Aneurysm Rupture Evaluation: Contributions of CFD
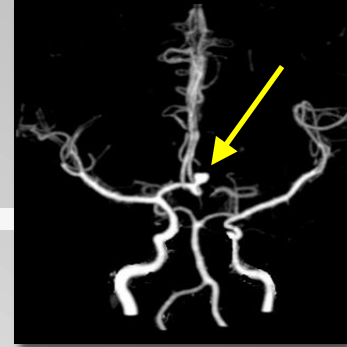
Juan Cebral, PhD

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Volgenau School of Engineering
George Mason University
Fairfax, Virginia, US

jcebral@gmu.edu

GEORGE MASON UNIVERSITY

Intracranial Aneurysms: The Problem

- High prevalence (3-8% of the population)
- Incidental aneurysms increasingly detected
- Rupture Risk (~0.1-3%) < Intervention Risk (10-14%)
- Many aneurysms preventively treated due to devastating consequences of SAH

⇒ Need: reliable risk assessment to recommend treatment or conservative observation (beyond size)

⇒ Requires: understanding the mechanisms of aneurysm pathogenesis and rupture

⇒ Challenge: define appropriate end points for clinical investigations and gather corresponding data
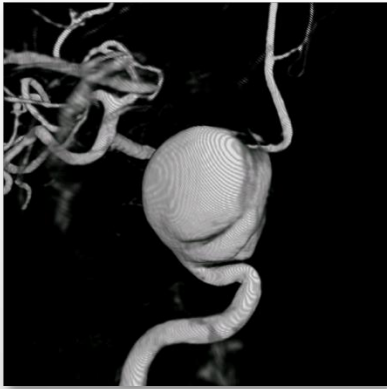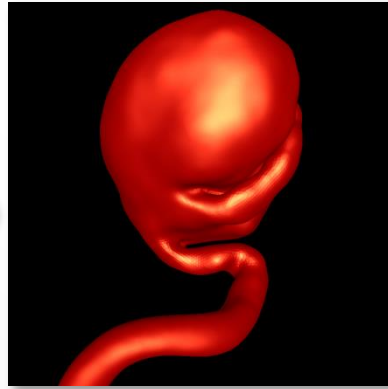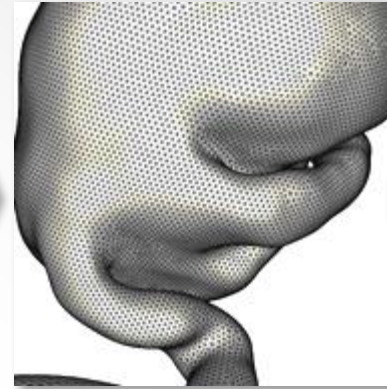
Mechanisms of Aneurysm Evolution
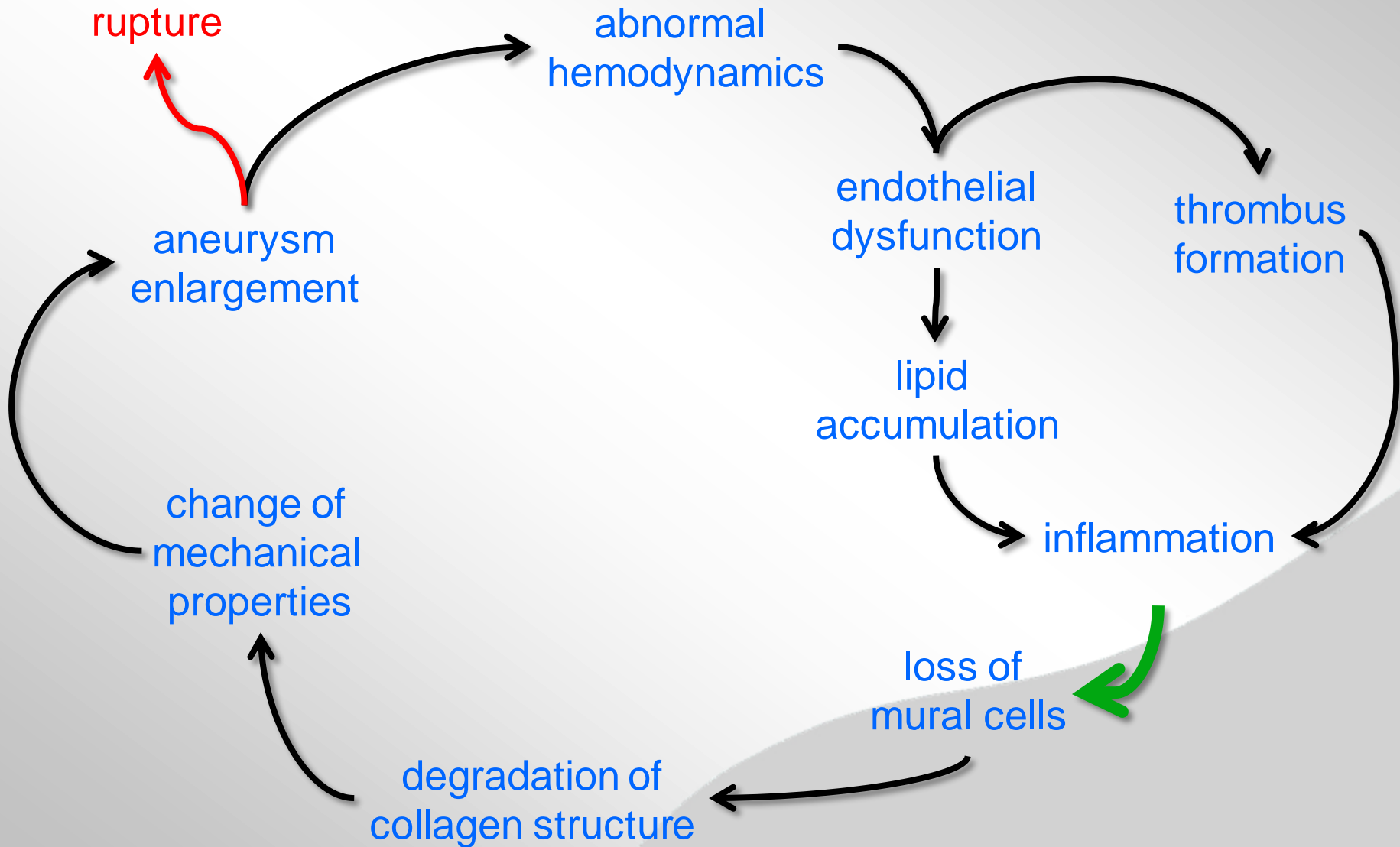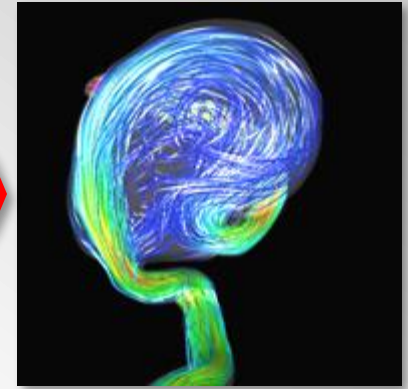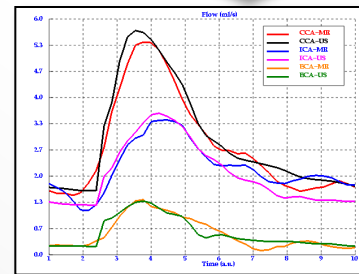
Image-Based CFD Modeling

imaging

geometry modeling

meshing

flow visualization
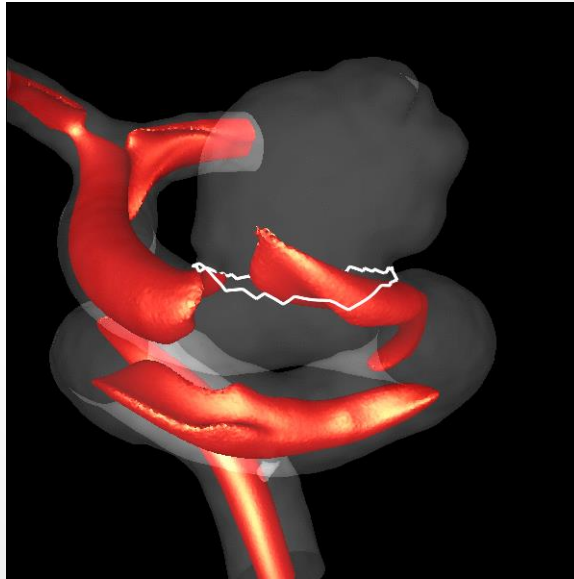

flow conditions

numerical solution

mathematical model

$$\rho \mathbf{v}_{,t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} + \nabla p = \nabla \mu \nabla \mathbf{v}$$
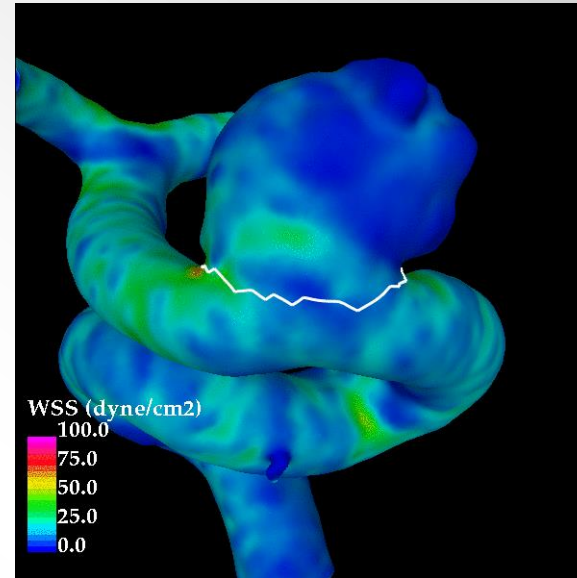
$$\nabla \cdot \mathbf{v} = 0$$

Cebral JR, Castro MA, Appanaboyina S, Putman CM, Millan D, Frangi A, "Efficient Pipeline for Image-Based Patient-Specific Analysis of Cerebral Aneurysm Hemodynamics: Technique and Sensitivity", *IEEE TMI* 24(4): 457-467, 2005.
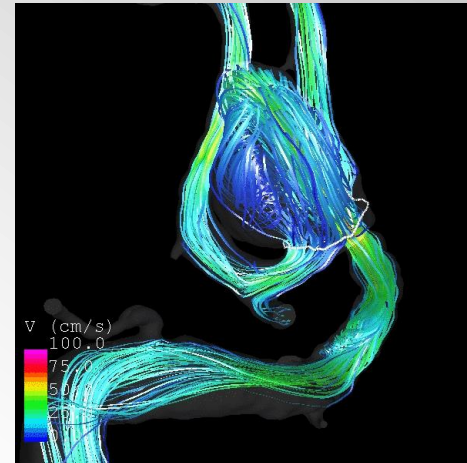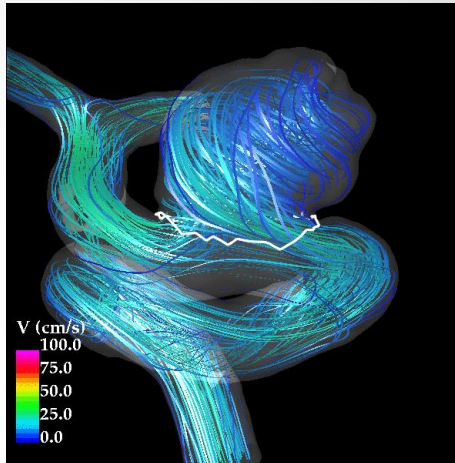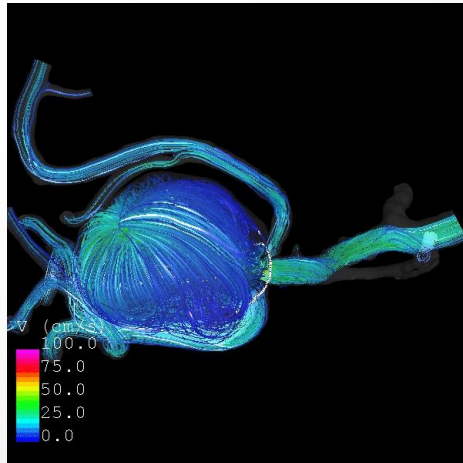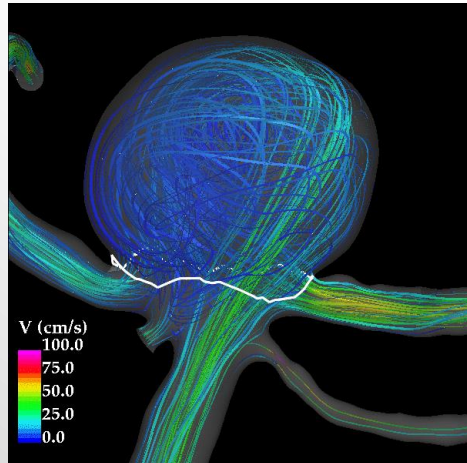
Aneurysm Flow Characteristics

