JOHNS HOPKINS UNIVERSITY

A Modeling Enabled Database for Aneurysm Hemodynamics and Risk Stratification:
A Semi-automated Method for Computational Modeling of Intracranial Aneurysm Hemodynamics

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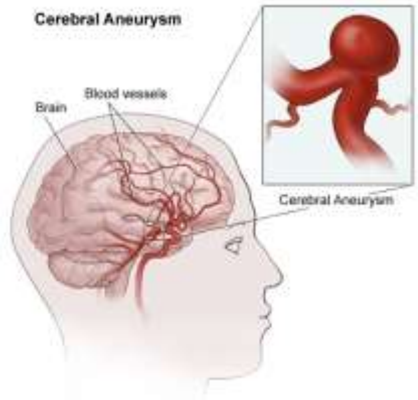
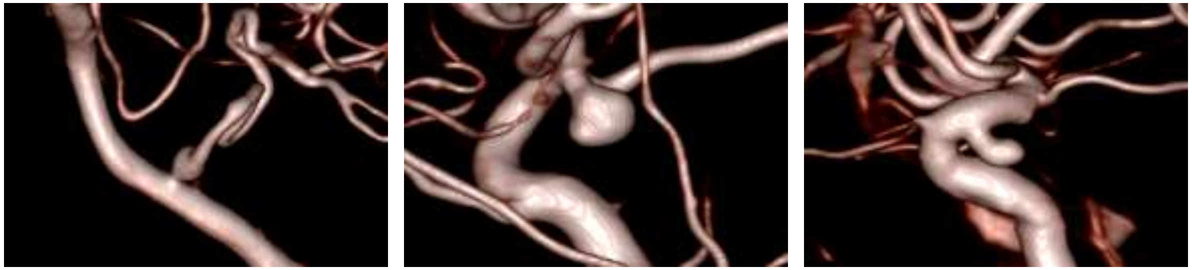
Cerebral Aneurysm



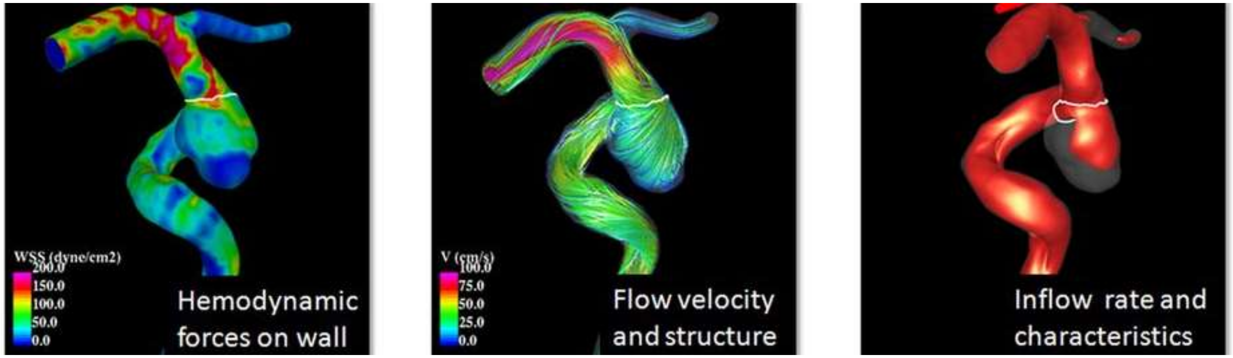
- Aneurysm is a localized, pathological bulge in the wall of blood vessel.
- Too large or one at the risk of rupture need to be treated:

- Estimation of growth/rupture risk is the key for the appropriate treatment
- Clinically, estimation of the risk is mostly based on the morphology.
- Cerebral aneurysms come in vast variety of morphologies (shape, size, and location)



3D angiograms of cerebral aneurysms

Hemodynamics and Risk Stratification



CFD analysis of cerebral aneurysm hemodynamics (***Sforza et al, J NeuroIntervent Surg , 2015***)

- The role of hemodynamics on the growth/rupture has been suggested and investigated by ***Computational Fluid Dynamics***.
- CFD studies provide insights and propose *hemodynamic metrics* associated with the risk: e.g. WSS, OSI, vortex core line length (CORLEN), and many more.
- Correlation btw hemodynamic metrics and the risk can be determined based on the statistical analysis.
- Due to vast variety of aneurysm morphology and the non-linearity of hemodynamics, statistical correlation should be based on **large number of samples** (> 1000).

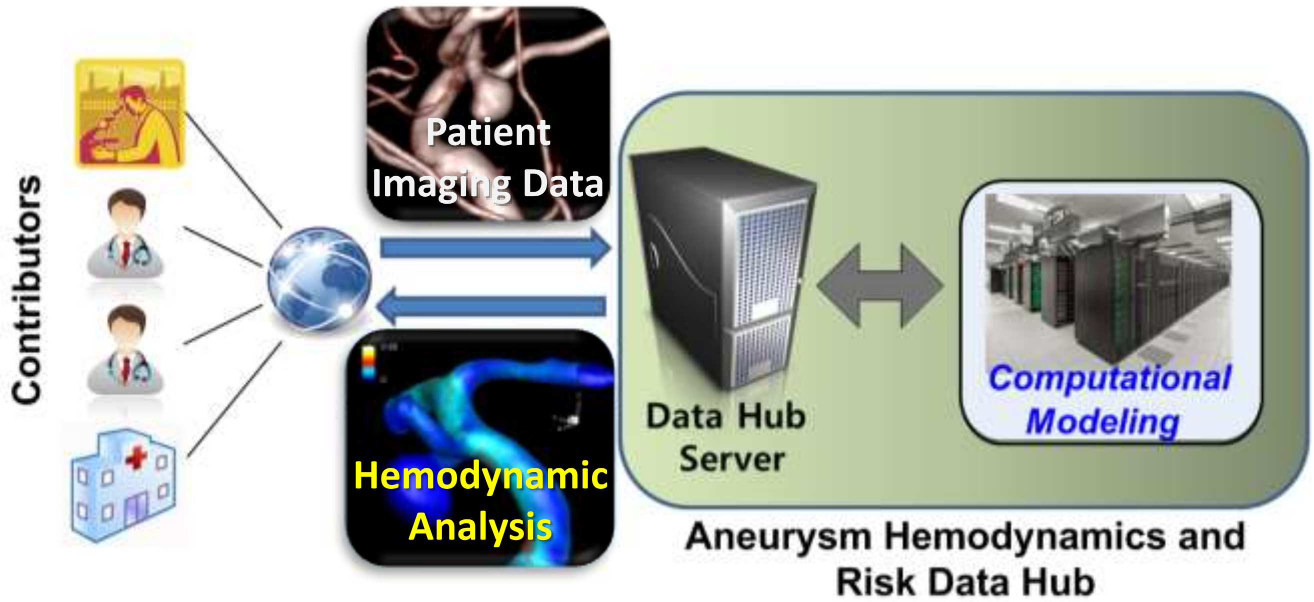
Hemodynamics and Risk Stratification

- Hemodynamic simulations/analysis for large number (>1000) of patient cases are essential to derive the metrics for the risk stratification.
- **Key issues:**
  - Access to large patient data set
  - Manual operations (segmentation, grid generation, pre-processing)
  - Computational costs

Required:

