Comprendre la progression des maladies vasculaires grâce à la simulation numérique

(Understanding vascular disease progression via advanced computational modeling)

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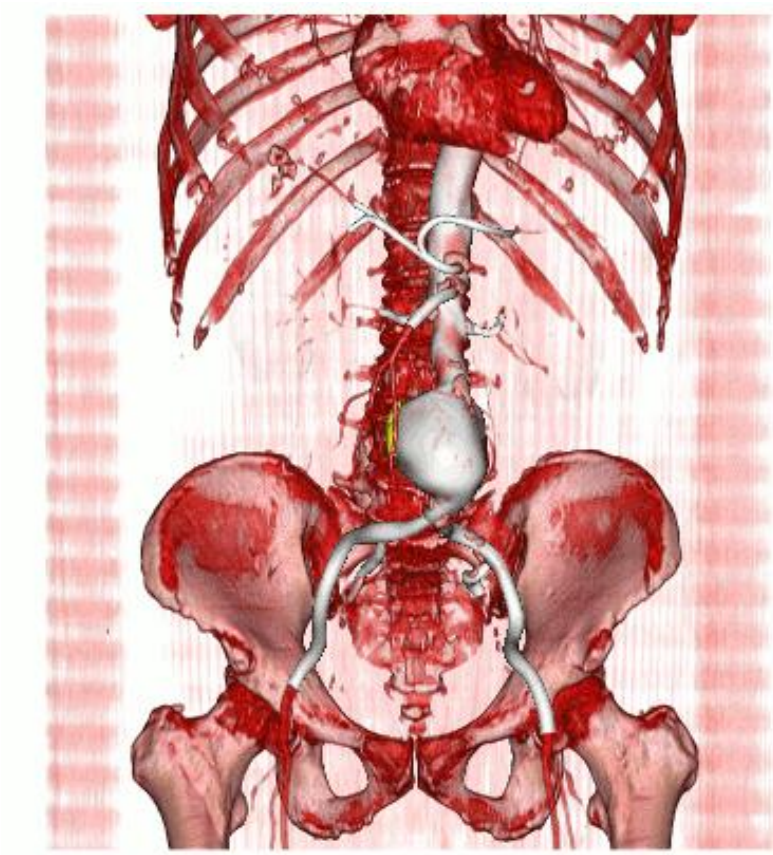
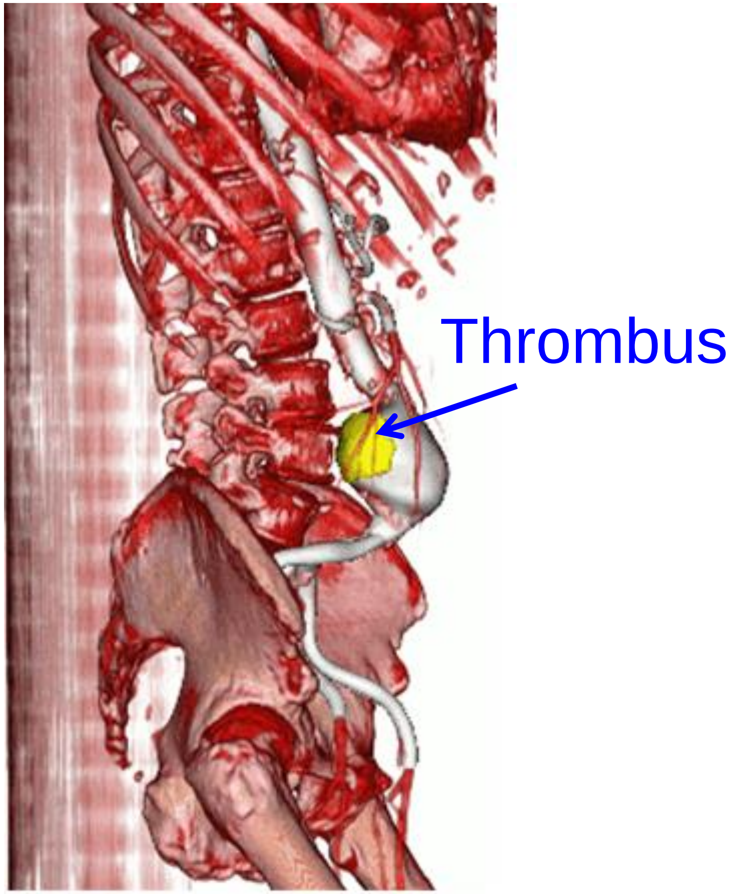
TERATEC 2017, Paris, France

The Clinical Dilemma - Abdominal Aortic Aneurysm (AAA)





AAA2 (6 cm maximum diameter)