Inflow jet

WSS

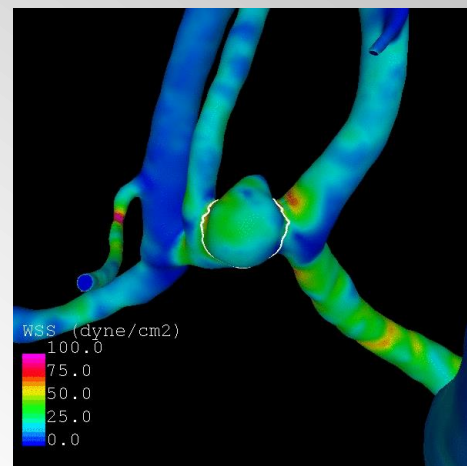Flow structure
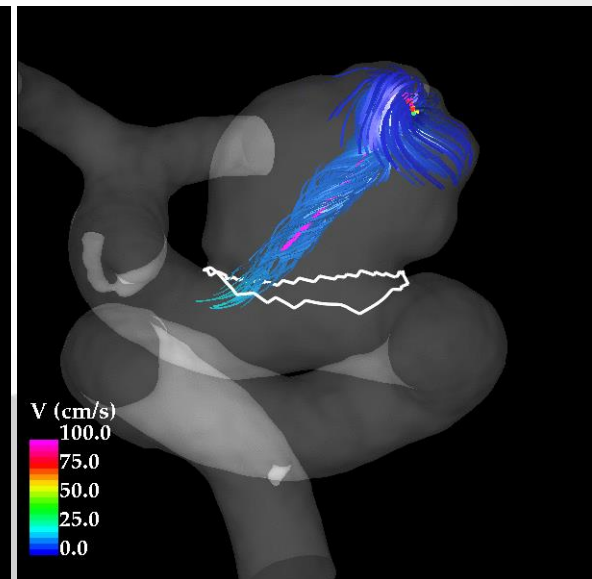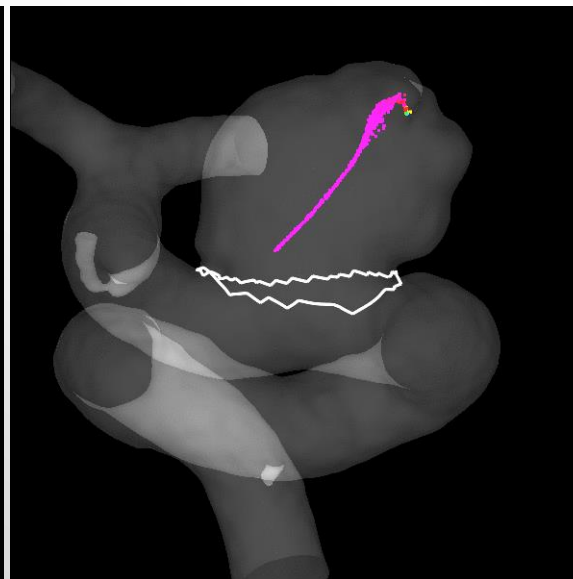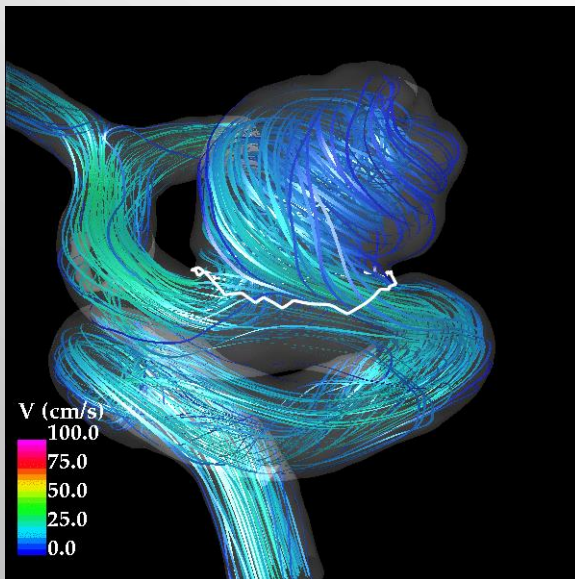
Example Inflow Jets
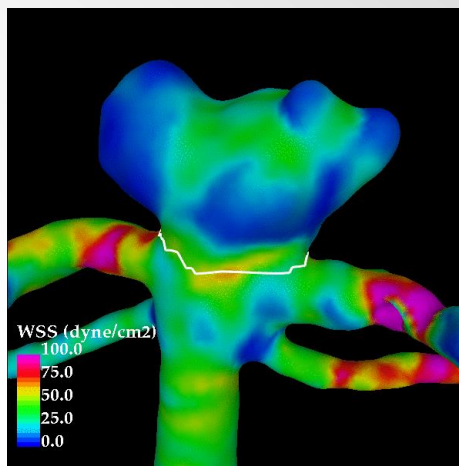
Strong Inflows
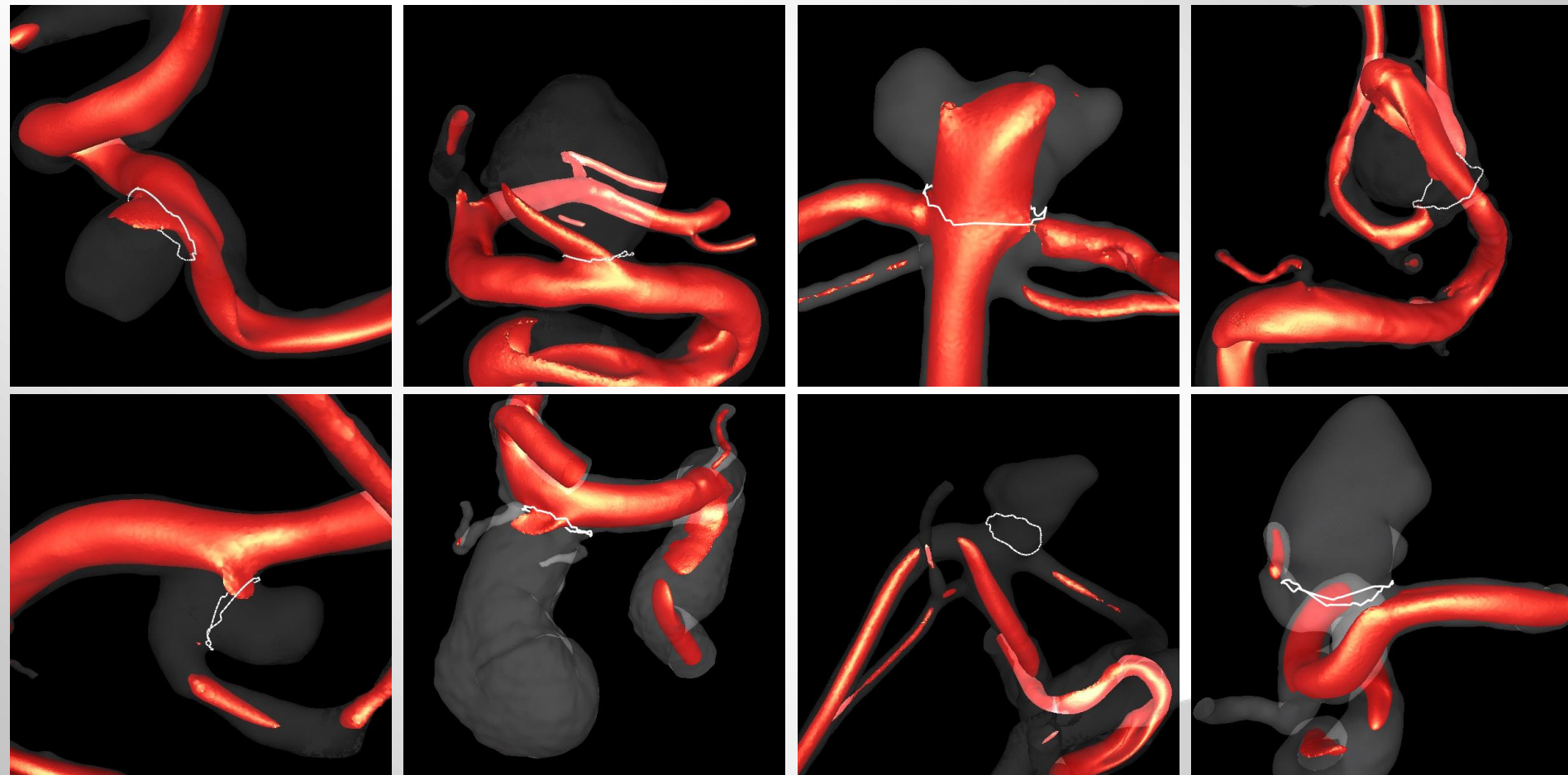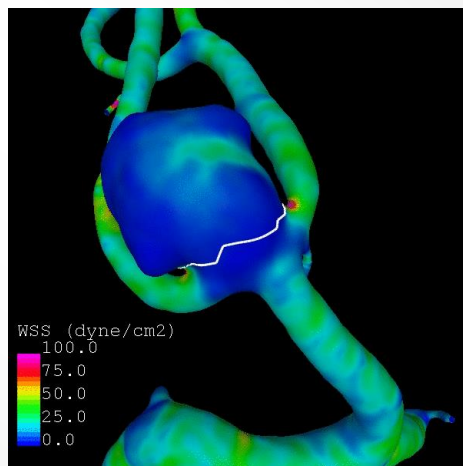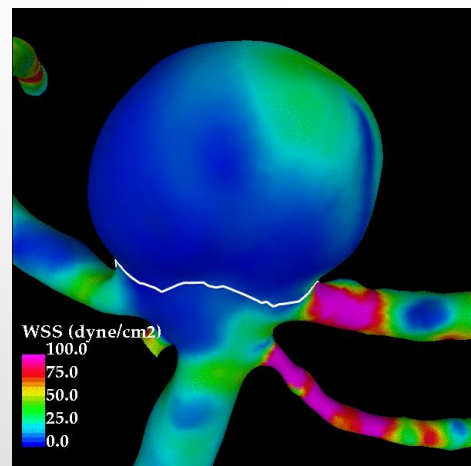