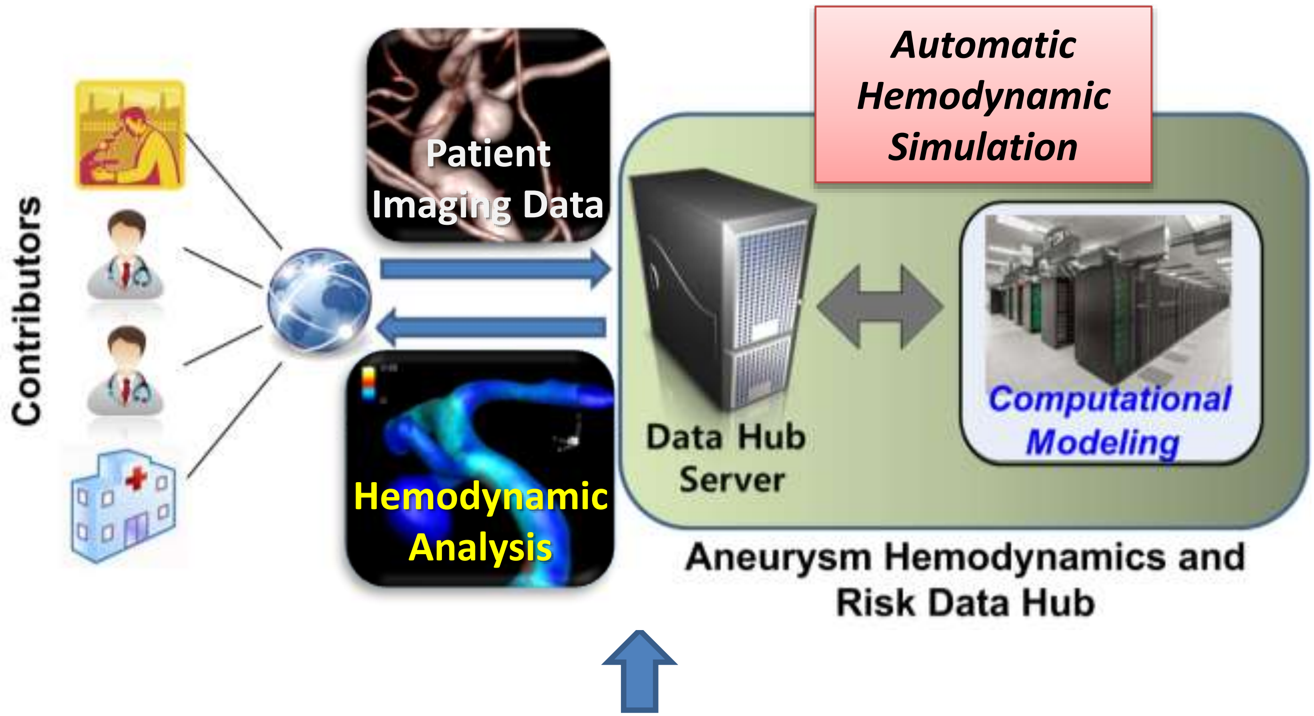
- ***Data hub for the patient data and hemodynamic analysis***
- ***Fast and automated method for the aneurysm hemodynamics simulation***

Aneurysm Hemodynamics and Risk Data Hub



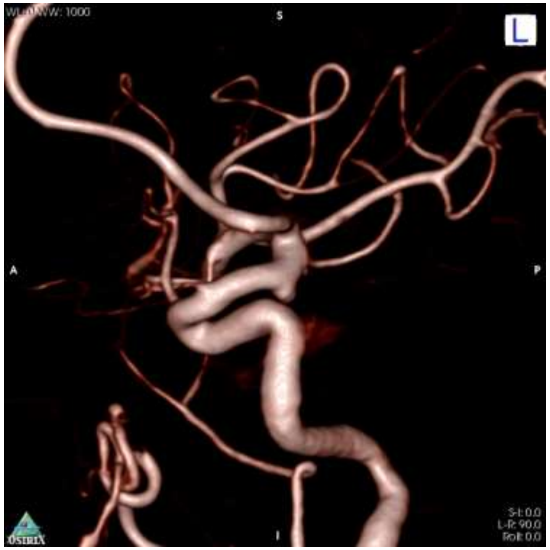
- Crowd sourced, computational modeling based aneurysm hemodynamics data hub
- Doctors/Researchers/Clinical facilities can submit anonymous patient imaging data.
- Hemodynamic analysis is performed by the "automated" simulations.
- Contributors can use the results for diagnosis/research/education.

Aneurysm Hemodynamics and Risk Data Hub



JHUIAD:
Johns Hopkins Intracranial Aneurysm Database (Dr. Rafael Tamargo)
-Over 3300 patient data (high-resolution angiogram)
-Growing at the rate of 300 datasets/year

Automated Hemodynamic Simulation



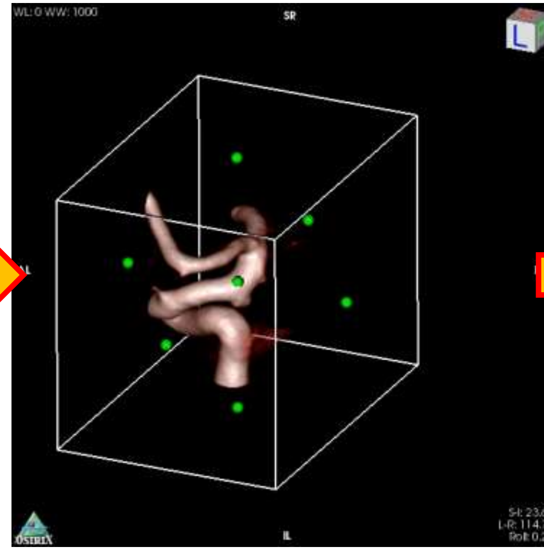
3D angiogram data (DICOM)

- 3D angiograms are represented by voxels (3D pixel) in Cartesian grid.
- Directly use the Cartesian voxel data to minimize manual operations.

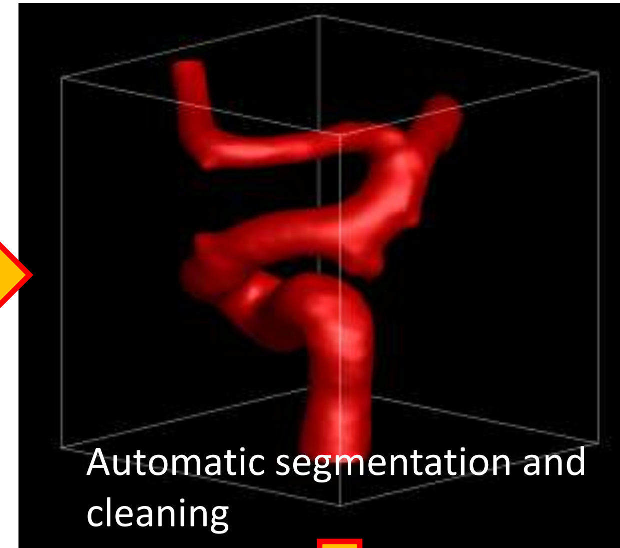
Hemodynamic Simulation by
Cartesian grid ***Immersed Boundary Method (IBM)***

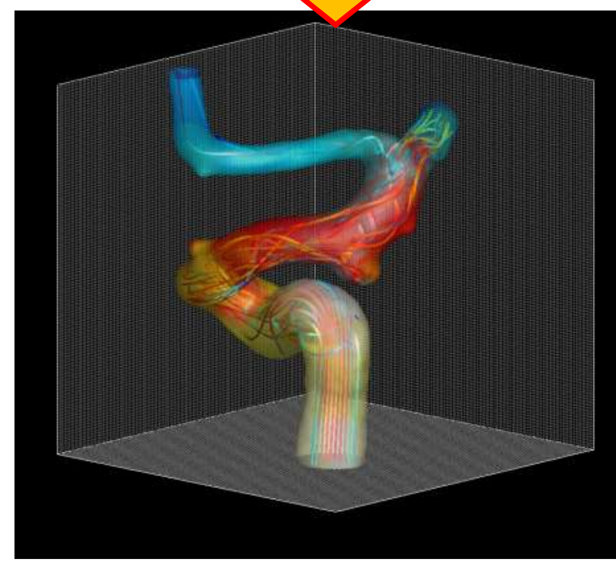
Semi-Automated Hemodynamic Simulation

3D angiogram data (DICOM)



