Transitional Flow in a Stenosed Carotid Artery

CSGF Final Presentation

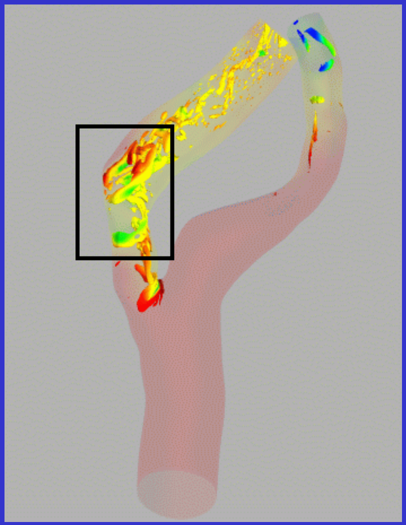
Date: 6/21/2005

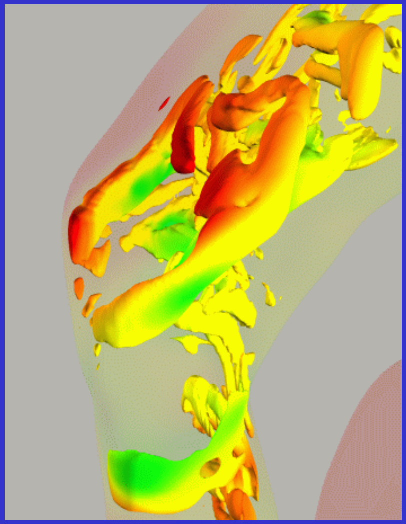
Seung E. Lee, MIT

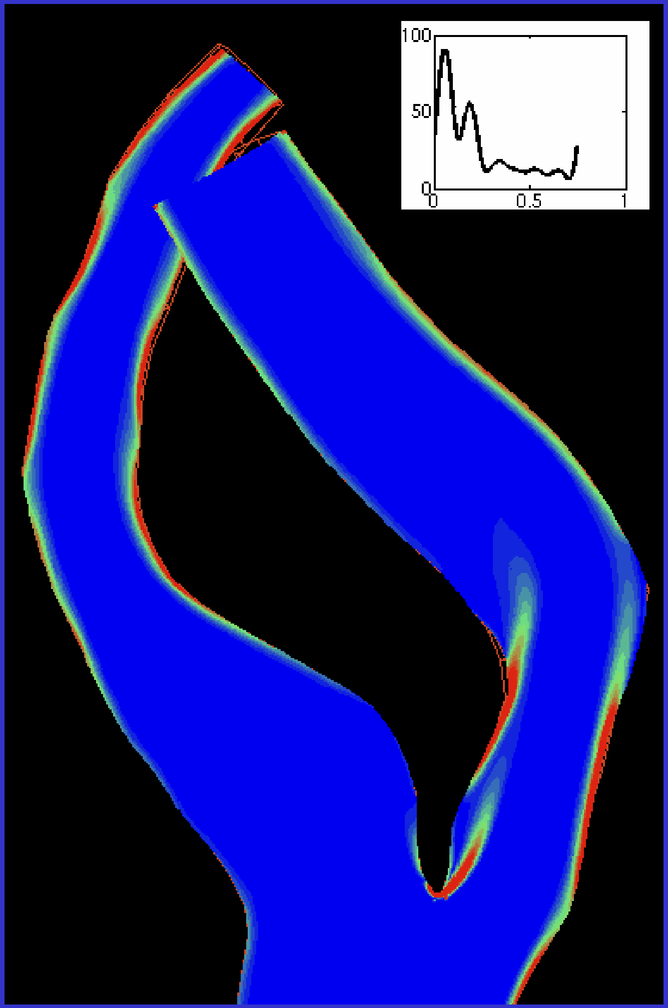
SangWook Lee, Univ. of IL at Chicago

Francis Loth, Univ. of IL at Chicago

Paul F. Fischer, Argonne National Lab





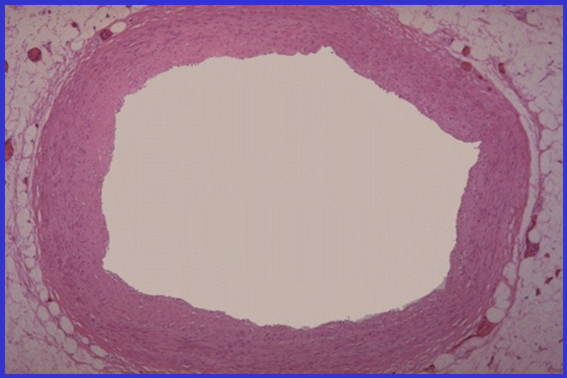


Outline

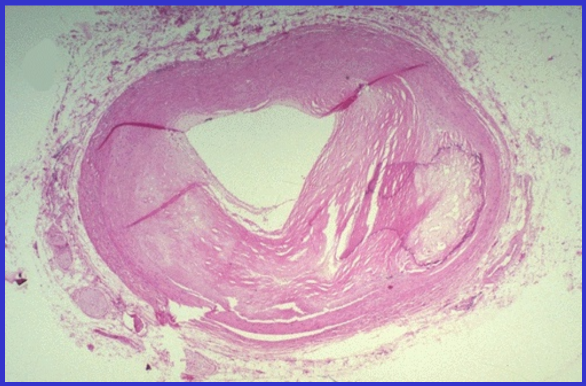
- Introduction
  - Background
  - Motivation
- Hexahedral Mesh generation
  - Simple O-grid mesh
  - High quality hexahedral mesh
- Pulsatile simulation in stenosed carotid
  - Introduction
  - Method
  - Result
- Validation
- Conclusion

Introduction

- Fluid mechanics of blood is shown to be important in arterial disease localization and progression [Giddens *et al*. 1993]
- Wall shear stress (WSS) - Localization of atherosclerosis [Ku *et al*. 1985, Zarins *et al*. 1987]
- Flow oscillation, arterial wall vibration, and etc. [Glagov *et al*. 1988]
- We are especially interested in bifurcation geometries



Normal



Severe stenosis

- **Many studies were done in normal (healthy) arterial bifurcations using both experimental and numerical simulations [Ku *et al*. 1987, Steinman *et al*. 1996]**
- **Diseased vessel may introduce disturbed (transitional) flow**
- **Disturbed (transitional) flow within vasculature may introduce additional health risks [Golledge *et al*. 2000]**
  - **Heart attack**
  - **Stroke**
- **Due to expensive computational cost of transitional flow, not many diseased bifurcations were studied**
  - **Idealized stenosed geometry [Long *et al*. 2001]**
  - **Severely stenosed on 2D projection [Stroud *et al*. 2002]**

Objective

- **Develop a methodology to translate a set of *in vivo* medical images to numerical solution of a full 3D pulsatile transitional flow**

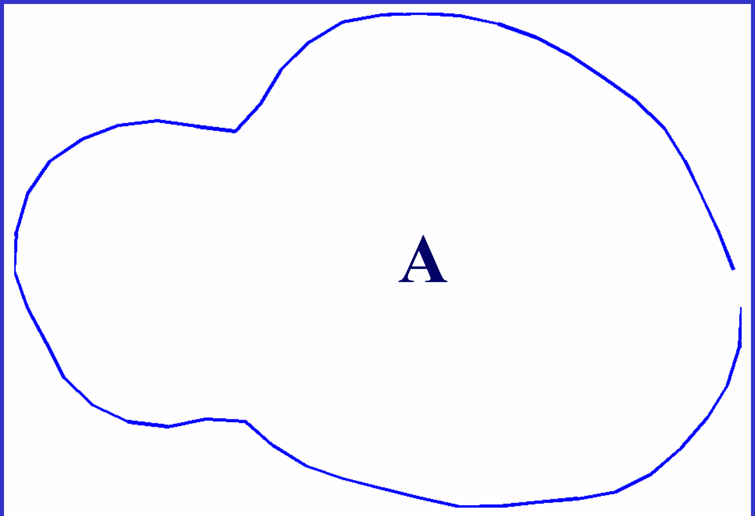
Numerical Method

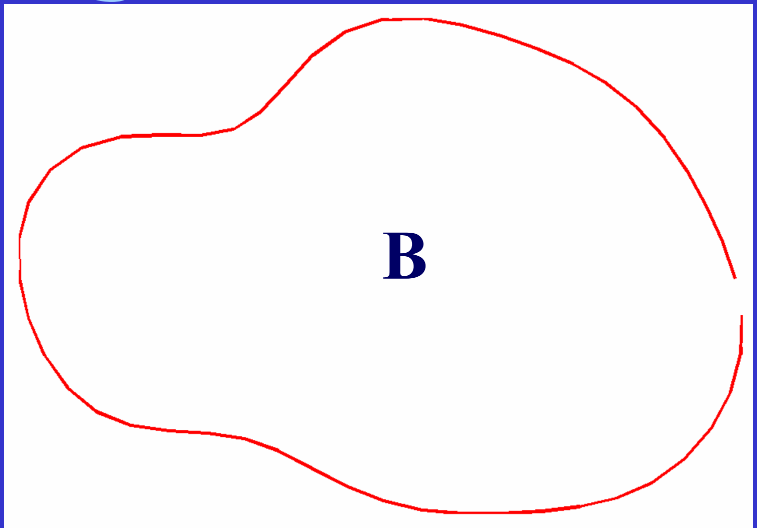
- Spectral element method, "Nekton" [Patera 84, Maday & Patera 89]
  - High-order spectral elements (N ~ 5-15)
  - 3rd-order accurate in time
- Minimal numerical dissipation/dispersion
- Direct Numerical Simulation
  - no turbulence modeling
  - does not require a separate model for different flow problems (carotid stenosis, coronary stenosis)
- Only takes quad- (2D) or hex- (3D) based meshes

Outline

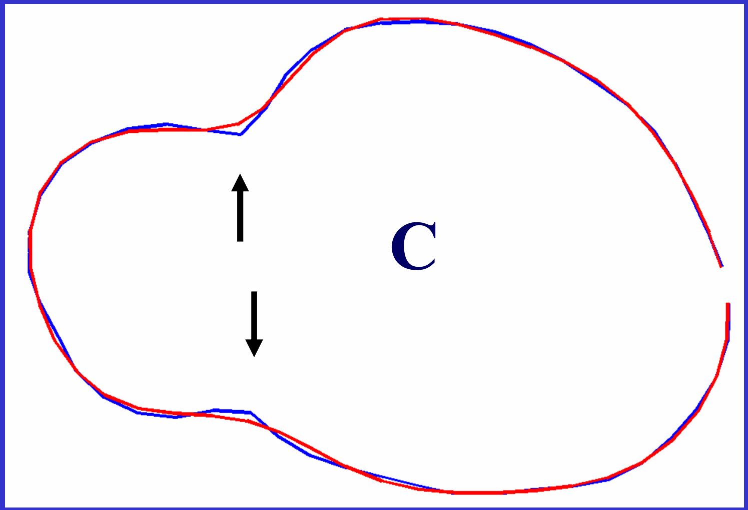
- Introduction
  - Background
  - Motivation
- Mesh generation
  - Simple O-grid mesh
  - High quality hexahedral mesh
- Pulsatile simulation in stenosed carotid
  - Introduction
  - Method
  - Result
- Validation
- Conclusion