Computational Model Construction

Hospital Radiology Unit

Imaging Database: Longitudinal CT, MRI

data collection

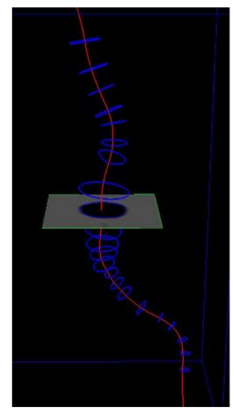
CTA or MRA

3D Level-Set

VMTK

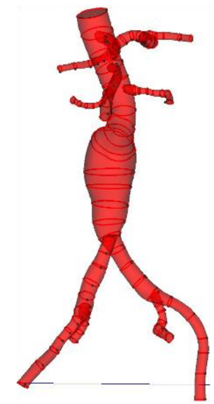
2D Segmentation

SimVascular

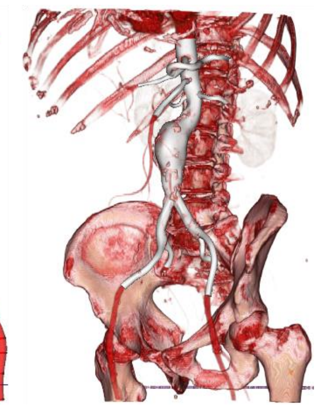


Lofting

SimVascular



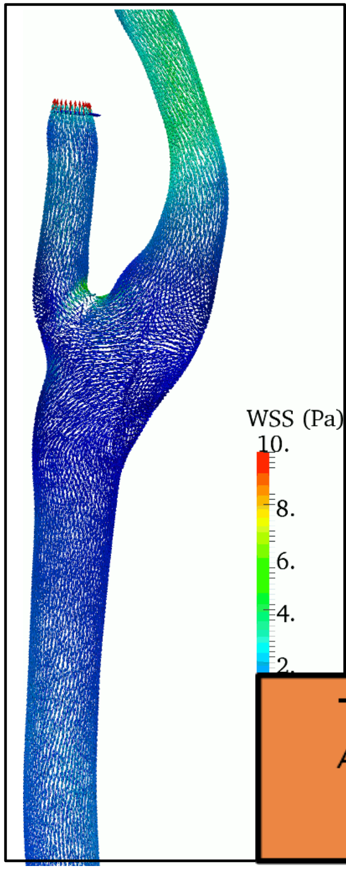
Geometric Model



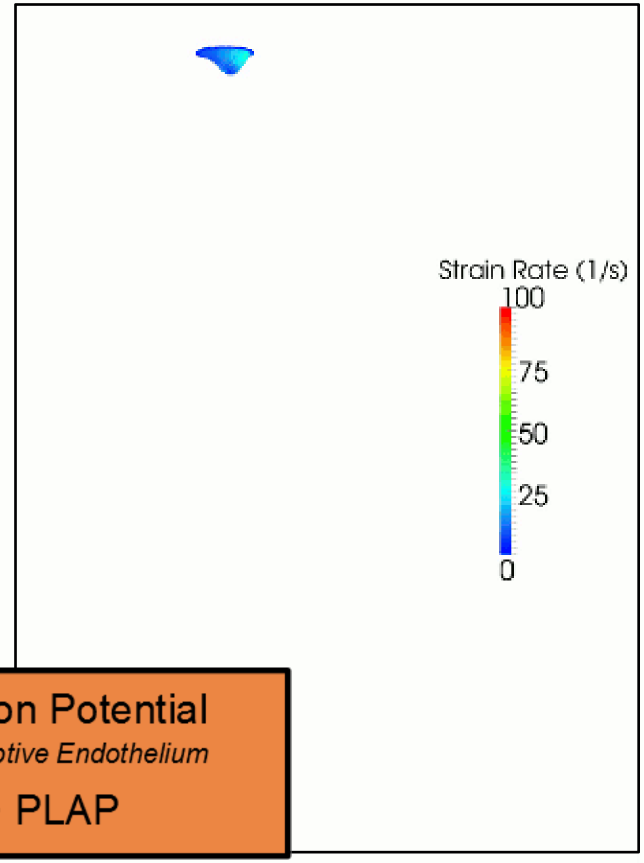
Hemodynamic Simulation Workflow

The Thrombus Formation Potential (TFP)