Subset for the ROI

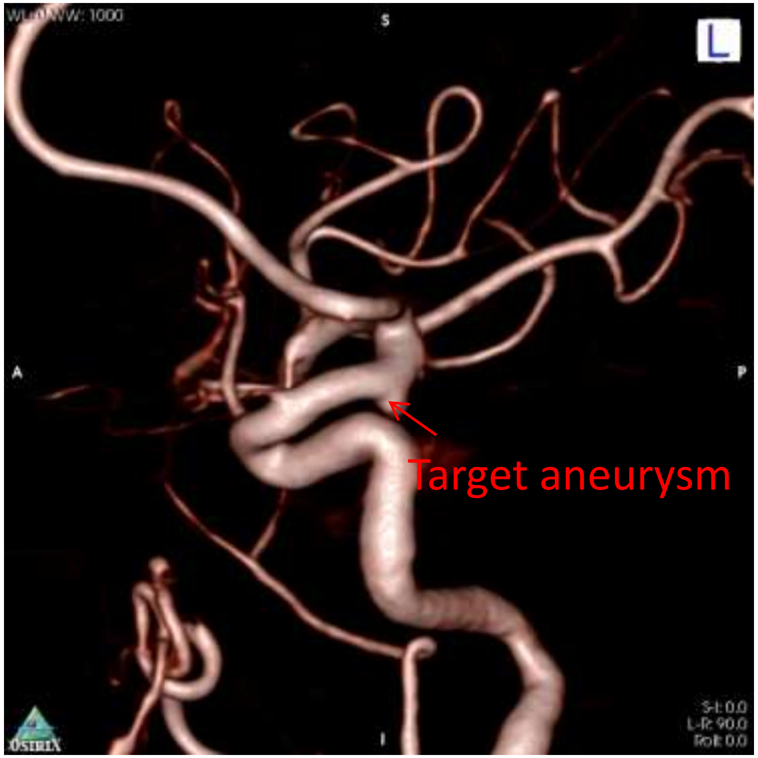


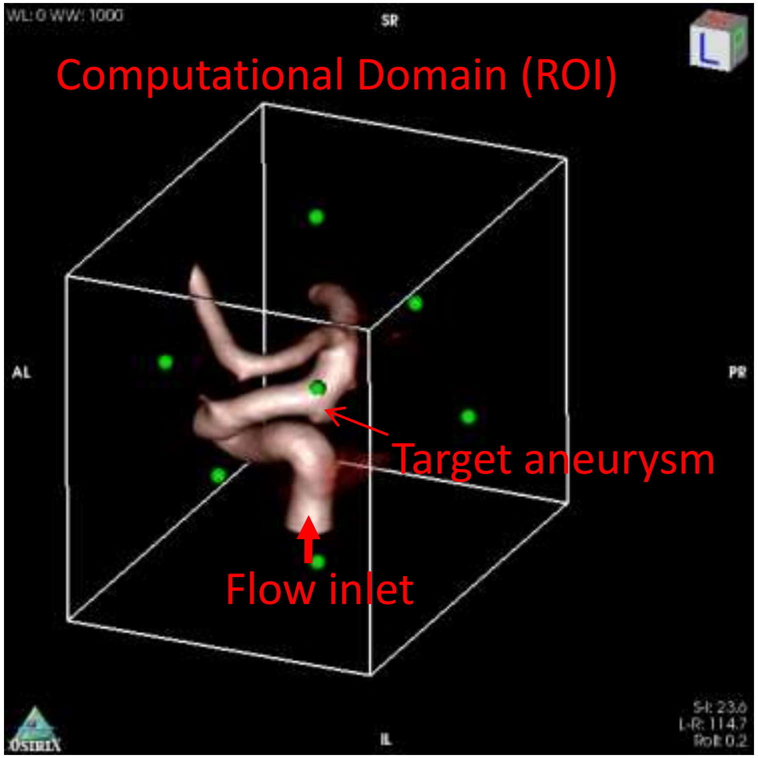


Directly using the Cartesian Voxel data to minimize manual operations

Hemodynamic simulation on the **Cartesian grid** using IBM
-No manual grid generation

Region of Interest and Boundary Condition



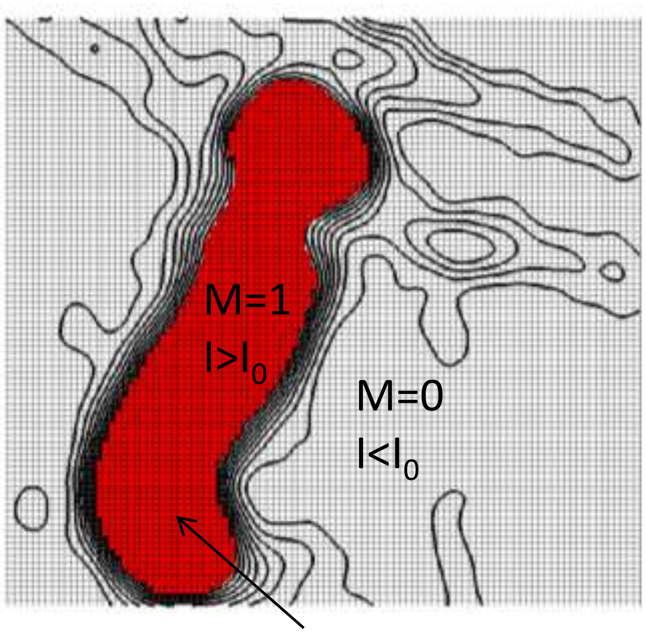


Required manual operations:

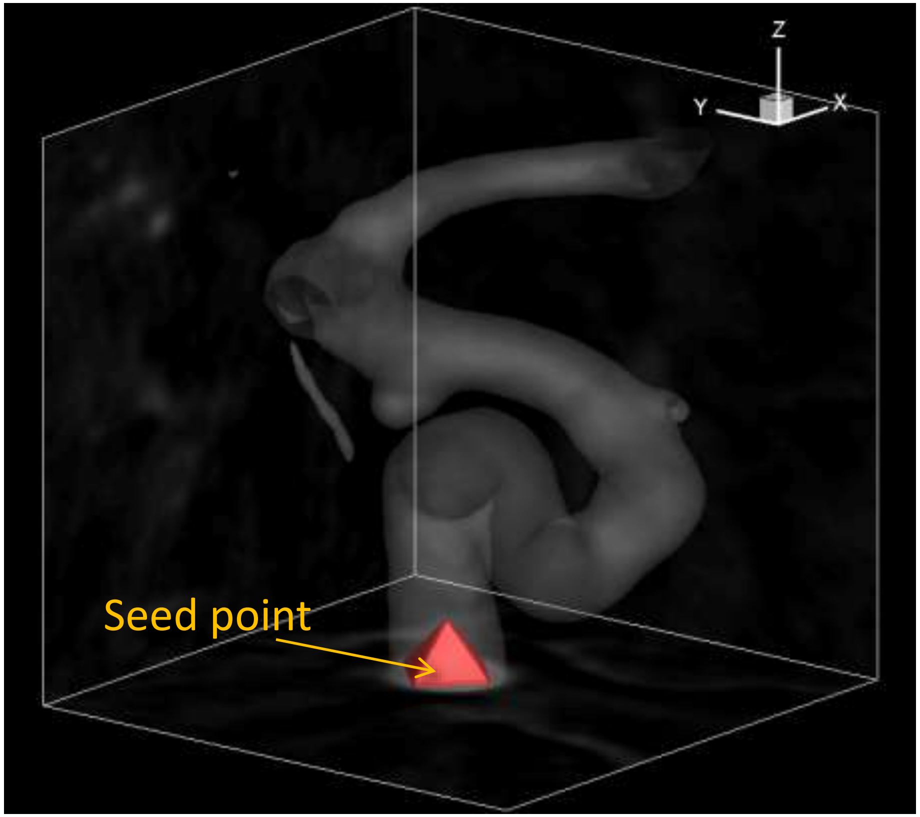
1. Visualize the vessel (set proper intensity range)
2. Set (Cartesian) ROI around the target aneurysm
3. Mark the inflow region and specify boundary condition (flow rate, etc)

Automatic Segmentation and Cleaning

Region growing:
Starting from a seed point,
find connected voxels satisfying the criteria;
$I>I_0$, $\Delta I<\Delta I_{max}$, and etc.

