Predicting Aneurysm Rupture: Computer Modeling of Geometry and Hemodynamics

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Acknowledgements

<u>Ma B, Harbaugh RE, Raghavan ML:</u> Three-Dimensional Geometrical Characterization of Cerebral Aneurysms. *Ann Biomed Eng* 32: 264-273, 2004

<u>Ma B, Harbaugh RE, Lu J, Raghavan ML:</u> Modeling the Geometry, Hemodynamics and Tissue Mechanics of Cerebral Aneurysms. *Proc Int Mech Eng Congress.* November 13-19, 2004, Anaheim, CA

<u>Raghavan ML, Ma B, Harbaugh RE:</u> Quantified Aneurysm Shape and Rupture Risk. *JNS* 102: 355-360, 2005

M. L. Raghavan, PhD

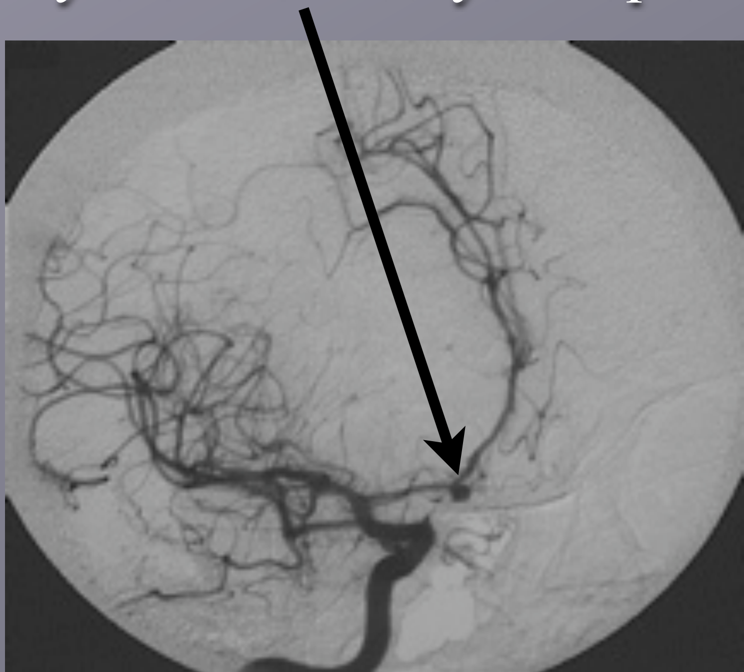
Baoshun Ma, PhD

Jia Lu, PhD

Aneurysm Growth and Rupture: Unanswered Questions

If aneurysms <10 mm rarely rupture, why do clinical series always demonstrate that most ruptured aneurysms are <10mm?

Why did this aneurysm rupture?



And this one didn't?

Predicting Rupture: Geometry

- Presently: size (maximum dimension) is used
- Is shape also an important factor?
  - Single-lobe vs. multi-lobular
  - Neck-to-height ratio
  - Ratio of neck to maximum diameter
  - Regular vs. irregular

Specific Aims of the Current Project

- Use anatomically realistic 3D geometry
- Geometrical quantification: local and global geometrical features from CTA/MRA/DSA 3-D mesh analysis
- Hemodynamic simulation: Simulation of blood flow in anatomically realistic cerebral vasculature and aneurysms
- Correlate geometry and biomechanics

Study Population

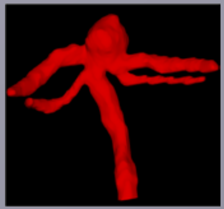
- CTA/MRA/DSA reconstructed human cerebral aneurysms along with the surrounding vasculature
- Analyze ruptured and unruptured aneurysms
- Hypothetical, axisymmetric models used to evaluate and validate the different indices.

Part 1: Quantifying Geometry

- Geometry
  - Size (objective) and shape (subjective)
  - Quantifying geometry: numerical rather than descriptive
- Global size indices: surface area, volume, maximum diameter
- Global shape indices
- Local and global curvature indices

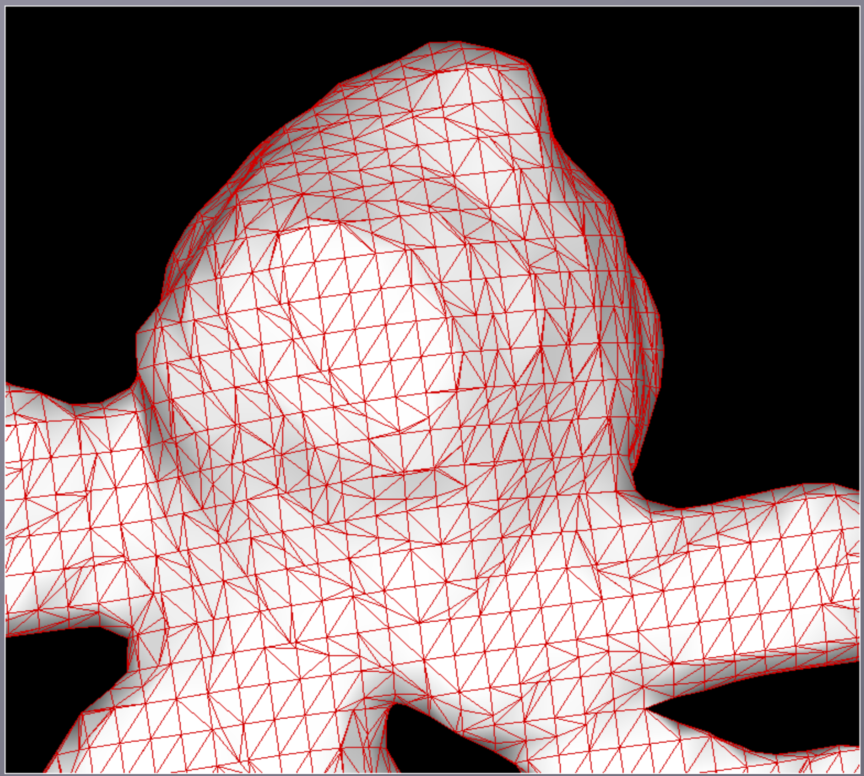
Quantifying Geometry: Overview

- Acquire 3-D digital data from CTA/MRA/DSA
- Develop algorithms for surface mesh refinement
- Isolate the aneurysm sac
- Quantify aneurysm volume and surface area
- Quantify aneurysm curvature
- Quantify other size and shape indices