Fourier-based non-shrinking smoothing



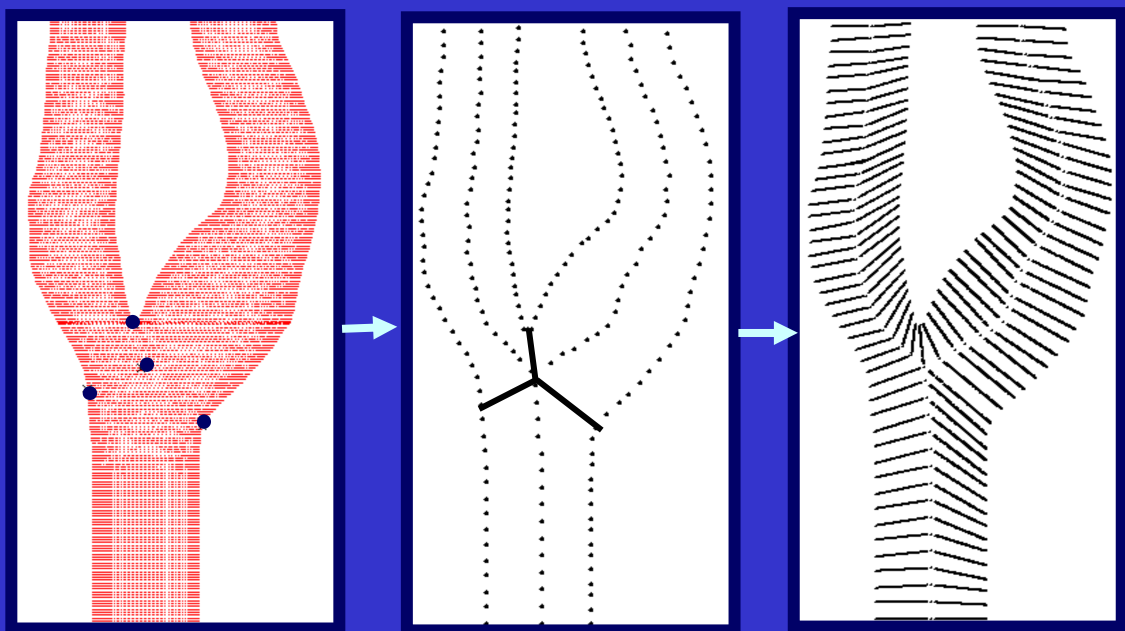


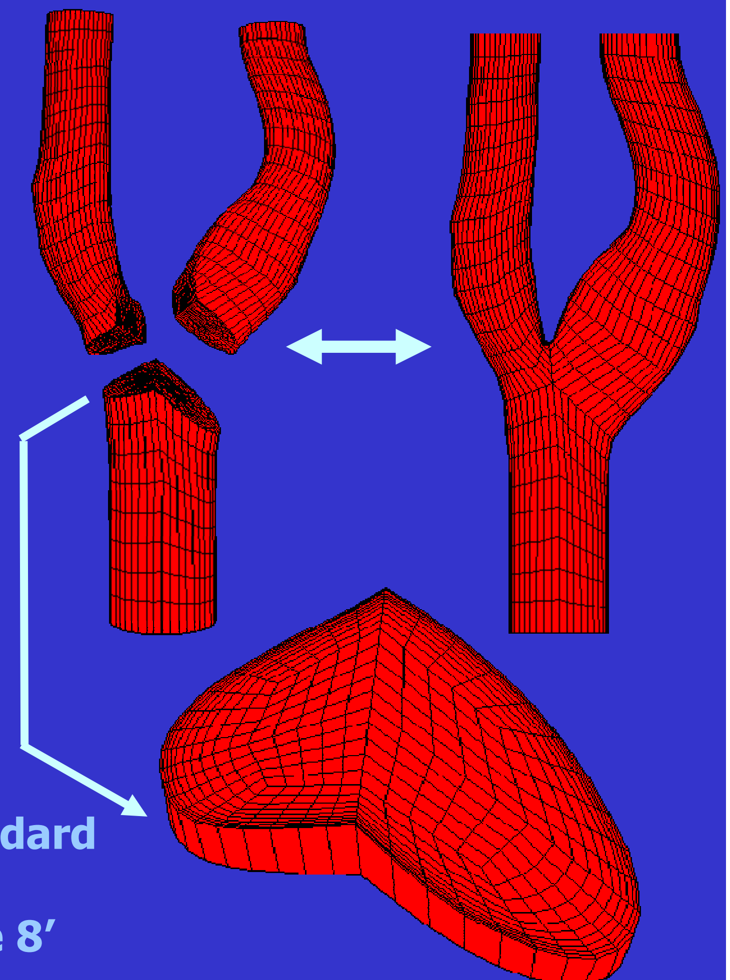
- A) A cross-section from medical image
- B) Nonshrinking Smoothing
- C) Comparison
- Developed by Fischer

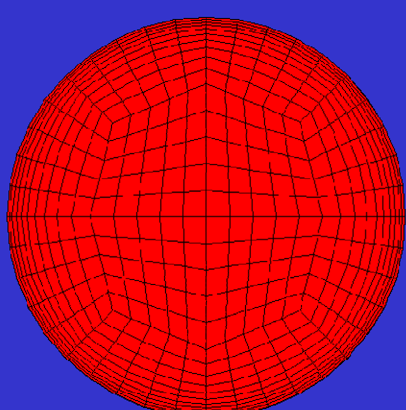


O-Grid Meshing Scheme

Partition bifurcation into 3 branches via user defined dividing sections







- Sweep each branch with standard hex-circle decomposition
- 3-way partition avoids 'figure 8' cross-section

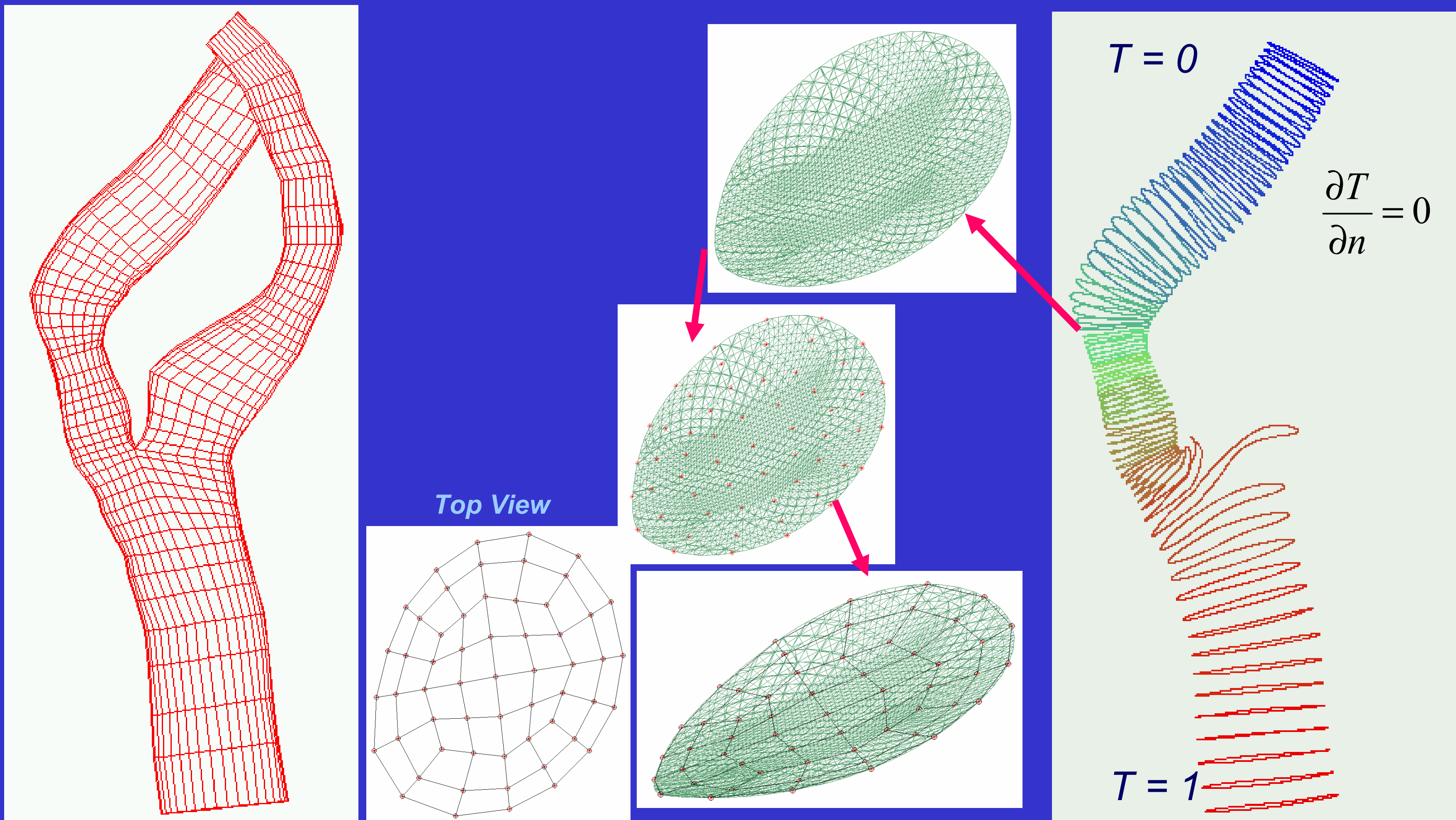
Mesh Generation Challenges

- **Need a mesh with a low number of elements**

- **Interior mesh geometry**
  - **Interior element distribution can have a *huge* impact on matrix conditioning and iteration counts [Fischer *et al*. 2002]**

- **Accurate surface representation & smoothing**
  - **Wall shear stress is very sensitive to surface details**

Meshing Based On Conduction Heat Solution

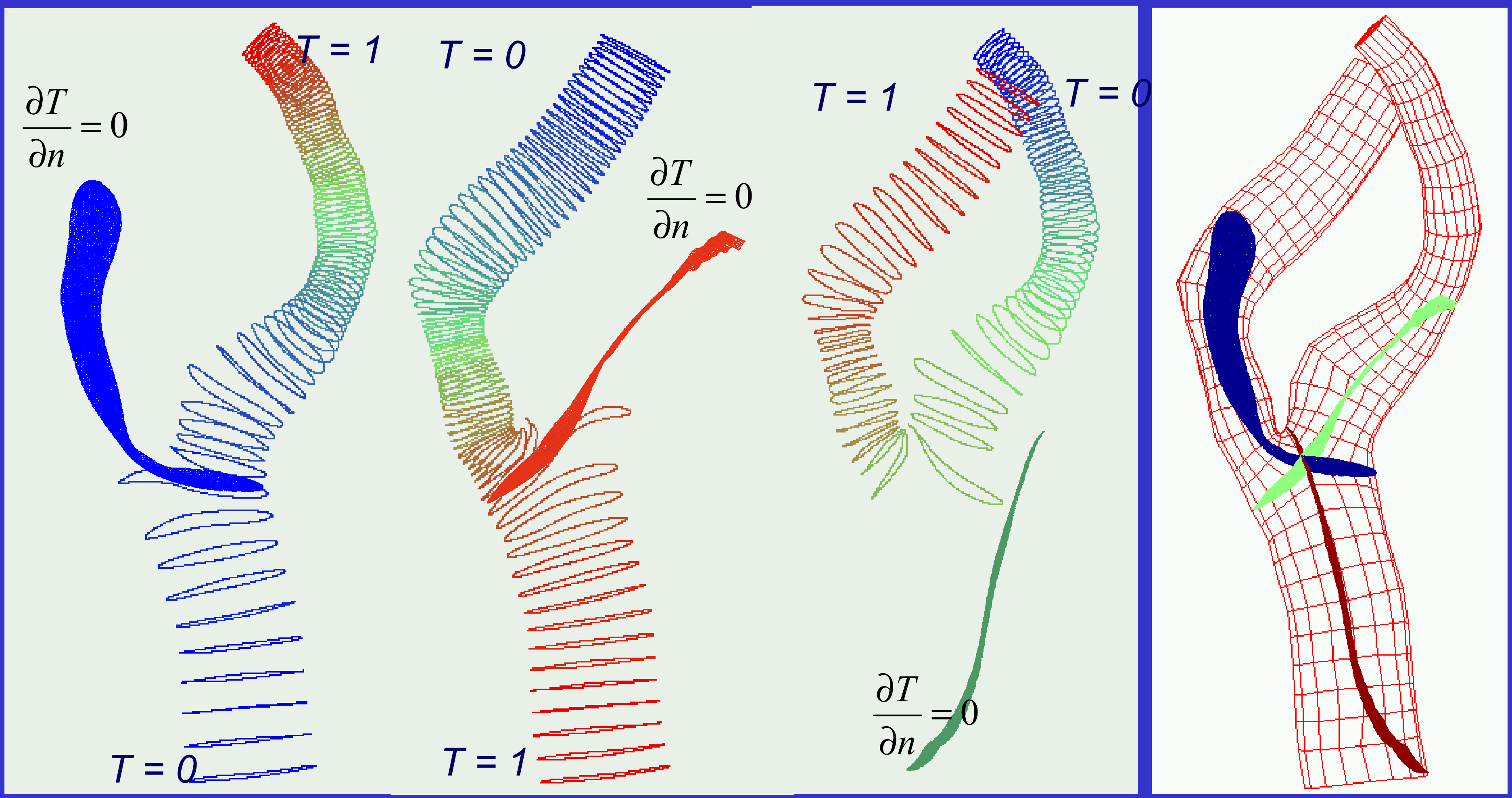


1) Preliminary mesh from commercial meshing software (ICEM-CFD)

