Université de Reims Champagne-Ardenne

CReSTIC
Centre de Recherche en Sciences et Technologies de l'Information et de la Communication

Laboratoire de Mathématiques de Reims

CHU DE REIMS

Hemodynamic Modeling of Cerebral Aneurysms: Coupling 4D Flow MRI and Finite Element Simulations

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FreeFEM Days – 12/19/2025

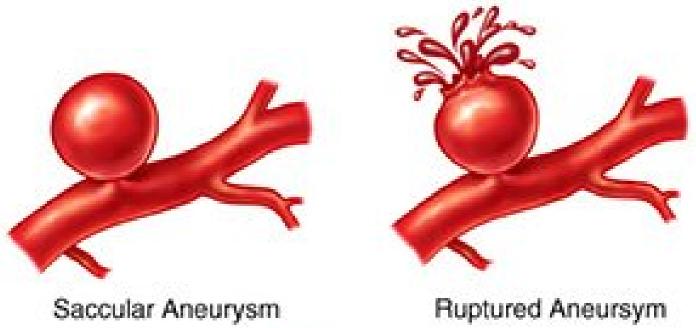
Contents

Clinical context

Cerebral aneurysms

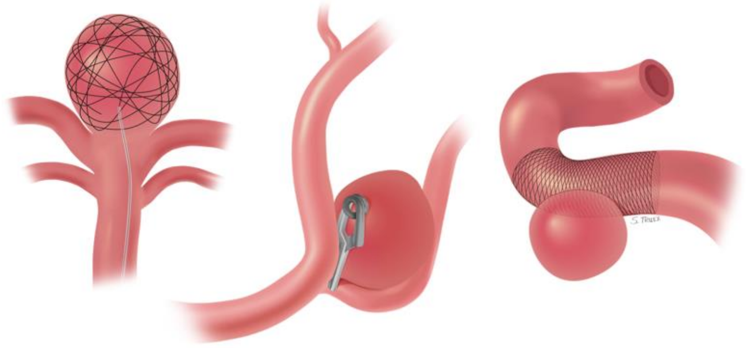
Key Statistics

- **Prevalence:** 5% of the population affected
- **Mortality:** 60% within 3 months post-rupture



Risk Factors

- **Exogenous:** Hypertension, age, ethnicity, smoking
- **Endogenous:** Size and location of the aneurysm



Treatment Options

- **Surgical:** Neurosurgery
- **Minimally Invasive:** Endovascular intervention

Clinical context

Innovation in vascular imaging: The 4D flow MRI sequence

Technology

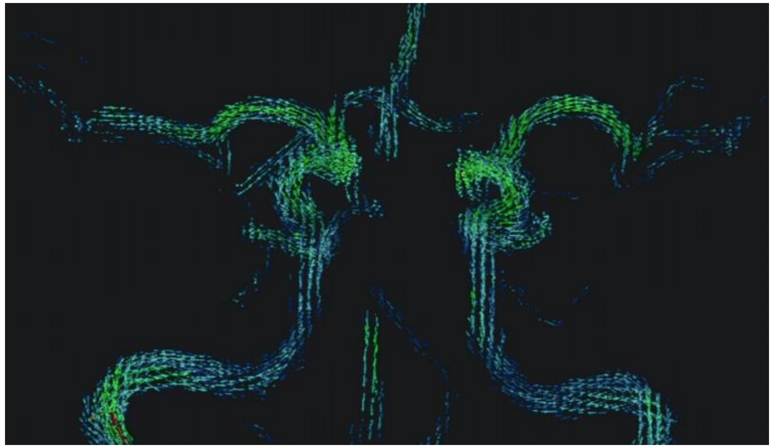
- Combines **morphological imaging** (anatomy) and **functional imaging** (blood flow).
- **4D = 3D spatial + temporal dimension**.
- **Velocity encoding**: The phase shift of proton spins is proportional to blood flow velocity: $\boldsymbol{\Delta\phi = \gamma v G t^2}$.

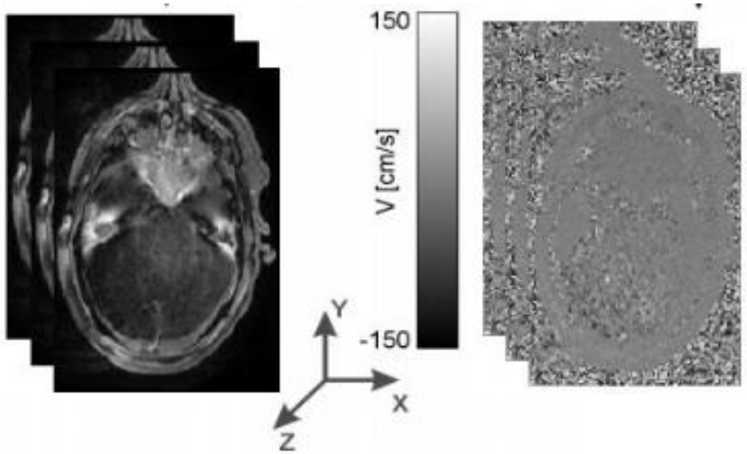
Advantages

- **Non-invasive visualization** of blood flow velocities $\boldsymbol{v(x,y,z,t)}$ and flow direction.
- Detection of **hemodynamic anomalies** (turbulence, stagnation zones).

Applications

- Assessing the **risk of rupture in cerebral aneurysms**.
- Analyzing **vascular malformations** (stenoses, fistulas).





Clinical context

Better diagnosis of aneurysm evolution

Objectives

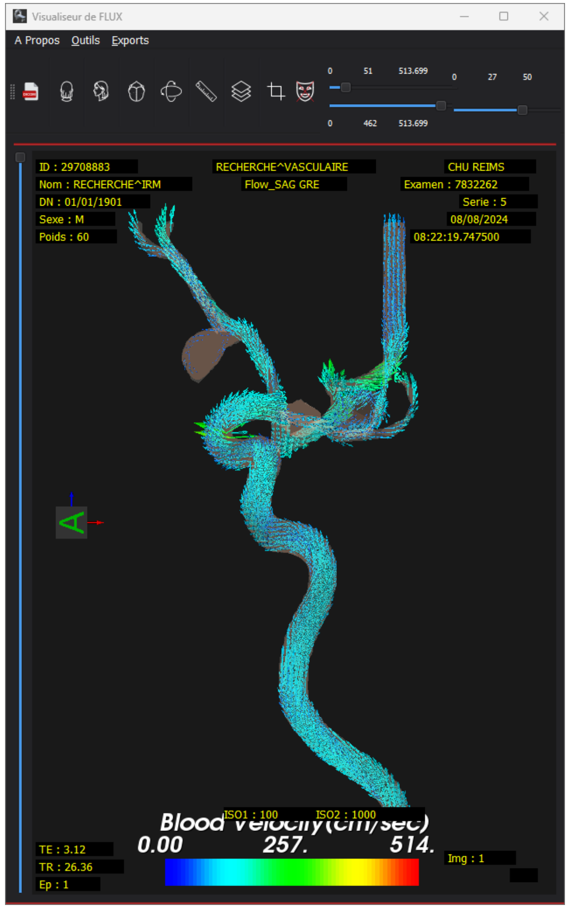
- **Direct assessment of aneurysm rupture risk** using MRI imaging
- **Using computational fluid dynamics (CFD)** to compute key markers of aneurysm evolution
- **Comparative analysis** between MRI images and simulation results to optimize and adapt simulation parameters

