Transitional Flow in a Stenosed Carotid Artery

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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
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
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)

2) Solve conduction heat transfer problem

3) Define new meshing sections on the isosurface

Top View

$T = 0$

$\frac{\partial T}{\partial n} = 0$

$T = 1$
Meshing Stenosed Carotid

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

\[
\frac{\partial T}{\partial n} = 0
\]

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)
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The Carotid Artery Bifurcation

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

ICA

ECA

CCA
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

- 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
Low pressure at the throat of stenosis
Shown to cause collapsing of arterial 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
- High mixing intensity downstream of stenosis – activate platelet
- High mixing intensity in the recirculation zone
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AV Graft Velocity Comparison
(Inlet Re = 1060 & outlet Re = 1900)

Comparison with LDA measurements (Arslan 99)
Steady Flow - Re = 1060
AV Graft Average Velocity Comparison
(Inlet Re = 1820 & outlet Re = 3200)

Velocity profile scaled to *in vivo* values.
Conclusion

- We have developed 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

Check out the vortex shedding frequency off of distal end of your stenosed internal carotid and magnitude of turbulence shearing... You definitely need an endarterectomy within next 23.7 days...
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Coherent Vortical Structure

Image created by ANL Visualization Lab using the $\lambda_2$ 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 \( 1/300 \)
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 $\lambda_2$ criterion of Jeong & Hussain (JFM'95)