3) Define new meshing sections on the isosurface

2) Solve conduction heat transfer problem

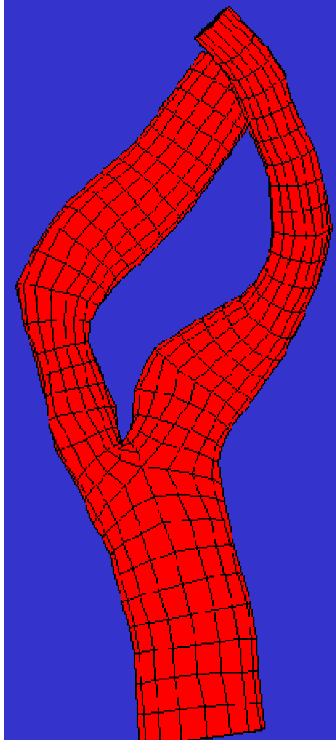
Meshing Stenosed Carotid

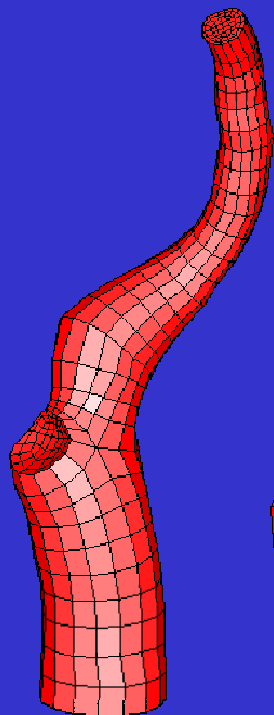


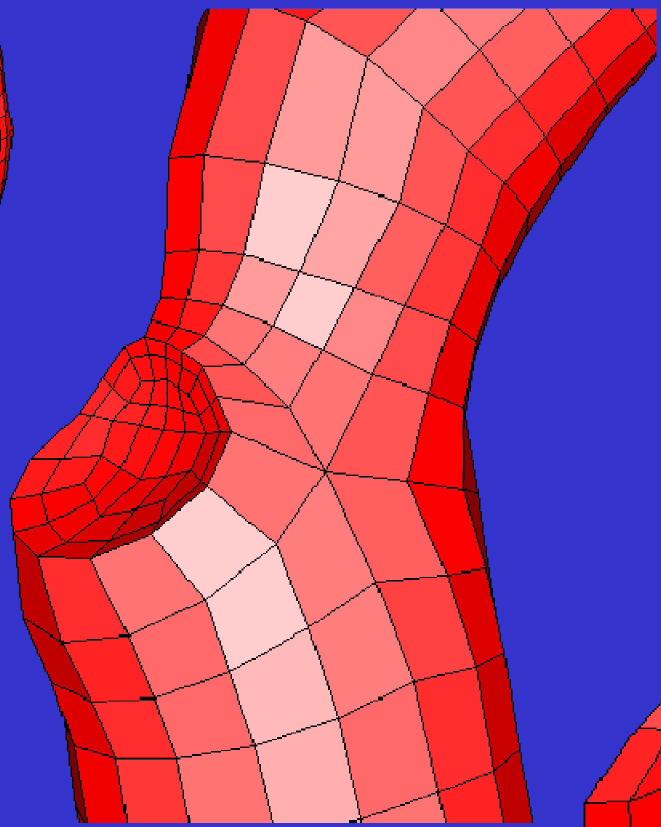
Three heat conduction solutions
Find the "principal" isosurfaces –
isosurface through the insulated branch

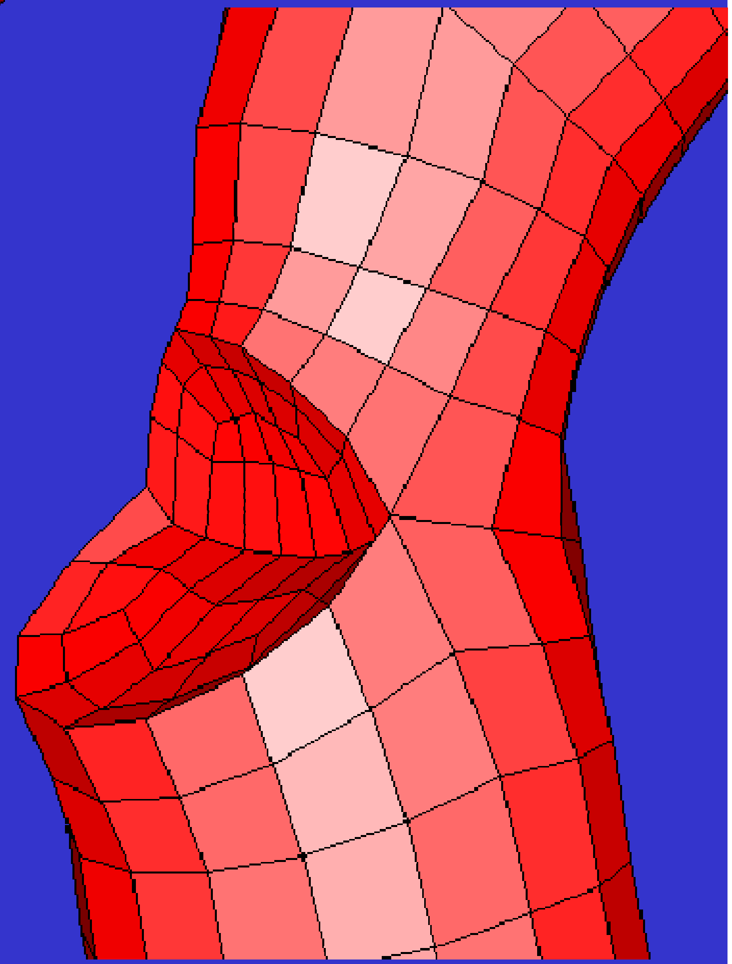
Automatically determine
Cutting surfaces

Mesh improvements





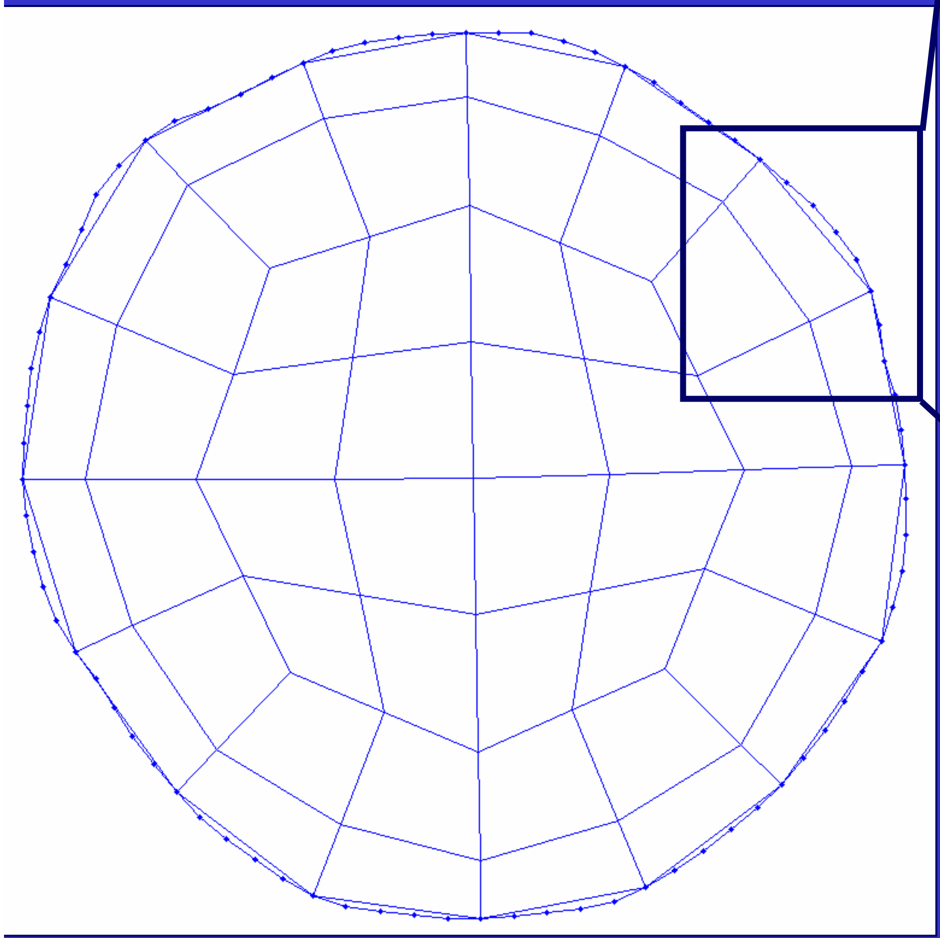


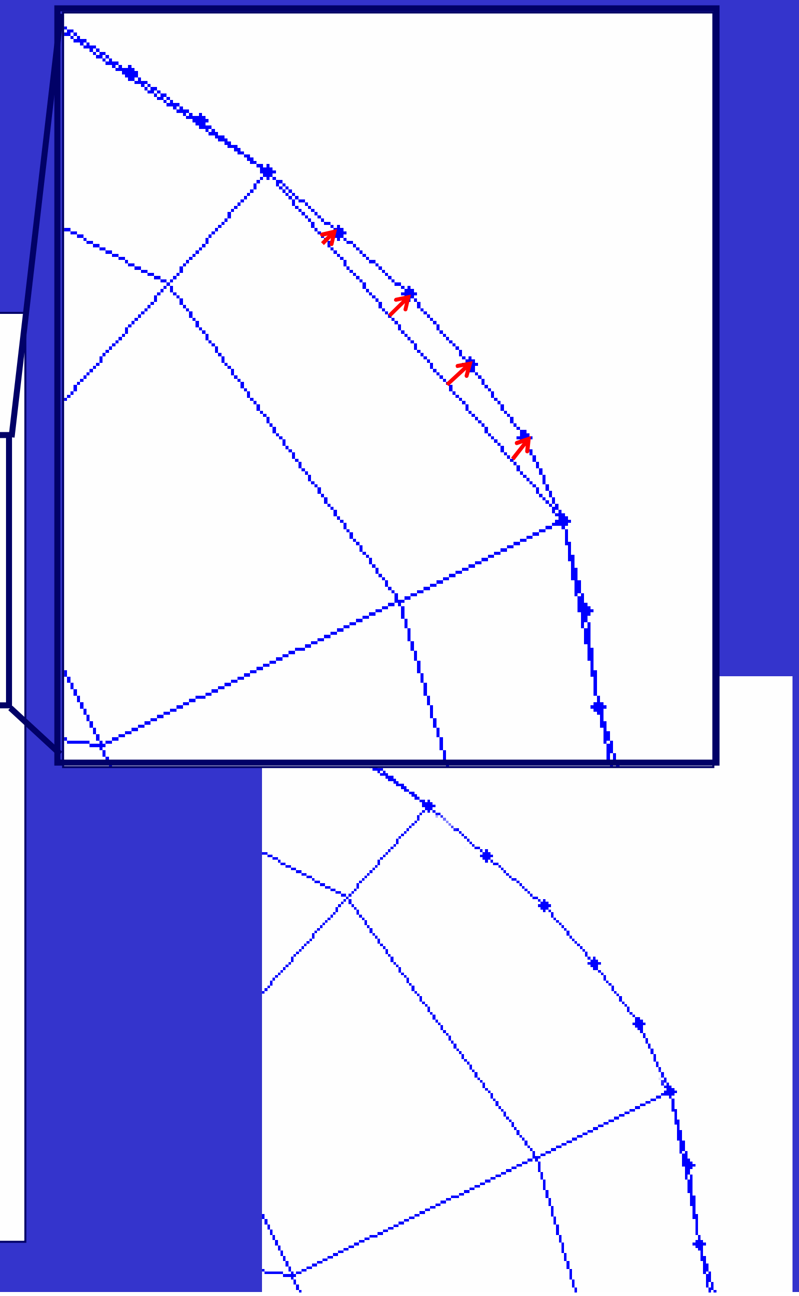


- Reduced number of elements: NEL ~ 2000
- High quality elements
  - Orthogonality
  - Minimal element deformation

How can we get away with such a crude mesh??