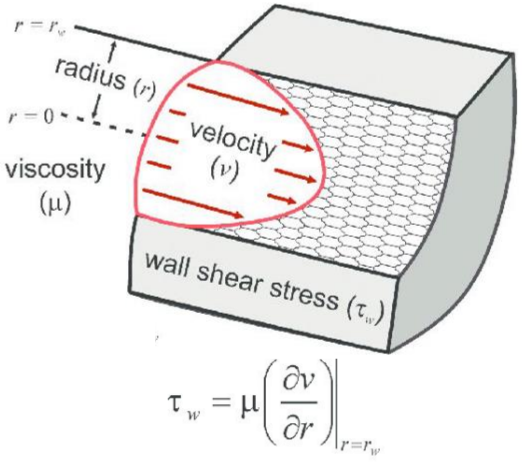
Key Markers of Aneurysm Growth

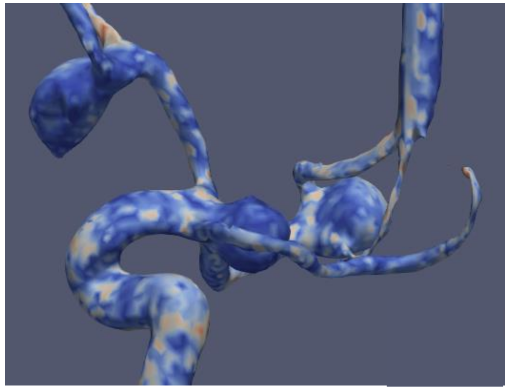
- **Hemodynamic markers**: Wall shear stress (WSS) and derived indicators
- **Flow dynamics**: Residence time (RT) as a critical parameter

Visualization for Clinical Application

- **Development of MRProject software**: An MRI-integrated tool for visualizing 4D flow images, volumetric data, and dynamic changes
- **Enhanced visualization**: Surface viewer with color-coded indicators for intuitive clinical interpretation







Steady Stokes

Steady Stokes Equations

- **Laminar flows** (Reynolds number < 2000)
- Approximation of **Navier-Stokes equations** for small cerebral arteries

Unknowns and Parameters

- $\boldsymbol{u}$ Blood velocity, p Pressure, μ Dynamic viscosity, $\boldsymbol{u_{in}}$ Inlet velocity
- Ω Study domain, Γ_{in} Inlet surface, Γ_{out} Outlet surface, Γ_{wall} Vessel wall
- g Outflow function of the fluid
- $V = H^1_{\Gamma_D}(\Omega)^3$ and $Q = L^2(\Omega)$

Convergence problems with high resolution problems (>200k tetrahedras)

$$\begin{cases} -\mu\Delta\boldsymbol{u} + \nabla p = 0 & \text{in } \Omega \\ \nabla.\boldsymbol{u} = 0 & \text{in } \Omega \\ \boldsymbol{u} = \boldsymbol{u_{in}} & \text{on } \Gamma_{in} \\ \boldsymbol{u} = 0 & \text{on } \Gamma_{wall} \\ \mu\dfrac{\partial\boldsymbol{u}}{\partial\boldsymbol{n}} + p.\boldsymbol{n} = g & \text{on } \Gamma_{out} \end{cases}$$

Find $(\boldsymbol{u}, p) \in V \times Q$ where

$$\begin{cases} \int_\Omega \left(\mu\nabla\boldsymbol{u}:\nabla\boldsymbol{v} - p(\nabla.\boldsymbol{v})\right)dx = \int_\Gamma g\,.\boldsymbol{v}ds & \forall\boldsymbol{v} \in V \\ \int_\Omega (\nabla.\boldsymbol{u})q\,dx = 0 & \forall q \in Q \end{cases}$$

Dimensionless Stokes

Parameters

- **Characteristic length scale** L (area, diameter, radius, etc.)
- ρ constant (density)
- ν dynamic viscosity (constant)
- **Characteristic velocity** U (maximal inlet velocity)

Dimensionless variables

- velocity $u^* = \frac{u}{U}$
- pressure $p^* = \frac{p}{\rho U^2}$
- gradient $\nabla^* = L\nabla$
- Laplacian $\Delta^* = L^2\Delta$

Spaces

- $V^* = H^1_{\Gamma_D}(\Omega)^3$ and $Q^* = L^2(\Omega)$

$$\begin{cases} -\frac{\nu}{L\rho U}\Delta^*\boldsymbol{u}^* + \nabla^* p^* = 0 & \text{in } \Omega \\ \nabla^* . \boldsymbol{u}^* = 0 & \text{in } \Omega \\ \boldsymbol{u}^* = \boldsymbol{u}^*_{in} & \text{on } \Gamma_{in} \\ \boldsymbol{u}^* = 0 & \text{on } \Gamma_{wall} \\ \mu\frac{\partial \boldsymbol{u}^*}{\partial \boldsymbol{n}} + p^* . \boldsymbol{n} = 0 & \text{on } \Gamma_{out} \end{cases}$$

Find $(\boldsymbol{u}^*, p^*) \in V^* \times Q^*$ where

$$\begin{cases} \int_\Omega \left(\frac{\nu}{L\rho U}\nabla^*\boldsymbol{u}^* : \nabla^*\boldsymbol{v}^* - p^*(\nabla^* . \boldsymbol{v}^*)\right) dx = 0 & \forall \boldsymbol{v}^* \in V^* \\ \int_\Omega (\nabla^* . \boldsymbol{u}^*) q^* dx = 0 & \forall q^* \in Q^* \end{cases}$$