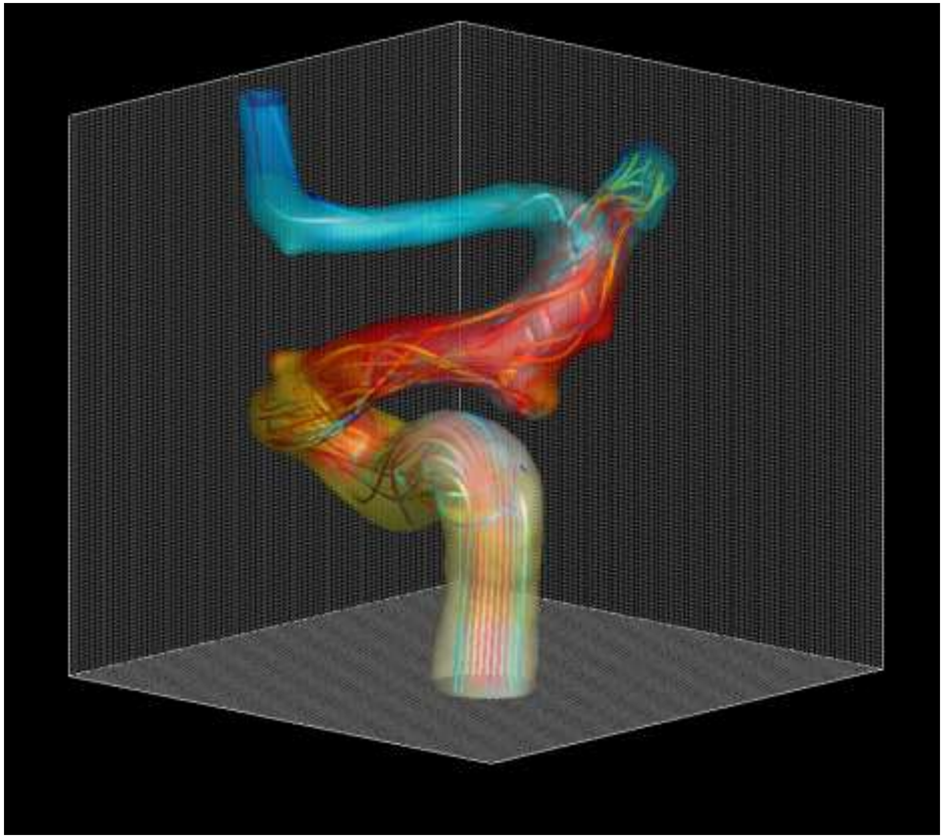


Region growing mask
M: Mask function



Evolution of 3D Region growing mask (M=1)

Hemodynamic Flow Simulation



- **Incompressible Navier-Stokes equation**
  - Fractional step method
  - Second-order finite difference
  - BiCGSTAB for Pressure Poisson
- **Cartesian grid**
  - Utilize voxel grid from 3D angiogram
  - voxel spacing = grid spacing
  - or re-sampling for finer grid spacing
- **Immersed boundary method**
  - Sharp-interface method using the level set function
  - Level set function is constructed based on the contrast intensity

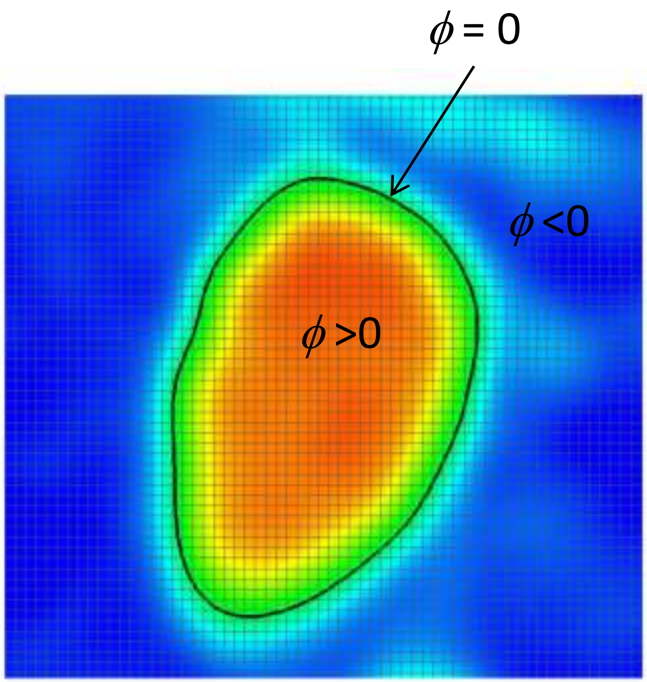
Contrast Intensity based Level-Set Function