- **SEM can incorporate curved facets (smooth lumen surface)**





Outline

- Introduction
  - Background
  - Motivation
- Mesh generation
  - Simple O-grid mesh
  - High quality hexahedral mesh
- Pulsatile simulation in stenosed carotid
  - Introduction
  - Method
  - Result
- Validation
- Conclusion

The Carotid Artery Bifurcation

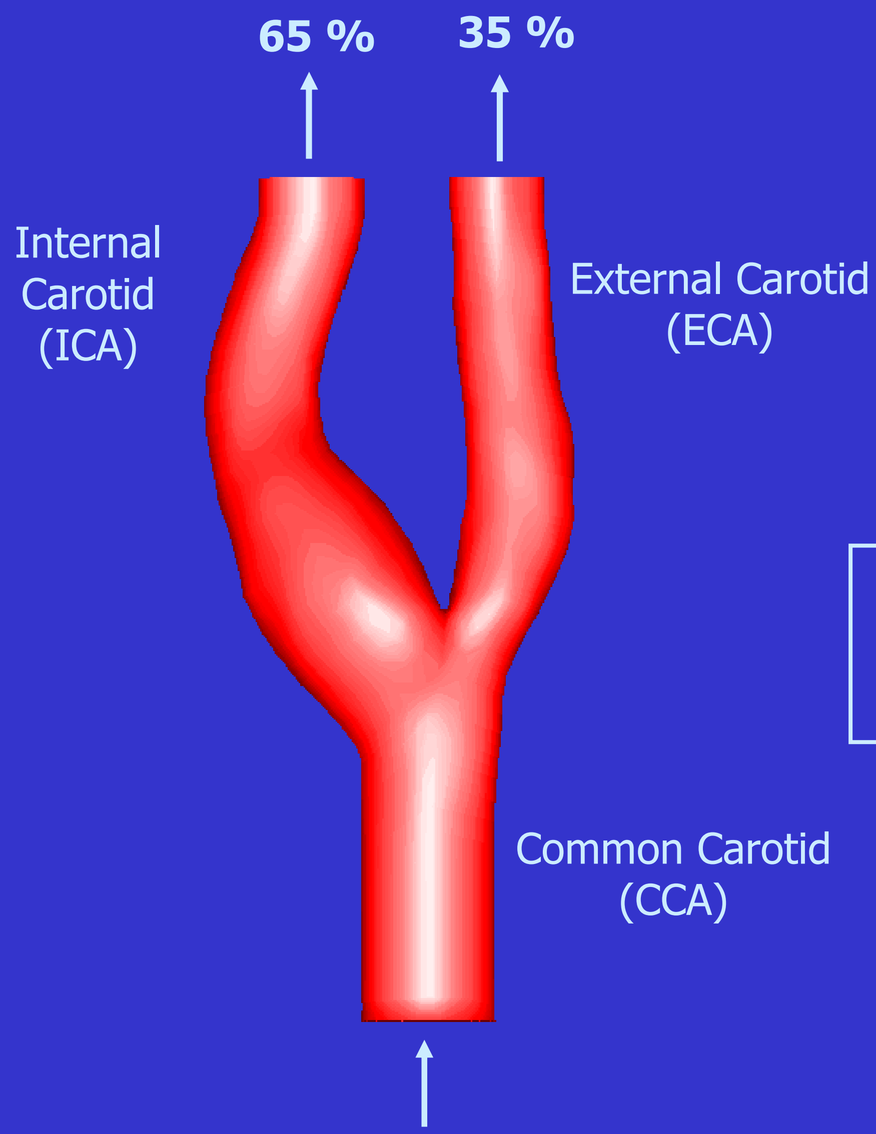
Internal Carotid

- Common Carotid Artery (CCA)
- Internal Carotid Artery (ICA) - Supplies blood to the brain
- External Carotid Artery (ECA) - Supplies blood to the face