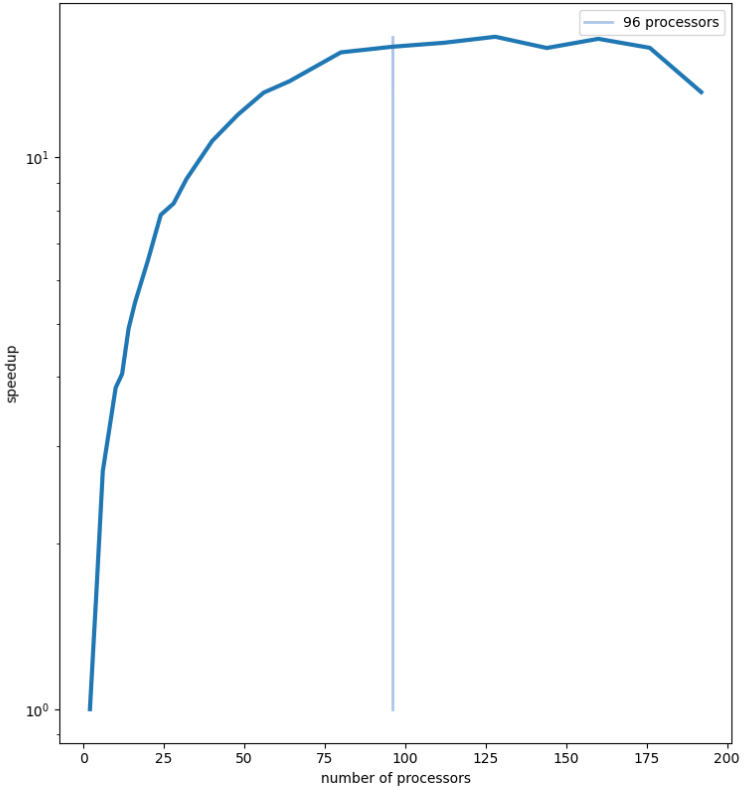
Parallel simulations

Parameters

- -pc_type lu -ksp_type preonly
- Petsc, P2-P1

Supercomputer Roméo

- Accelerated Computing Module (ARM+GPU architecture)
- **Scalar CPU Computing Module**
  - **44 AMD64 servers**, each equipped with **2 AMD EPYC 9654 processors** (96 cores each).
  - **192 CPU cores per server** and **1152 GB of memory** (with 4 "Fat" servers offering 1536 GB each).
  - **Total resources**: 8,448 x86 CPU cores and 53 TB of memory.
- **Use of container tools** like Apptainer and Singularity



Speedup $\left(S(p) = \frac{T_{exec}(1)}{T_{exec}(p)}\right)$

Parallel simulations

HPC Center ROMEO Centre de Calcul Régional

Parameters

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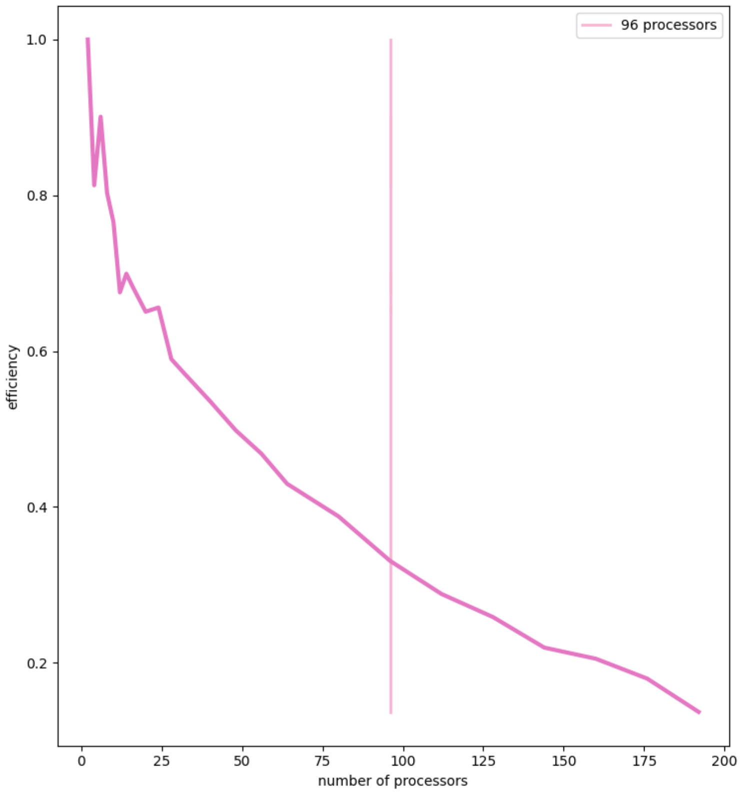
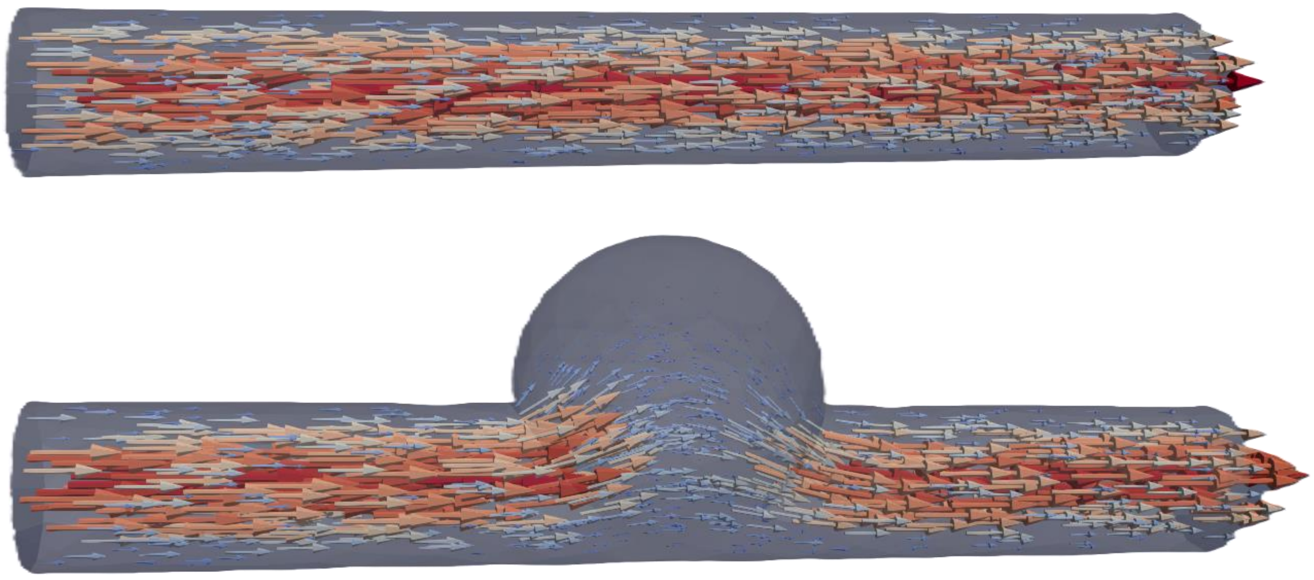