Weak Inflows

Flow Patterns
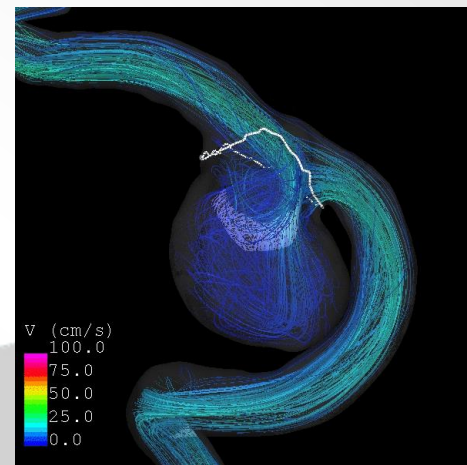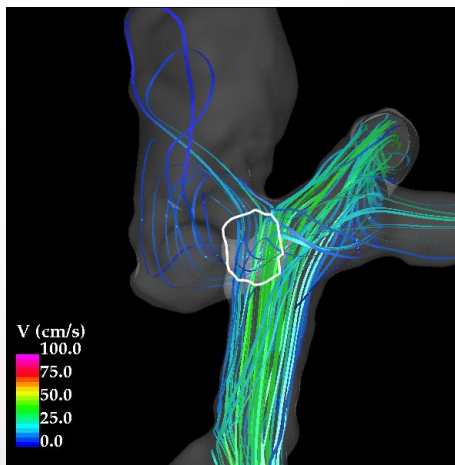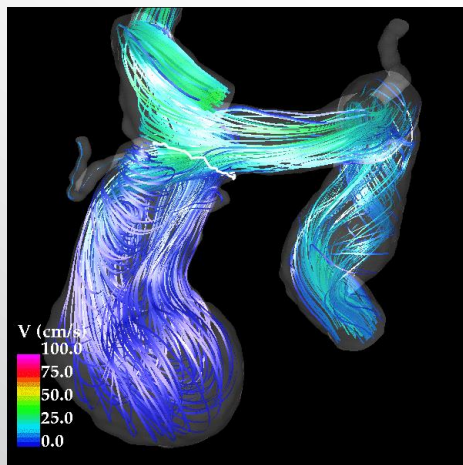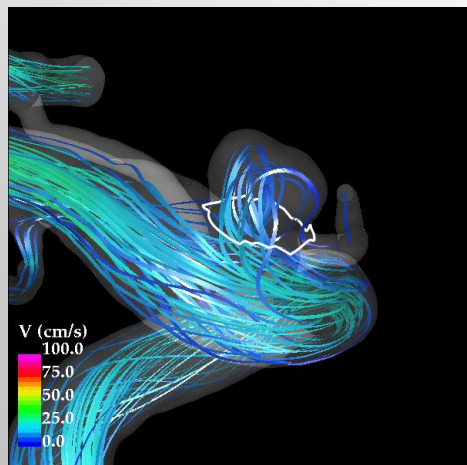
Flow Structures
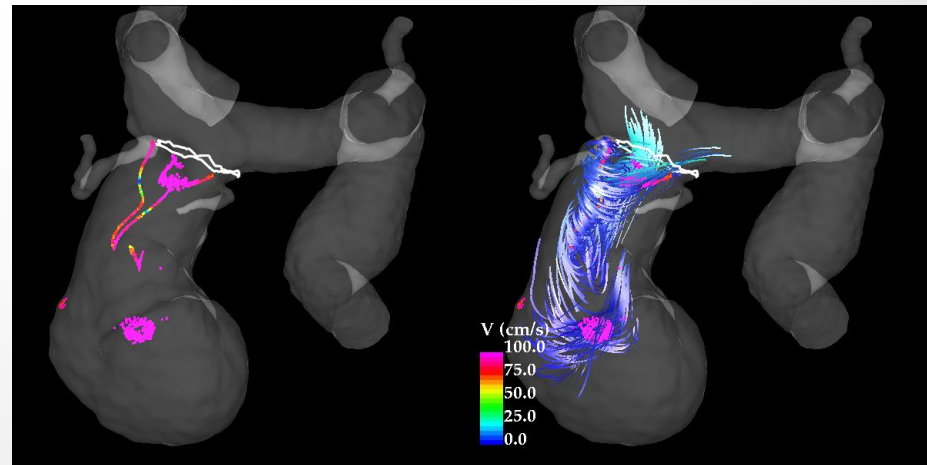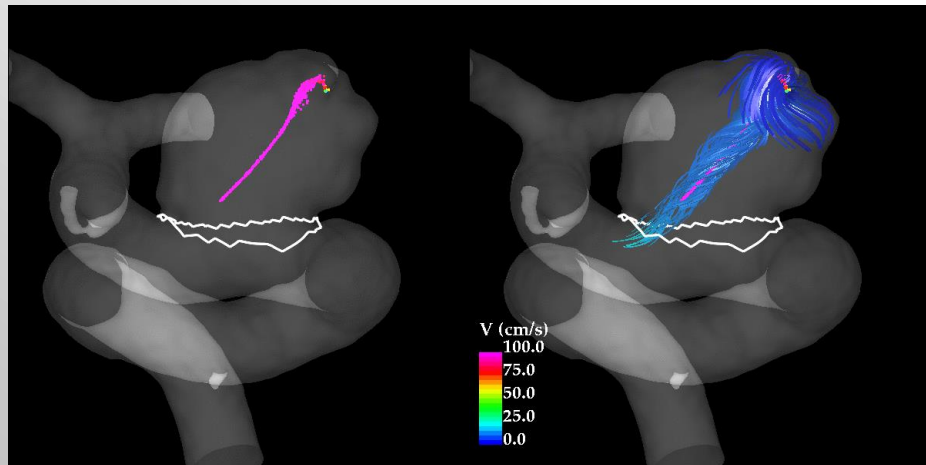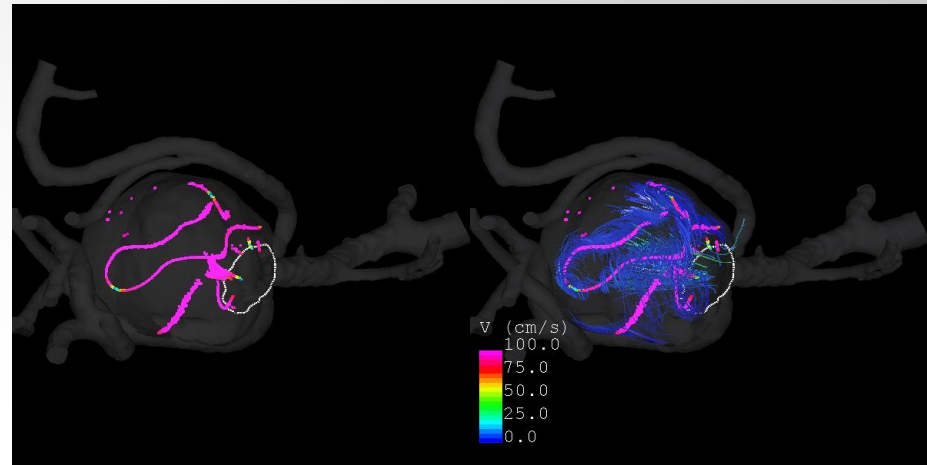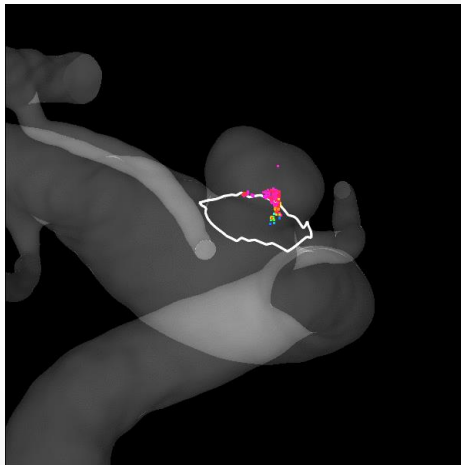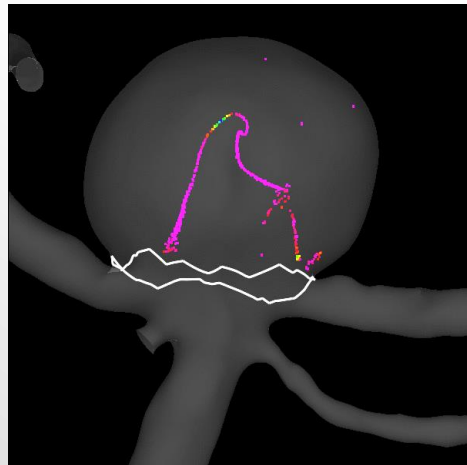
Wall Shear Stress Distributions
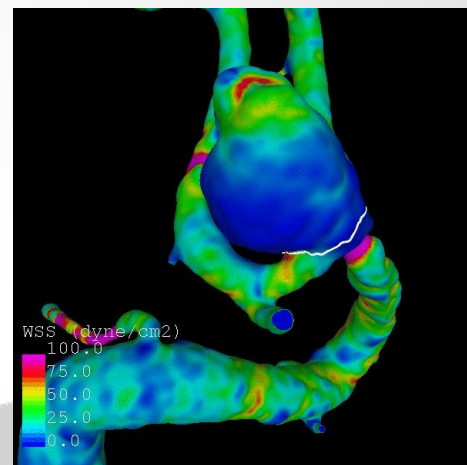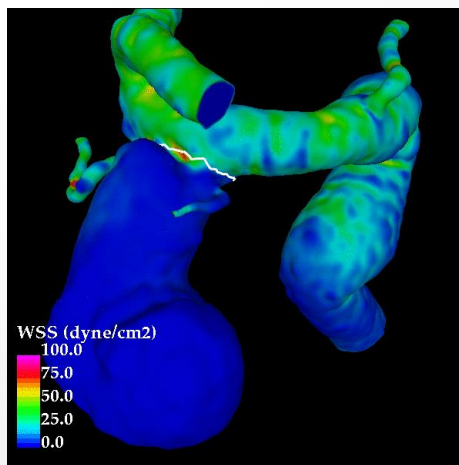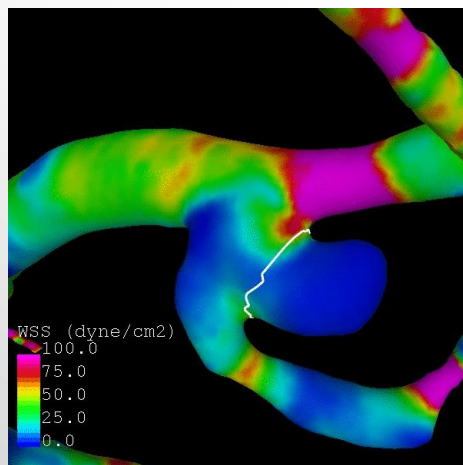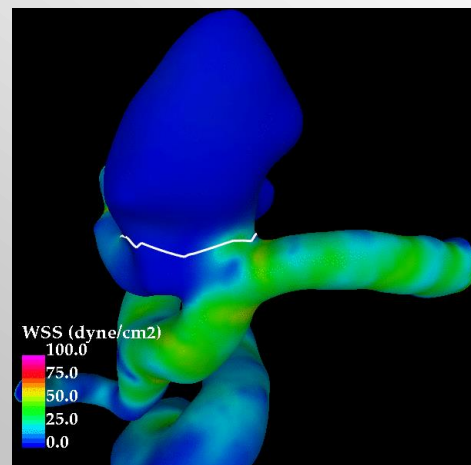
Hemodynamic Characterization

Inflow Jet:

- Inflow rate
- Inflow concentration

Flow Pattern:

- Velocity
- Kinetic energy
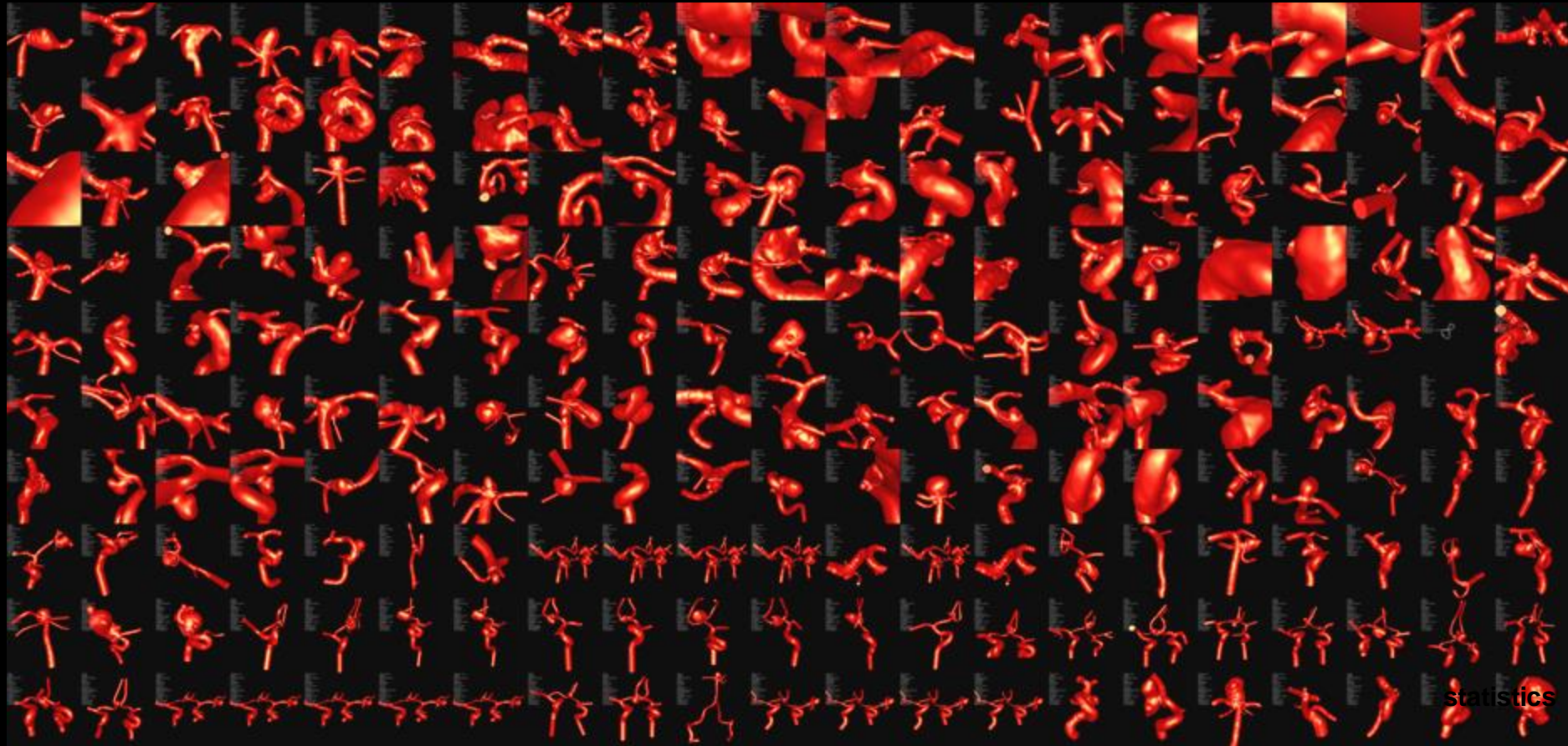- Viscous dissipation
- Vorticity
- Shear rate

Flow Structure:

- Vortex core-line length
- POD entropy

WSS Distribution:

- Mean, Max, Min
- Area under low WSS
- WSS concentration
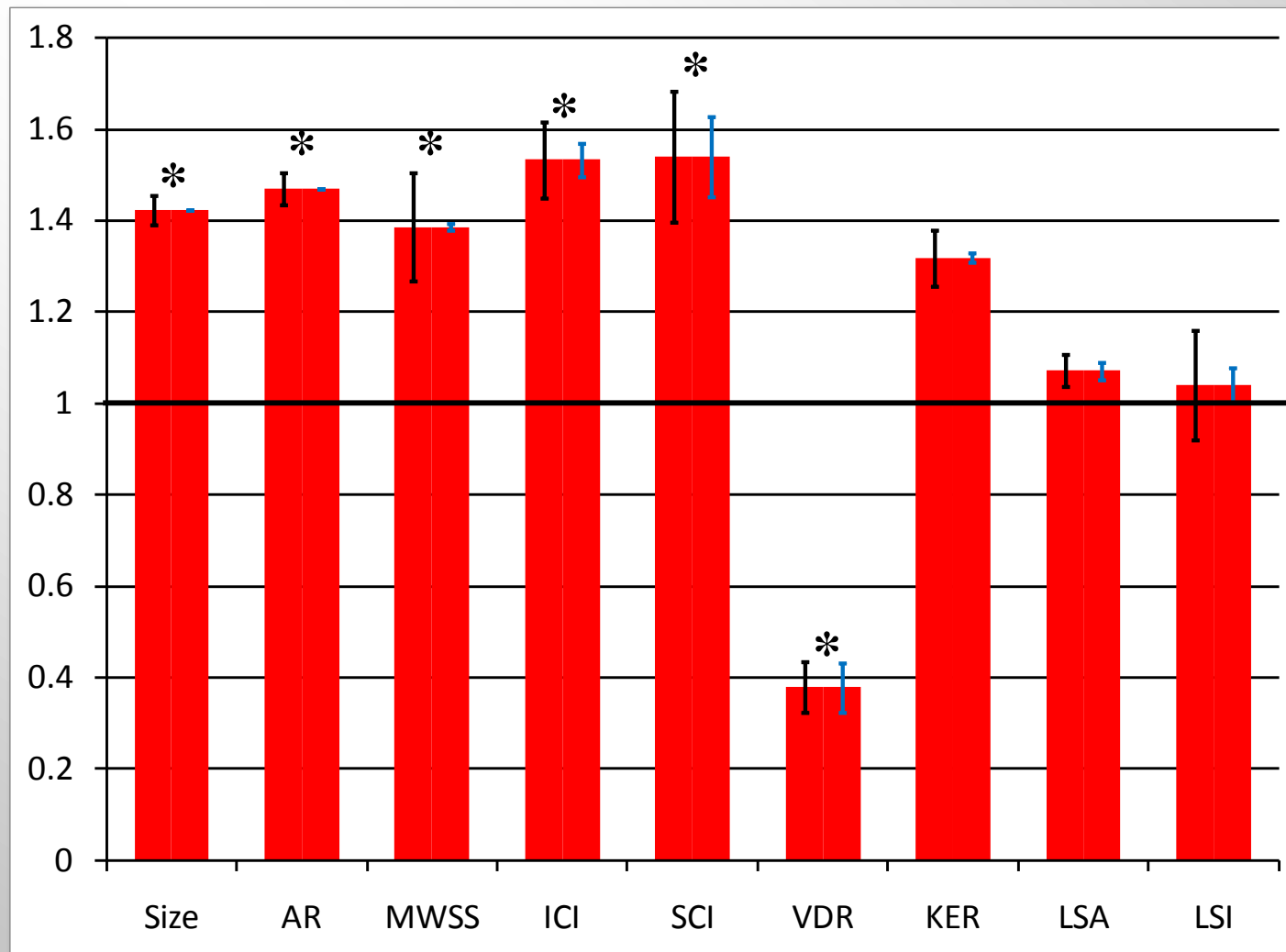- Oscillatory shear index

Aneurysm Database

~2000 aneurysms: clinical info + 3DRA images
>1400 aneurysm CFD models
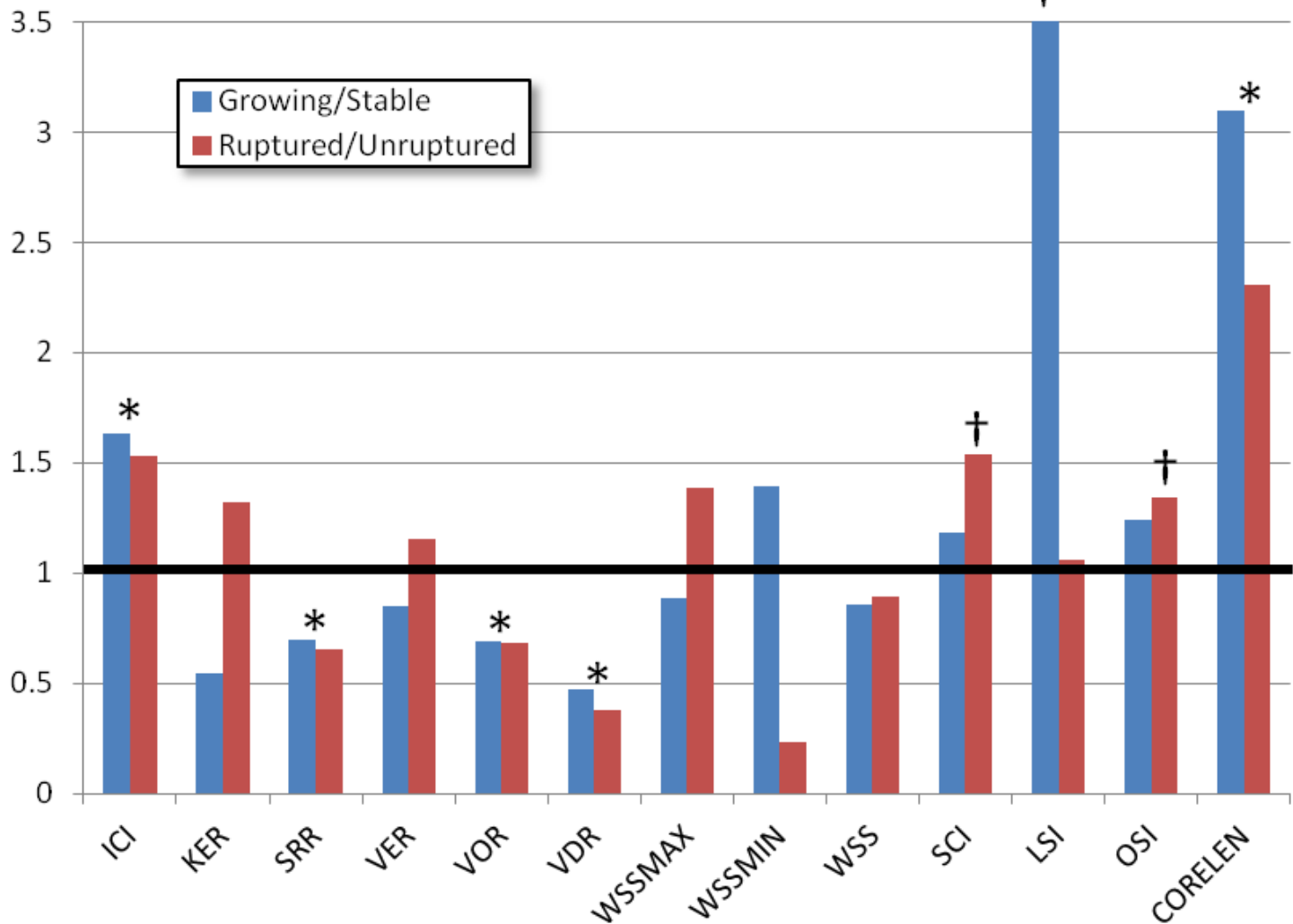Contributions: Inova, Mt. Sinai, Medellin, UCLA

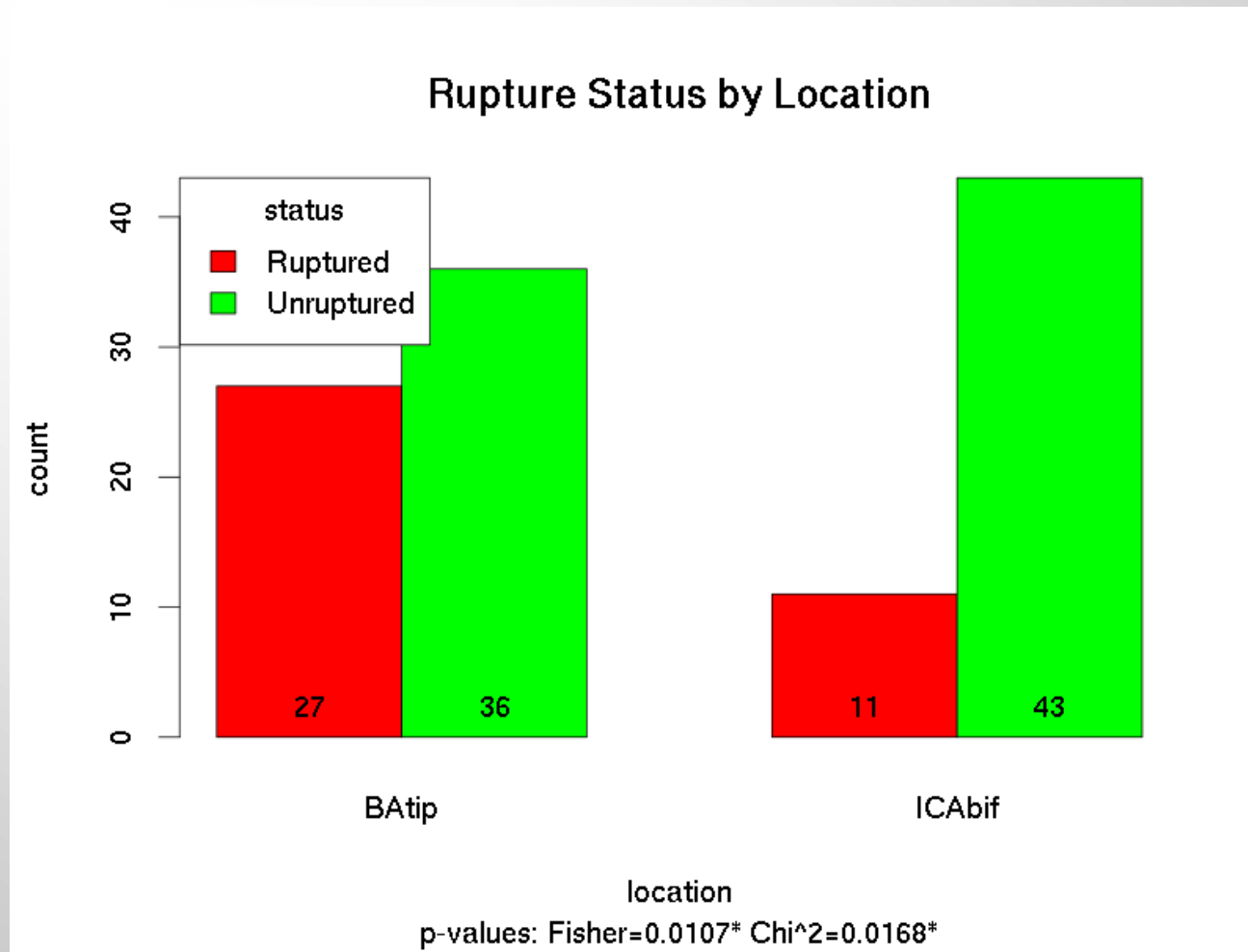# Ruptured vs Unruptured: Cross Sectional Data

N=210

Growing vs Stable: Longitudinal Data

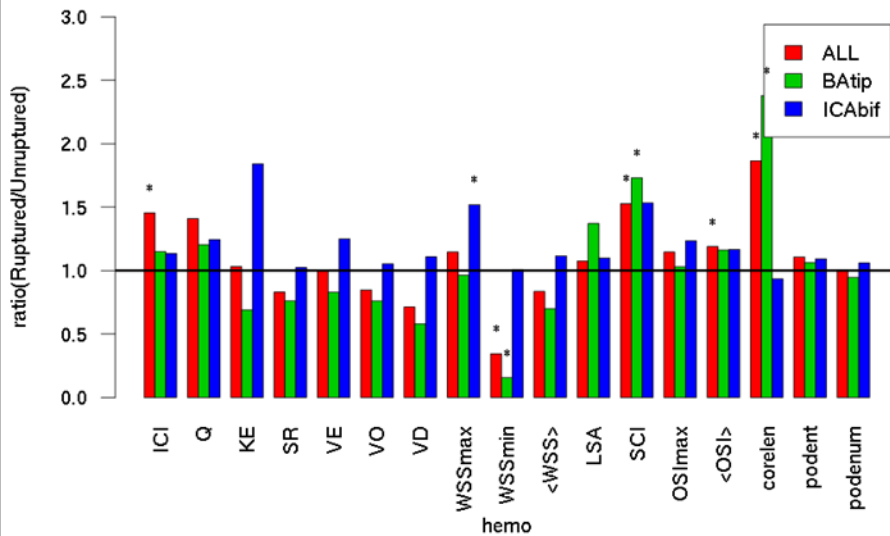# Posterior vs Anterior Circ.: BAtip vs ICAbif

Rupture Status by Location

All BAtip
& ICAbif
aneurysms
in our DB
(N~1800)

n=117

BAtip and ICAbif aneurysms have different rupture rates
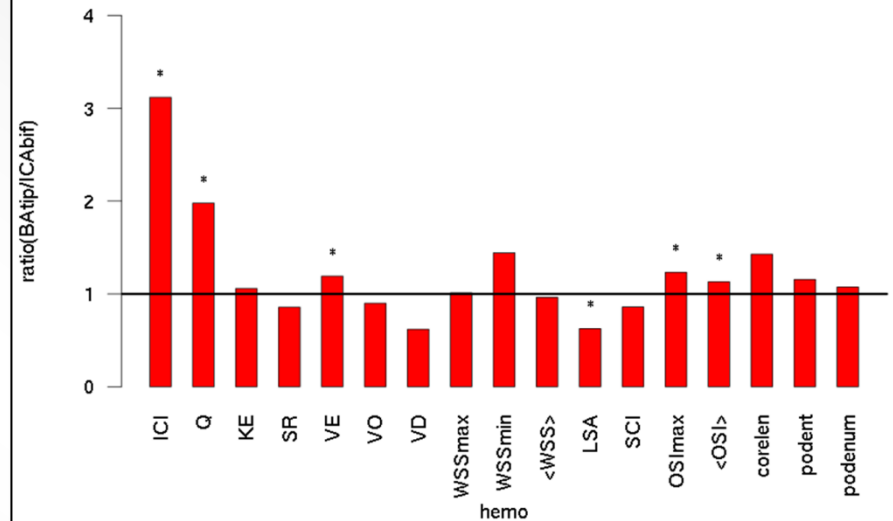➔can hemodynamics explain this difference?