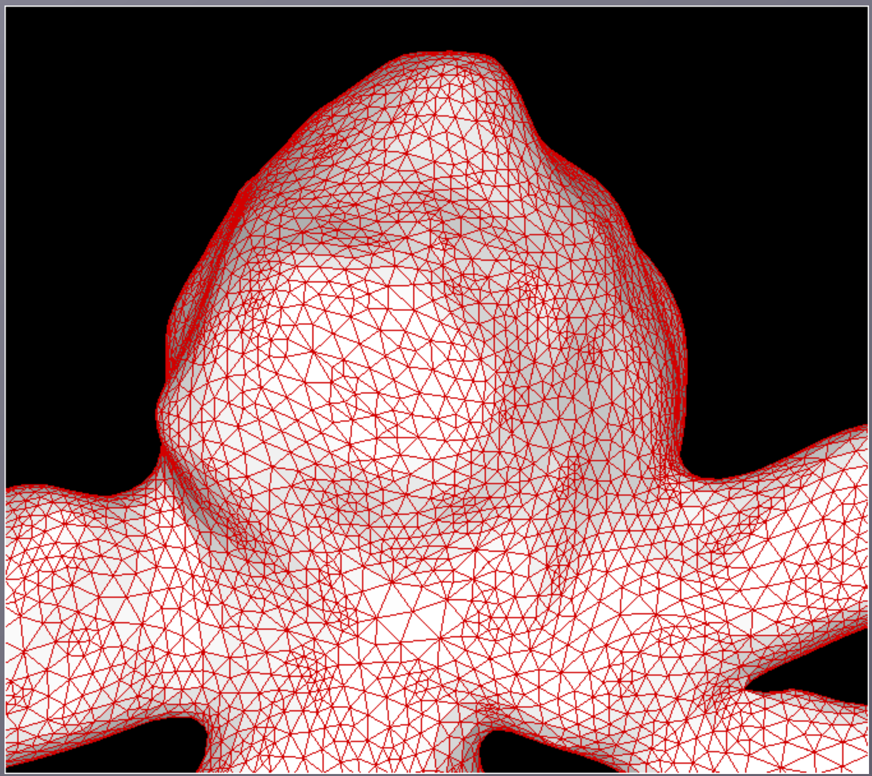


Mesh Refinement

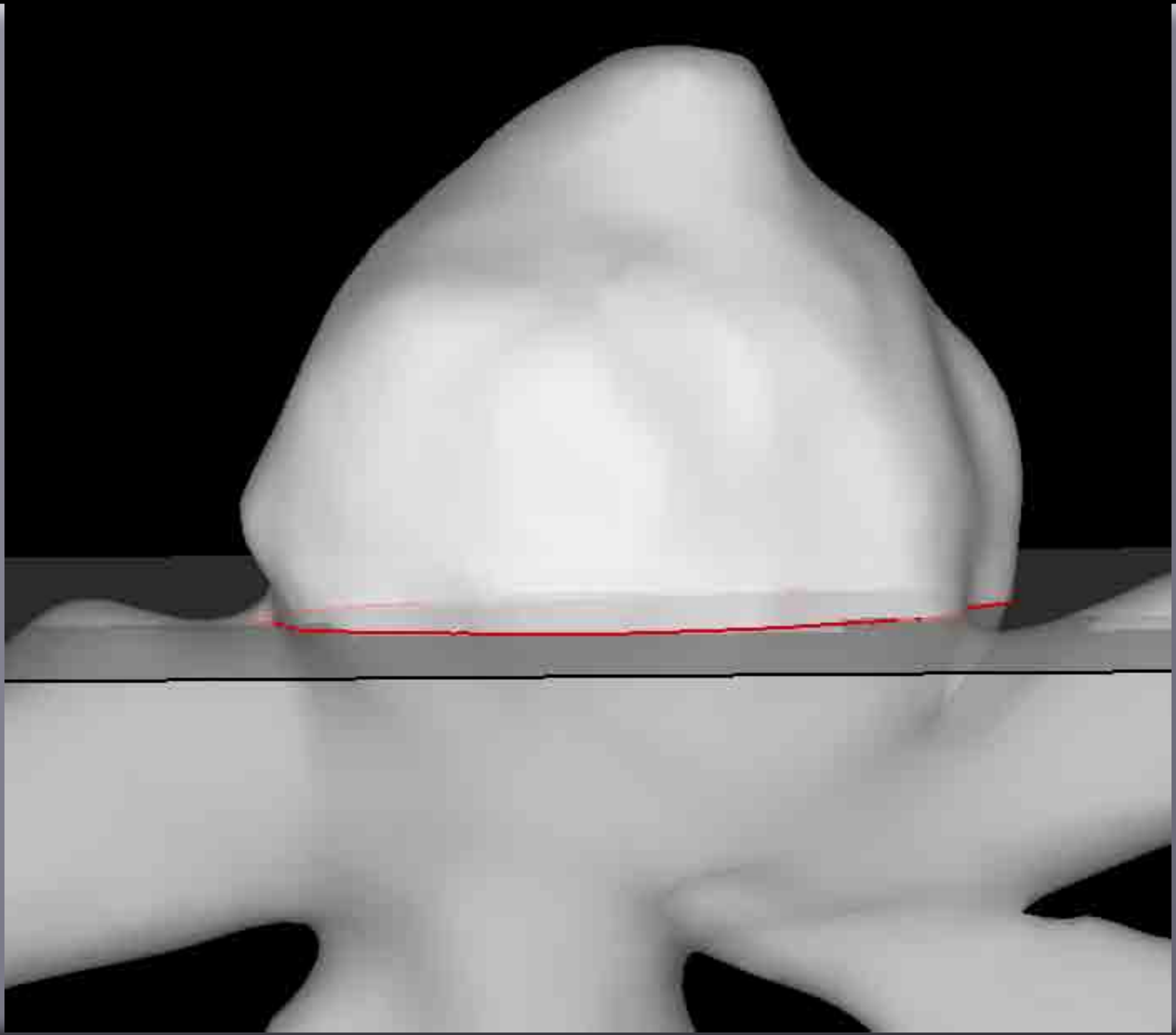
Raw



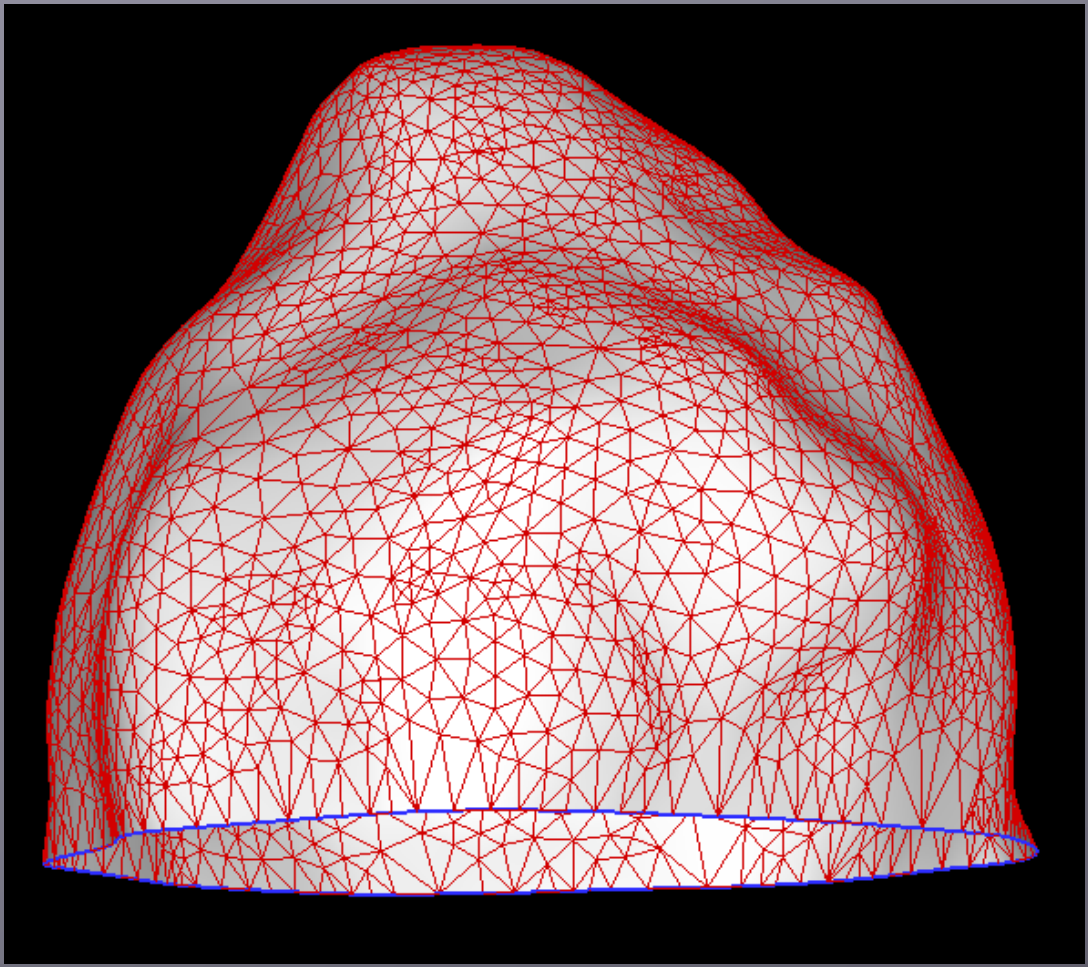
Refined



Isolating the Aneurysm



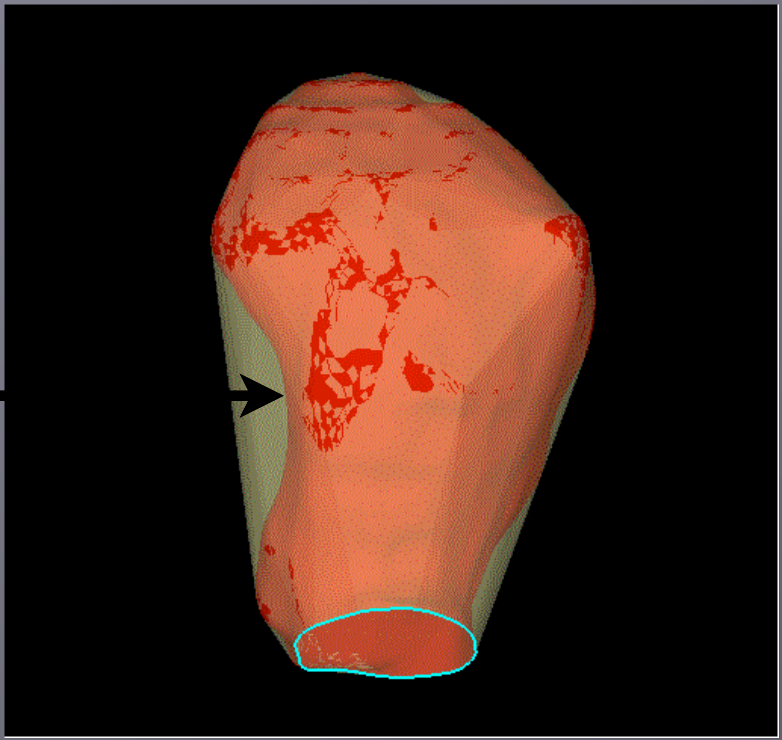
Final Aneurysm Mesh for Analysis



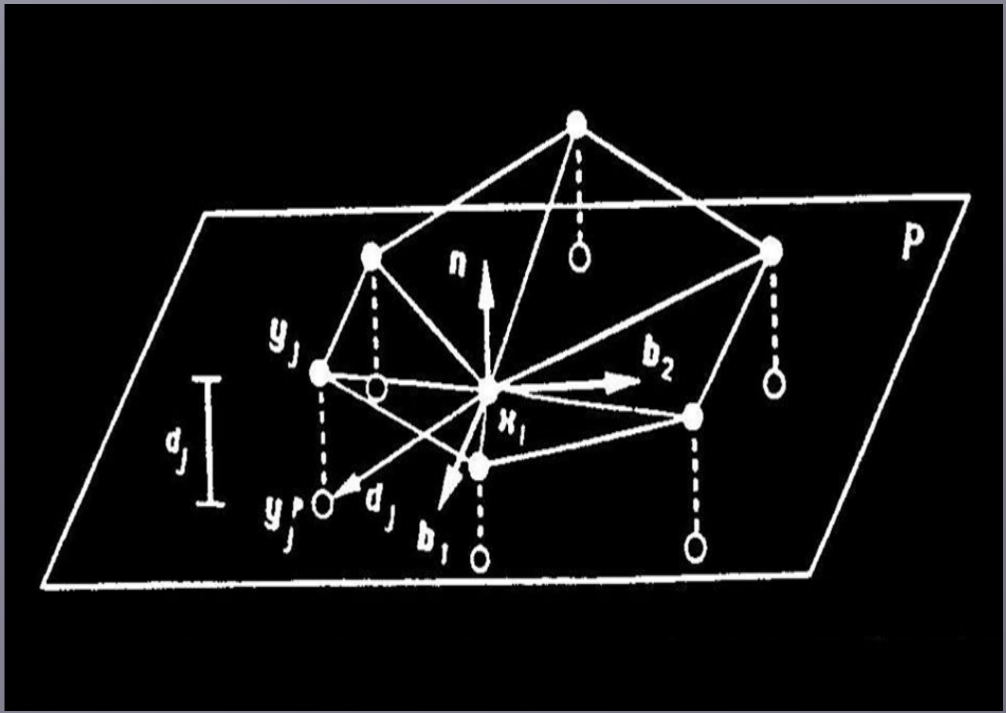
Convex Hull of Aneurysm

Convex Hull: The smallest encompassing surface that is convex at all points

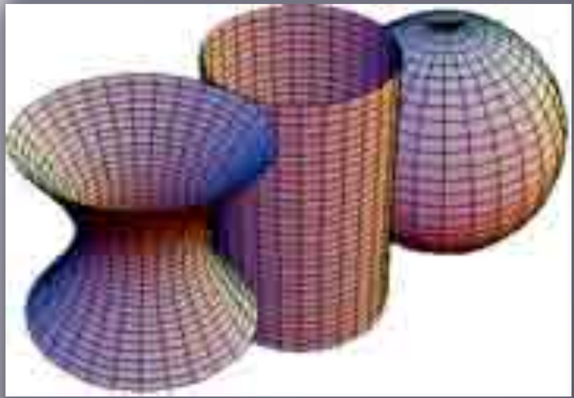
Convex Hull



Estimation of Principal Curvatures

