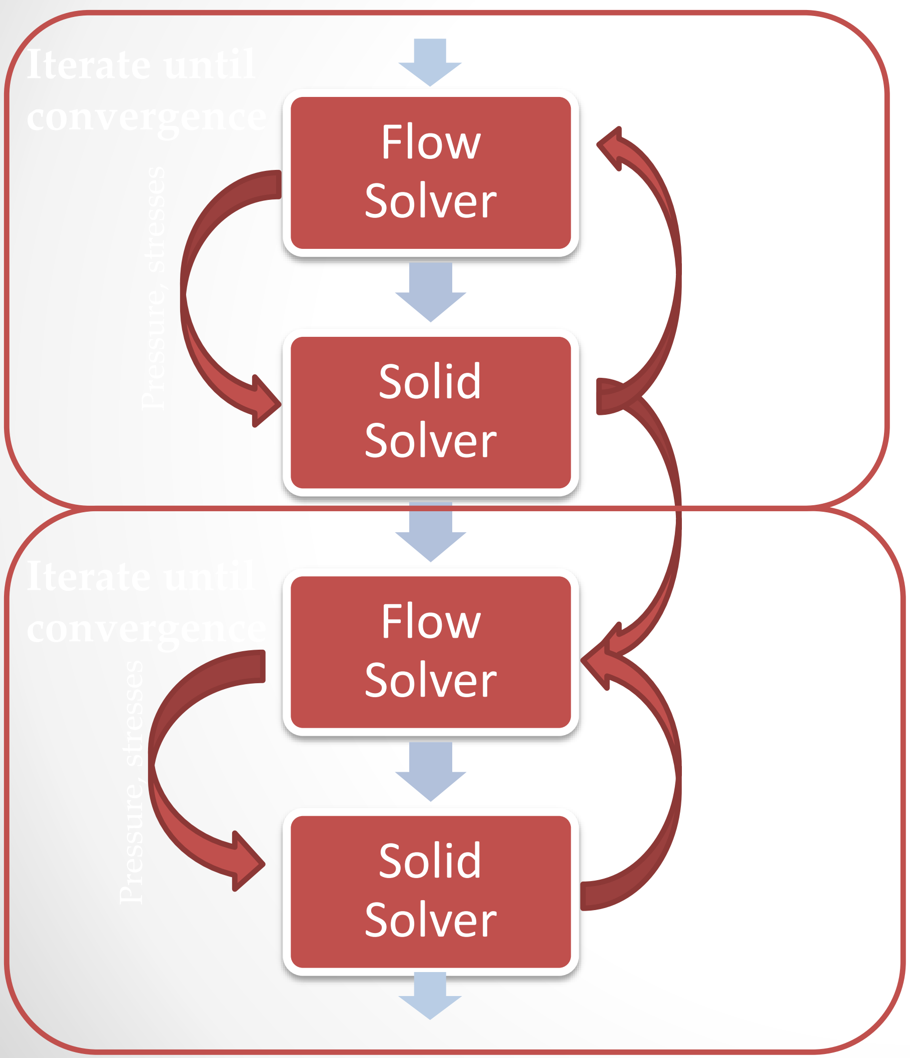
$$\mathbf{u}_s = \mathbf{u}_f \; ; \quad \left(\frac{\partial p}{\partial \mathbf{n}}\right)_f = -\rho_f \mathbf{a}_s \cdot \mathbf{n}$$

Dynamic compatibility:

$$\boldsymbol{\sigma}_f \cdot \mathbf{n} = \boldsymbol{\sigma}_s \cdot \mathbf{n}$$