Results

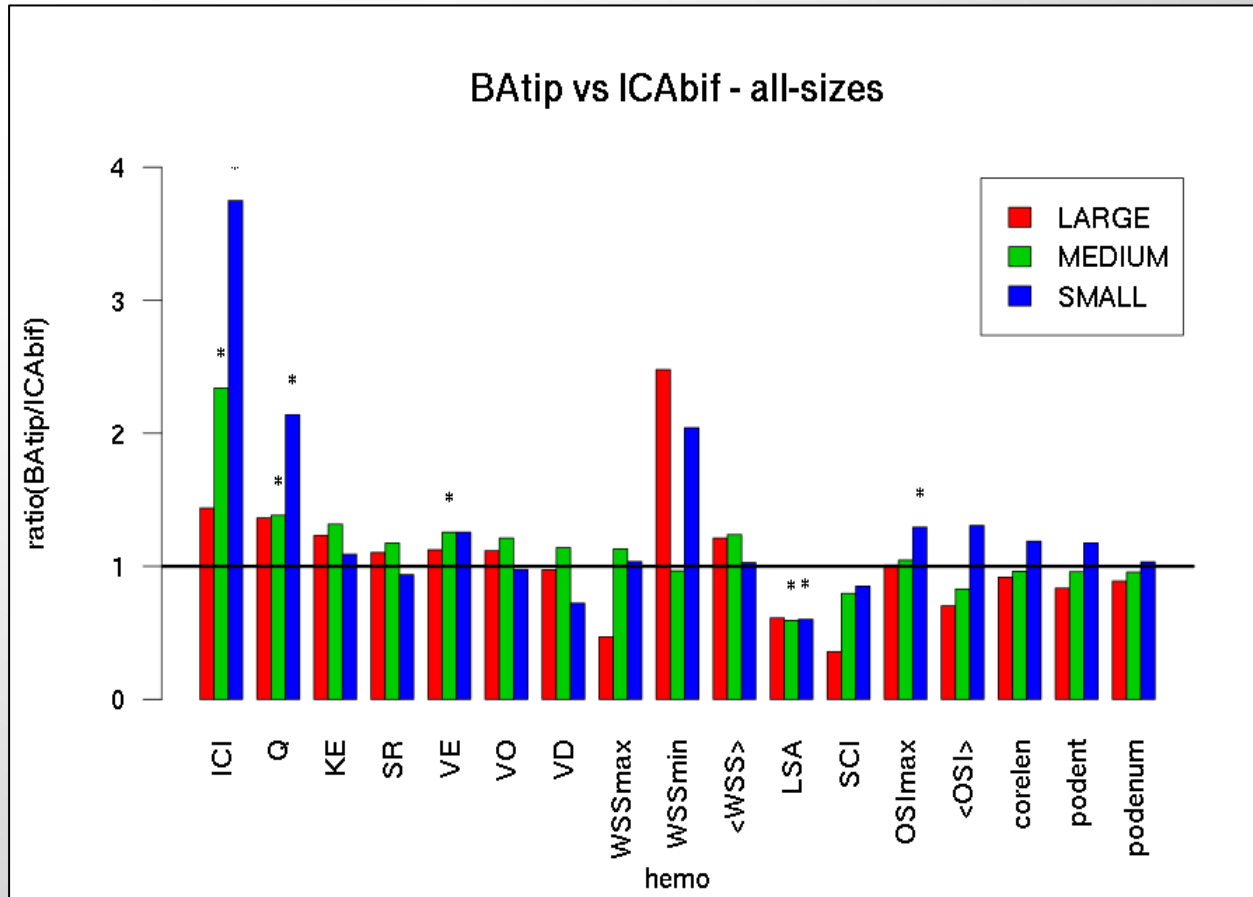Higher flow conditions & more complex flows in R aneurysms
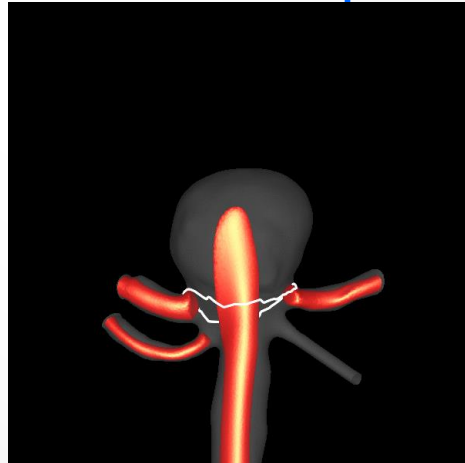
Higher flow conditions in BAtip aneurysms

Results

Hemodynamic differences between BAtip and ICAbif aneurysms more important in small and medium size aneurysms
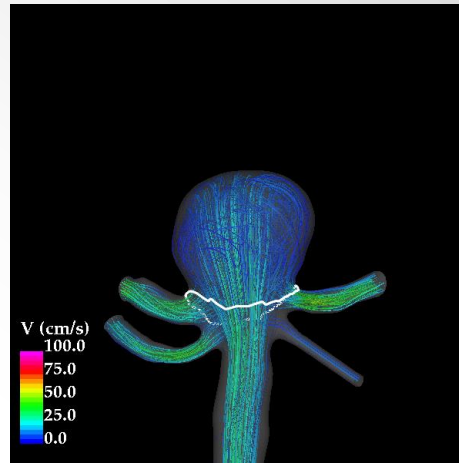
Examples: BAtip

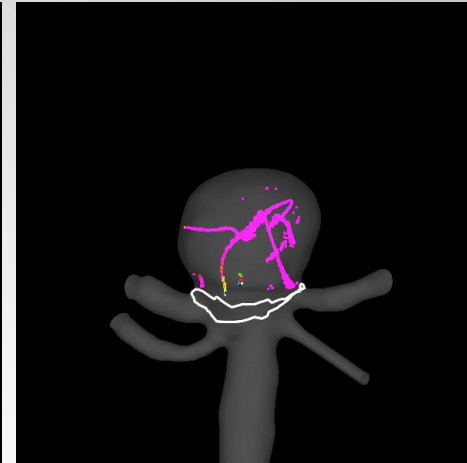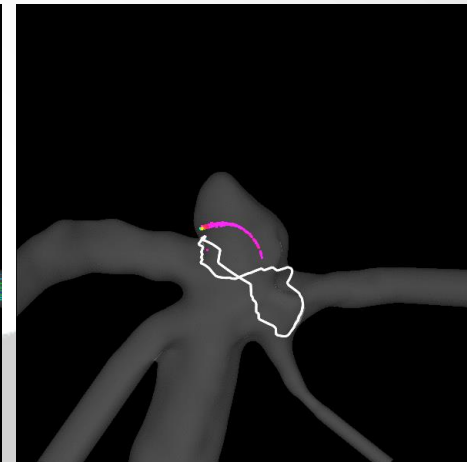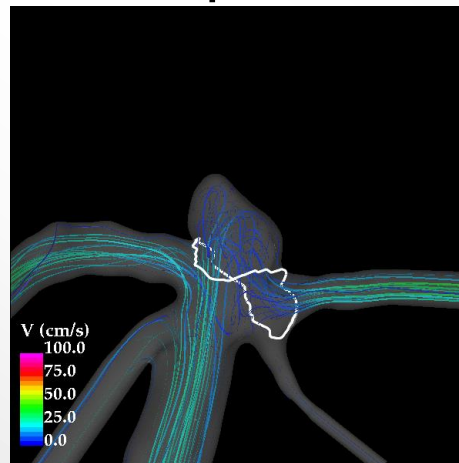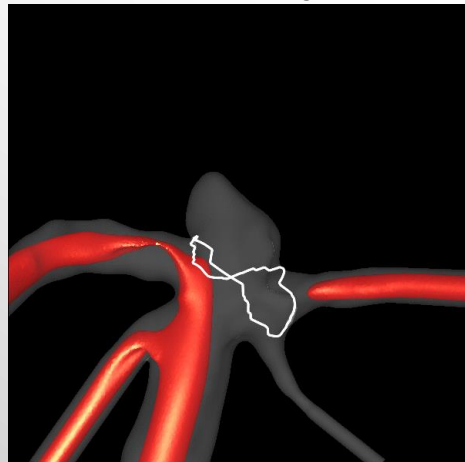WSS   inflow jet   flow pattern   vortex cores
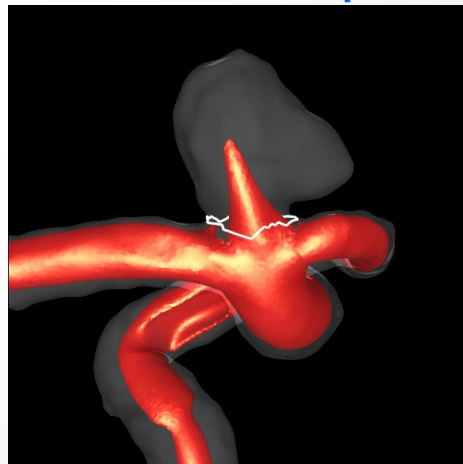
Examples: ICAbif
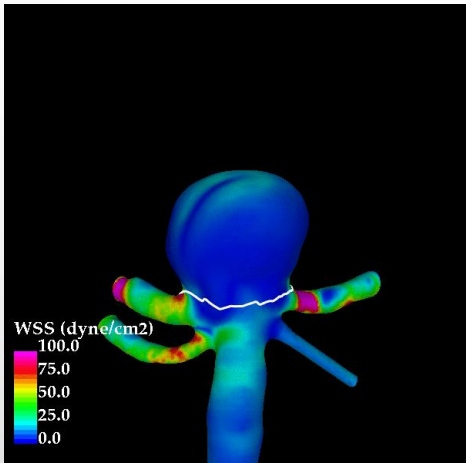
Ruptured
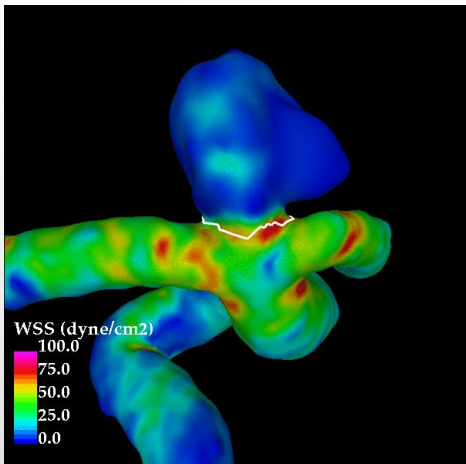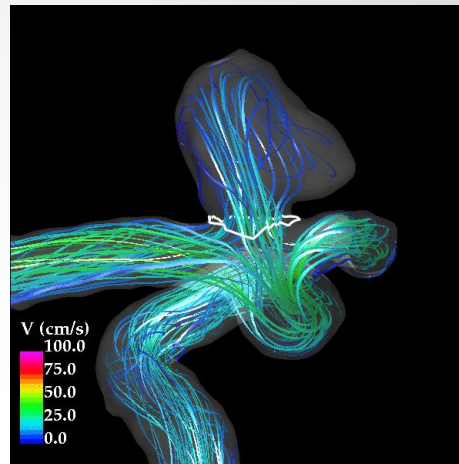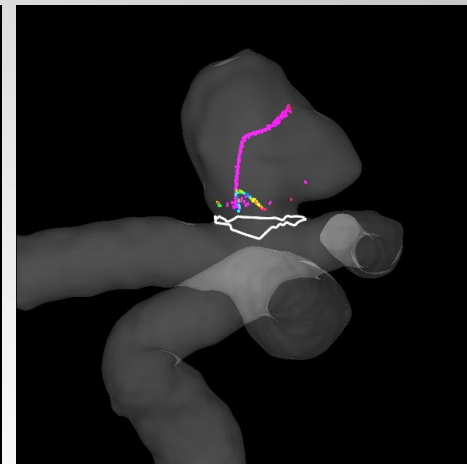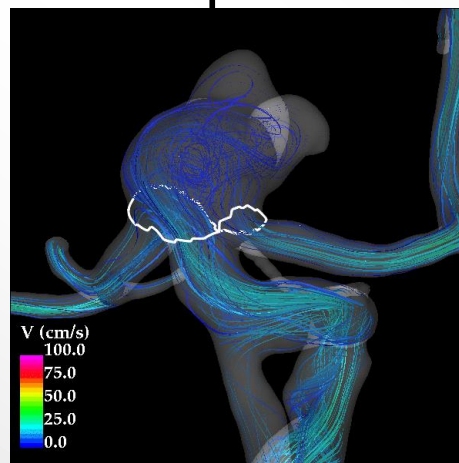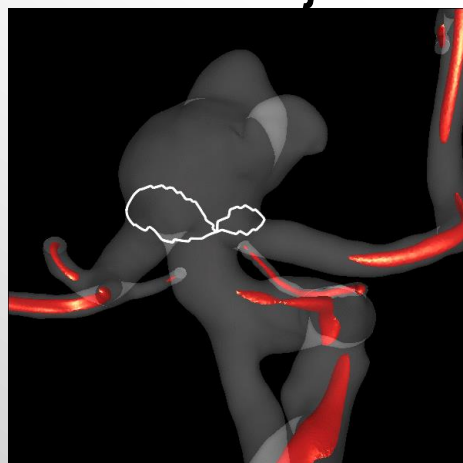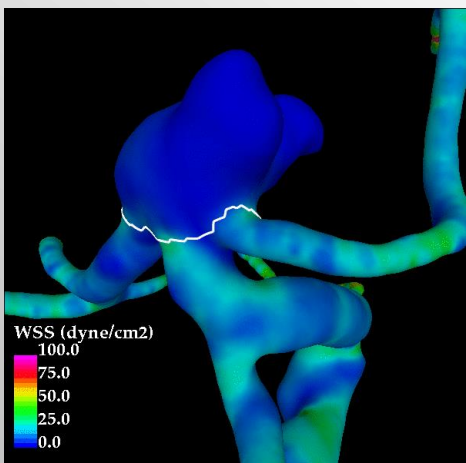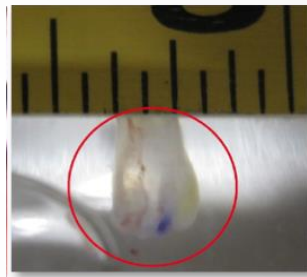
WSS   inflow jet   flow pattern   vortex cores
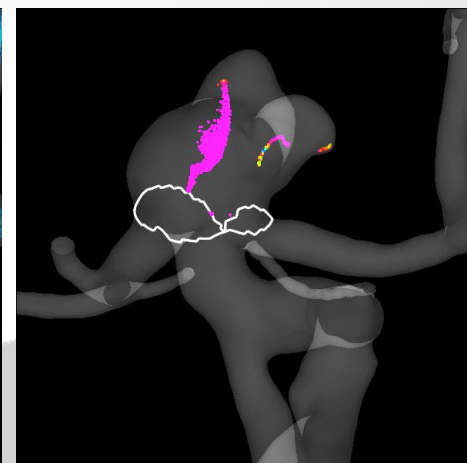
Unruptured