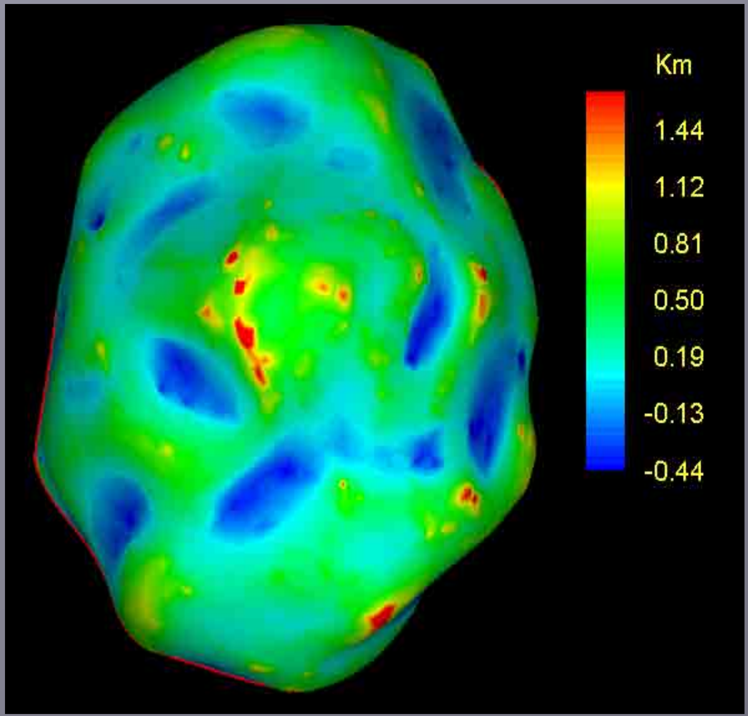


Hamann, B. (1993). Curvature approximation for triangulated surfaces. in Geometric Modeling. G. F. e. al, Springer-Verlag: 139-153.

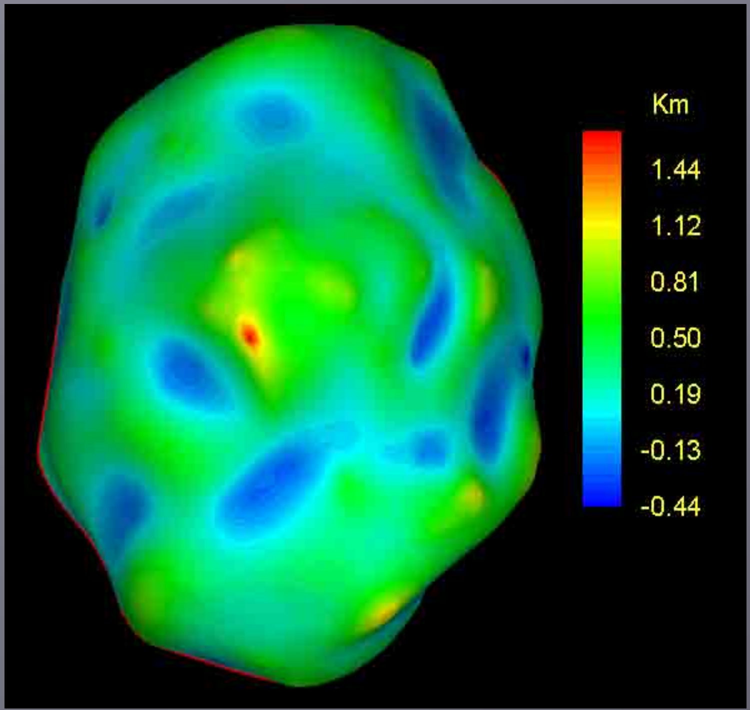


Negative, Zero and Positive Gaussian Curves

Mean and Gaussian Curvatures



Initial estimation



Refined 2 times by Contextual Peer Review technique

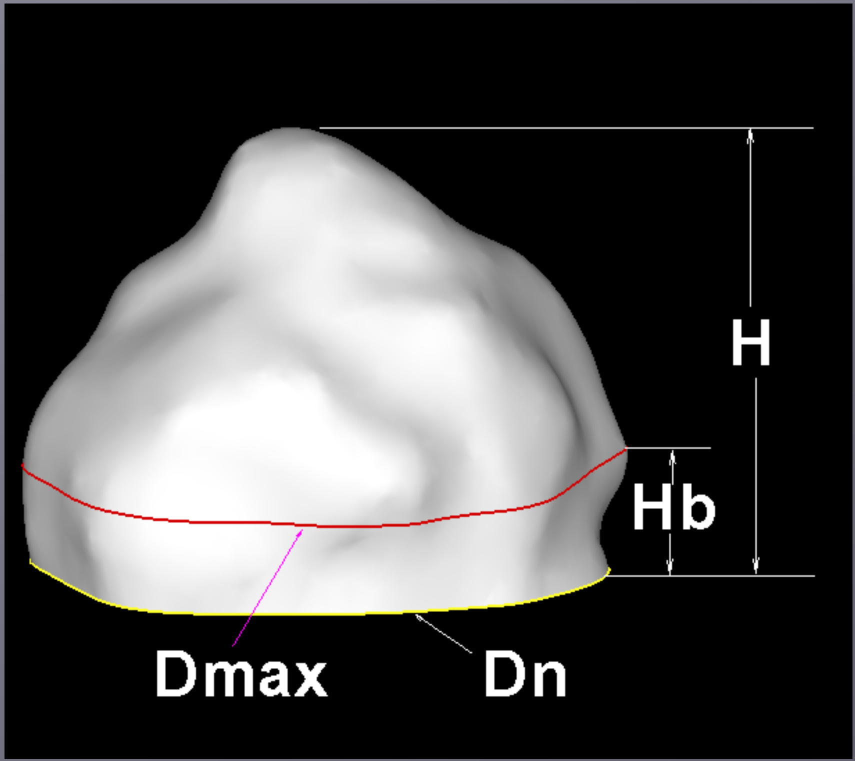
1 and 2 Dimensional Quantified Geometrical Indices