Strongly coupled FSI Solver

n



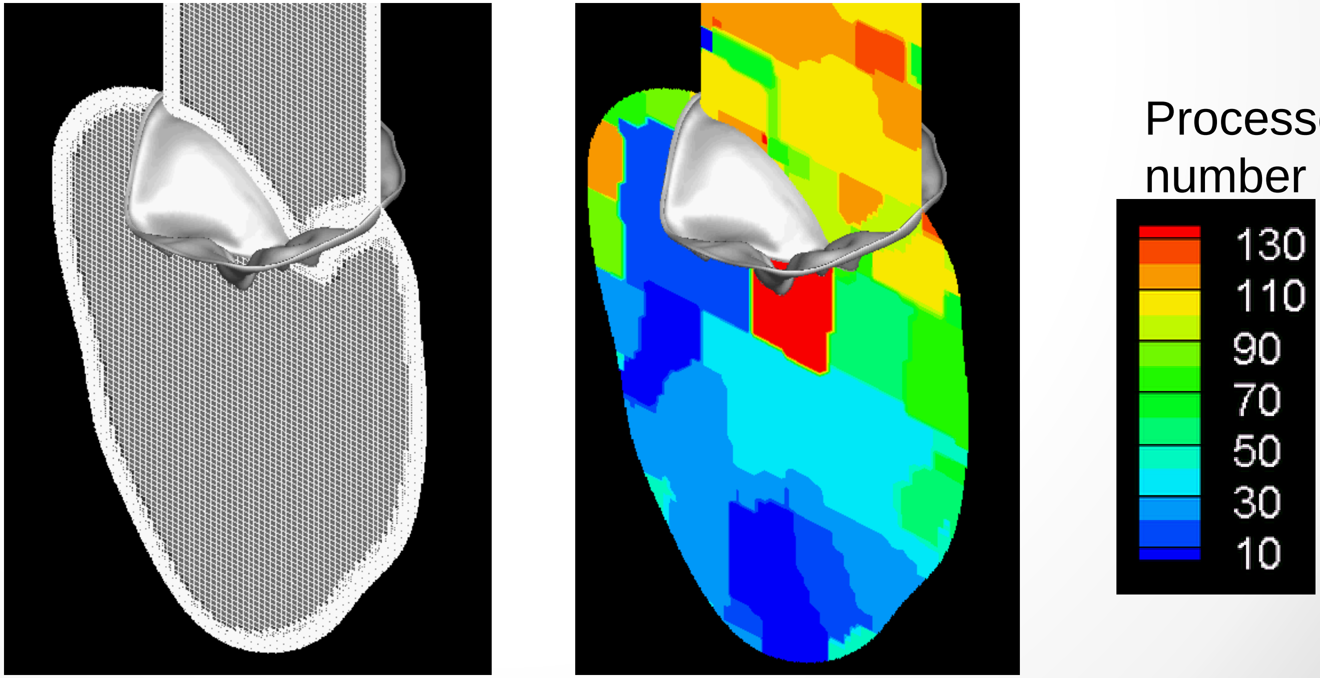
n+1

- Strongly coupled via sub-iterations with Aitken dynamic under-relaxation
- With implicit coupling, fluid and structural solutions are solved simultaneously
- Through the pressure equation, fluid responds to structural displacements as the solution converges
- Numerical stiffness is overcome

Parallelization and Local mesh refinement

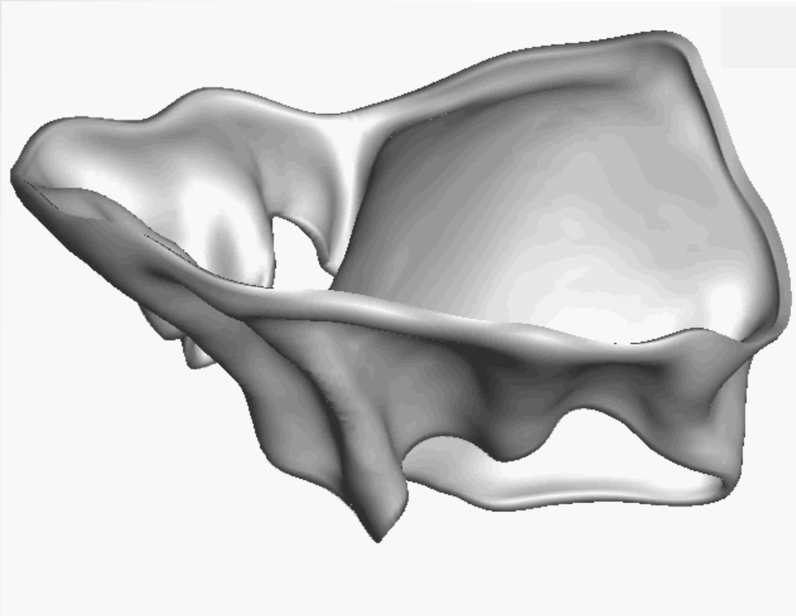
- Parallelization done using Message Passing Interface (MPI) with dynamic processor recruitment
- Local mesh refinement : 3 levels of refinement/time-step
- Initial grid size ~ 10 million, Final grid size ~ 18 million
- Simulation carried out in Helium high performance computer (The University of Iowa) with 144 processors