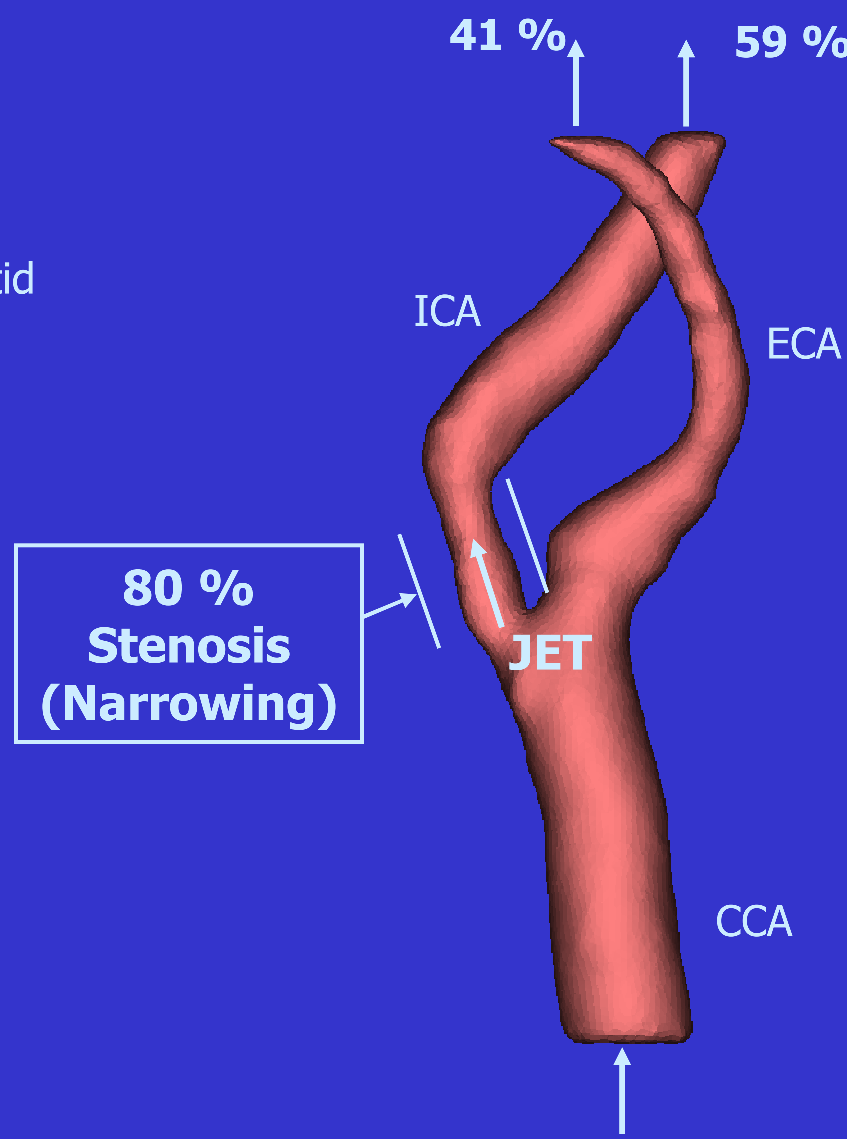
External Carotid

Common Carotid

Healthy and severely stenosed carotid bifurcations



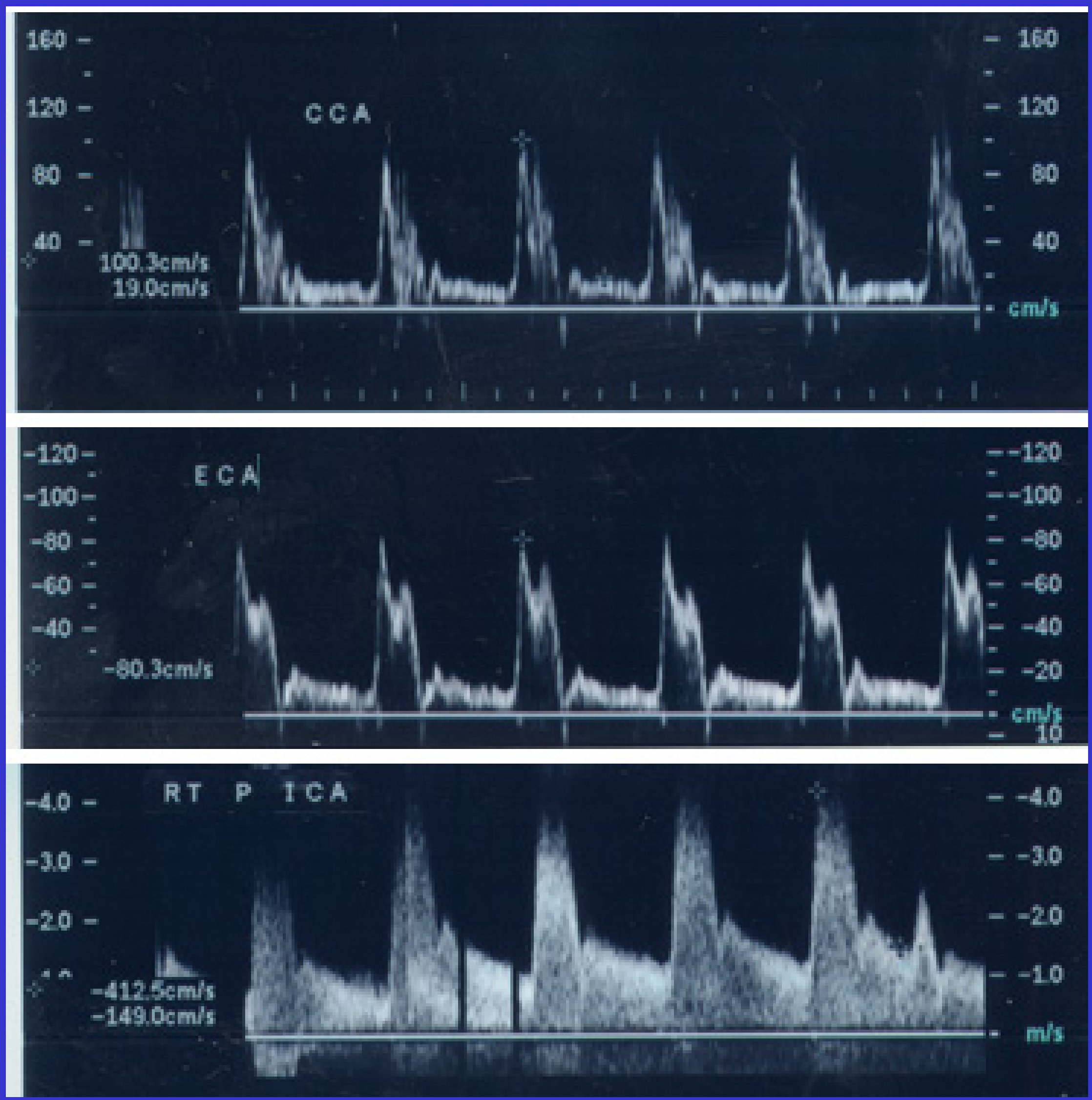
Healthy Carotid Bifurcation

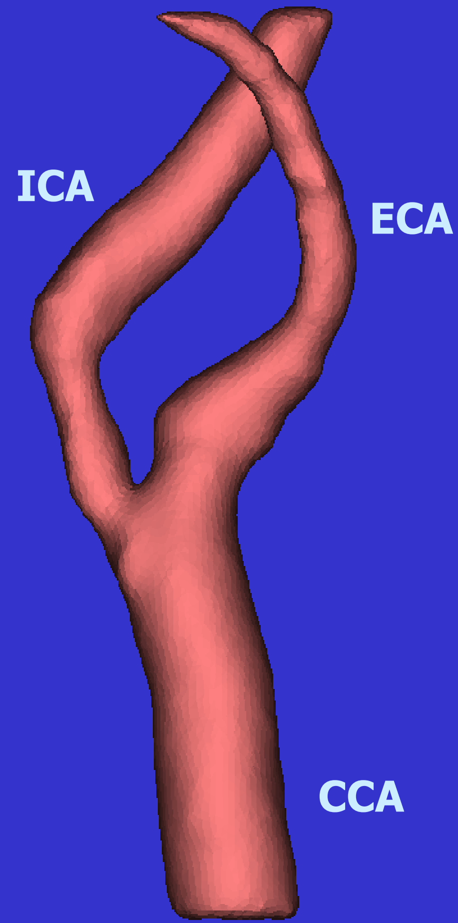


Stenosed Carotid Bifurcation

Healthy carotid simulation done by Piersol, N. 2001 MS Thesis

Ultrasound velocity data

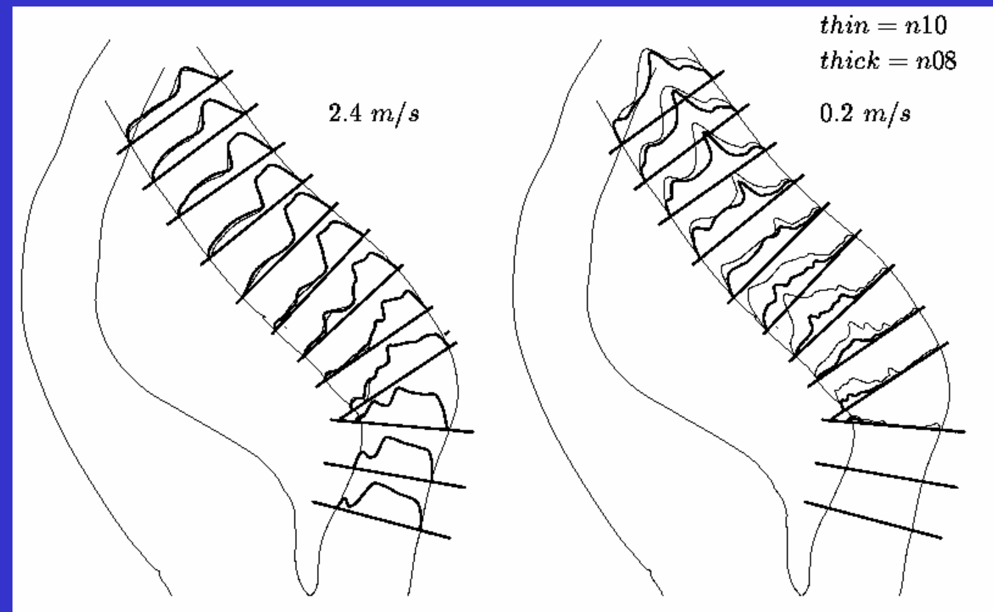




Grid independence test (Steady inlet)

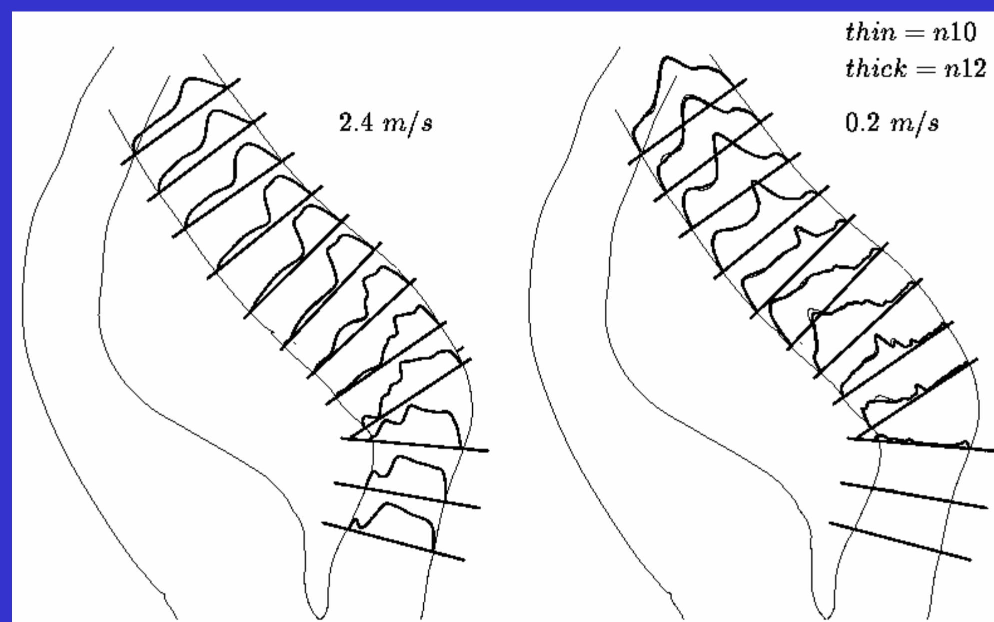
- Comparison between N = 08 and N = 10

- Left = velocity
- Right = RMS

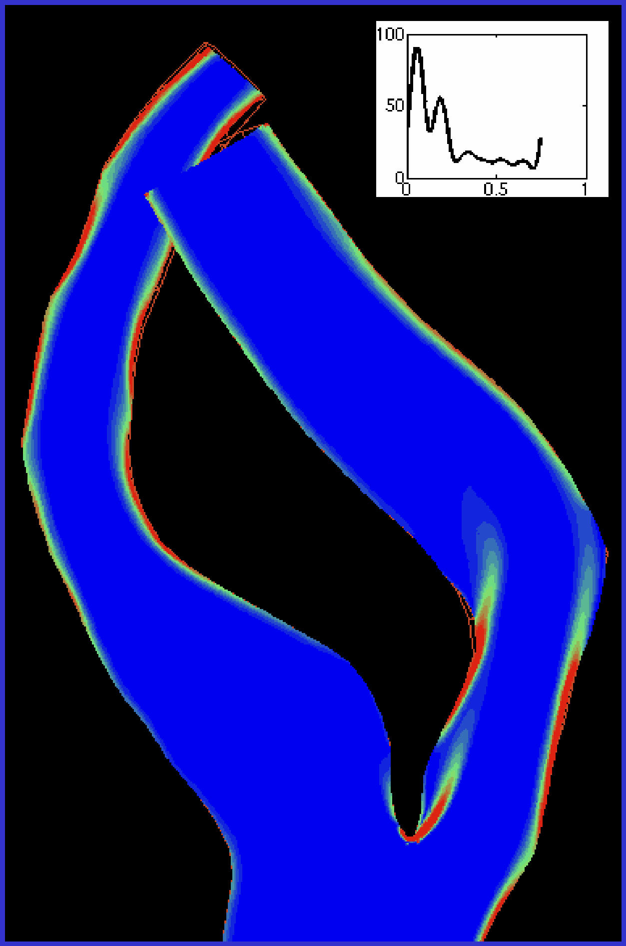


- Comparison between N = 10 and N = 12

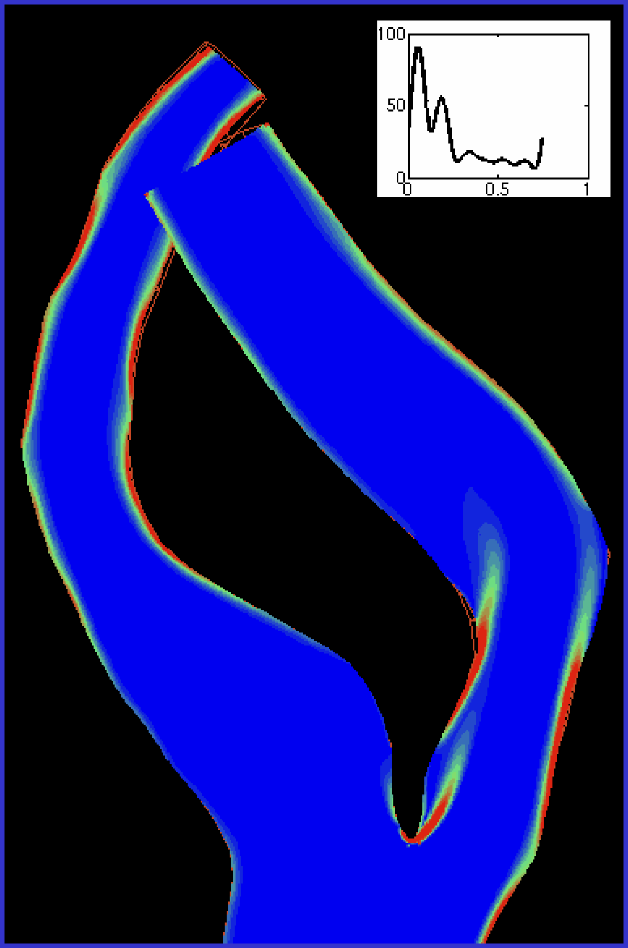
- Left = velocity
- Right = RMS



Vorticity Animation In Stenosed Carotid



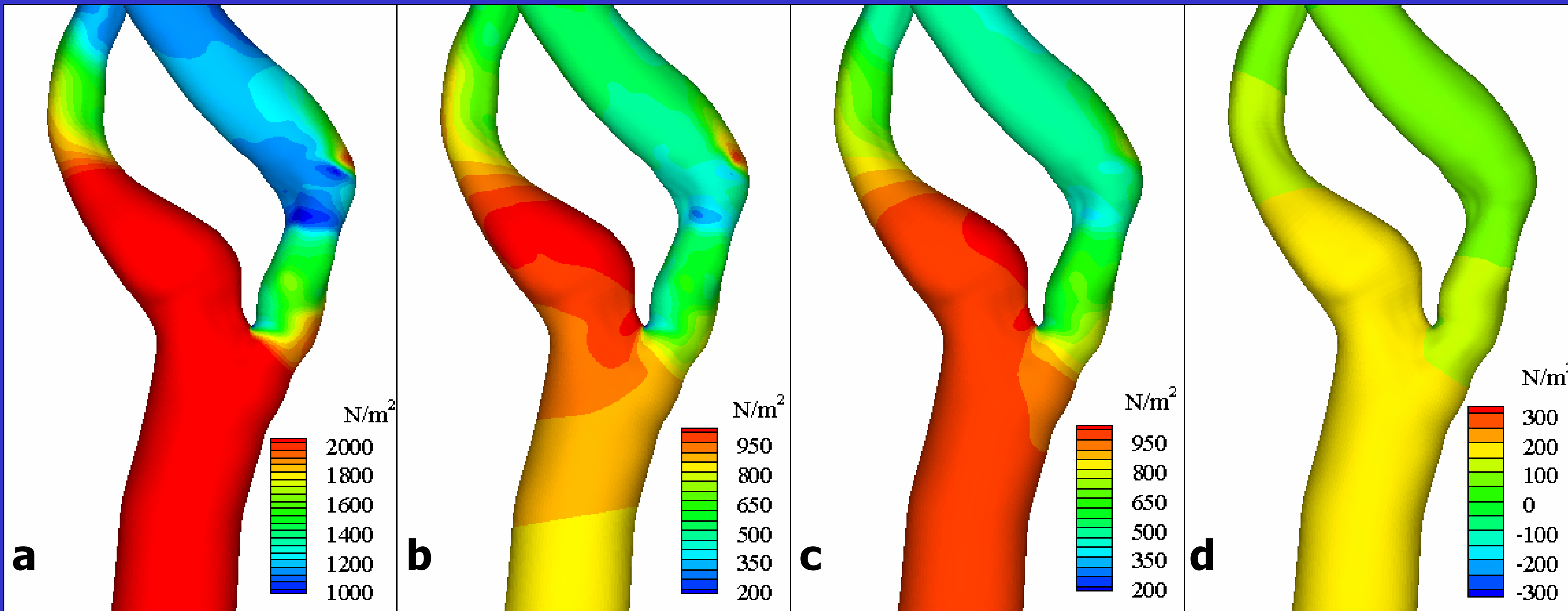
Vorticity at midplane



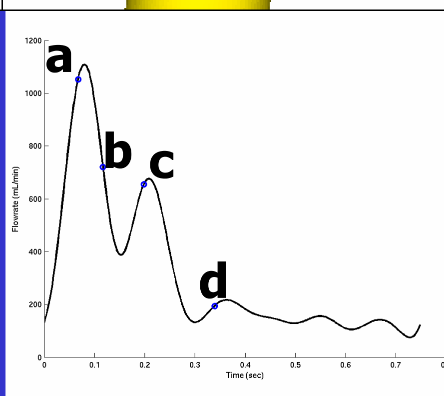
Vorticity at midplane
Only first peak systole