- 1-D size indices:
  - Height (H)
  - Maximum Diameter (D_{max})
  - Neck Diameter (D_n)
- 2-D shape indices:
  - Aspect Ratio:

    $AR = H/D_n$
  - Bottleneck Factor:

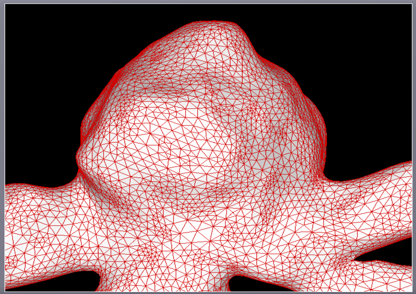
    $BF = D_{max} / D_n$
  - Bulge Location:

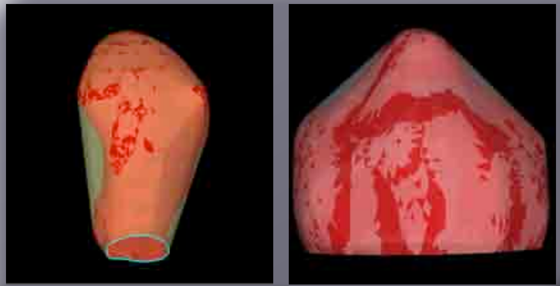
    $BL = H_b / H$

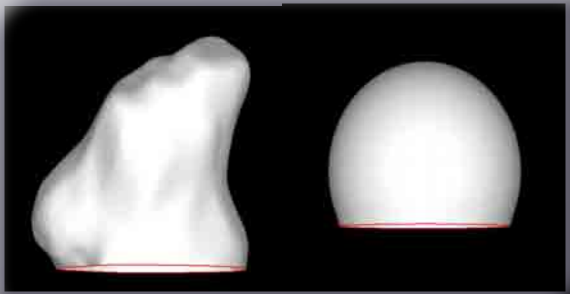


3 Dimensional
Quantified Geometrical Indices

- Size Indices
  - Surface Area - sum of triangles
  - Volume - $V = \frac{1}{18}\left|\sum_{\text{all triangles}} (\mathbf{L}_{i12} \times \mathbf{L}_{i13}) \times (\mathbf{X}_{i1} + \mathbf{X}_{i2} + \mathbf{X}_{i3})\right|$
- Shape Indices
  - Convexity Ratio - CR $CR = \frac{V}{V_{CH}}$
    - Inversely proportional to irregularity
  - Isoperimetric Ratio - IPR $IPR = \frac{S}{V^{2/3}}$
    - Proportional to Irregularity