Automatic refinement and coarsening based on flow

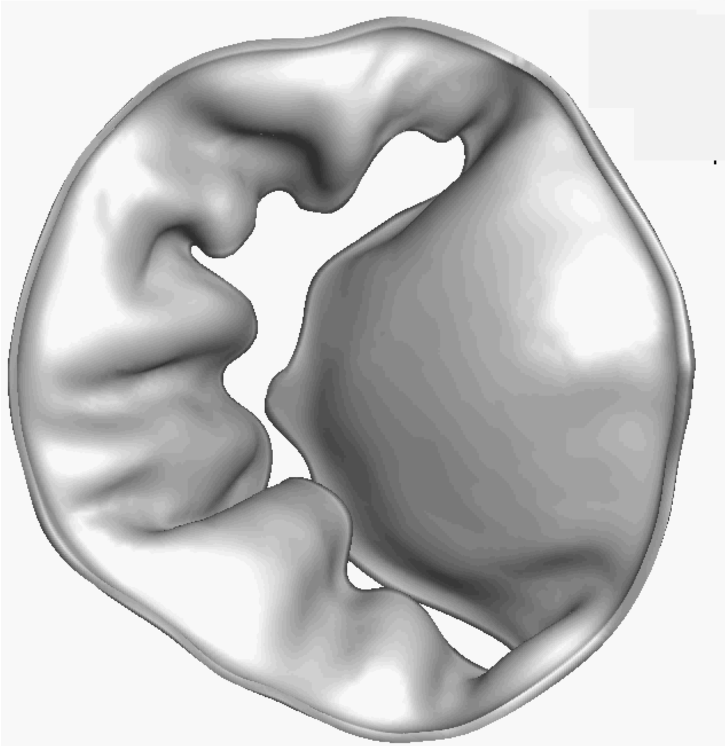


FSI modeling captures realistic leaflet deformation

m orifice in

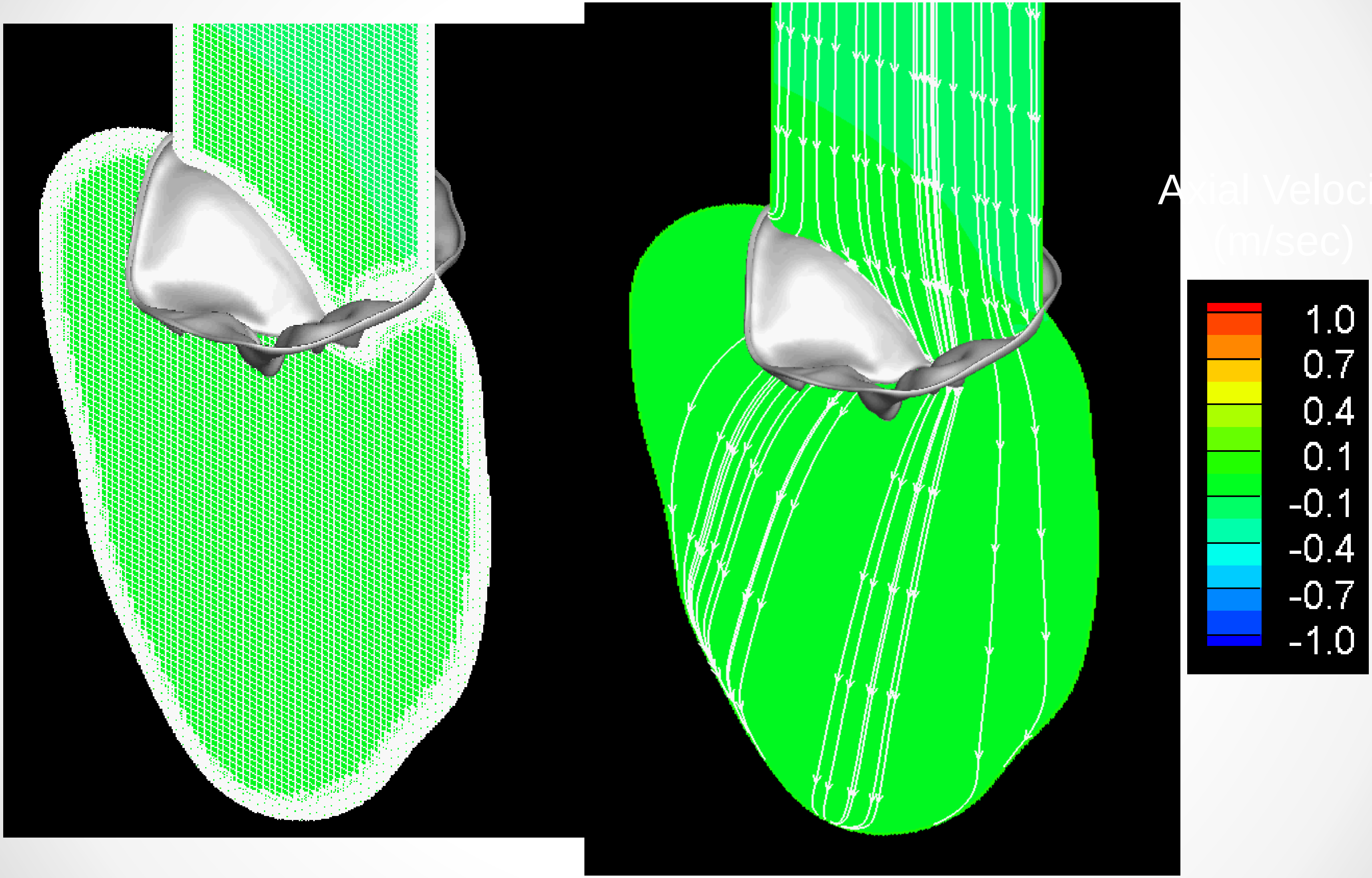