Carotid Bifurcation



Abdominal Aortic Aneurysm



Thrombus Formation Potential

Activated Platelets on Receptive Endothelium

$$TFP = ECAP \cdot PLAP$$

Endothelial Cell Activation Potential

Low and Oscillatory Shear Stress Regions

$$ECAP = \frac{OSI}{TAWSS}$$

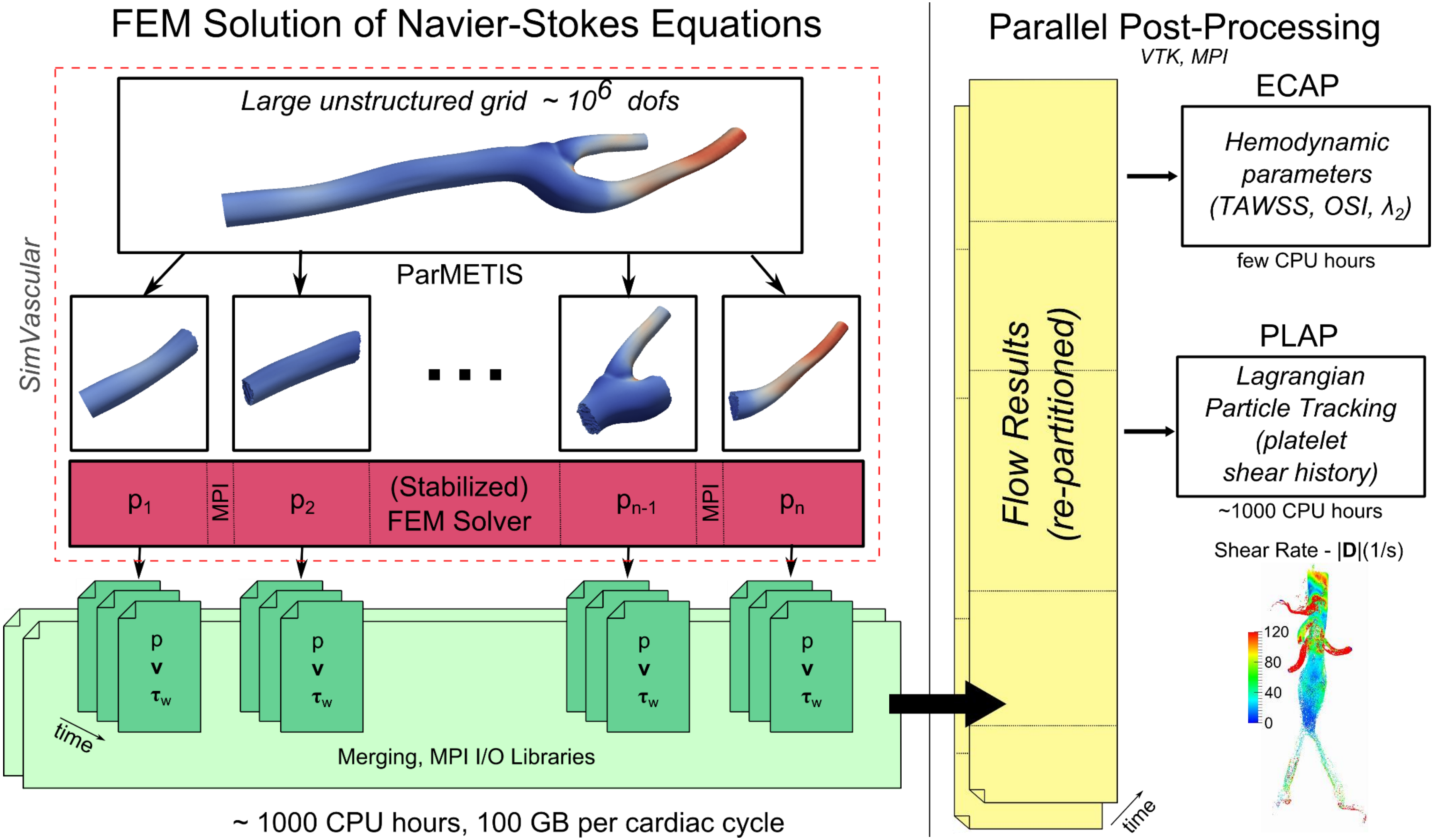
Platelet Activation Potential

Regions of Endothelium Exposed to Activate Platelets

$$PLAP = \int_{t-2\tau}^{t} |\mathbf{D}(\mathbf{x},t)|\, d\tau$$

Shadden and Hendabadi 2013 - BMMB

Large-scale Computational (Hemodynamic) Simulations

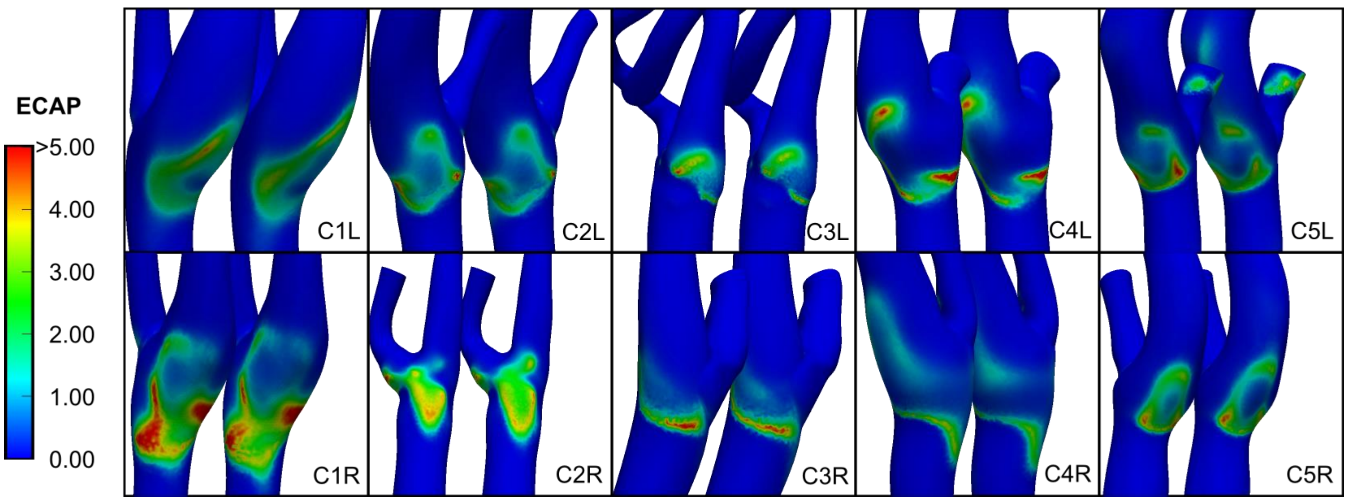