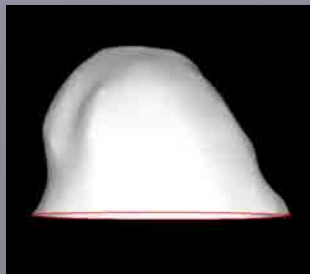




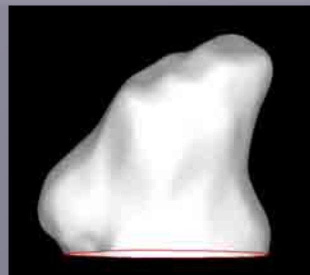
Sunday, August 9, 2009

Testing on Hypothetical and Real Aneurysms

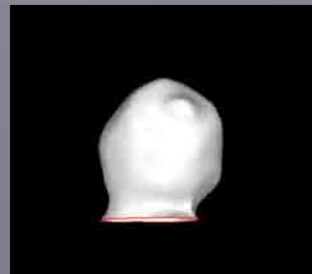
A1
CR: 0.98
IPR: 4.11



A2
CR: 0.98
IPR: 4.15

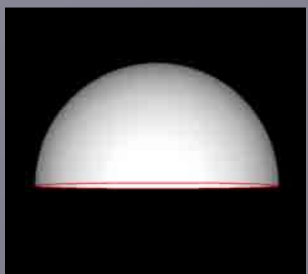


A3
CR: 0.88
IPR: 4.68

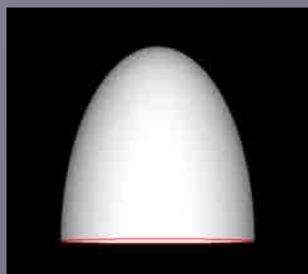


A4
CR: 0.97
IPR: 4.61

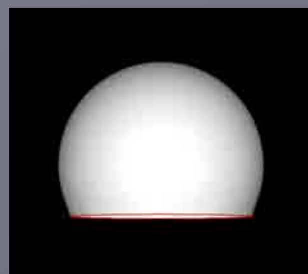
A5
CR: 0.96
IPR: 4.30



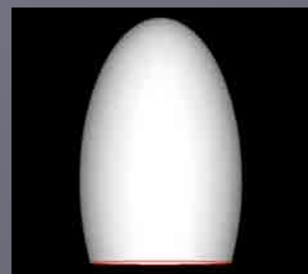
Hemisphere
CR: 1
IPR: 3.84



1/2 Ellipsoid
CR: 1
IPR: 4.13



¾ Sphere
CR: 1
IPR: 4.05

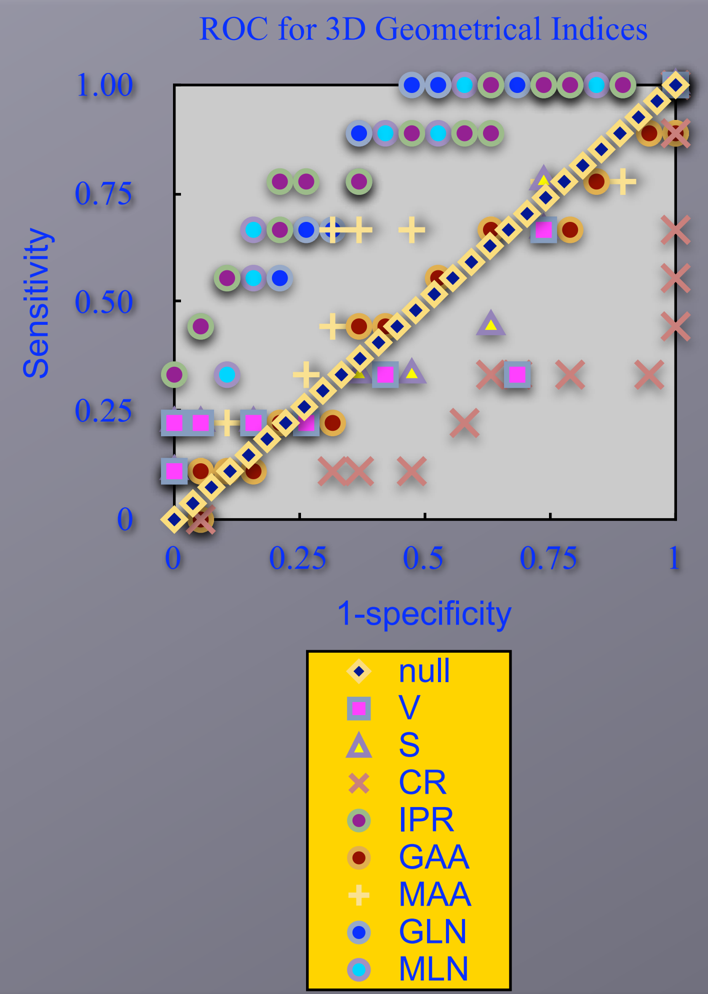


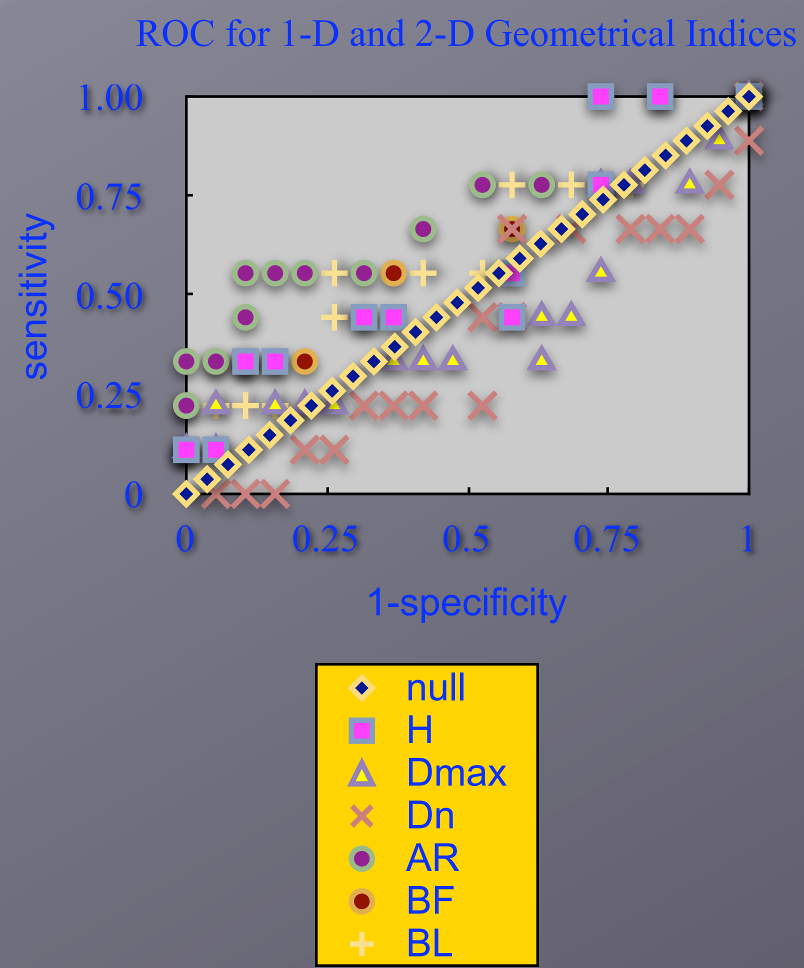
¾ Ellipsoid
CR: 1
IPR: 4.57

Ruptured vs. Unruptured Aneurysms

- Blinded analysis of ruptured and unuptured aneurysms asking which indices reliably predicted ruptured or unruptured state
  - Two-tailed Student's t-test: $p < 0.05$
  - ROC (Receiver Operating Characteristics) analysis: sensitivity vs. 1-specificity
    - Measure of predictive value - the more deviation from null, the better

ROC Curves for Geometrical Indices





Order of Predictive Capabilities

Order	ROC deviation from null	Index	Type	p value	p < 0.05
1	0.33	Isoperimetric Ratio	3D, shape	0.002	TRUE
2	0.32	Gaussian Curvature	3D, shape	0.015	TRUE
3	0.31	Convexity Ratio	3D, shape	0.001	TRUE
4	0.30	Mean Curvature	3D, shape	0.007	TRUE
5	0.22	Aspect Ratio	2D, shape	0.018	TRUE
6	0.12	Neck Diameter	1D, size	0.318	FALSE
7	0.11	Bottleneck Factor	2D, shape	0.065	FALSE
8	0.10	Bulge Location	2D, shape	0.517	FALSE
9	0.08	Height	1D, size	0.207	FALSE
10	0.06	Volume	3D, size	0.297	FALSE
11	0.06	Maximum Diameter	1D, size	0.910	FALSE
12	0.02	Surface Area	3D, size	0.274	FALSE

Summary: Geometric Predictors

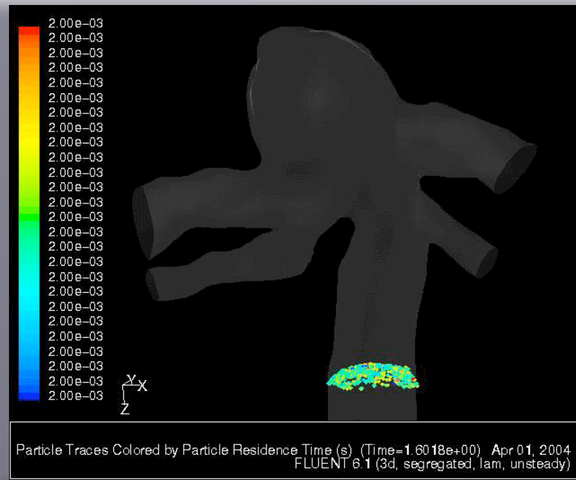
- Shape indices are better predictors of rupture than size indices
- All 3D shape indices show statistically significant differences between the ruptured and unruptured group, while no size indices show significant differences
- The results by ROC and Student's t-test agree well in finding good predictors of rupture