Efficiency $\left(E(p) = \frac{T_{exec}(1)/p}{T_{exec}(p)}\right)$

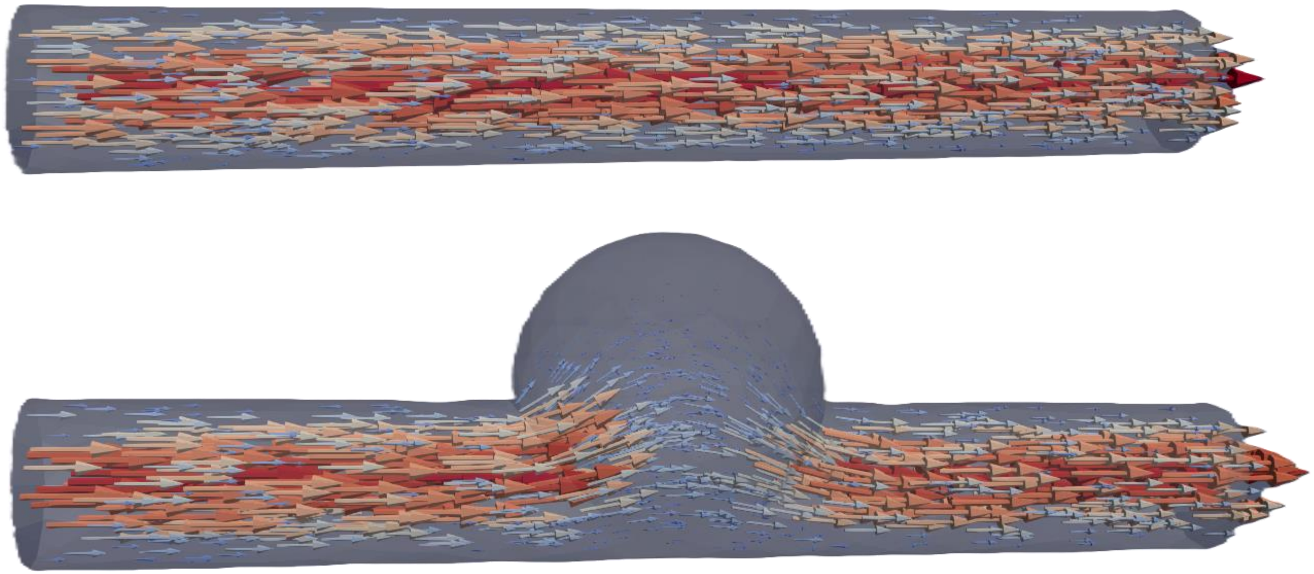
Preliminary results



Convergence of the dimensionless Stokes solution on ideal meshes

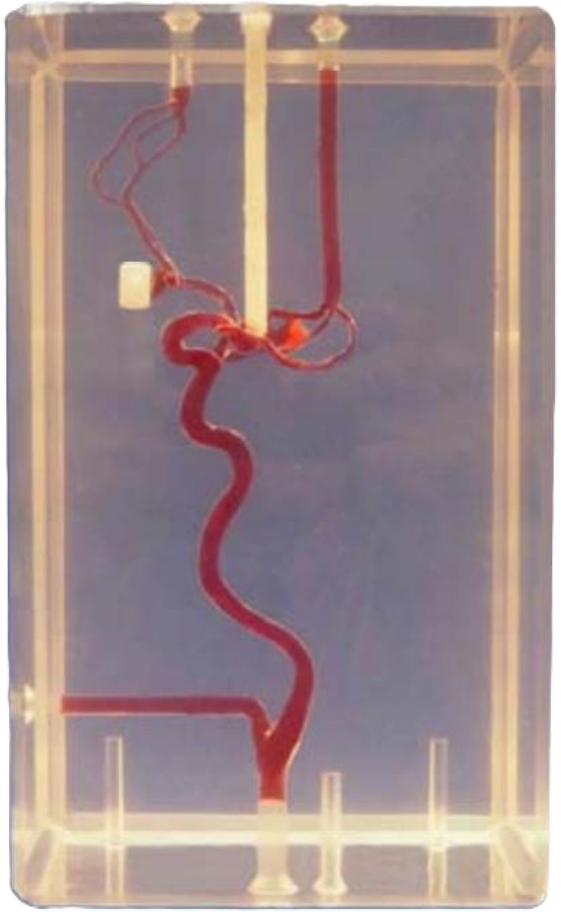
- 2M degrees of freedom (meshes of 460k tetrahedras)

Preliminary results



Convergence of the dimensionless Stokes solution on ideal meshes

- 2M degrees of freedom (meshes of 460k tetrahedras)



- **Realistic vascular geometry**
- **Vascular phantom**: A silicone model based on real patient geometry, featuring **three aneurysms**.
- **Consistent geometry** enables reliable and repeatable testing in MRI.

The mesh pipeline

MRI Segmentation Process

- Apply thresholding to the anatomical series of the 4D flow sequence at a resolution of **1 mm³**.
- Extract vessel geometry from MRI data.
- Export results in **VTK** (for visualization) and **MHA** formats.