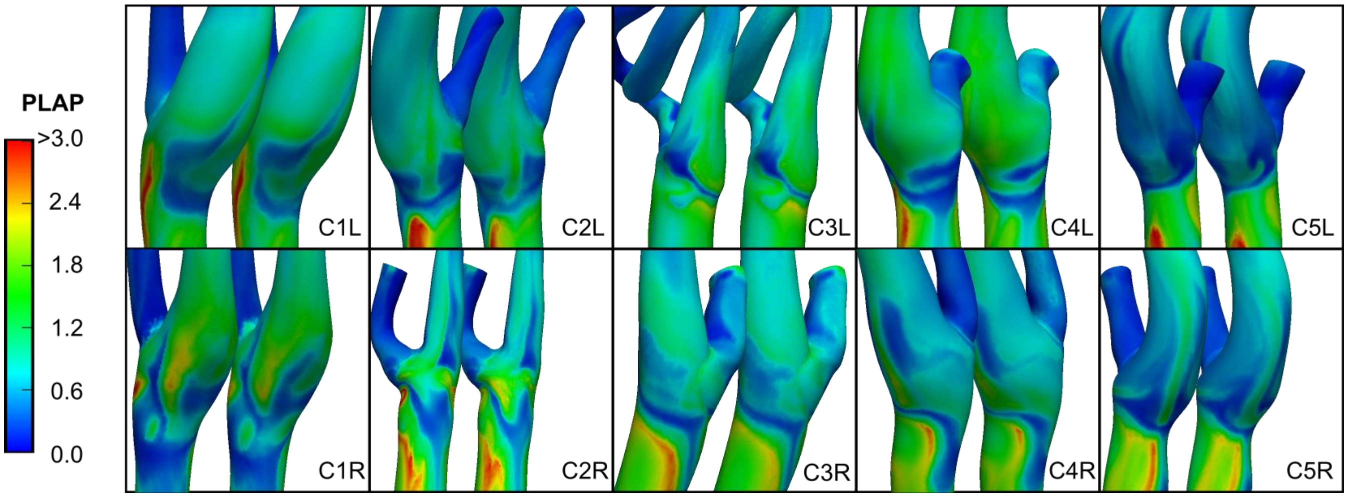
Typical Computational Workload

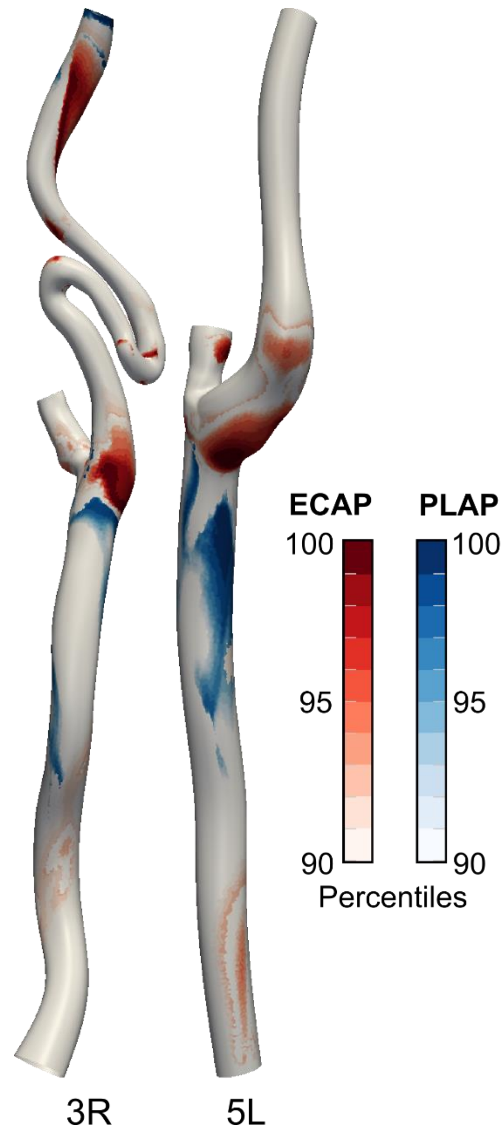
Typical Blood Flow Simulation (5 heart beats)

- $5 \cdot 10^6$ degrees of freedom (patient-specific model)
- 10^4 time steps (unsteady Navier-Stokes)
- 256 cores (max limit for linear scaling of our solver)
- $5 \cdot 10^3$ CPU hours = $4 \cdot 10^3$ CPU hours for solution + 10^3 for parallel post-processing (particle tracking, advection diffusion)
- 50 GB storage/simulation *after* reduction (elimination of transients, efficient storage in HDF5 files)