- Womersley inlet – flow waveform from Ultrasound
- Constant flow split specification – 59:41 (ICA:ECA)
- Rigid wall
- N = 10
- K = 2544
- Computation time = 11 hrs with 256 processors

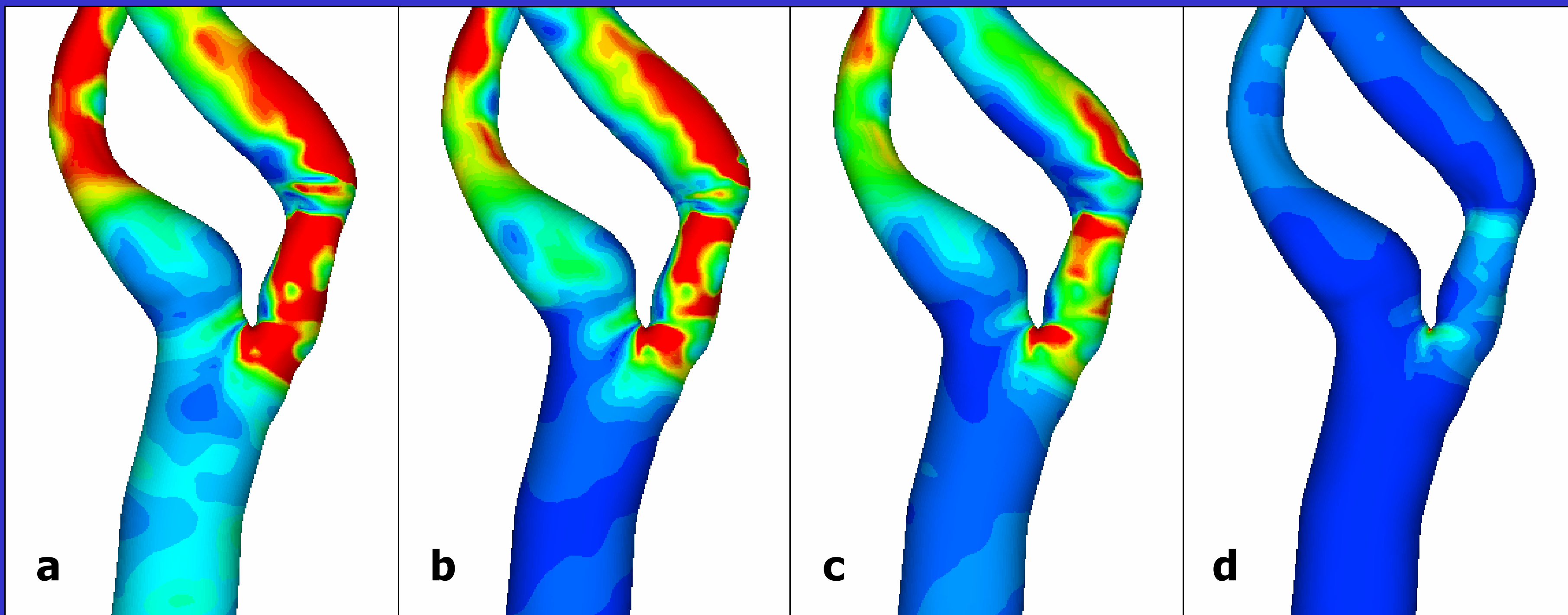
Pressure Distribution

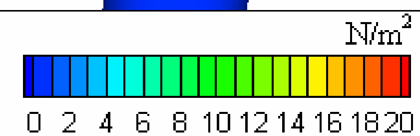


- Low pressure at the throat of stenosis
- Shown to cause collapsing of aterial wall [blah 2000]
- Correlate sharp pressure drop with plaque rupture vulnerability

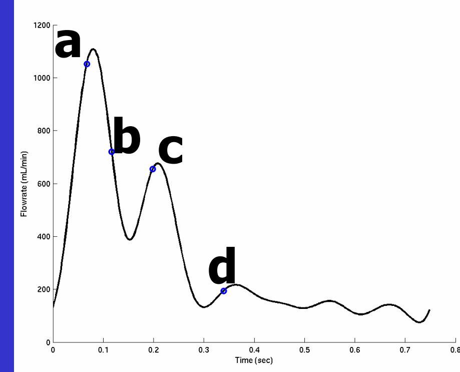


Wall Shear Stress Distribution

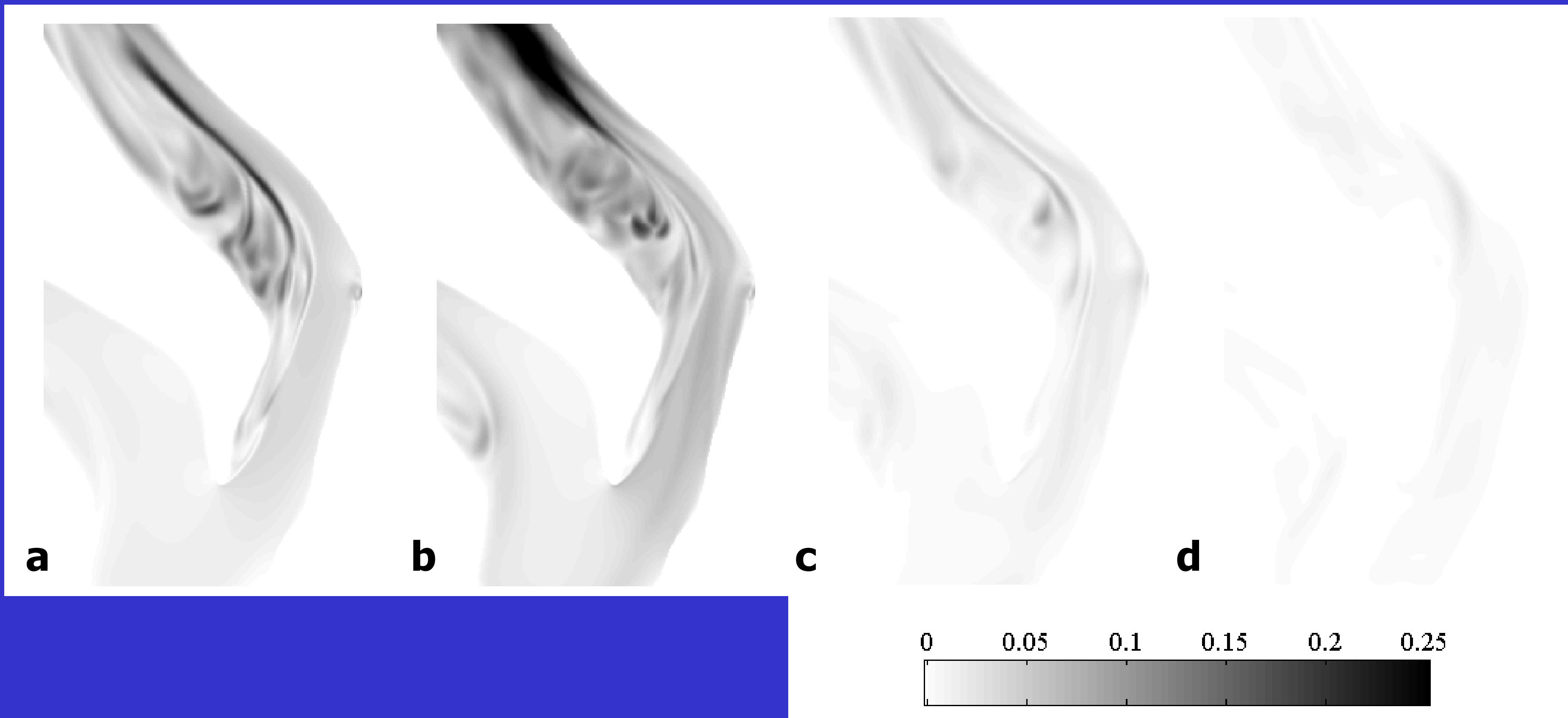


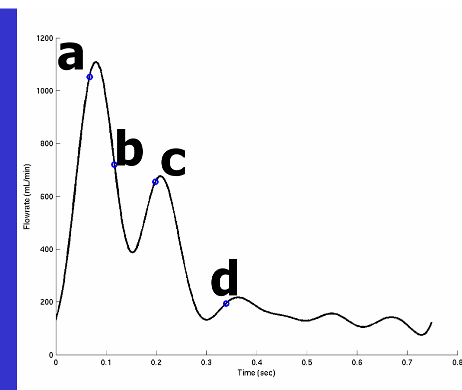


- Distribution of very high and very low WSS – typical value is around 1.5 N/m²
- Disease progression
- Damage endothelial cells and red blood cells
- Fatigue plaque to cause rupture
- Trigger thrombosis
- Correlation study needed



Turbulence Intensity



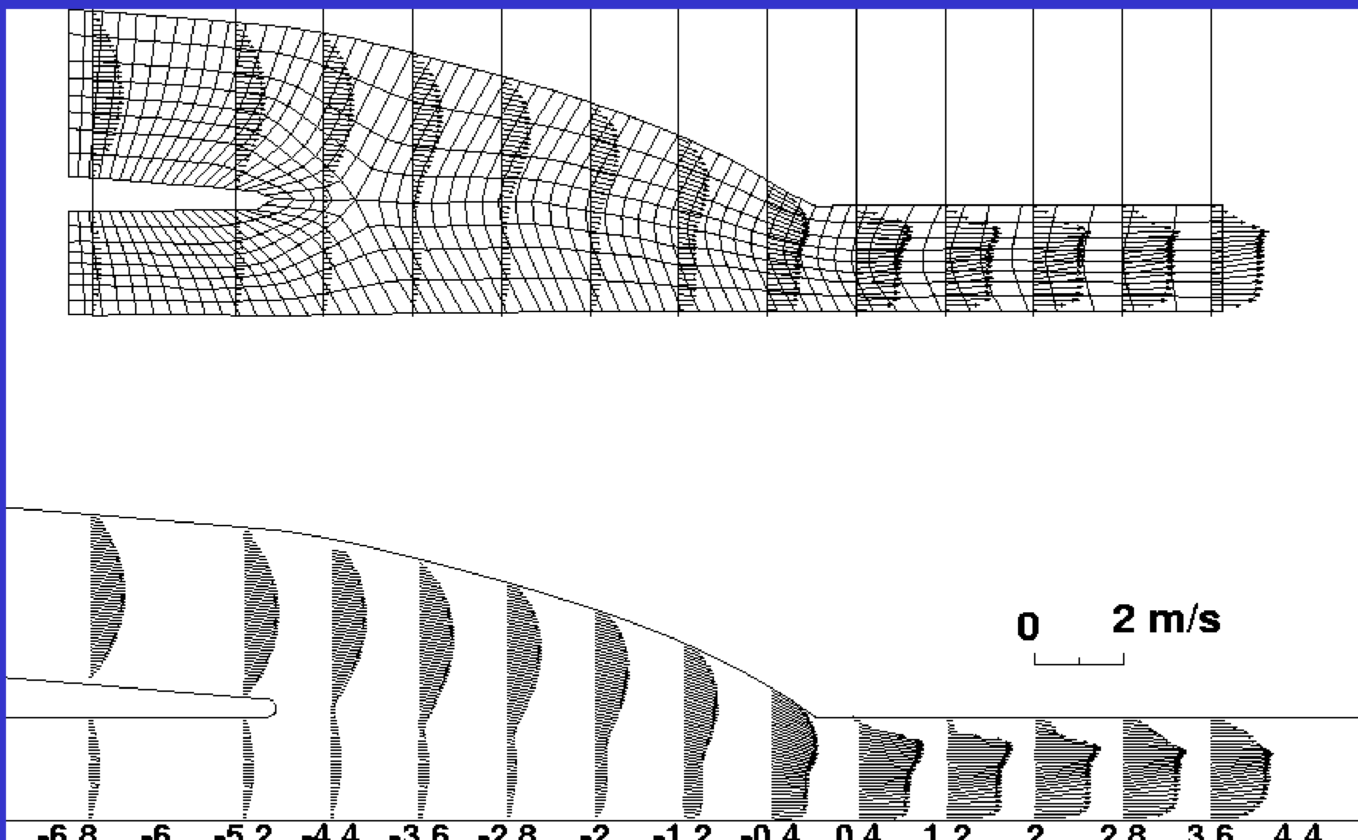


- High mixing intensity downstream of stenosis – activate platelet
- High mixing intensity in the recirculation zone