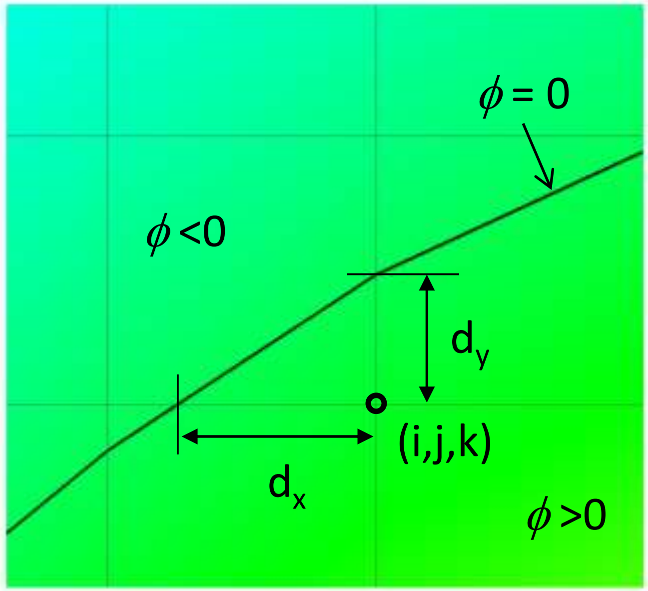
Level-set function

$$\phi(i,j,k) = I(i,j,k) - I_0$$

(i,j,k): voxel grid index, I_0: threshold intensity

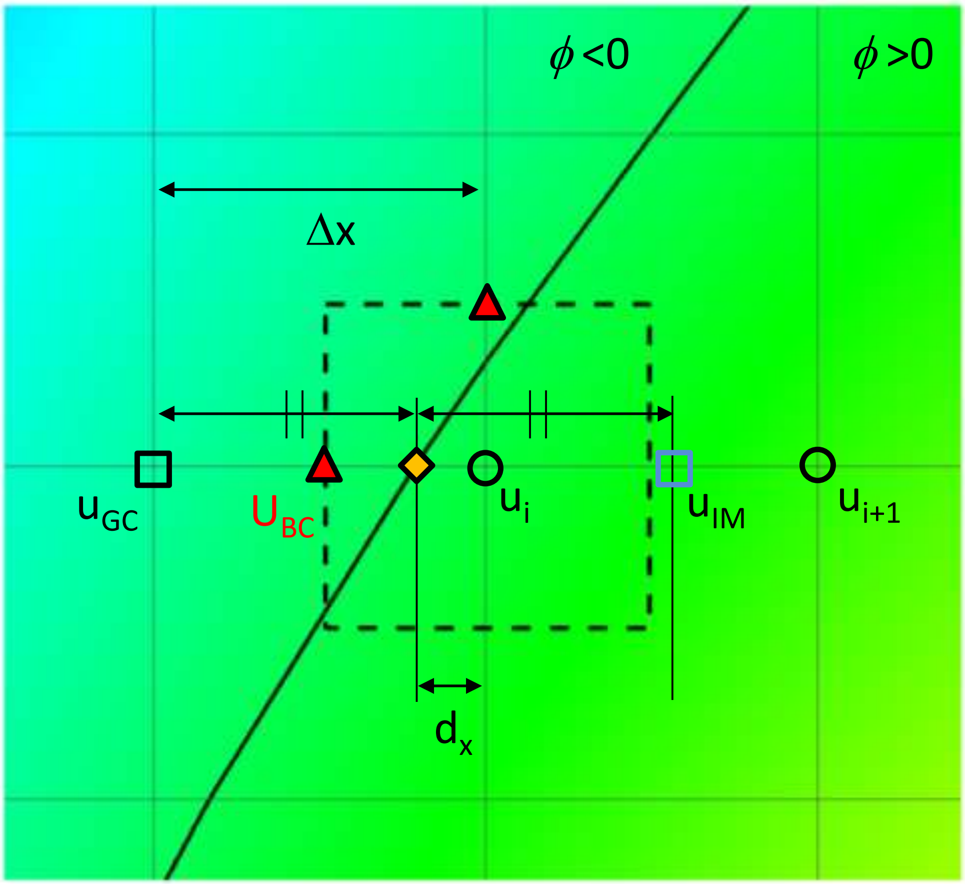
ϕ =0 : lumen boundary, ϕ >0 : flow region





$$d_x = \frac{\phi}{\partial\phi / \partial x}, \quad d_y = \frac{\phi}{\partial\phi / \partial y}$$

Immersed Boundary Method



Boundary condition is applied by imposing cell face velocity, U_{BC}

U_{BC} is obtained by interpolation/extrapolation with u_w and interior point values, u_i

For no-slip, stationary wall (u_w=0)

i) if $d_x \geq \Delta x/2$

$$U_{BC} = u_i \left(1 - \frac{\Delta x}{2d_x} \right)$$

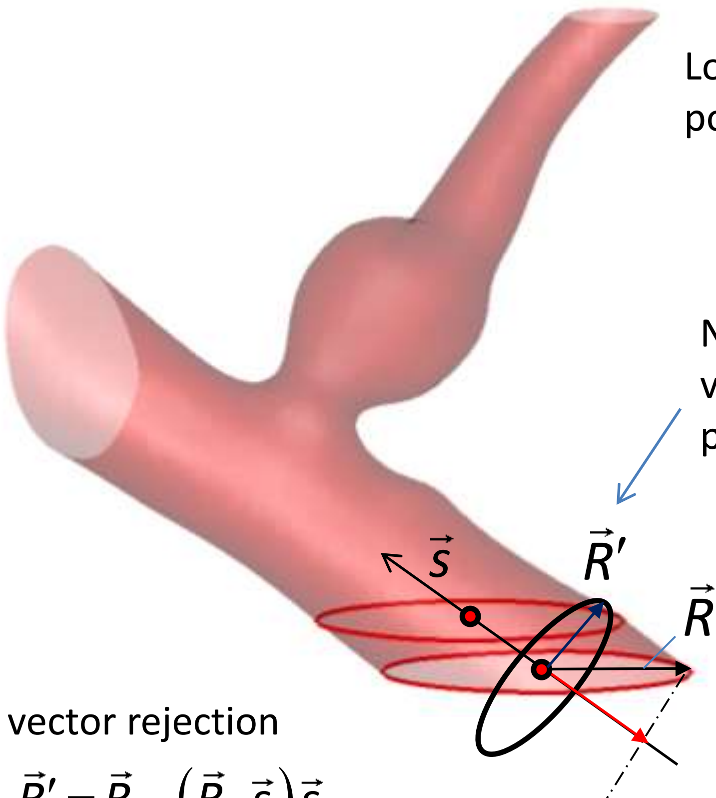
ii) if $d_x < \Delta x/2$
(Ghost-fluid method)

$$u_{GC} = -u_{IM}$$

$$u_{IM} = u_i + \frac{u_{i+1} - u_i}{\Delta x}(\Delta x - 2d_x)$$

$$U_{BC} = \frac{1}{2}(u_{GC} + u_i) = \frac{u_i - u_{i+1}}{\Delta x}\left(\frac{\Delta x}{2} - d_x \right)$$

Imposing Inflow Velocity BC



Local center line vector is determined with the center point:

$$\vec{x}_c = \frac{\sum M \cdot \vec{x}}{\sum M}$$

Normal to center line radius vector is calculated by the vector rejection with the center line vector and the in-plane radius

vector rejection

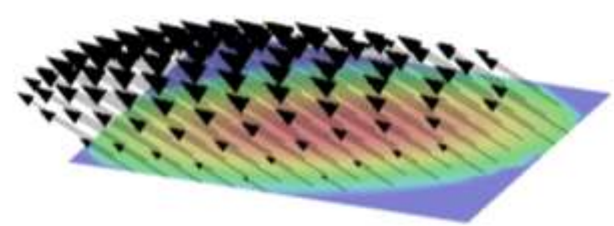
$$\vec{R}' = \vec{R} - \left(\vec{R} \cdot \vec{s}\right)\vec{s}$$

velocity profile can be specified by

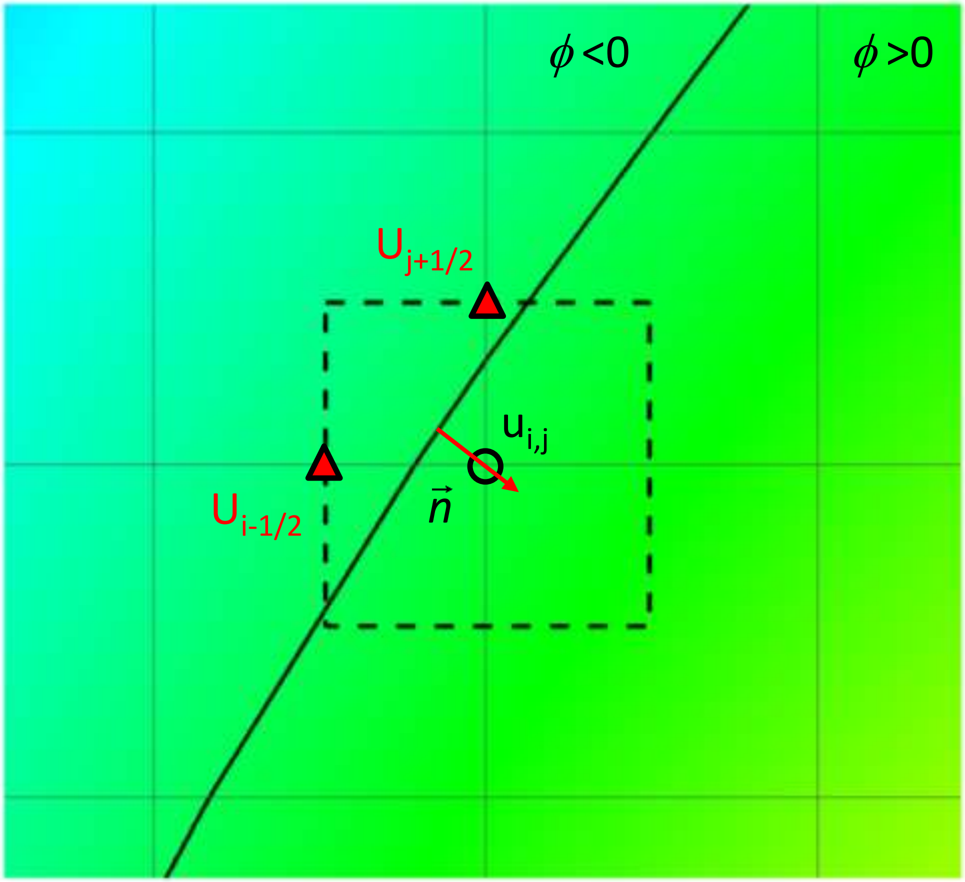
$$f\left(R'\right), \;\; R' = \left|\vec{R}'\right|$$