AngioTK Pipeline

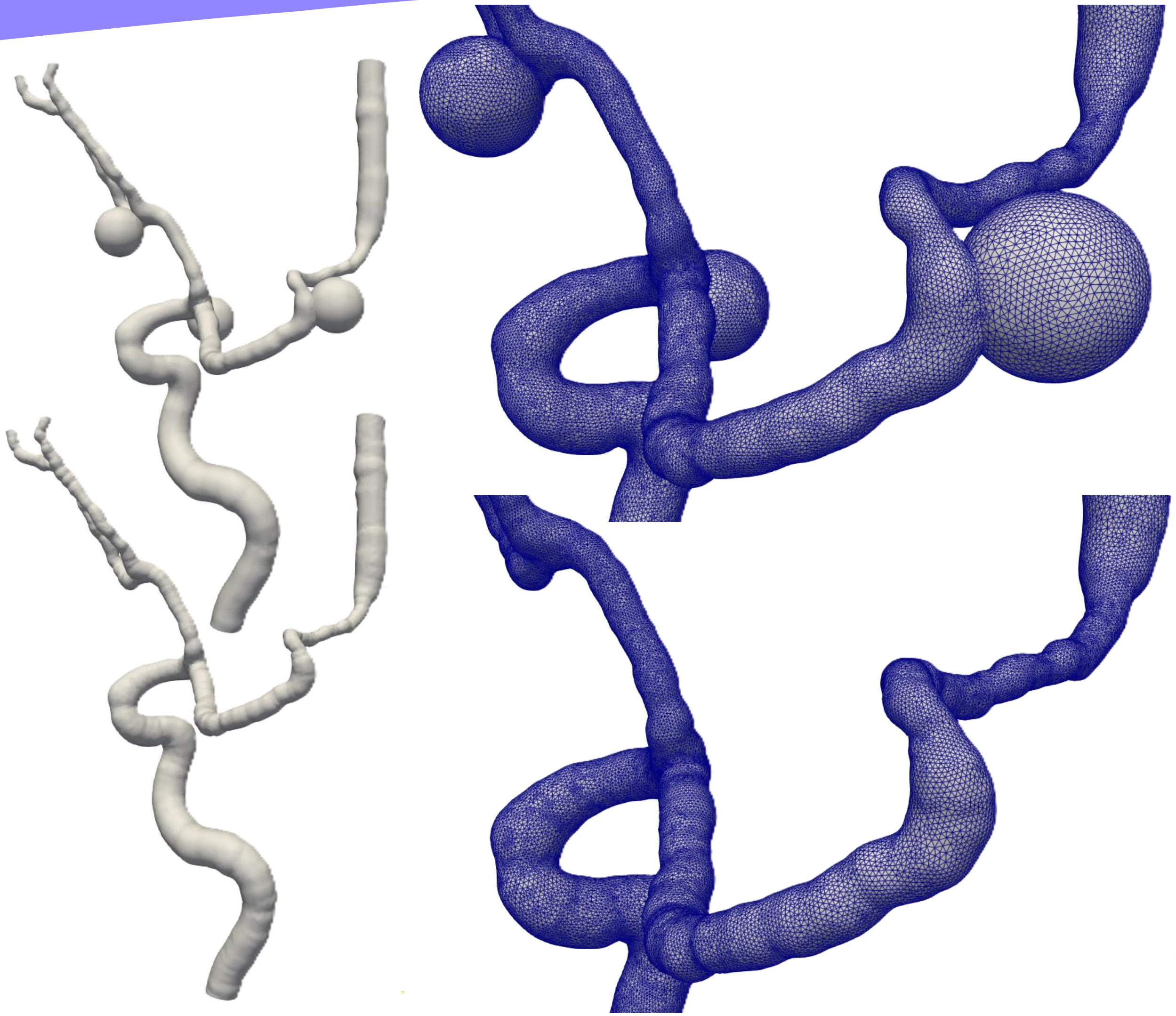
- Manually place entry and exit seeds for each vessel segment.
- Compute centerlines and rays using **VMTK**.
- Generate and clean the surface mesh using **VMTK**, **Gmsh**, and **Mmg**.

Aneurysm Integration

- Use **CAD software** (e.g., FreeCAD) to model aneurysms as spheres.
- Merge aneurysm meshes with the vessel geometry.
- Validate anatomical accuracy by comparing with MRI data.

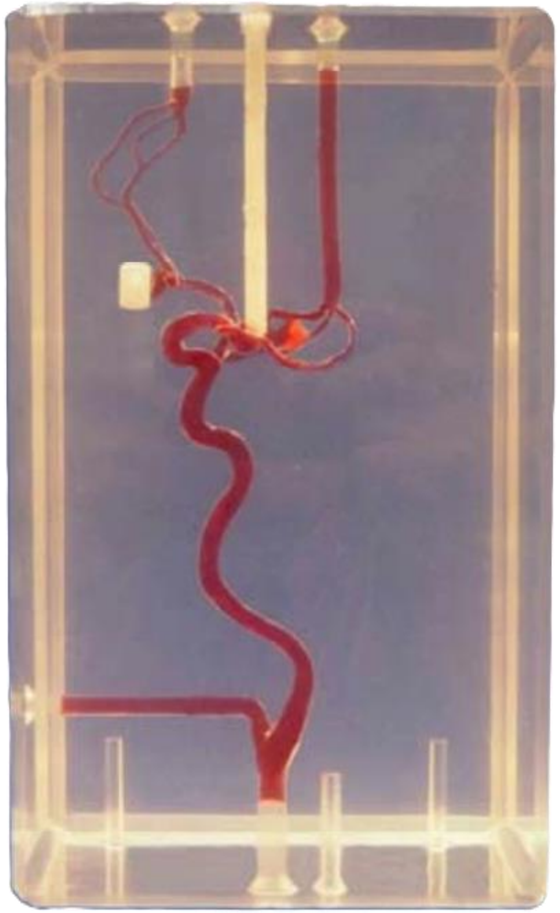
Adaptive Mesh Refinement

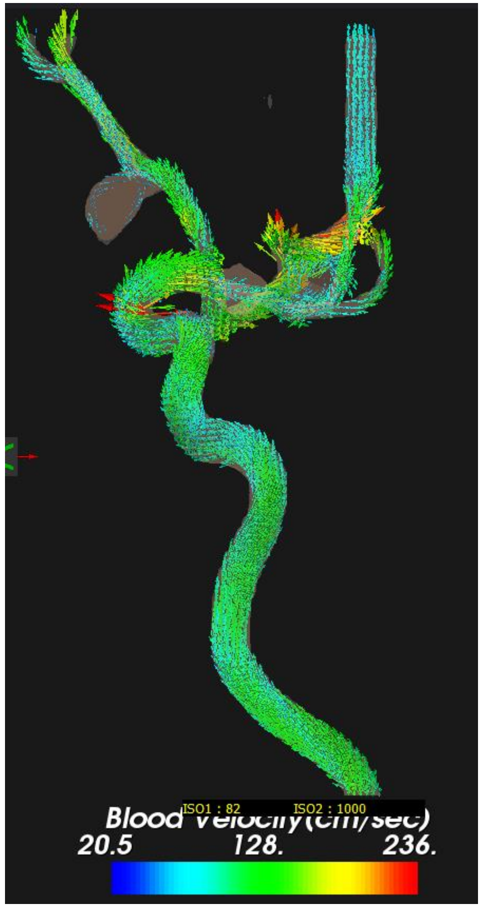
- Refine mesh using **Mmg** and adjust labels for consistency and clarity.
- Vessel mesh: **600k tetrahedras**, vessel with aneurysm mesh: **650k tetrahedras**.