Flow & Wall Inflammation & Degeneration: Histology Data

Results: Inflammation

Results: Flow Conditions

High Flow Associated w Inflammation

High Flow Associated w Endothelium Damage
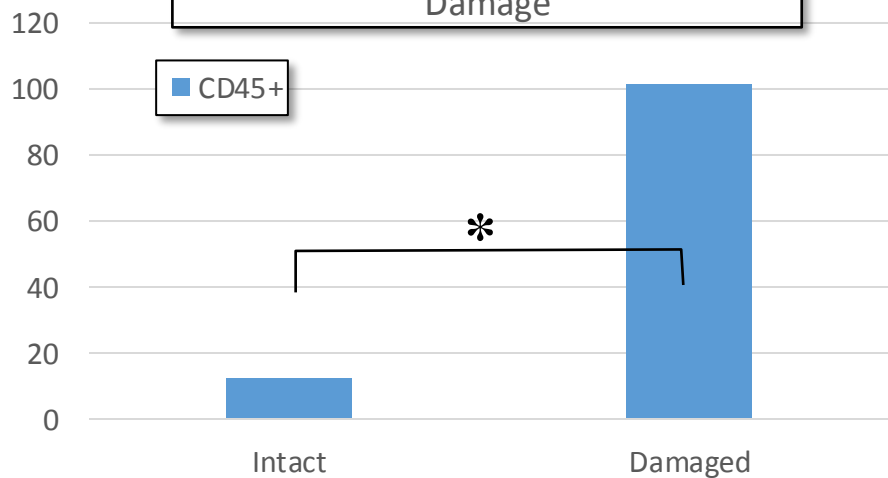
Low Min WSS Associated w Organized Thrombus
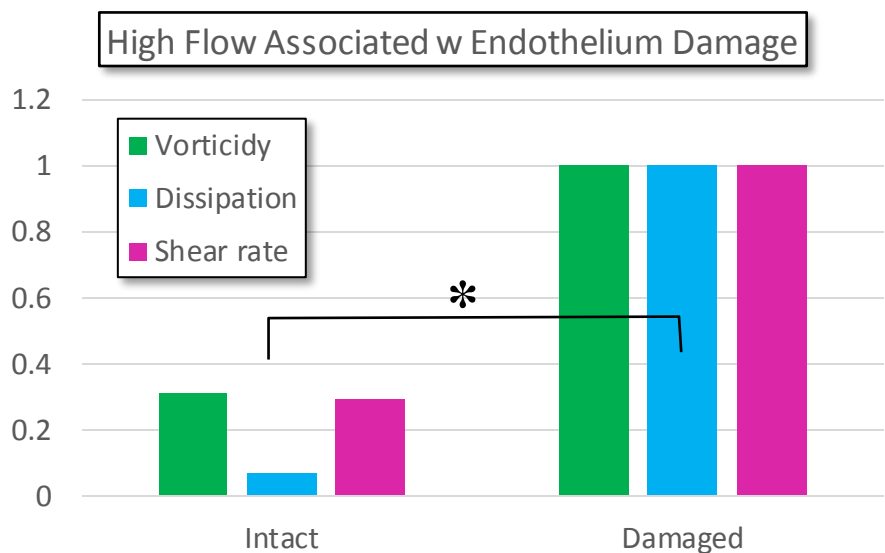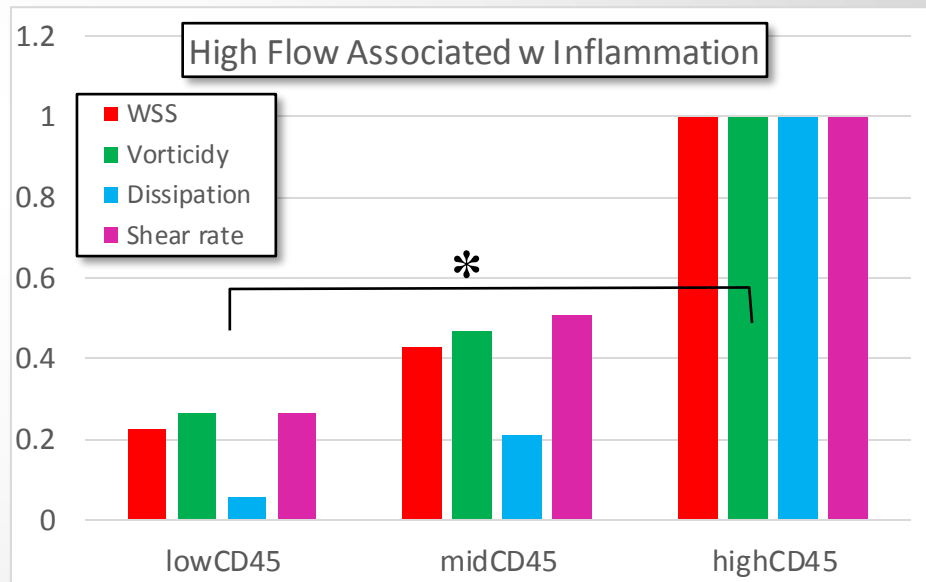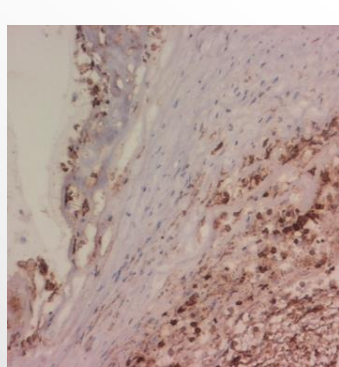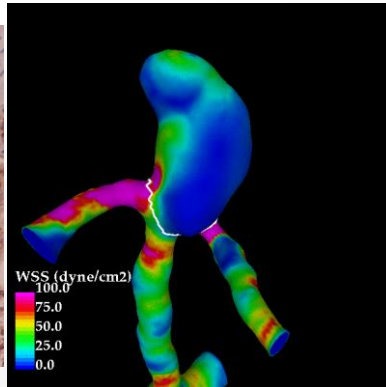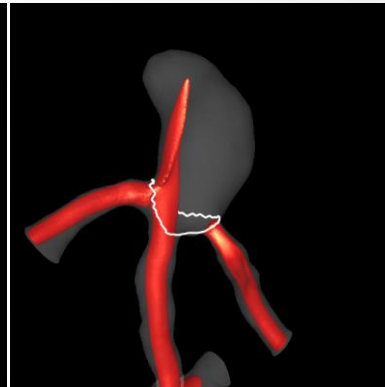
Examples

CD45   WSS   inflow jet   flow pattern vortex centers
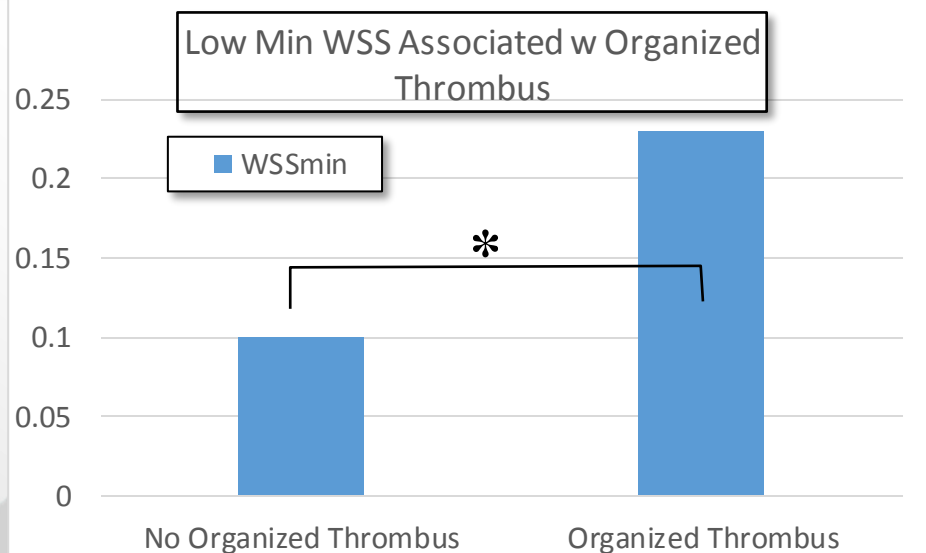
No Inflammation

brown=leukocytes
blue=cell nuclei
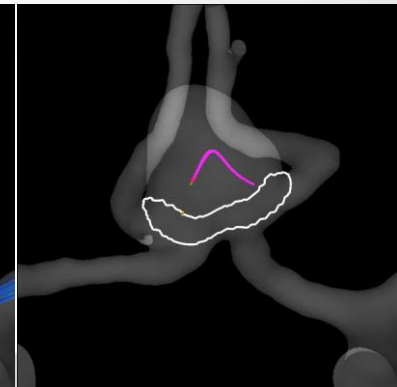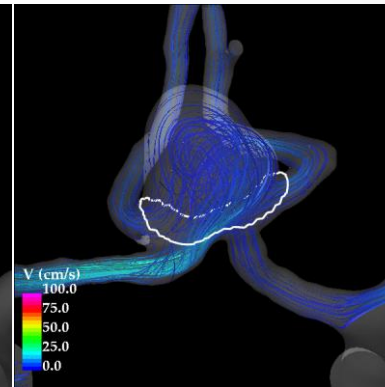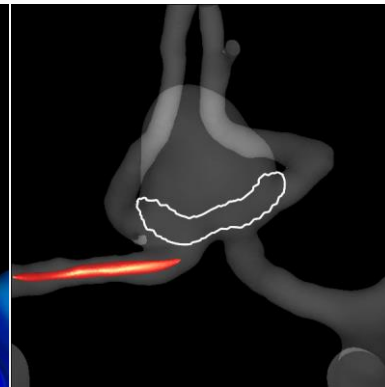
Flow and Wall Structure & Mechanics: Tissue Data