ECAP & PLAP do not Co-localize in Carotids

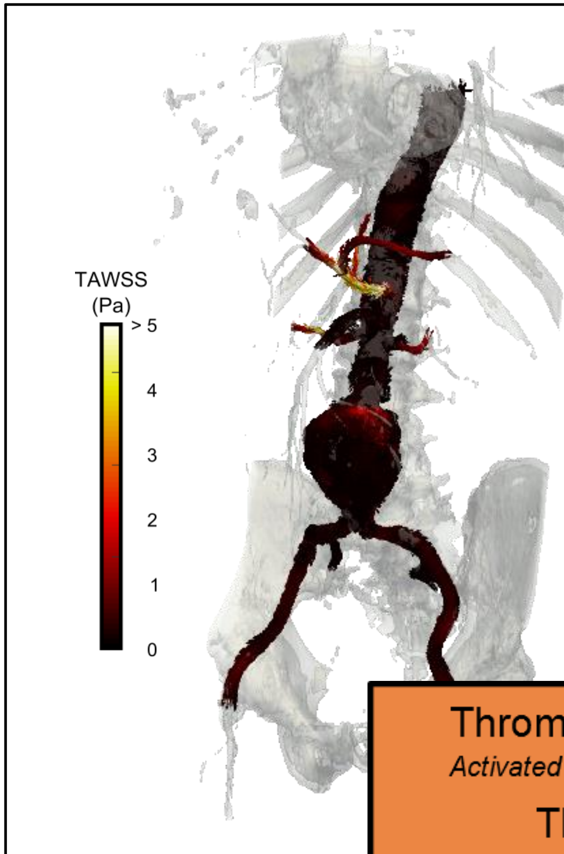




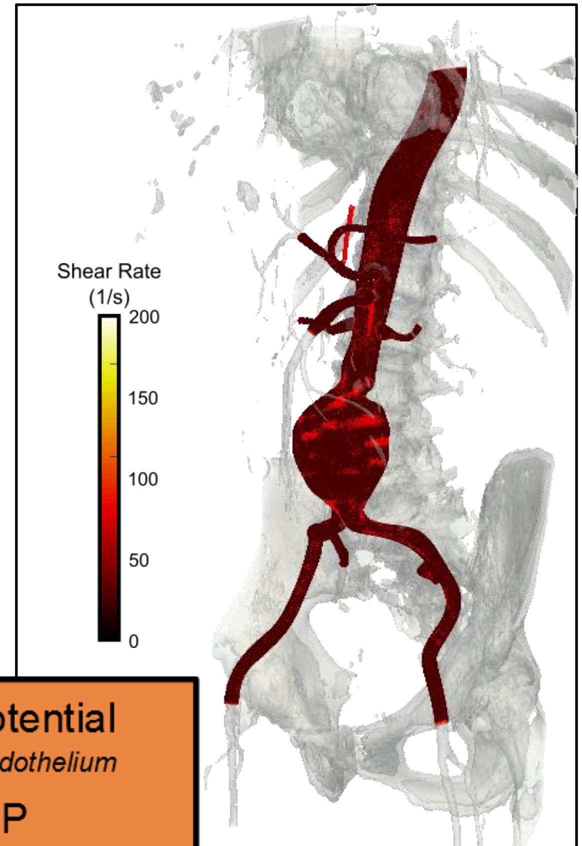


Thrombus Formation Potential for AAAs

Computational Fluid Dynamics



Particle Tracking



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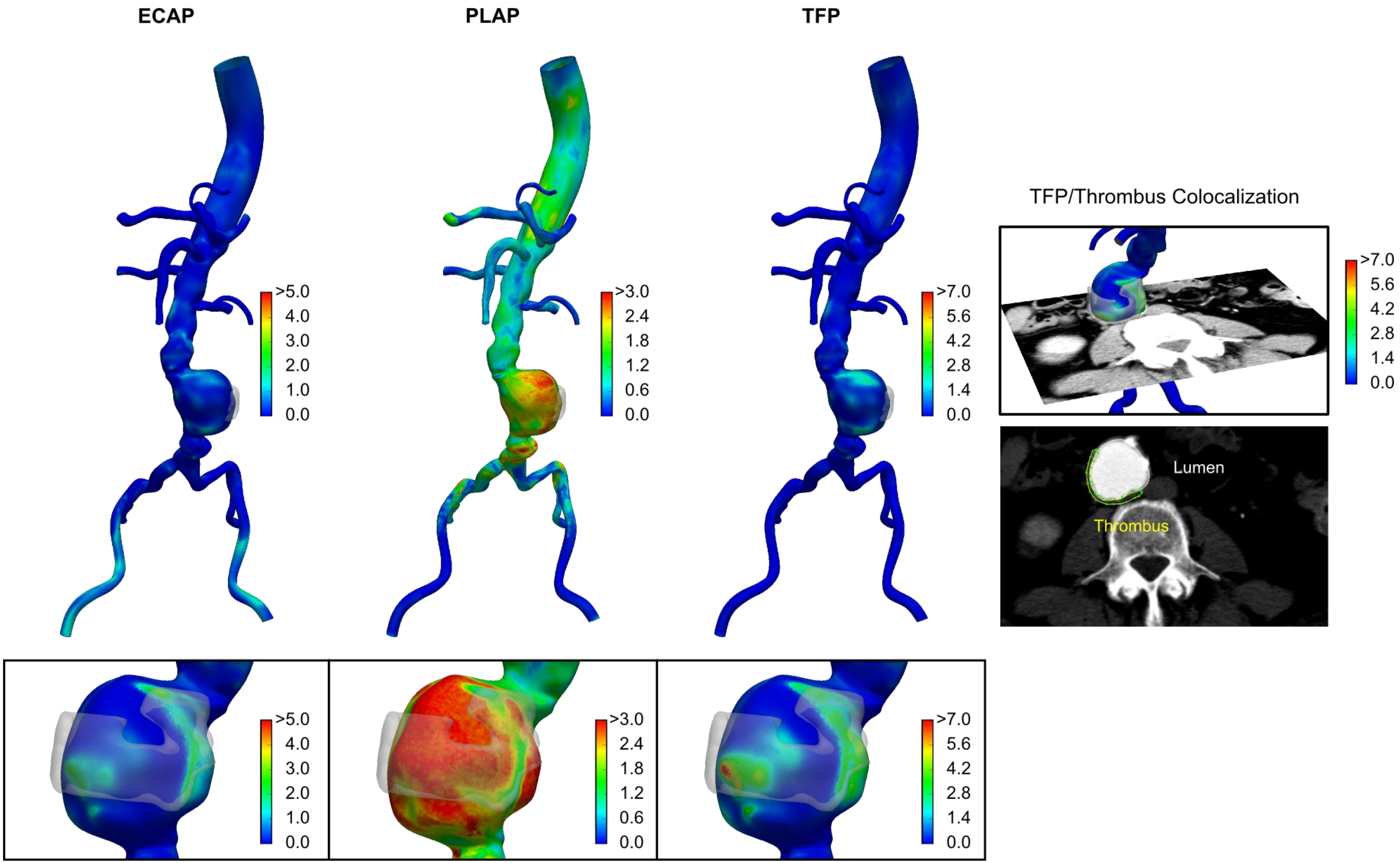
Shadden and Hendabadi 2013 - BMMB

ECAP & PLAP Co-localize in AAAs – Promote Thrombus



Di Achille et al. (2014)

Hemodynamic Metrics of Thrombus Formation

Thrombus Formation Potential
initiation

Endothelial cells

$$TFP(\boldsymbol{x}) = \frac{OSI(\boldsymbol{x})}{\overline{TAWSS}(\boldsymbol{x})} \cdot \overline{PLAP}(\boldsymbol{x}),$$