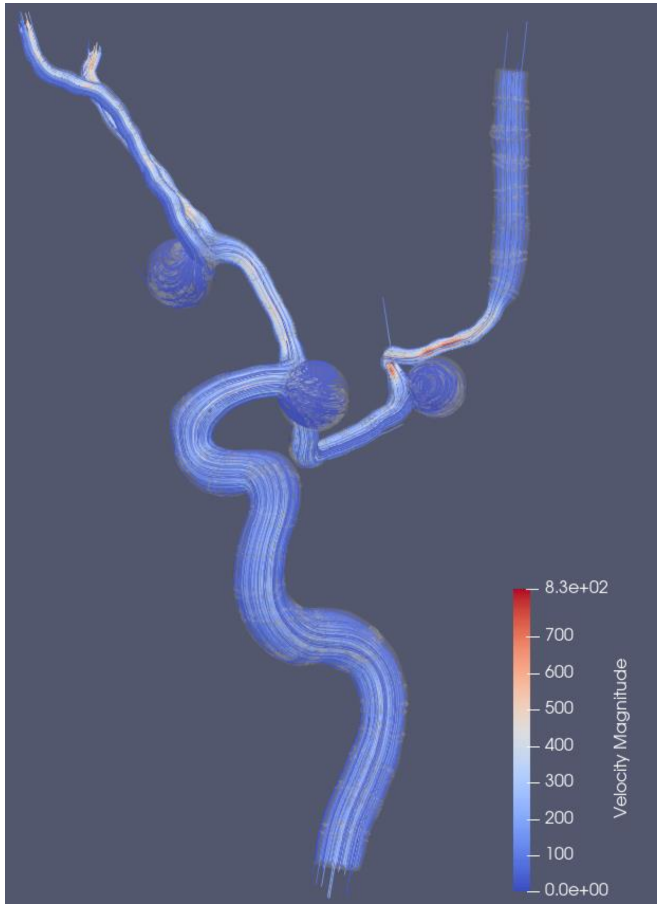


Results

MRI vs. CFD



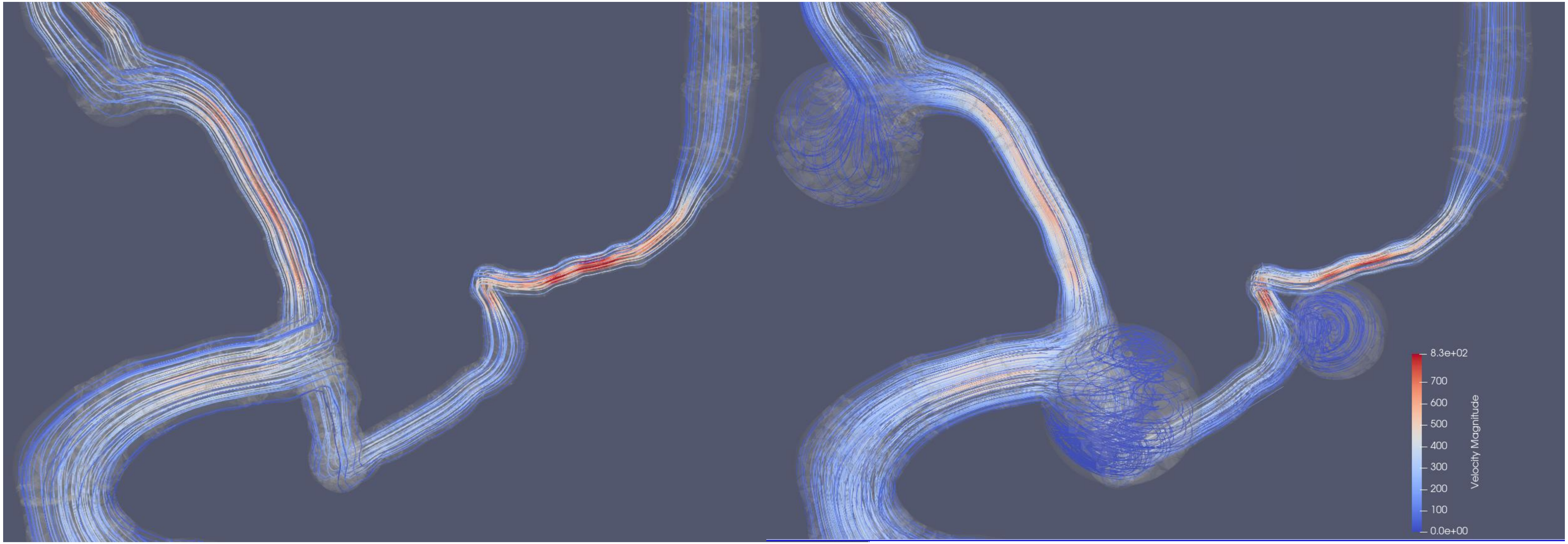




- ➢ **Global vessel geometry** is respected.
- ➢ **Tiny vessels**, not visible on MRI, are excluded from CFD computations.
- ➢ **Aneurysm geometry** is represented in a simplified form on the mesh.