Velocity at the inlet plane
e.g. parabolic profile

$$\vec{U}(\vec{R}) = U_{\max}\left[1 - \left(\frac{R'}{R'_{\max}}\right)^2\right]\vec{s}$$



Wall Shear Stress Calculation



$$\frac{\partial u}{\partial x} \approx \frac{u_{i,j} - U_{i-1/2}}{\Delta x / 2}, \quad \frac{\partial u}{\partial y} \approx \frac{U_{j+1/2} - u_{i,j}}{\Delta y / 2}$$

wall normal vector:

$$\vec{n} = \frac{\nabla \phi}{|\nabla \phi|}$$

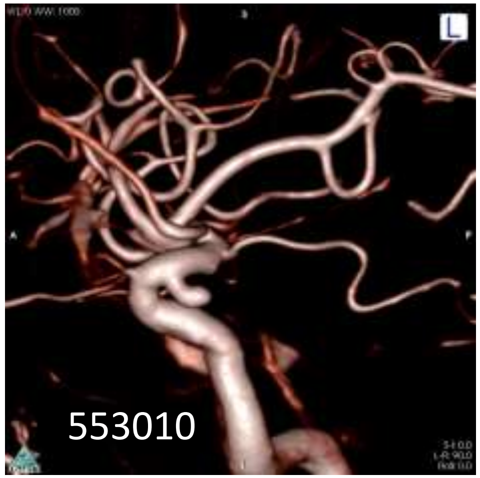
wall shear stress:

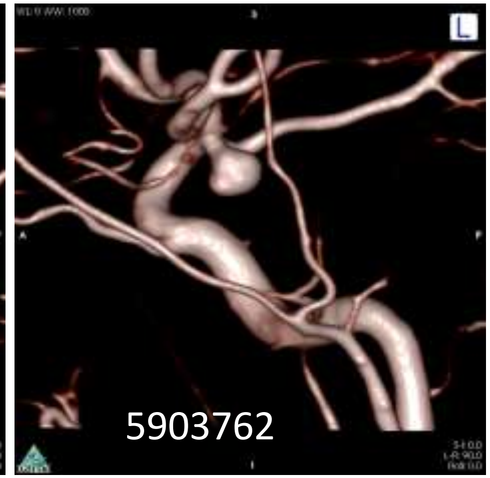
$$\vec{\tau}_w = \mu \frac{\partial \vec{u}}{\partial n}, \quad \frac{\partial \vec{u}}{\partial n} = \nabla \vec{u} \cdot \vec{n}$$

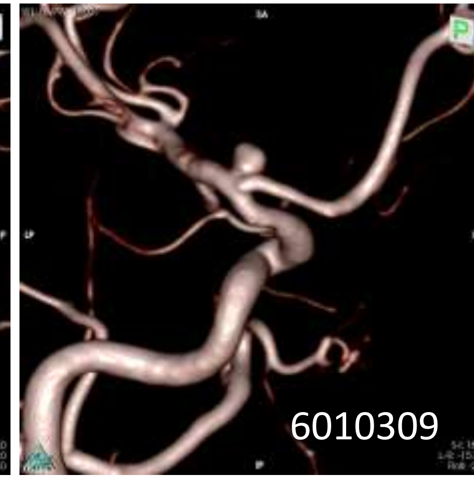
WSS is stored at the nearest cell center node