Outline

- Introduction
  - Background
  - Motivation
- Mesh generation
  - Simple O-grid mesh
  - High quality hexahedral mesh
- Pulsatile simulation in stenosed carotid
  - Introduction
  - Method
  - Result
- Validation
- Conclusion

AV Graft Velocity Comparison (Inlet Re = 1060 & outlet Re = 1900)

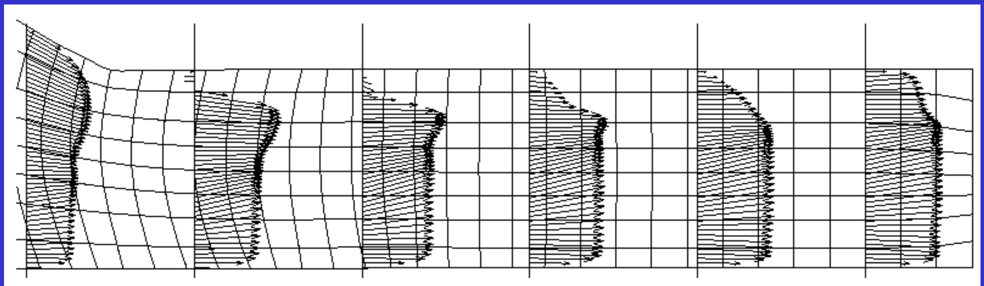


Numerical

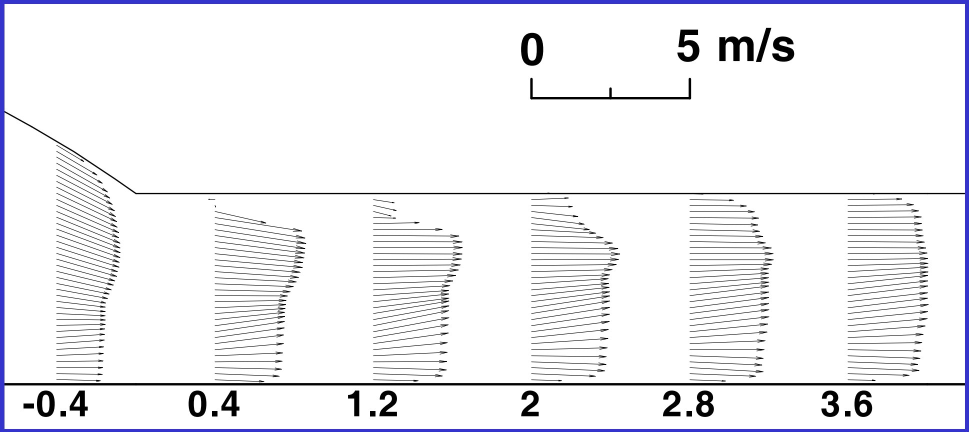
Experimental

Comparison with LDA measurements (Arslan 99)
Steady Flow - Re = 1060

AV Graft Average Velocity Comparison (Inlet Re = 1820 & outlet Re = 3200)



Numerical



Experimental

Velocity profile scaled to *in vivo* values.

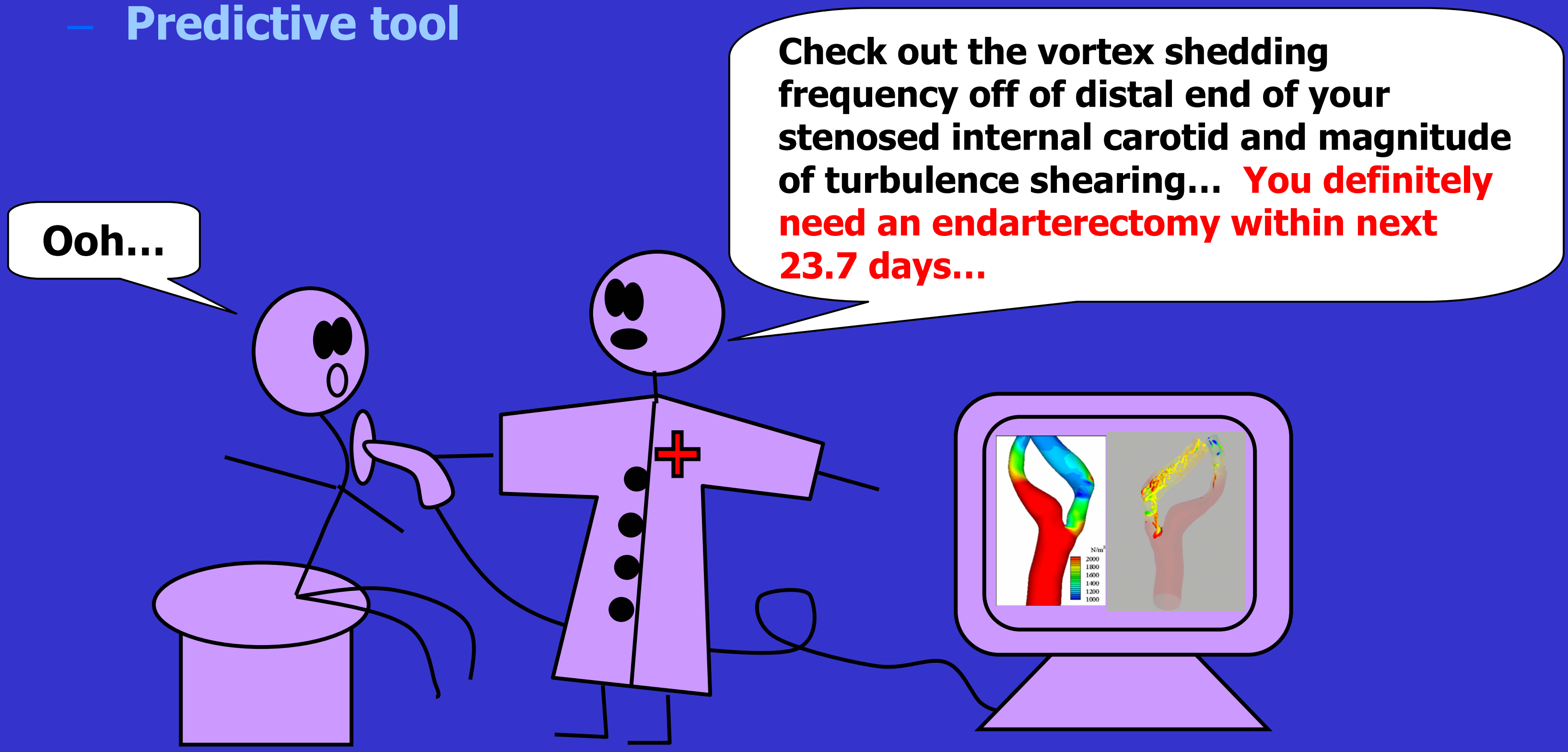
Conclusion

- We have develop a methodology to translate a set of *in vivo* medical images to numerical solution of a transitional flow in a stenotic bifurcation
- Patient-specific, full cardiac cycle transitional flow calculation obtainable in 12 hours with 256 processors
- Quantification of flow parameters in stenosed carotid
- Consistent with experimental and other numerical observations

Future Goal

- Further research to correlate arterial disease with hemodynamic parameters

- Non-invasive way to quantify Hemodynamic parameter
  - Diagnostic tool
  - Predictive tool



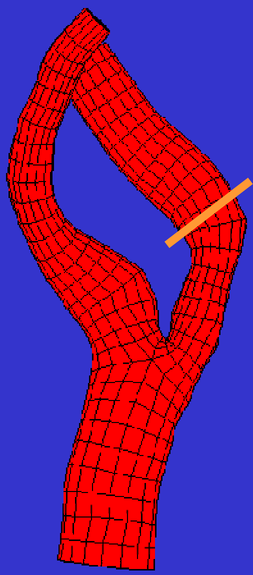
Acknowledgements

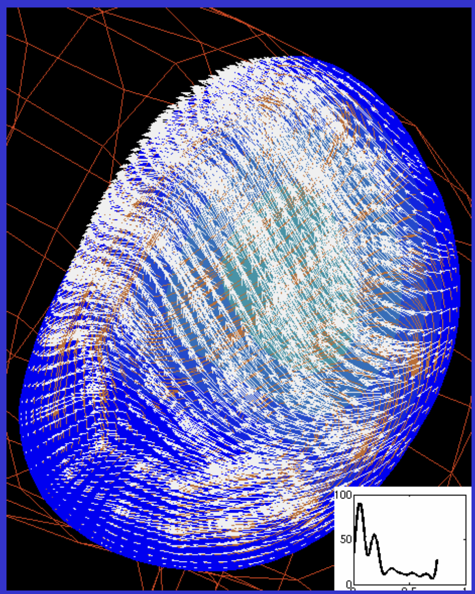
- Francis Loth, PhD
- Paul F. Fischer, PhD
- SangWook Lee, MS
- Krell Institute