Platelets

Thrombus Deposition Potential
propagation

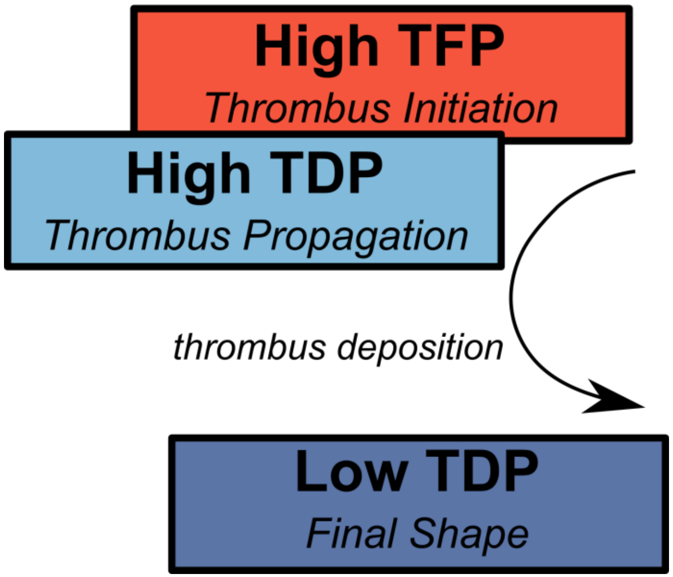
Thrombogenic

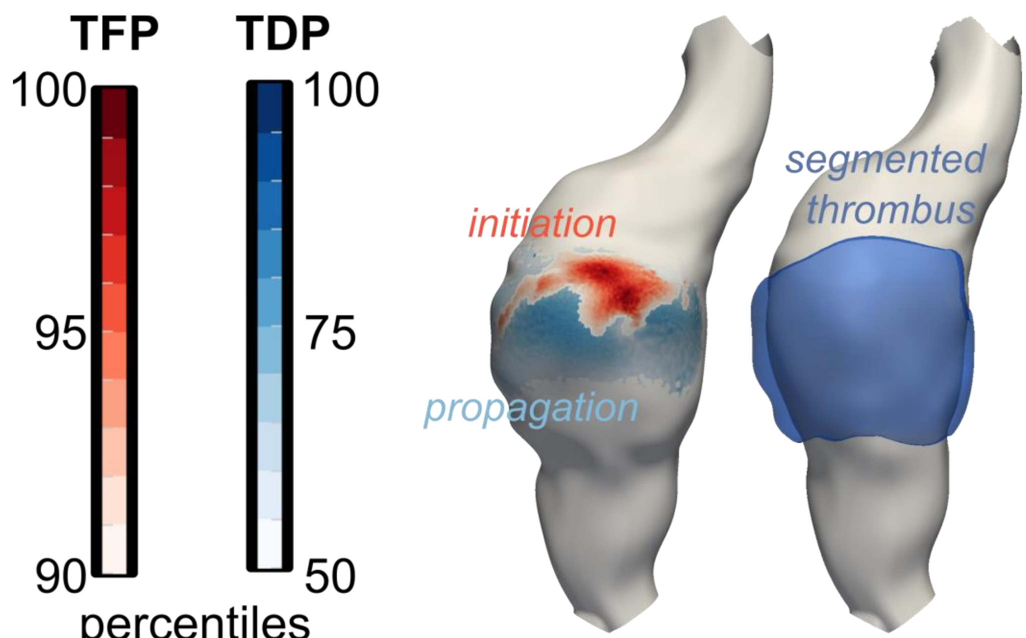
$$TDP(\boldsymbol{x}) = 0.5\,(1 + [FBG](\boldsymbol{x}))$$