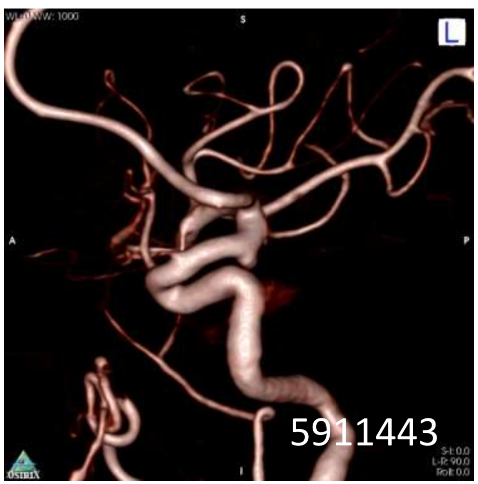
Sample Cases

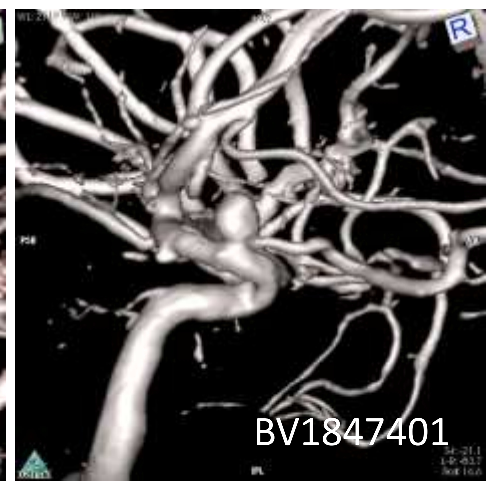
Randomly picked from **JHUIAD**







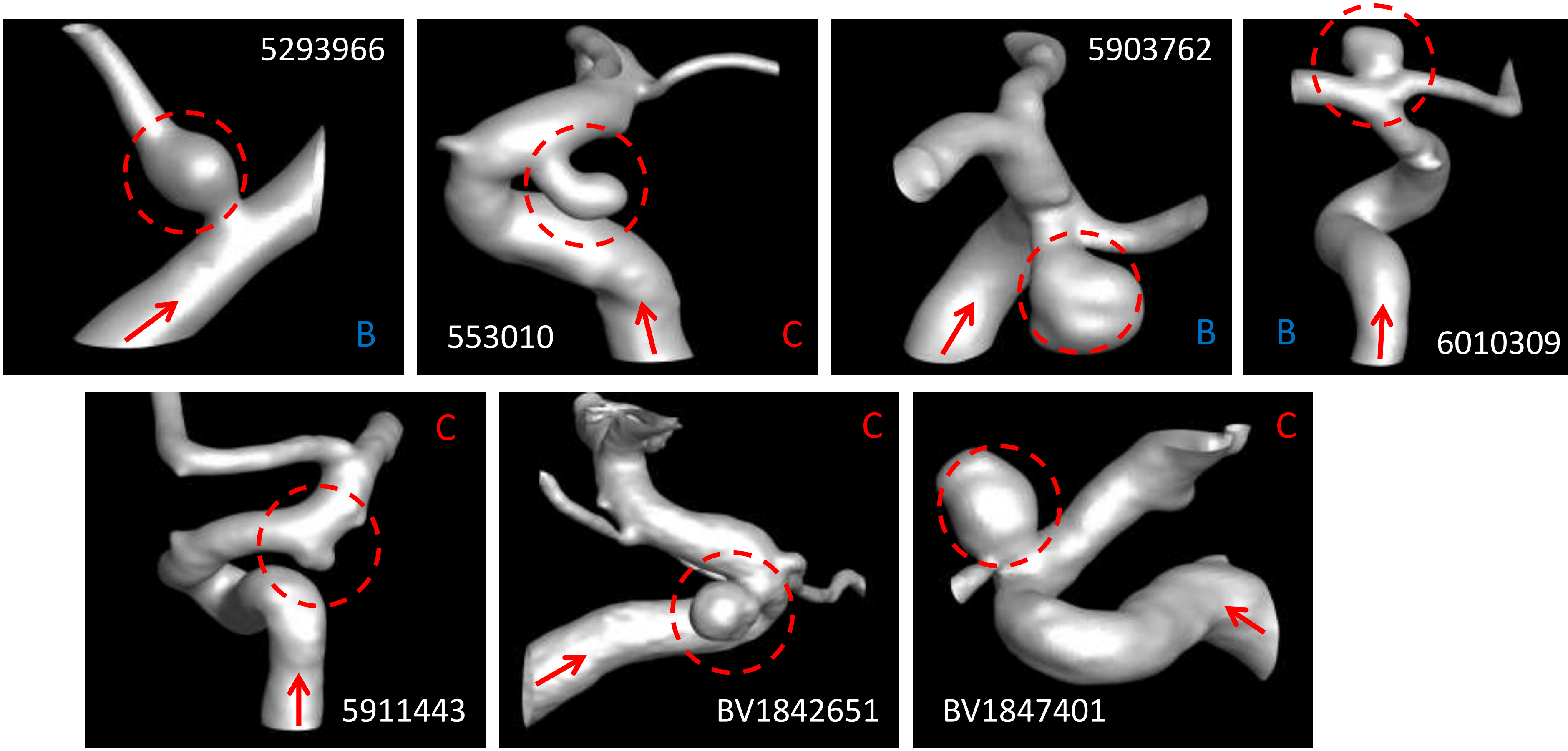




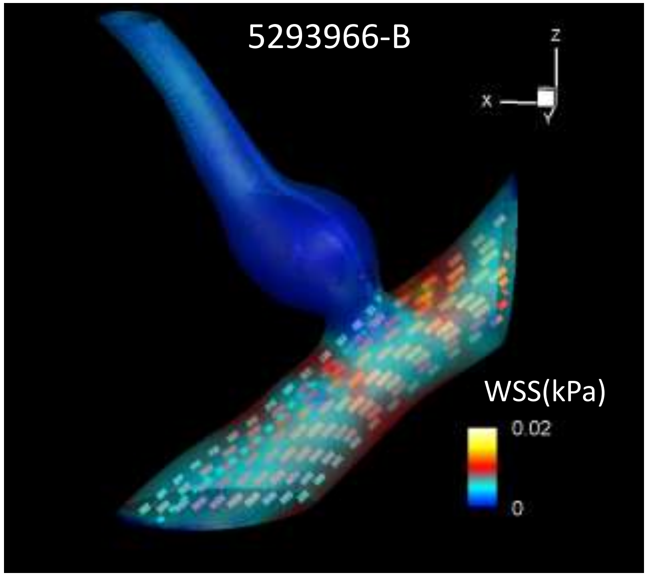
Sample Cases

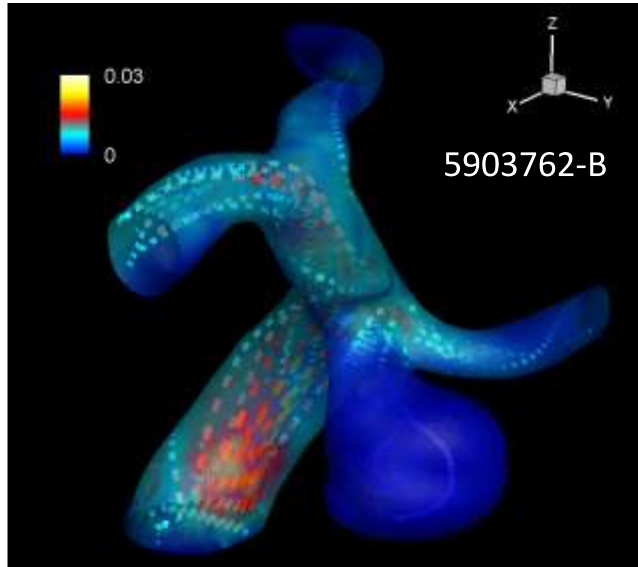
Automatically segmented for the specified ROI
Voxel size: 0.21 ~ 0.27 mm, Domain size: 64 ~ 128 voxels