- Funding
  - UIC Graduate Fellowship
  - Gates Millennium Scholarship
  - CSGF

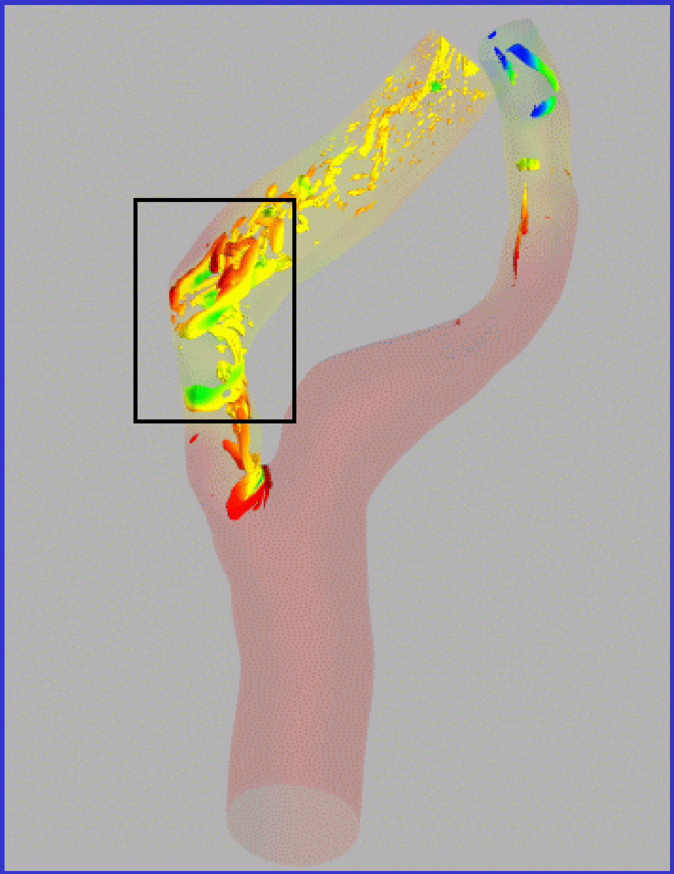
- A very special thanks to…

Computational Science Graduate Fellowship





Coherent Vortical Structure



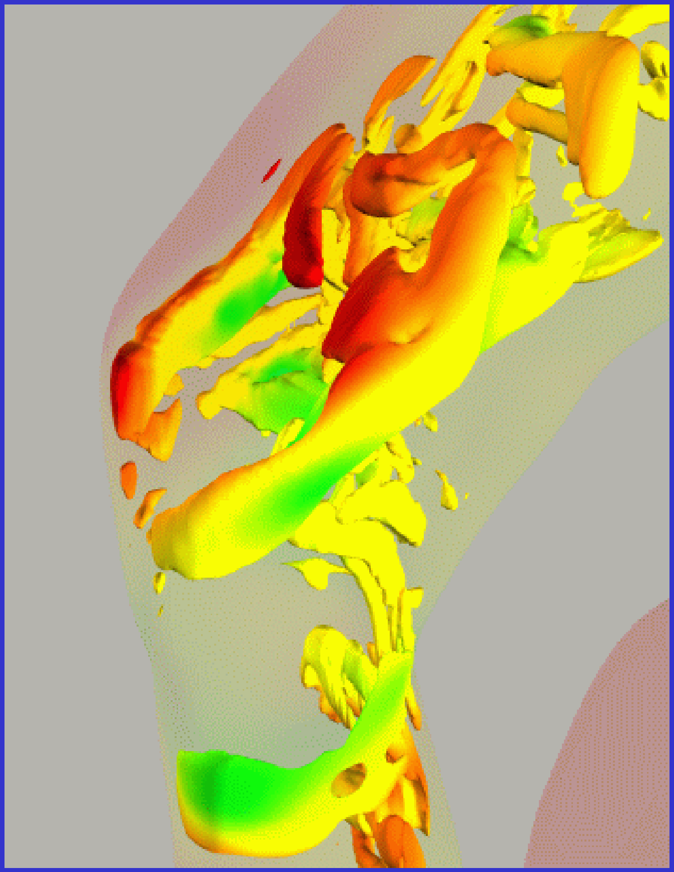
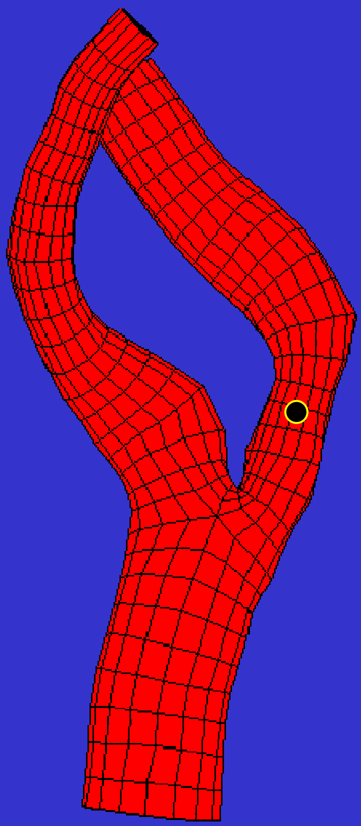
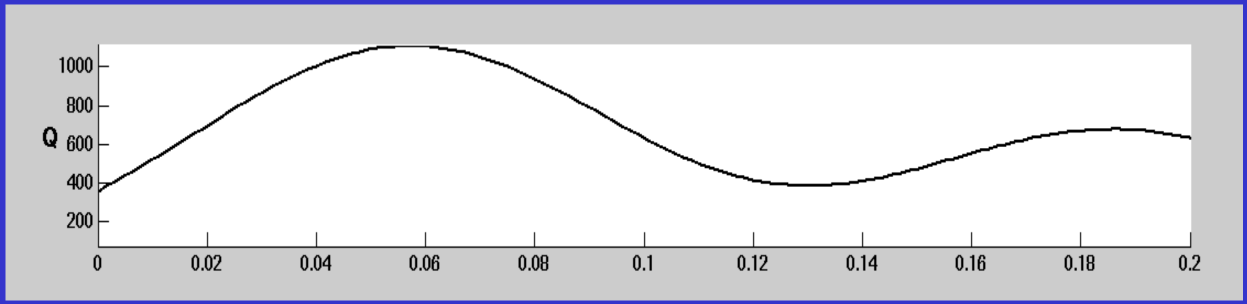


Image created by ANL Visualization Lab using the λ_2 criterion of Jeong & Hussain (JFM'95)

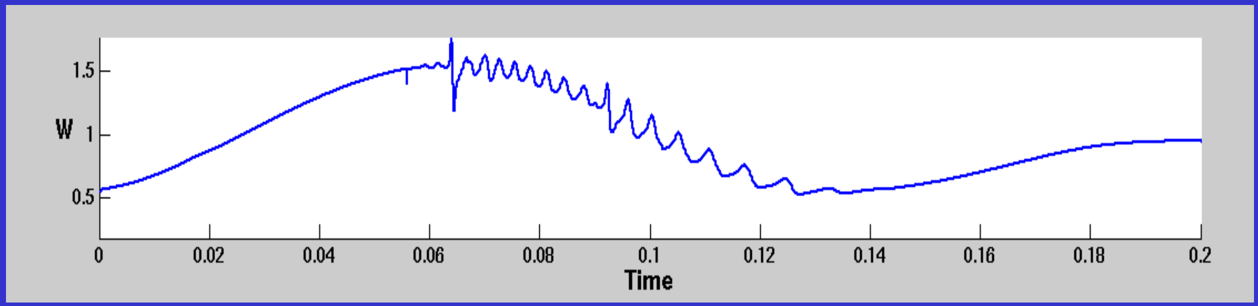
Velocity Time Trace in ICA



Inlet flow waveform

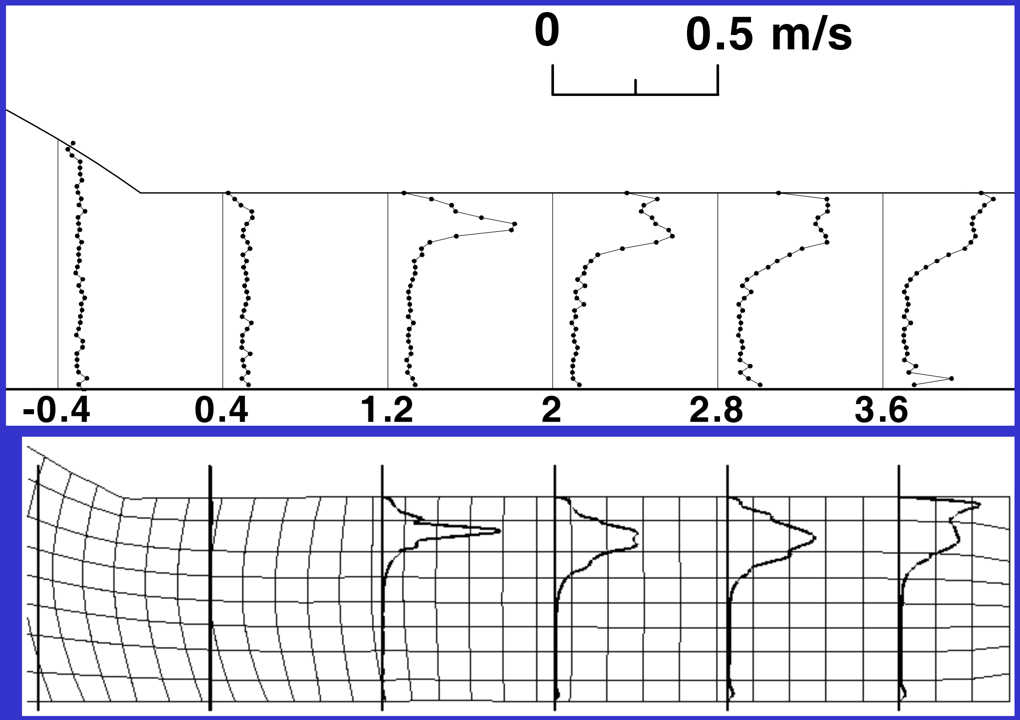


Z-component velocity



- Velocity fluctuation ~ 300 Hz
  - Within audible band (100 – 500 Hz)
- Time step used, dt = 1e-5, is much less than 1/300

Urms (Re=1820)

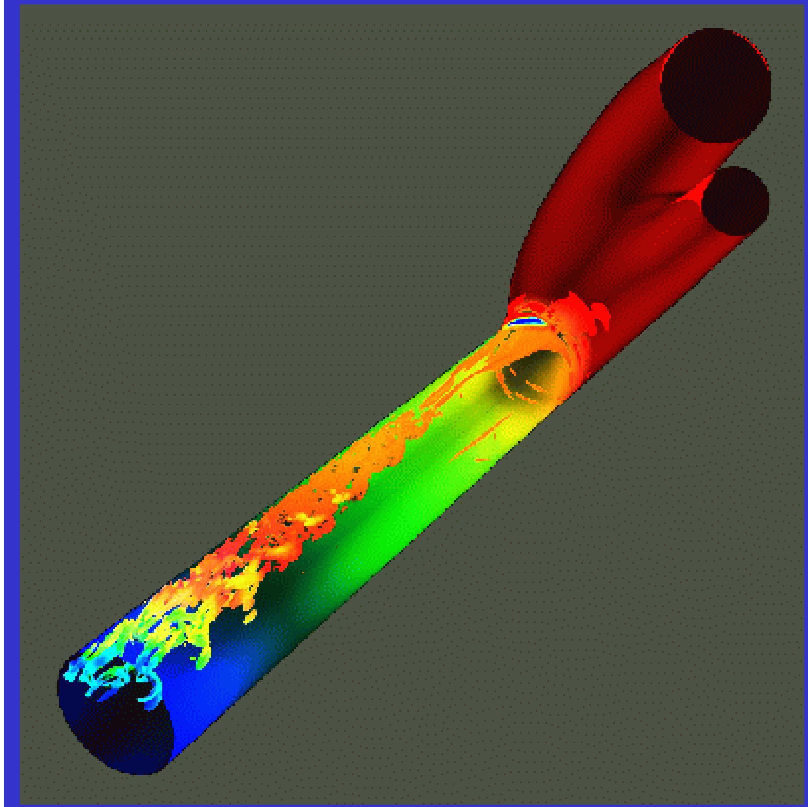


Experimental

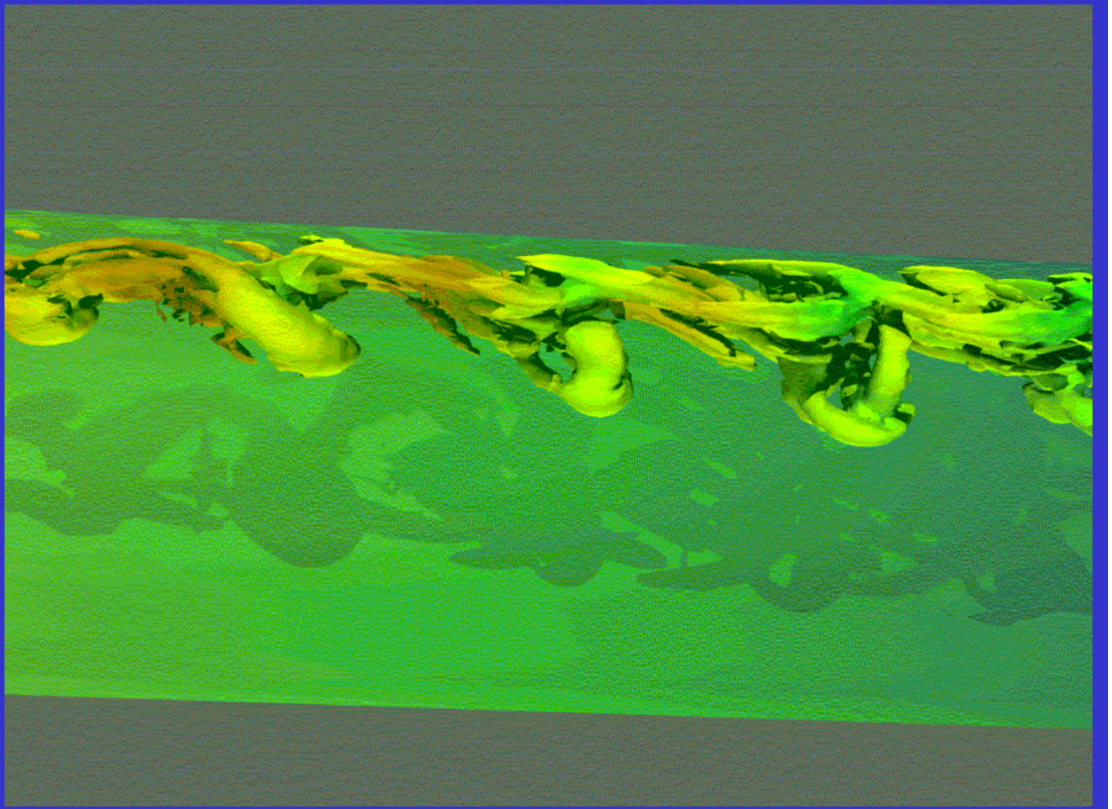
Numerical

Turbulent intensities (Urms) in PVS scaled to in vivo values.

Coherent Vortical Structure



Transitional flow in PVS



Close-up of coherent vortical structures in PVS visualized with the λ_2 criterion of Jeong & Hussain (JFM'95)