Isometric vi



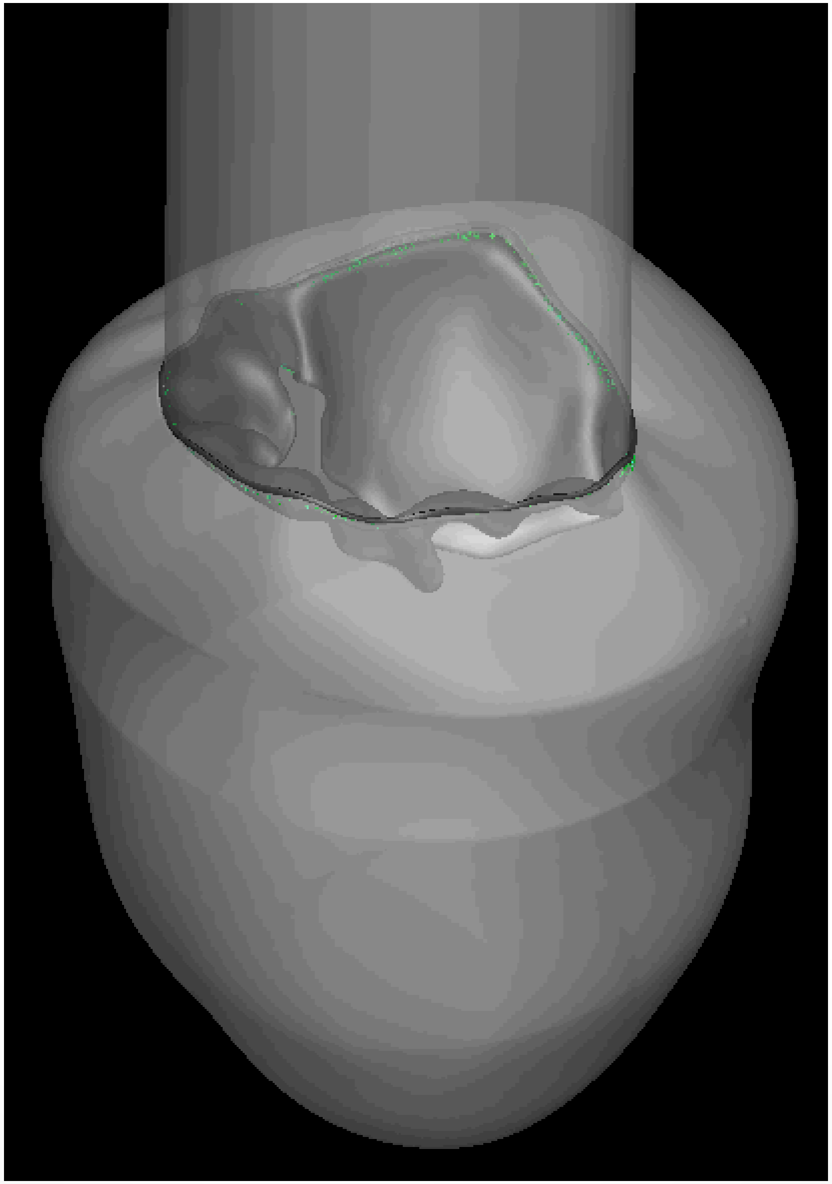
Top view

Local Mesh refinement captures the complex flow structures in the ventricle during valve deformation