$$-k_1^2\overline{OSI}(\boldsymbol{x}) - k_2^2\overline{TAWSS}(\boldsymbol{x})$$

Friction

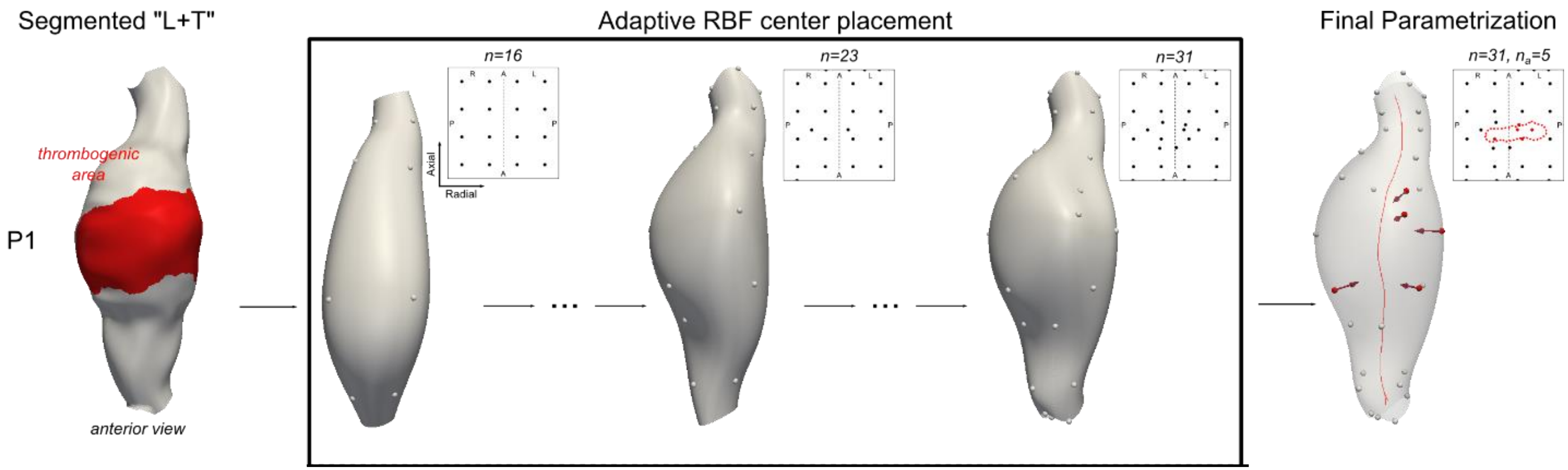
Proposed Mechanism



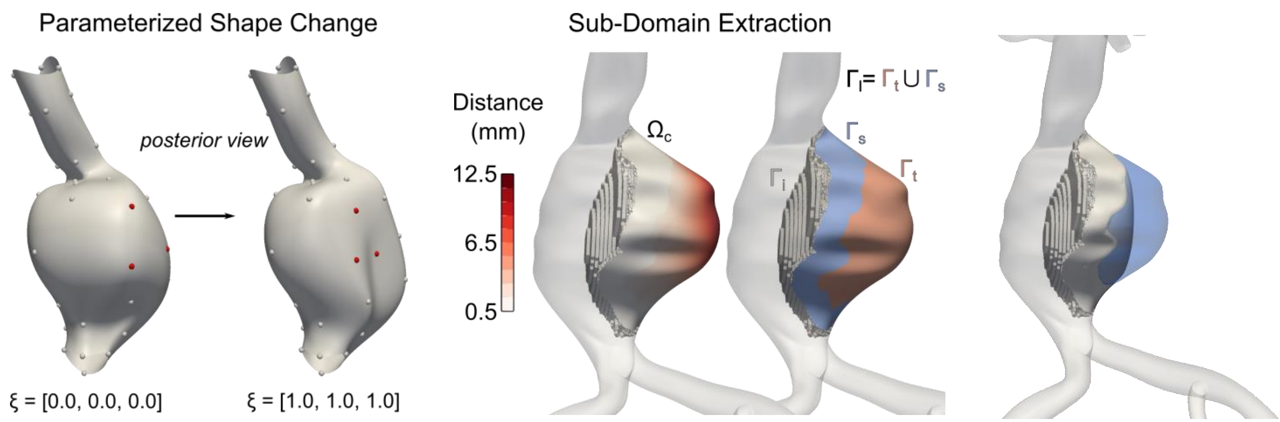


Updated Hemodynamics Post-Formation

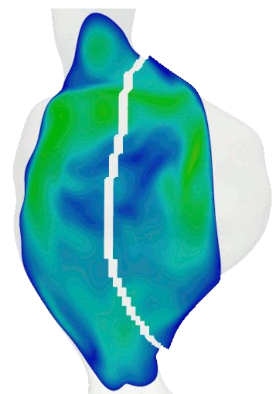