Surgical Clipping
AGH / Helsinki

Tissue Harvest

Mechanical Testing
5 mm
UPitt

Wall Properties

3D Imaging

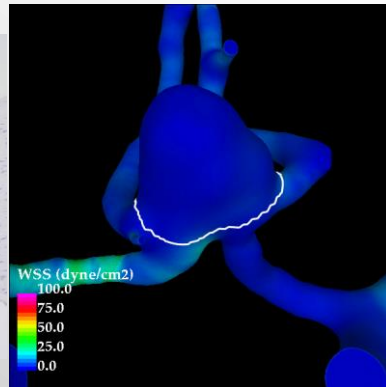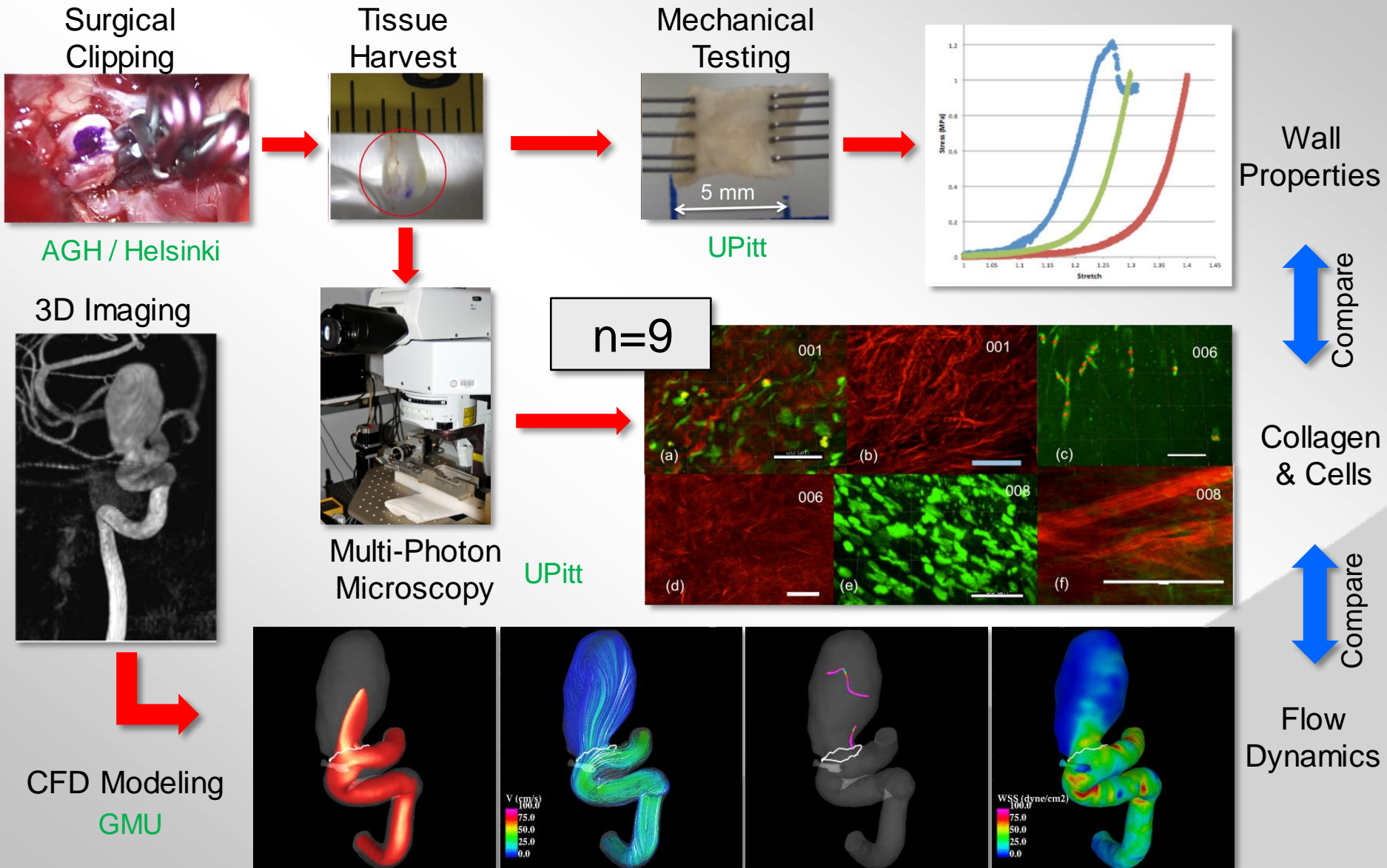Multi-Photon Microscopy
UPitt

n=9

Collagen & Cells

CFD Modeling
GMU

Flow Dynamics

Compare

Compare

Mechanical Behavior of Unruptured Aneurysms
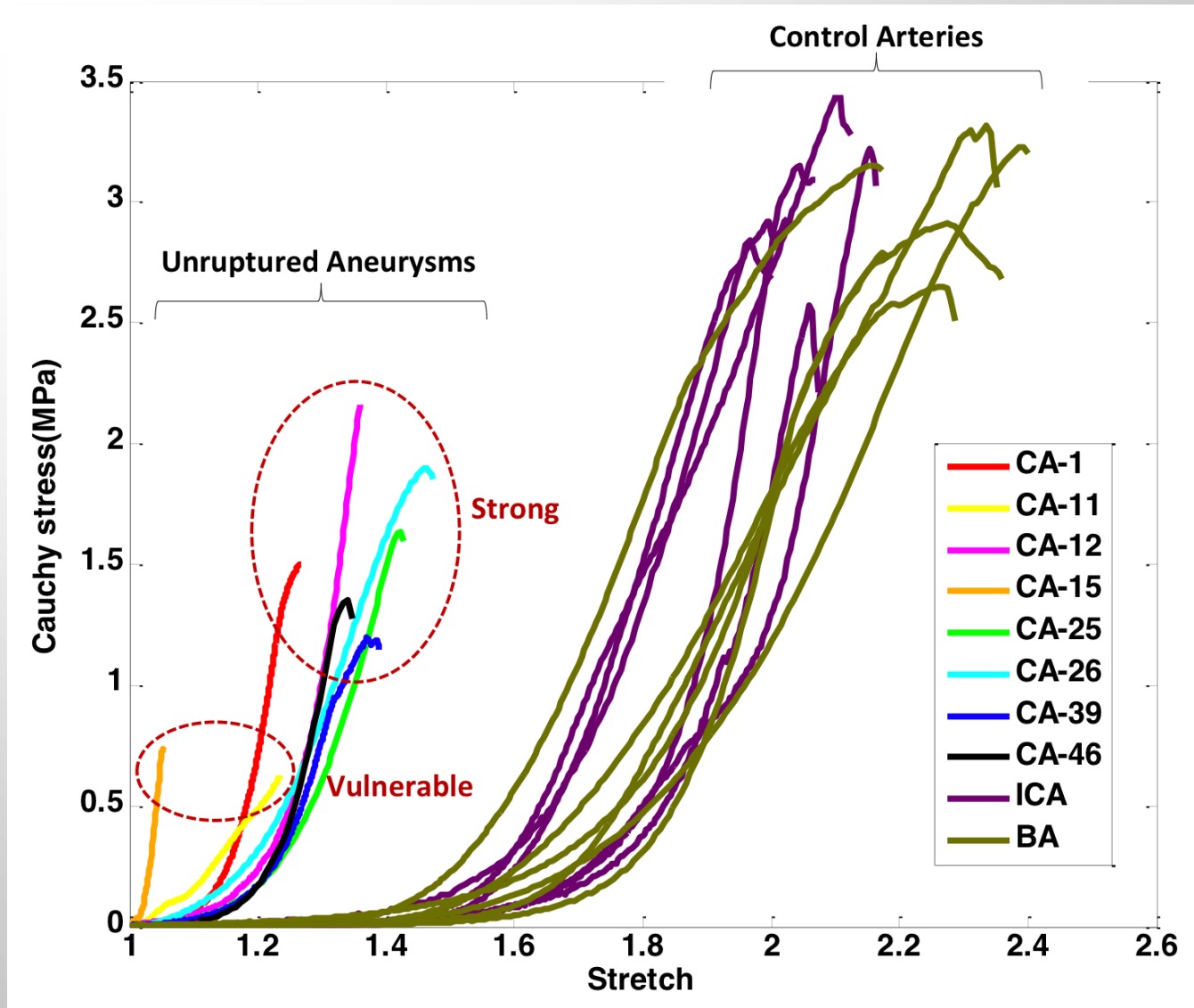
Flow & Ultimate Strain (Strength)