Maximum Re ~ 5700

Highly 3-D Vortical structures develop in the ventricular chamber during diastole



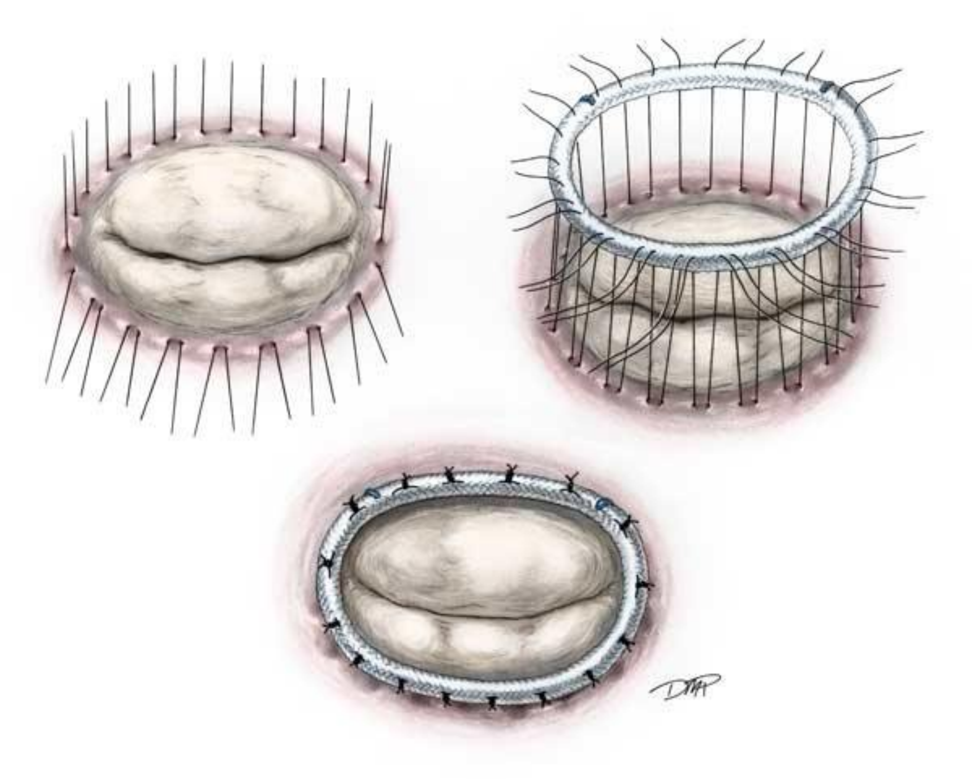
Further developments

1. Extend the simulation for complete opening of the valve

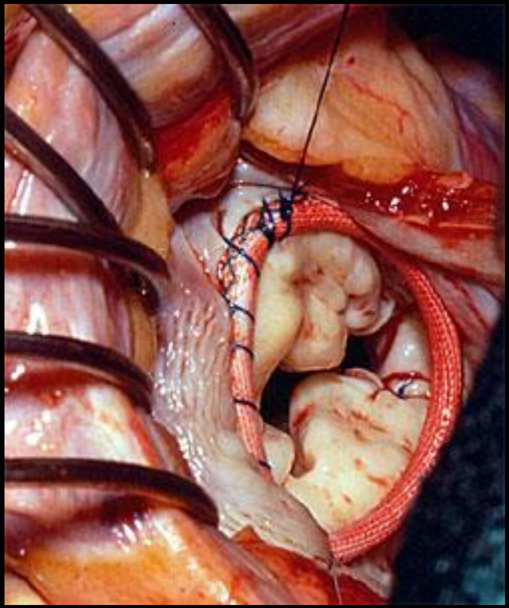
2. Continue the simulation for the closing of the valve