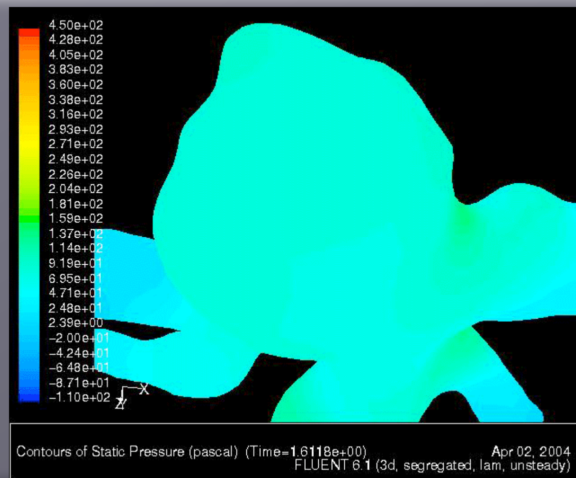
Part 2: Hemodynamics

Use refined 3D models

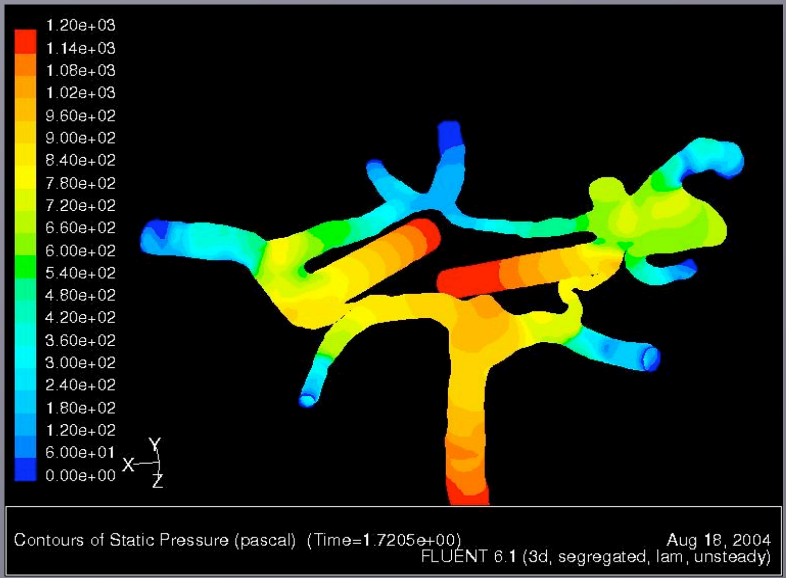
Assumptions

- Laminar flow
- Newtonian fluid
- Ignore gravity

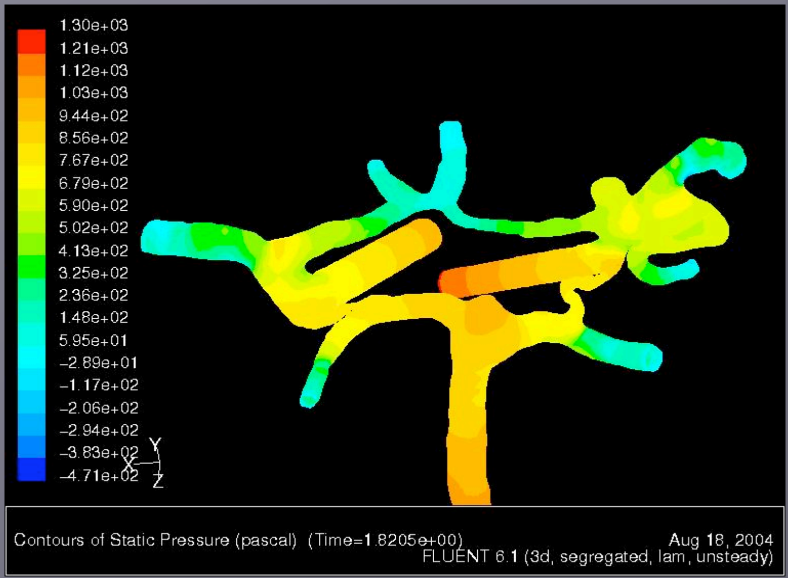




Pulsatile Flow in the Circle of Willis: Static Pressure

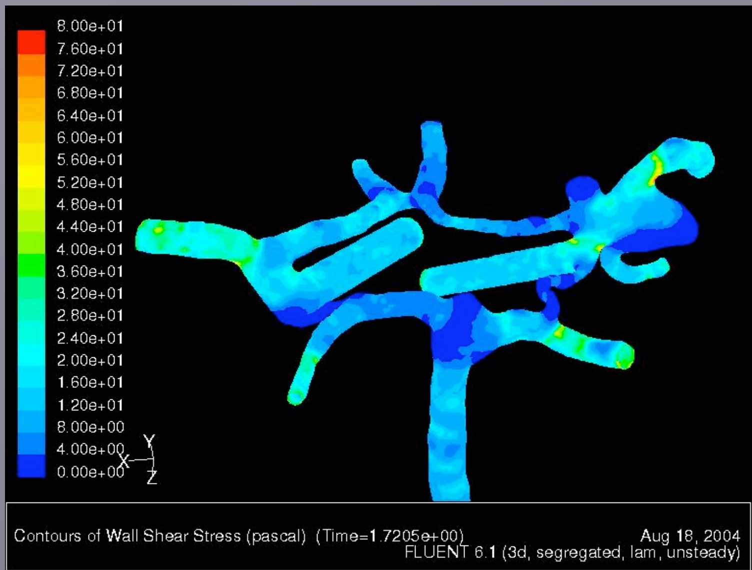


Systolic phase

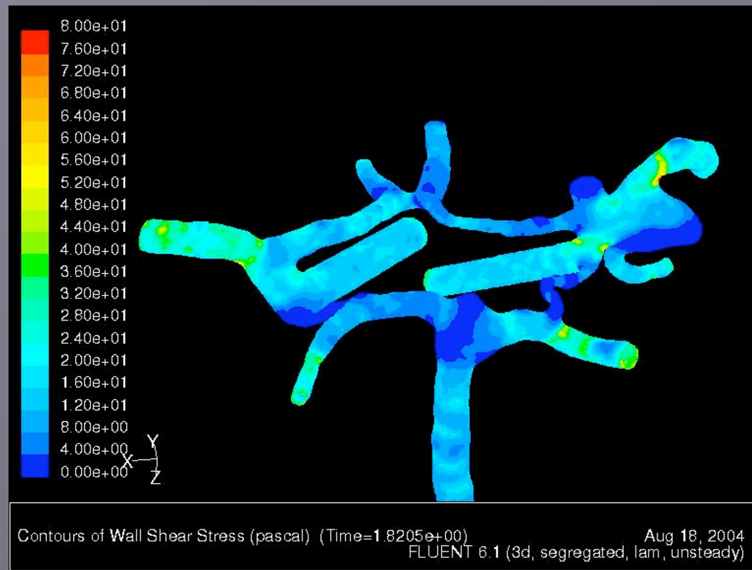


Diastolic phase

Pulsatile Flow in the Circle of Willis: Shear Stress

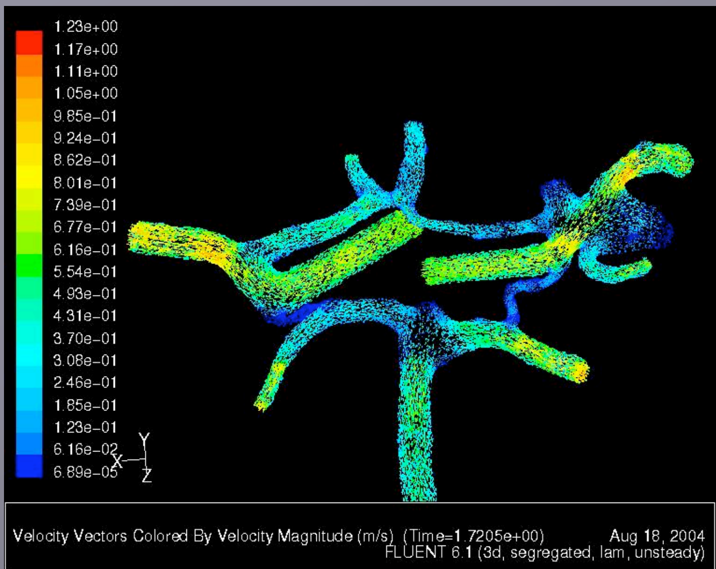


Systolic phase

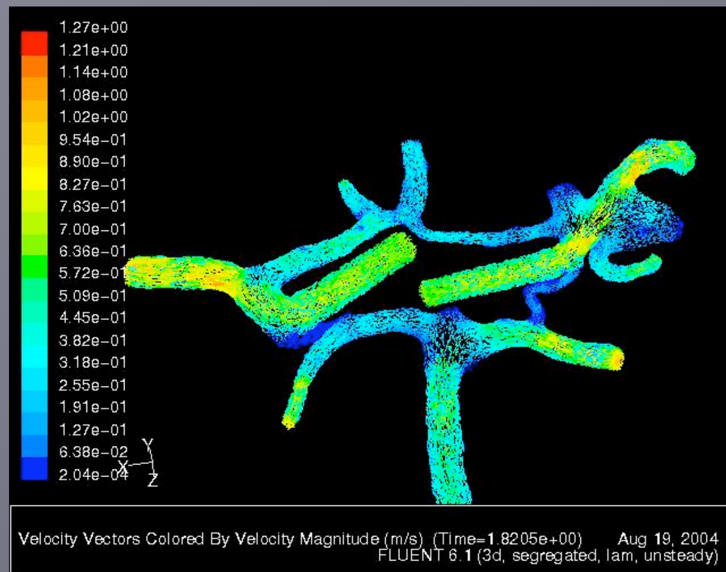


Diastolic phase

Pulsatile Flow in the Circle of Willis: Velocity Vector



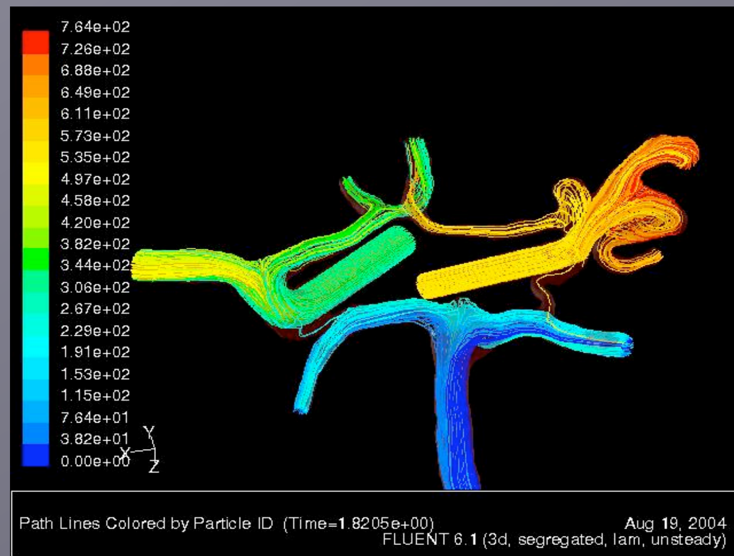
Systolic phase



Diastolic phase

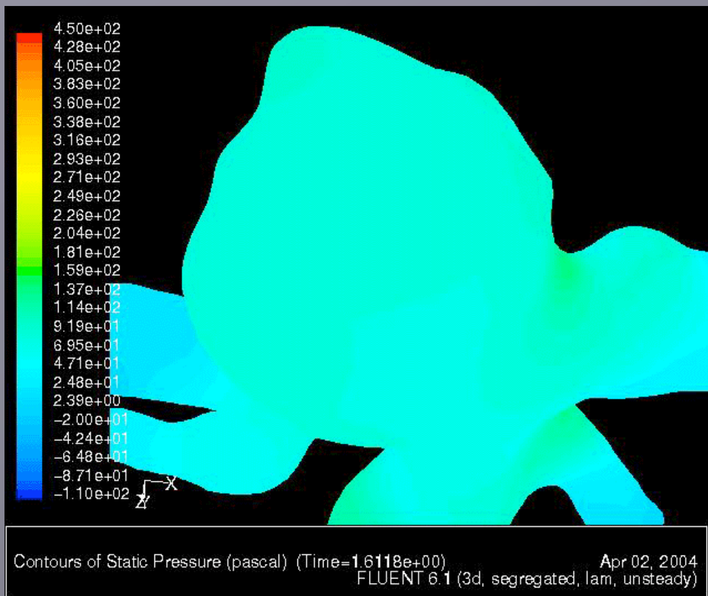
Pulsatile Flow in the Circle of Willis: Pathlines