Results

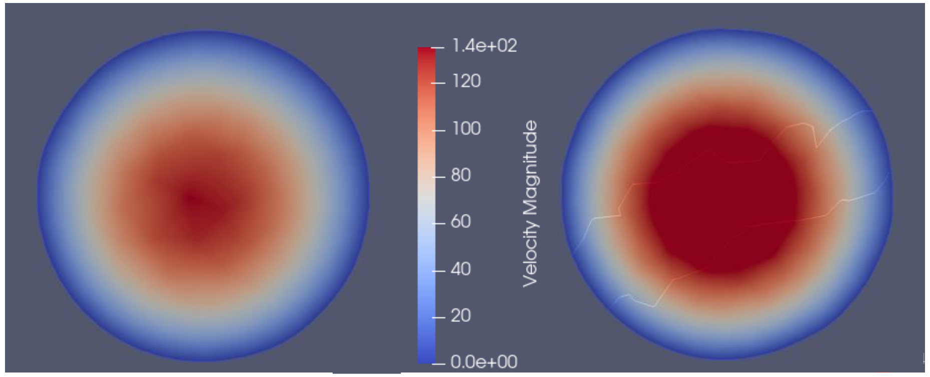
With and without aneurysms



Results

Slices with and without aneurysms

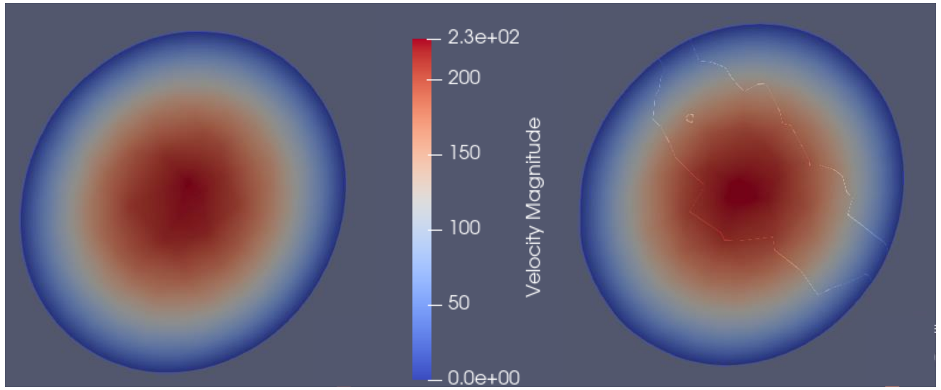
1



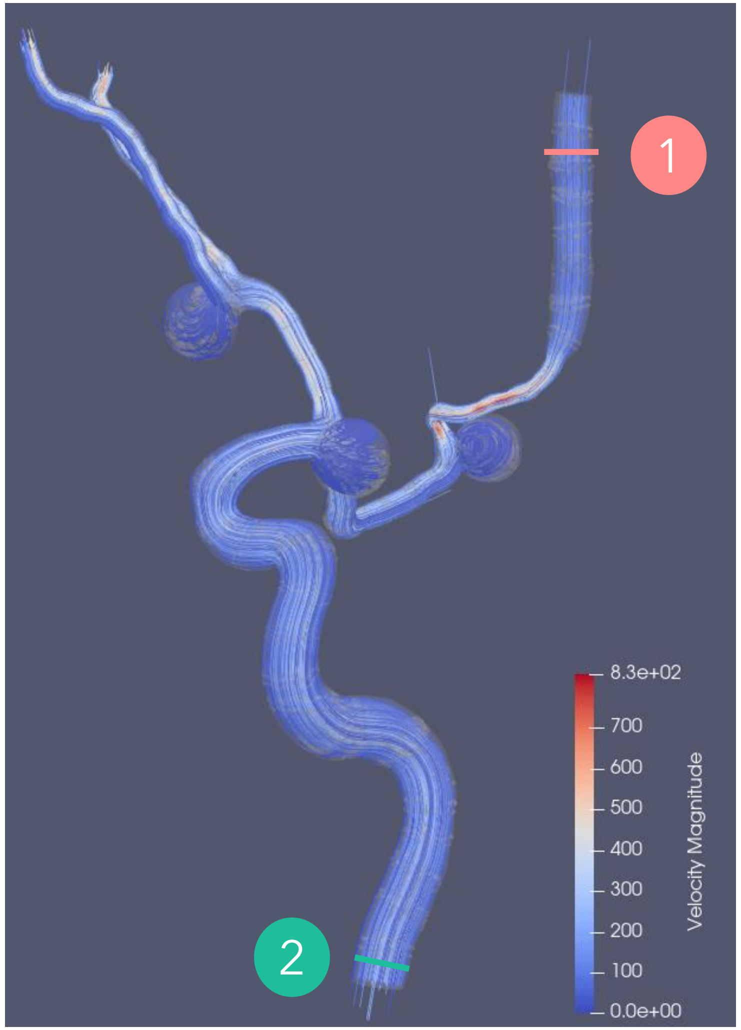
With aneurysm

Without aneurysm

2



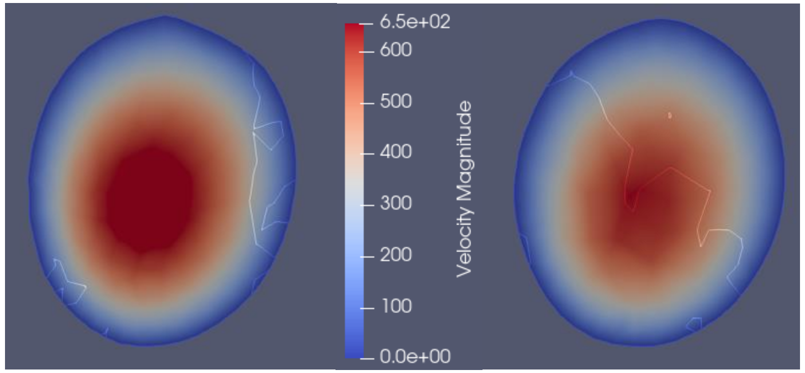
- Impact of the aneurysm: lower velocity at the outlet
- Same inlet (parameter)