3. Incorporate patient-specific left ventricular chamber

MV Annuloplasty



. Schematic of MV annuloplasty



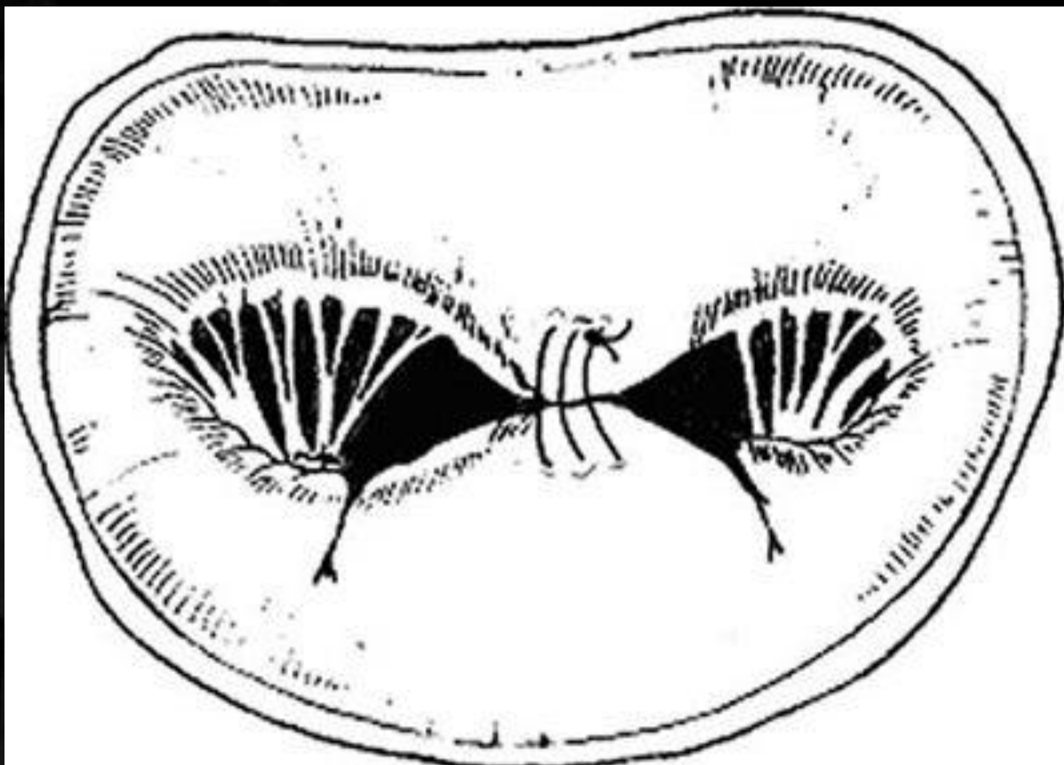
Photograph of MV annuloplasty

Riley R, Kon ND, Mitral Valve Repair, CTSNet, 2005

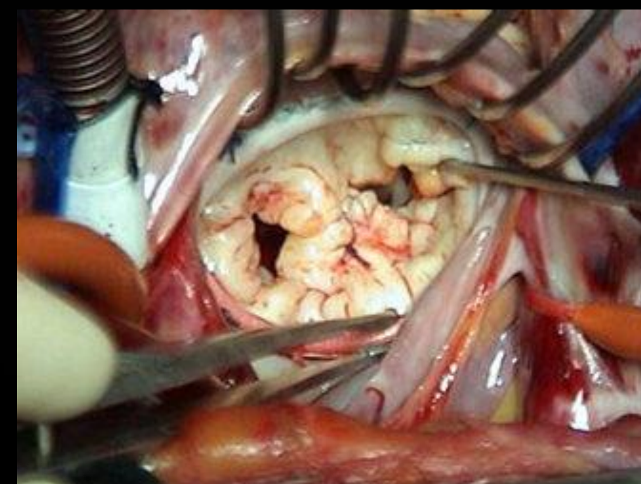
http://www.ctsnet.org/sections/clinicalresources/adultcardiac/expert_tech-2.html

http://www.heart-valve-surgery.com/heart-surgery-blog/2009/09/15/failure-of-mitral-regurgitation-treatments

Edge-to-Edge MV Repair



Schematic of the edge-to-edge technique for double orifice repair



Photograph of surgical correction by the edge-to-edge technique followed by ring annuloplasty

Alfieri O et al. The Edge-to-Edge Technique for Barlow's Disease, Cirugía Cardíaca, 2003

http://www.fac.org.ar/tcvc/llave/c366/alfieri.htm

Potential applications

1. Understanding the complex physiology and mechanics of normal valvular function

2. Understanding the etiology and effects of diseases of the valves

3. Treatment planning by virtual simulations of procedures to objectively arrive at an optimal solution.