B: Aneurysm is around bifurcation
C: Aneurysm is around high curvature



Flow Pattern and Wall Shear Stress

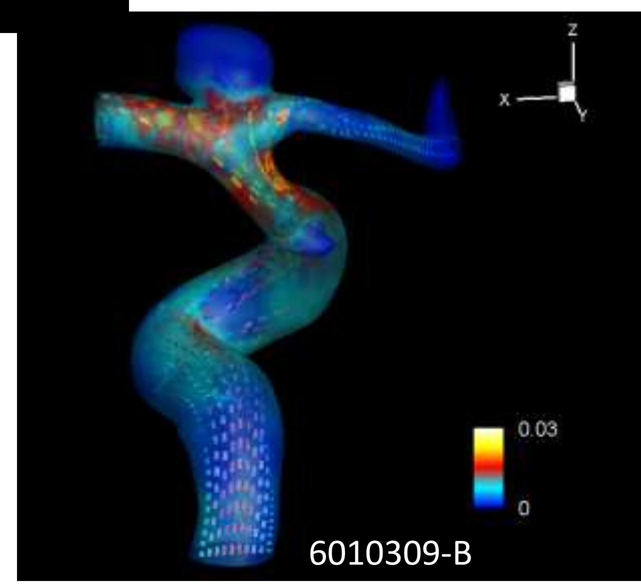




Bifurcation aneurysm cases

Steady flow with inflow mean velocity 0.5 m/s

iso-surface at $\phi = 0$, colored with the WSS



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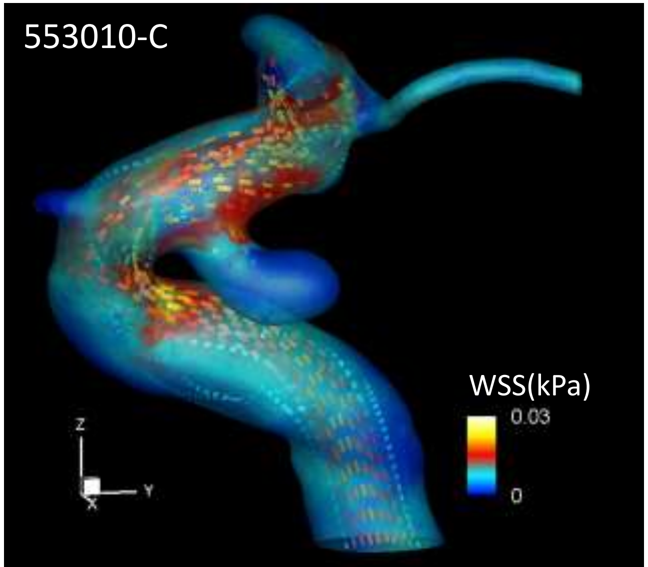
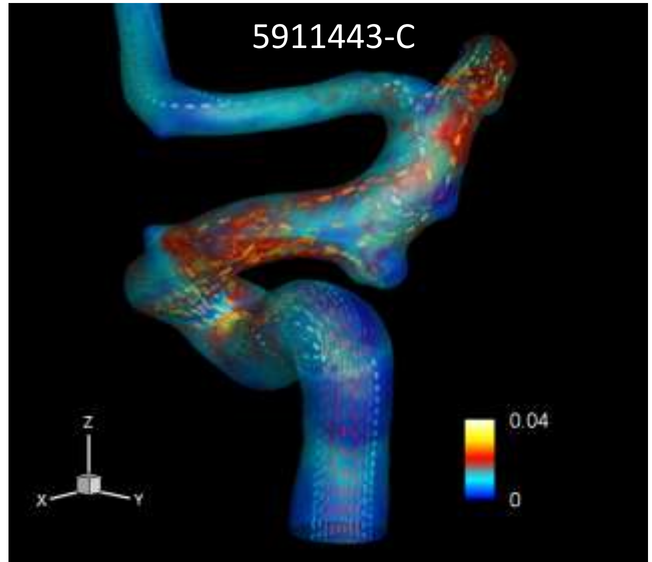
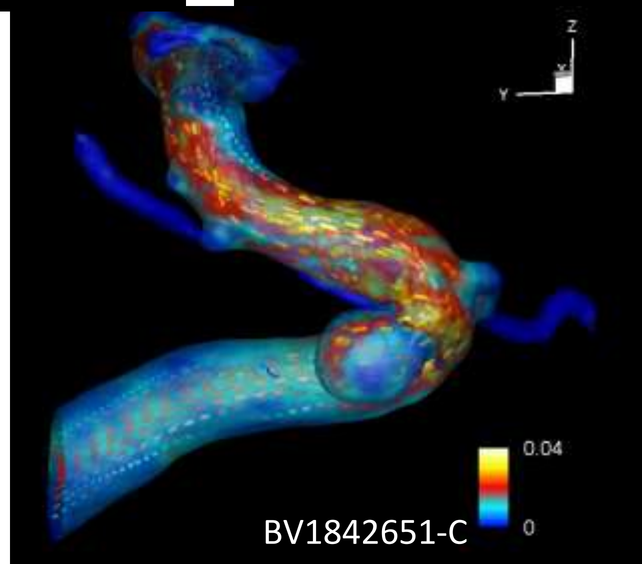
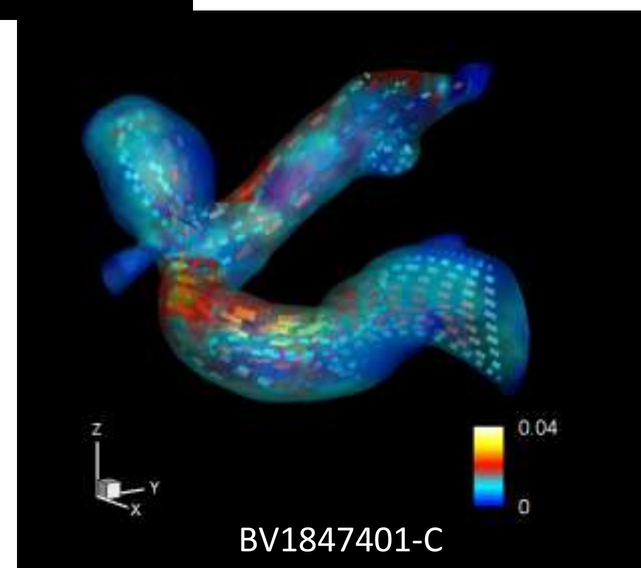




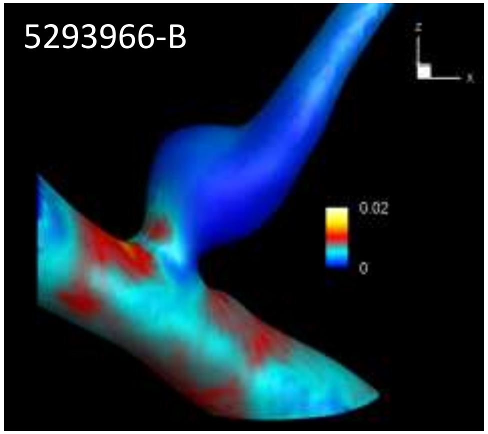
Curvature aneurysm cases

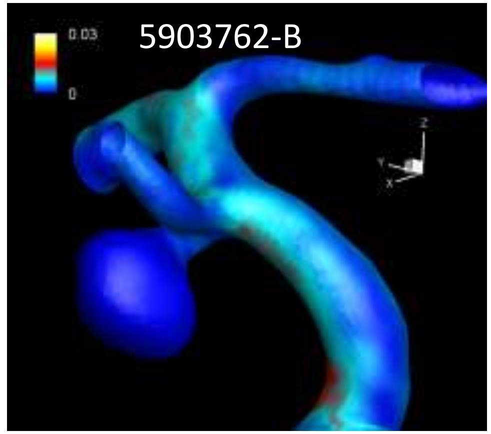


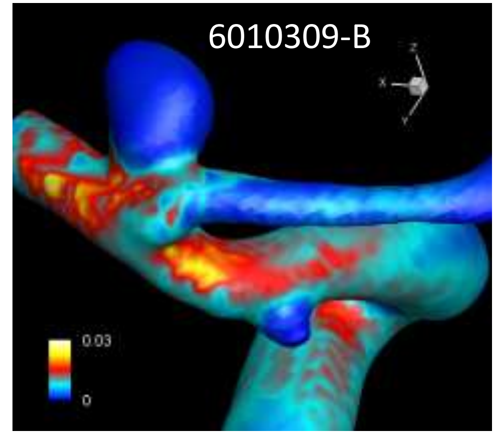


Wall Shear Stress

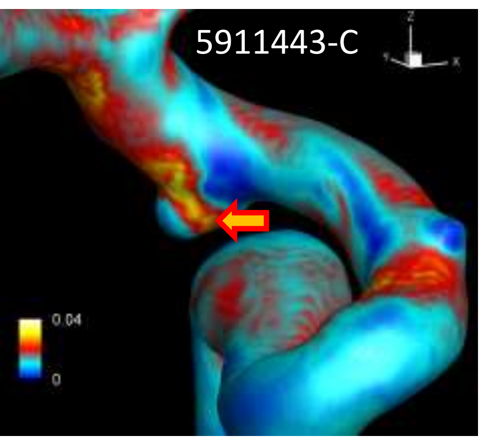
Bifurcation aneurysms: Low WSS in the aneurysm

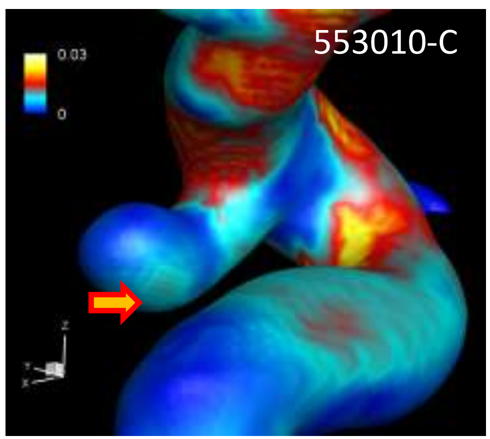


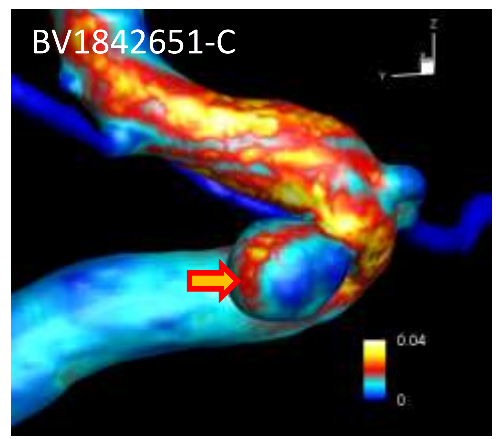


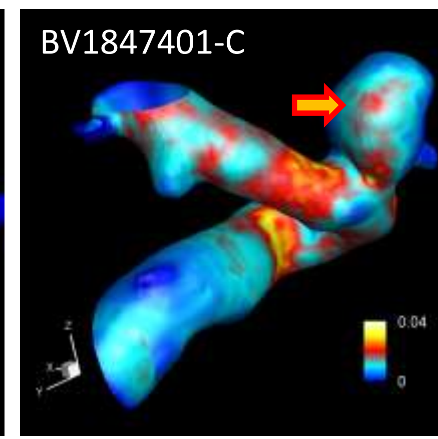


Curvature aneurysms: Local high WSS in the aneurysm









Aneurysm Hemodynamics and Risk Data Hub