Systolic phase

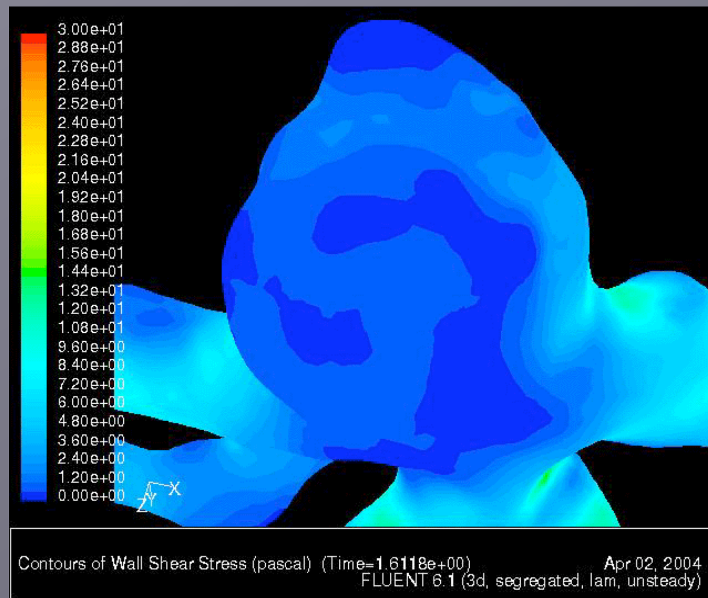


Diastolic phase

Pulsatile Flow in a Basilar Artery Aneurysm

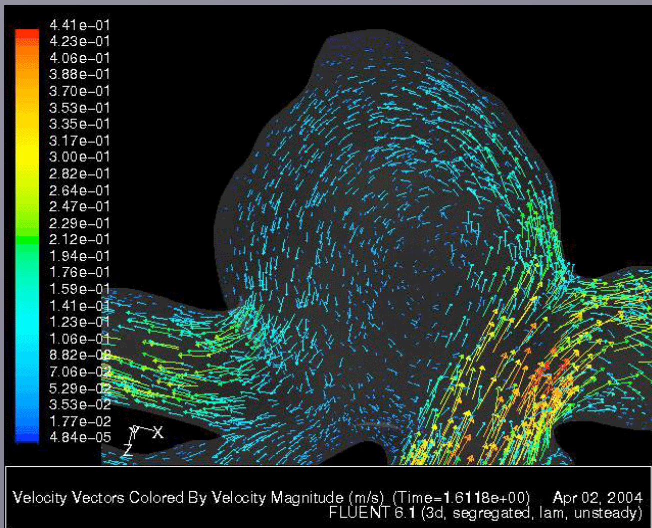


Static Pressure

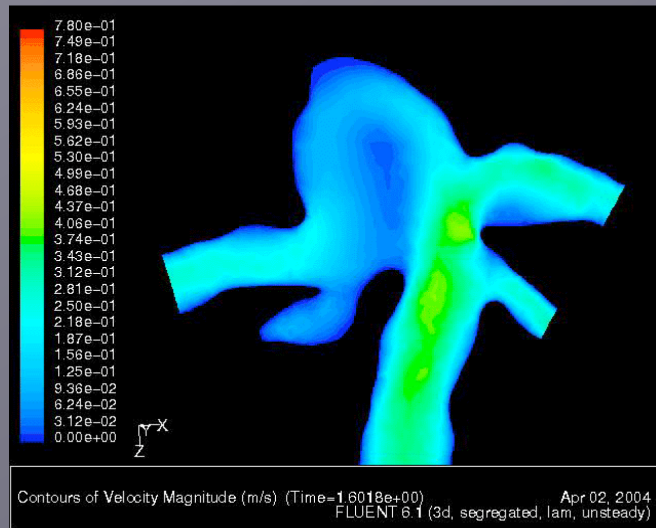


Shear Stress

Pulsatile Flow in a Basilar Artery Aneurysm



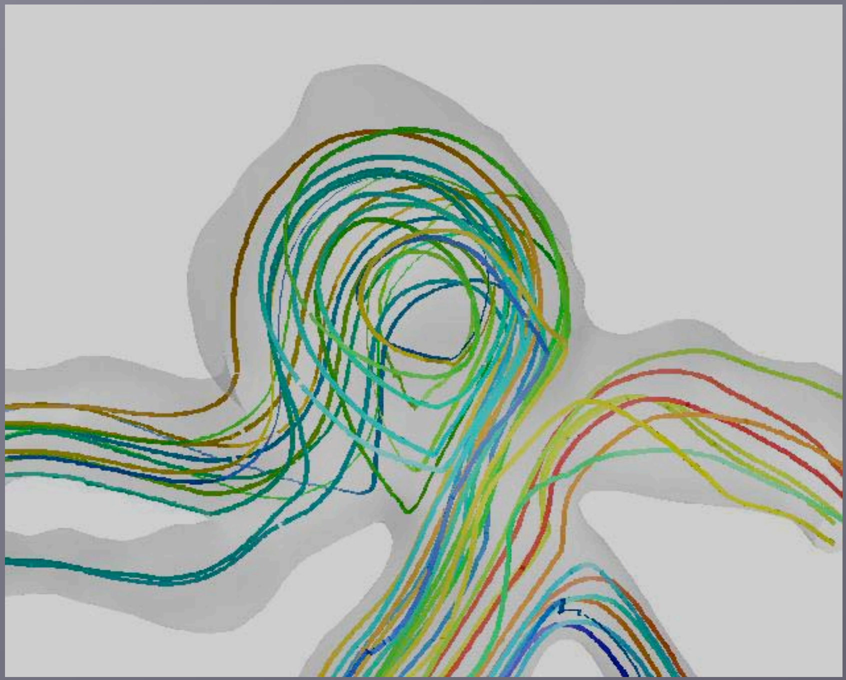
Velocity Vector



Velocity Magnitude

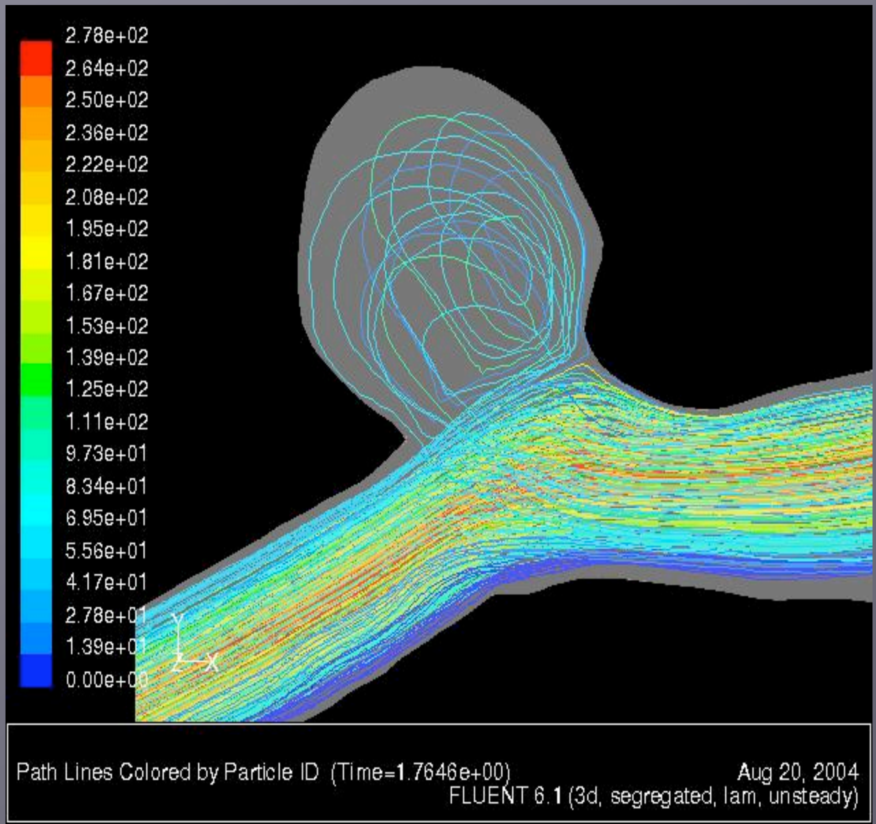
Pulsatile Flow in a Basilar Artery Aneurysm