Example 1

inflow

flow pattern

luminal side

V (cm/s)
100.0
75.0
50.0
25.0
0.0

vortex cores

WSS

WSS (dyne/cm2)
100.0
75.0
50.0
25.0
0.0

cross-section

Example 2

inflow

flow pattern

luminal side

V (cm/s)
100.0
75.0
50.0
25.0
0.0

vortex cores

WSS

abluminal side

120-200 μm

0-120 μm

WSS (dyne/cm2)
200.0
150.0
100.0
50.0
0.0
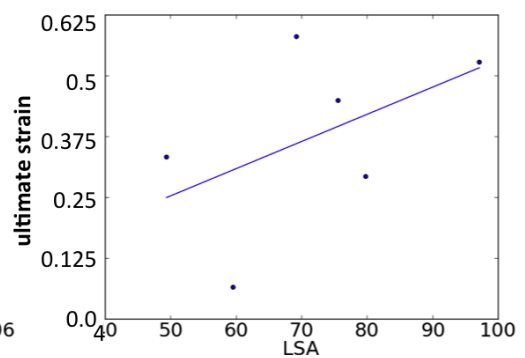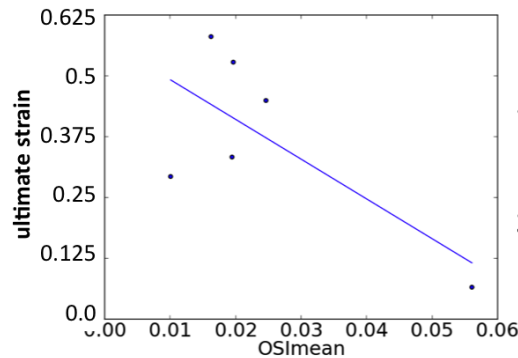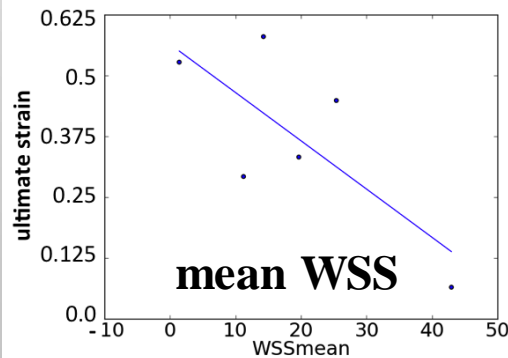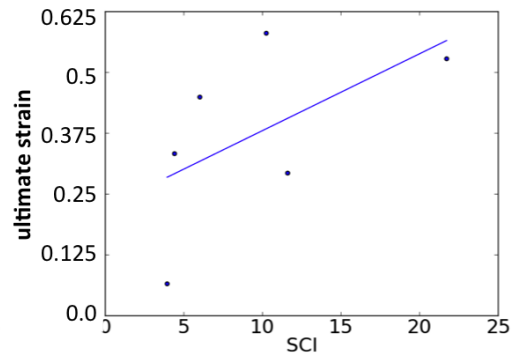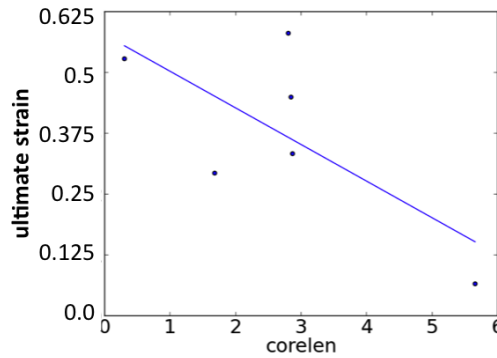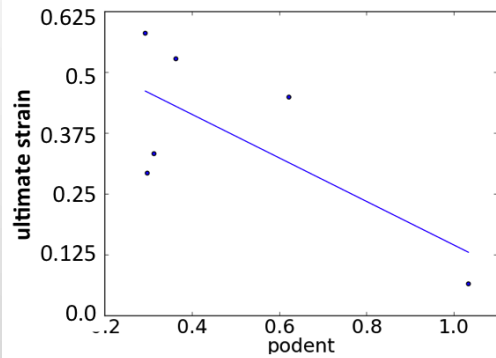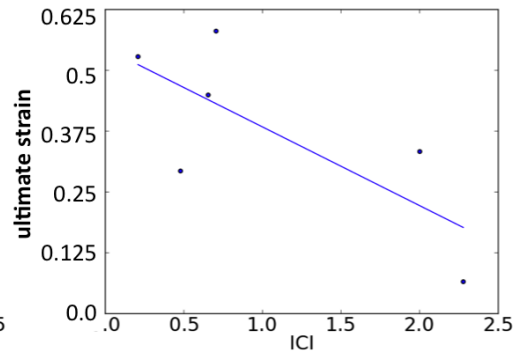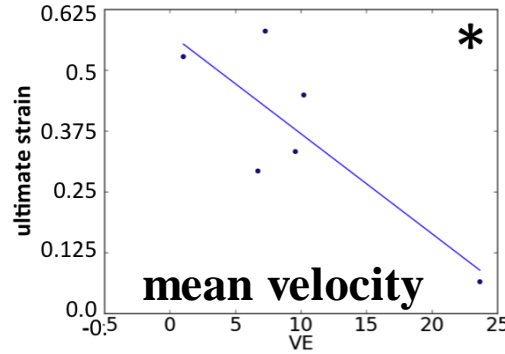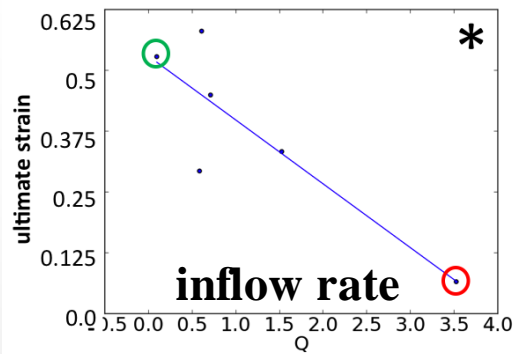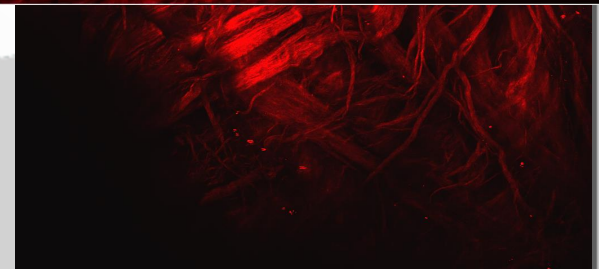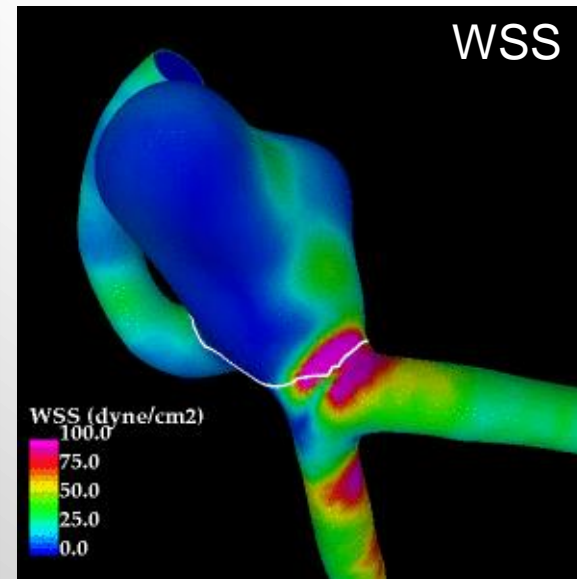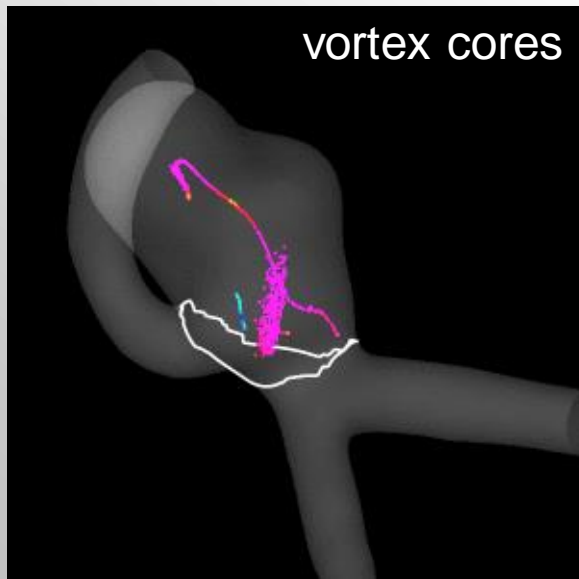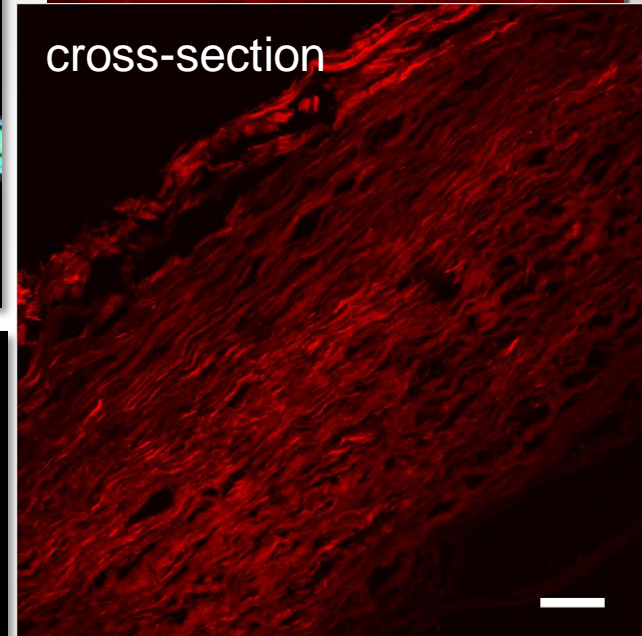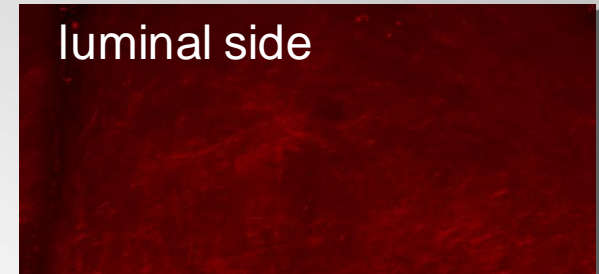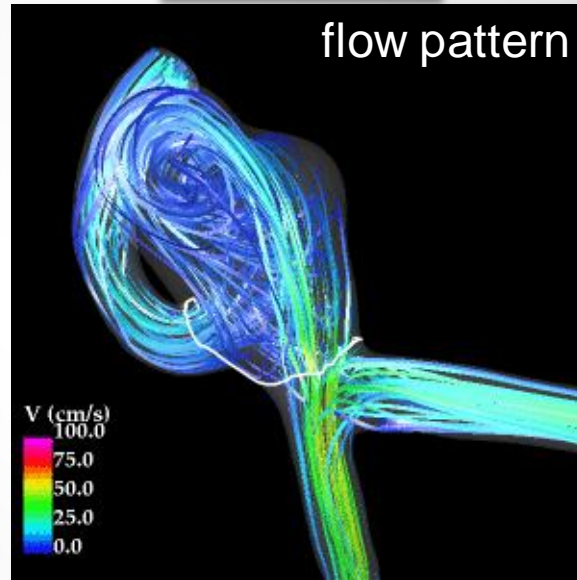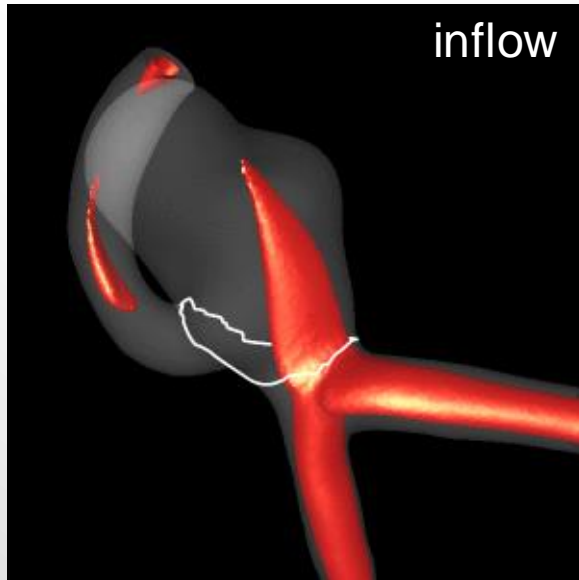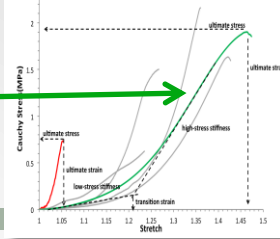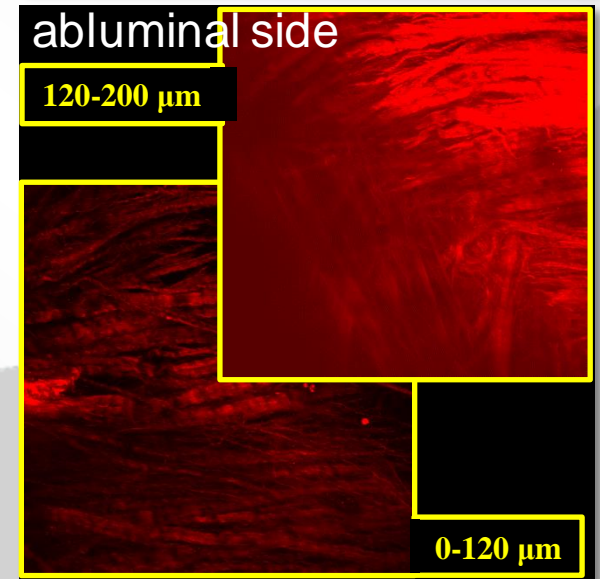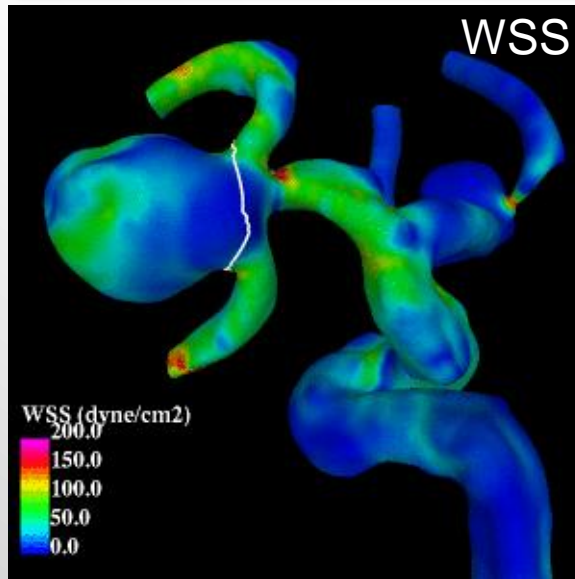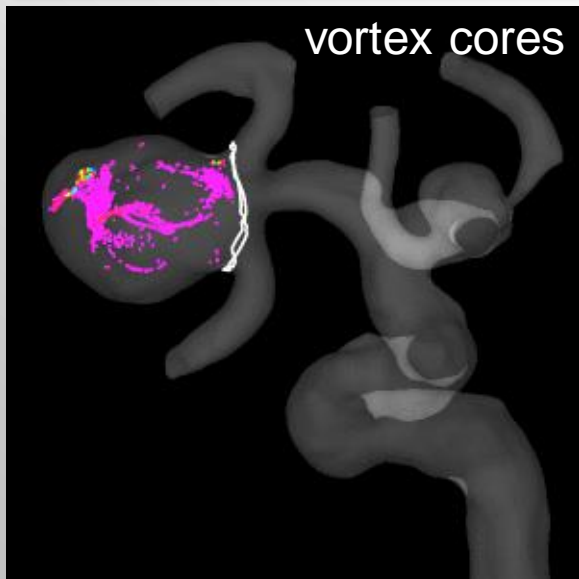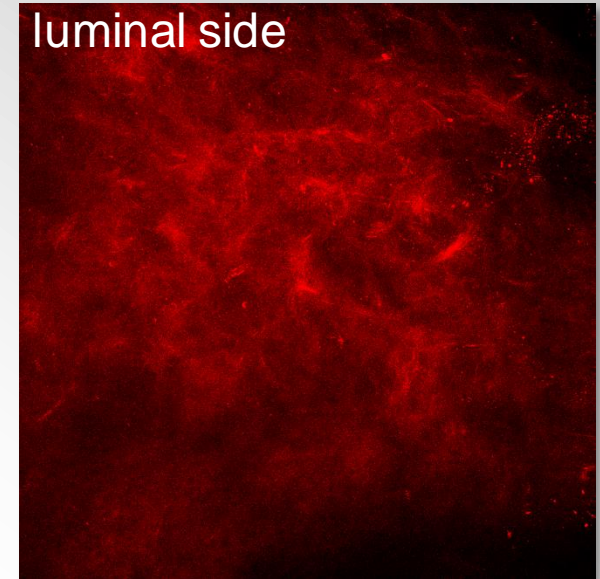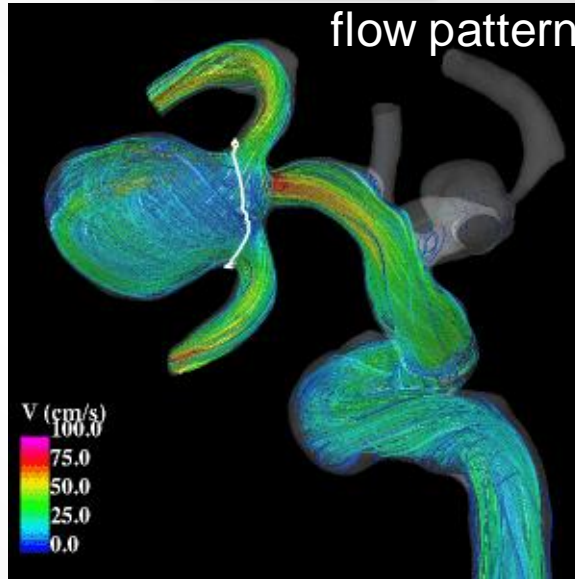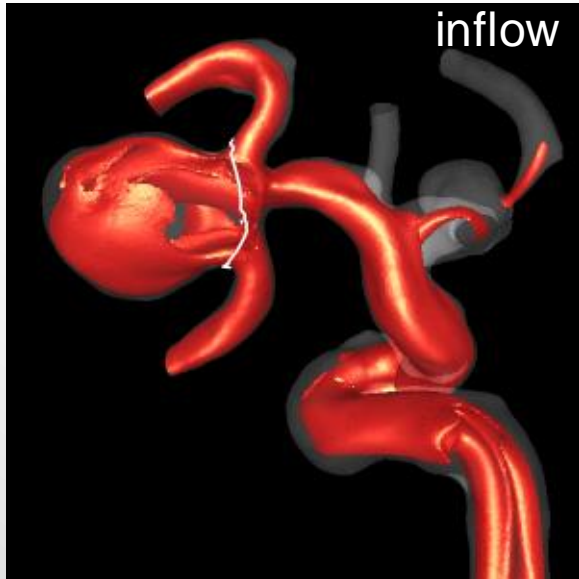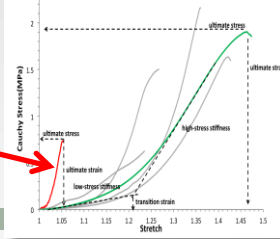
Conclusions

- There is a connection between intra-aneurysmal flow characteristics and aneurysm growth and rupture

- Inflamed walls seem to be associated with higher levels of wall shear stress (& high flow conditions in general)

- There seem to be two sub-populations of unruptured IAs: one with vulnerable walls, another with stronger walls

- High flow conditions seem also to be associated with weaker and stiffer aneurysm walls

- Hemodynamics could potentially be used to identify aneurysms with weaker walls, at risk of growth and of developing inflammation and undergo rupture

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