Results

Slices with and without aneurysms

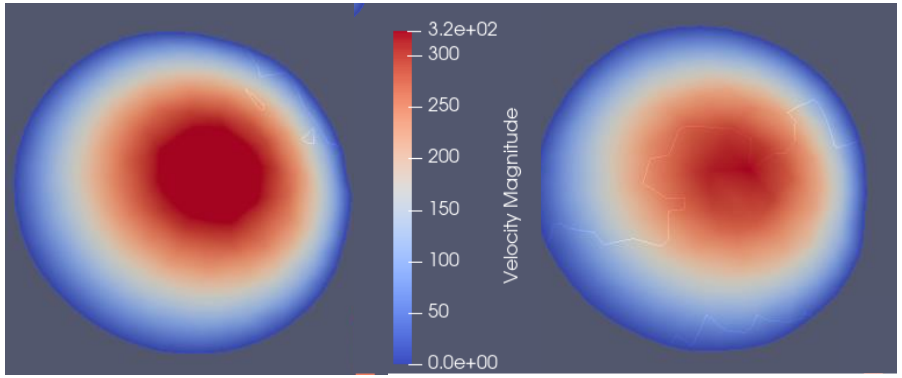
3



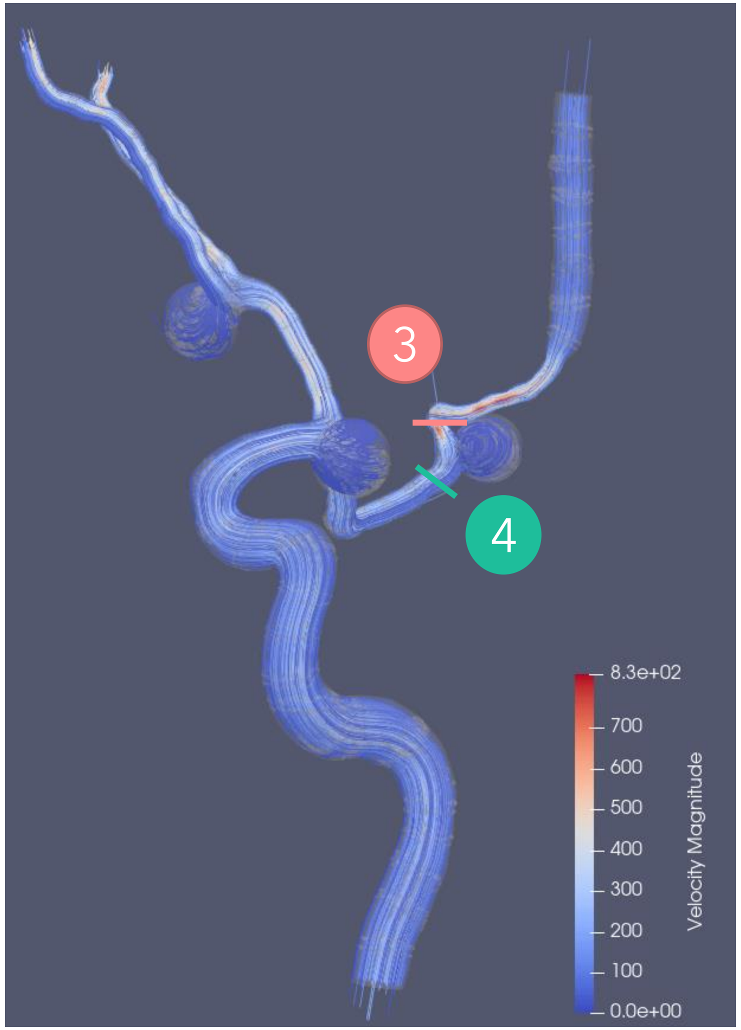
With aneurysm

Without aneurysm

4

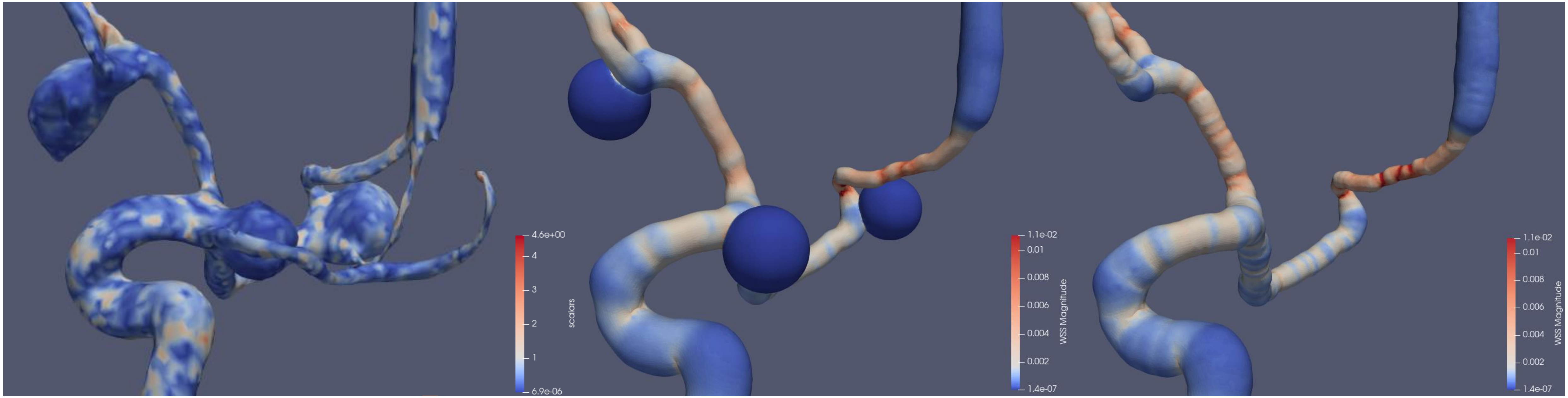


- Higher velocity right after the aneurysm (acceleration)
- Higher velocity right before the aneurysm (aspiration)



Results

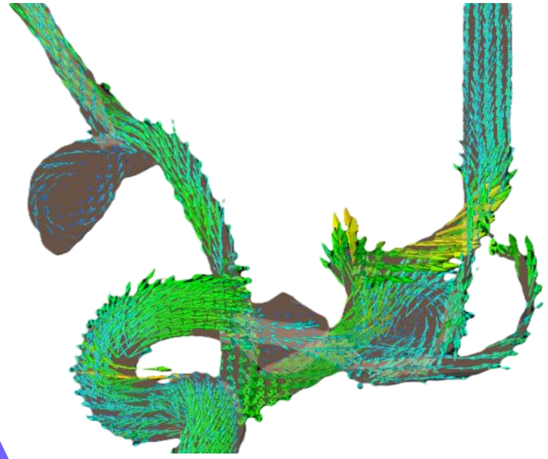
Wall Shear Stress

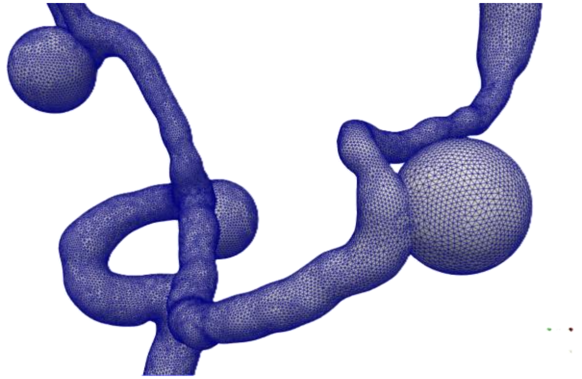


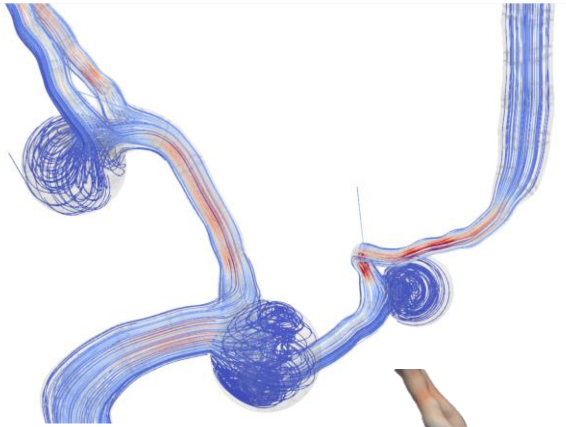
- **Scale-related challenges** affect the analysis.
- **Aneurysm regions exhibit near-zero WSS.**
- **MRI data is highly noisy**, impacting accuracy.

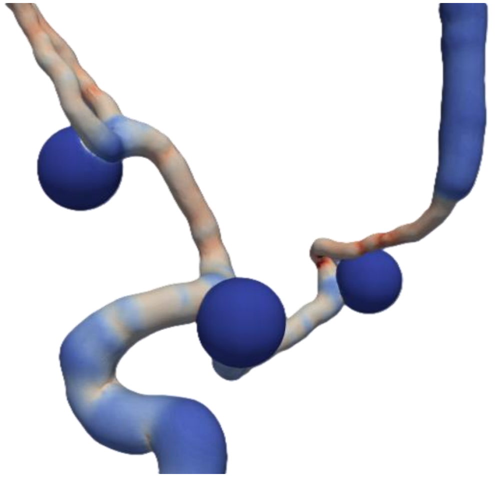
Conclusions

- **Direct use of MRI images** to generate a mesh compatible with CFD simulations
- **Parallel fluid dynamics simulations** using dimensionless Stokes equations on a vascular phantom
- **Challenges identified**:
  - Wall shear stress (WSS) computations **not yet aligned** with MRI data
  - **Improved segmentation of the aneurysms** required for accurate analysis
  - **Need for comparison metrics** both in cross-sectional slices and across the entire volume









Thank you for your attention!

Any questions?

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