Pathlines at maximum velocity



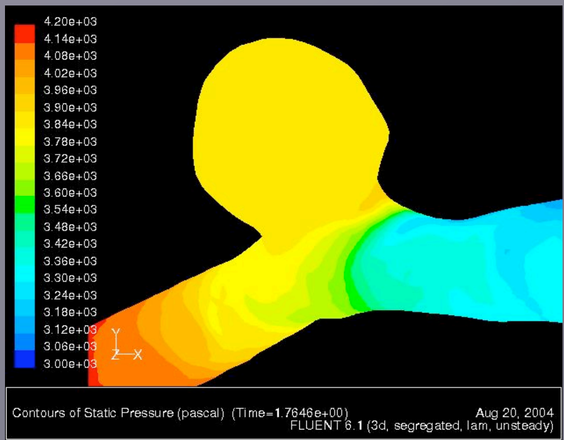
Pulsatile Flow in a Side-Wall Aneurysm

Pathlines at maximum velocity

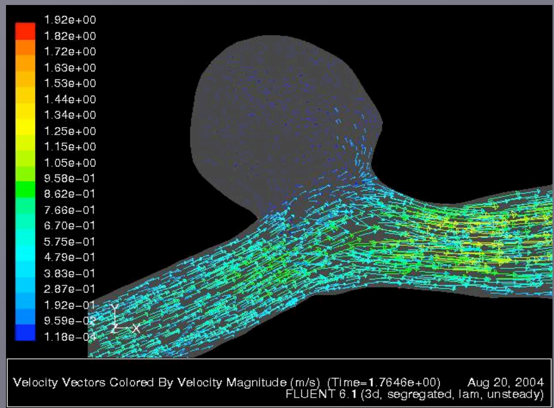


Pulsatile Flow in a Side-Wall Aneurysm

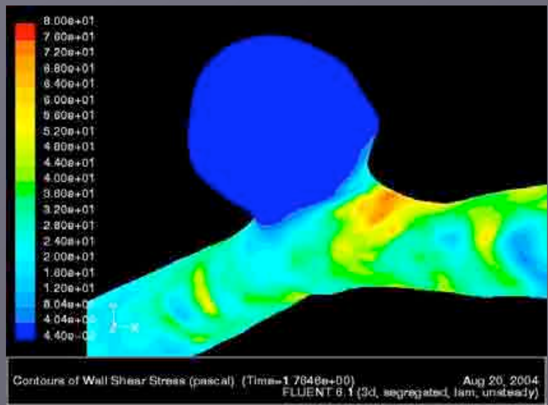
Static Pressure



Velocity Vector

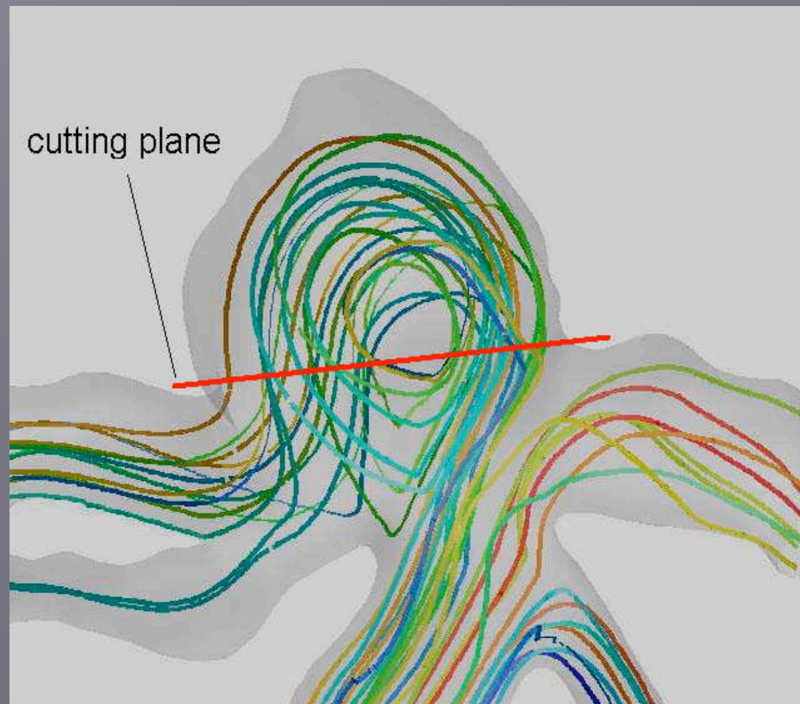


Shear Stress



Particle Residence Time

- Particle Residence Time was defined as the time interval from first entry into the aneurysm sac until last exiting from it
- Most particles enter the aneurysm sac only once, while some may cross the neck (cutting) plane multiple times

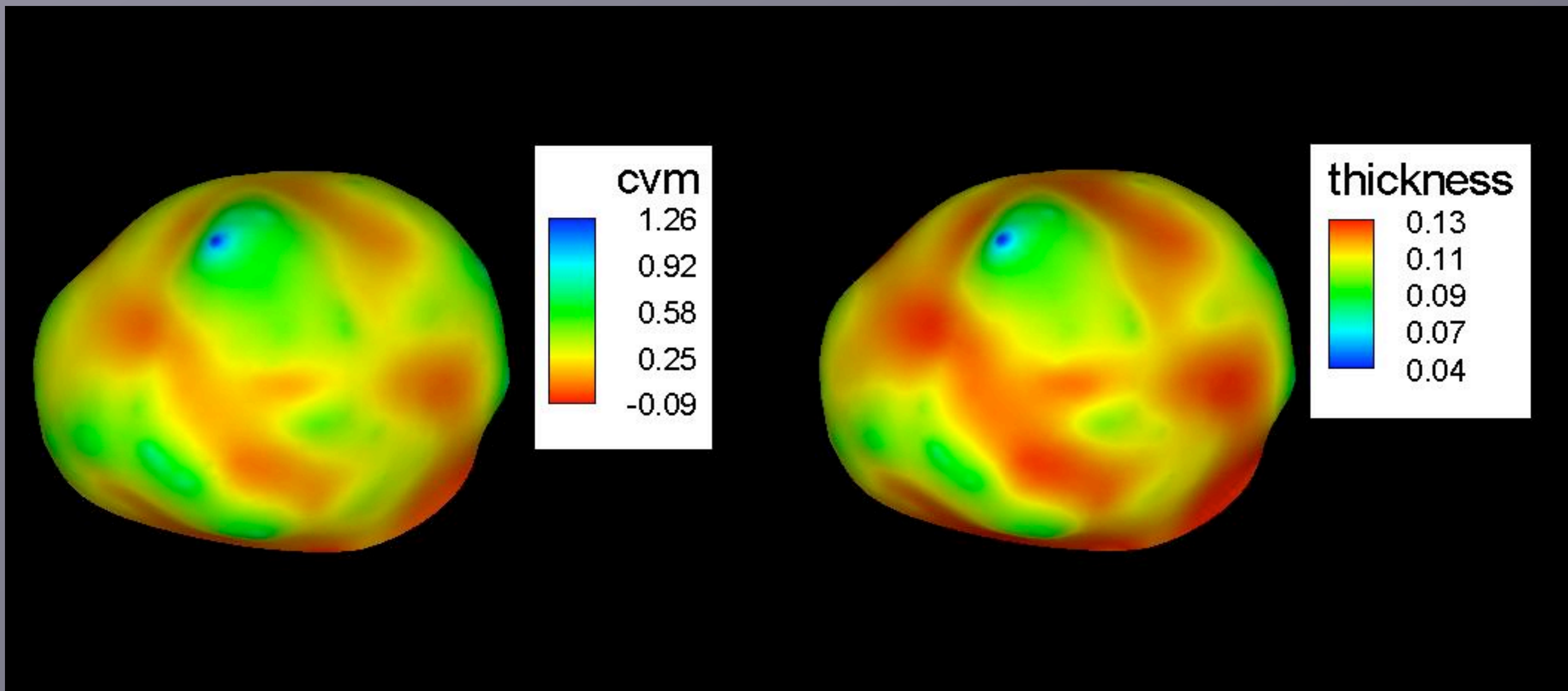


Summary: Hemodynamics

- The 3D flow field in the circle is very complex.
- There is little mixing among flow fields supplied by the input arteries.
- Pressure is the dominant hemodynamic load on aneurysm - shear stress is no more than 1% of pressure load.
- The maximum shear stress value can be larger than that regarded to cause endothelial damage.
- 3D vortices form inside all aneurysms.
- The velocity vector field varies very little during the cardiac cycle.
- Average particle residence times inside saccular aneurysms is < 0.2 s.

Aneurysm Wall Thickness

Linking thickness with curvature



Summary of the Project to Date

- Combined geometry-biomechanics modeling methodology
- The geometrical analysis demonstrates that shape is more closely correlated with rupture than size
- NIH RO1 grant supported prospective study at Penn State, University of Iowa, MGH and Jefferson is underway

Thank You For Your Attention

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Neurosurgery

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