1. Parameterization of Lumen Shape with Radial Basis Functions (RBF)



2. Updated hemodynamics via Coupled Simulations



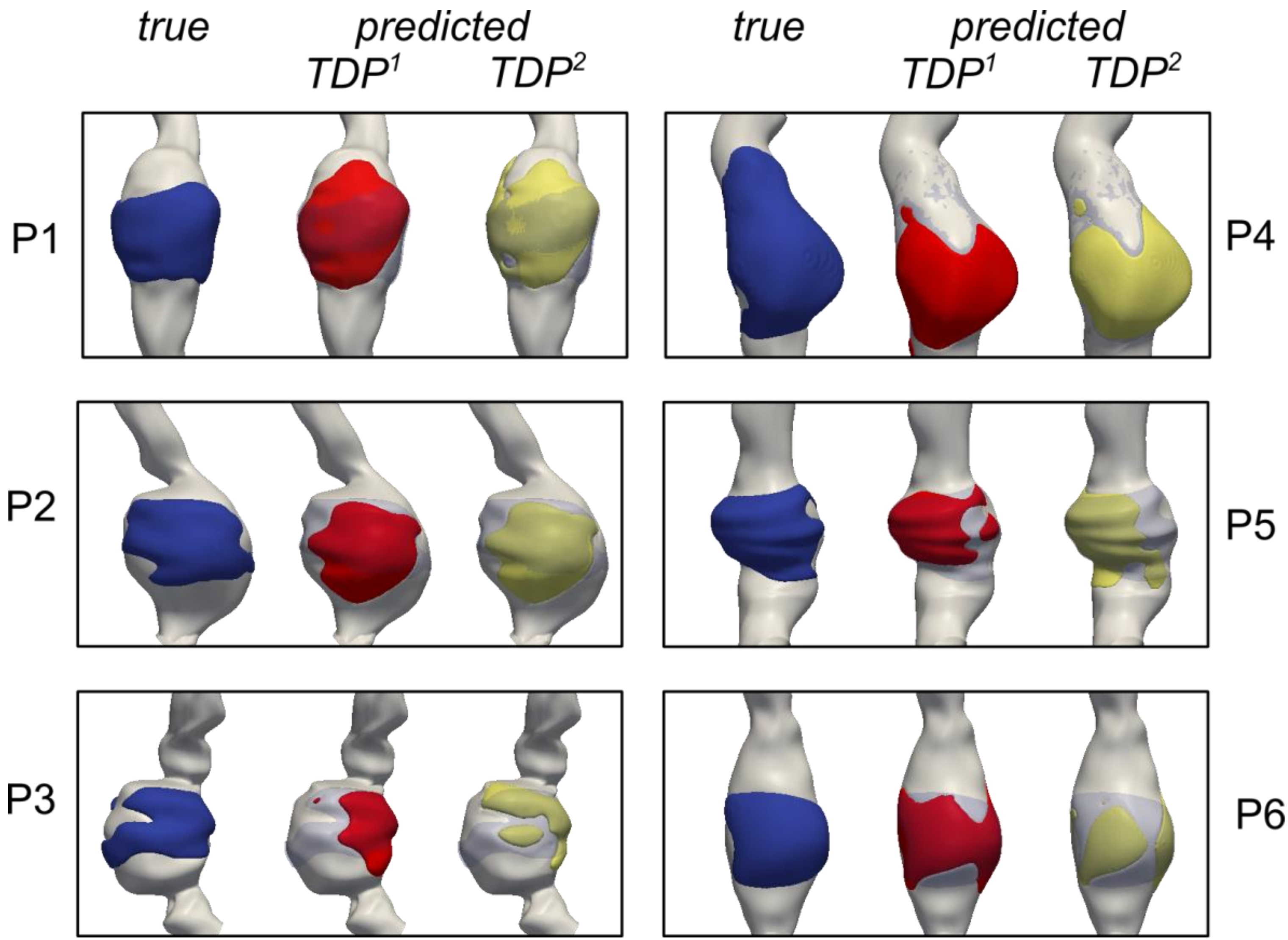
Robin-like BC



Coupled Simulation

Di Achille et al. (2016)

Predicted Thrombus Deposition



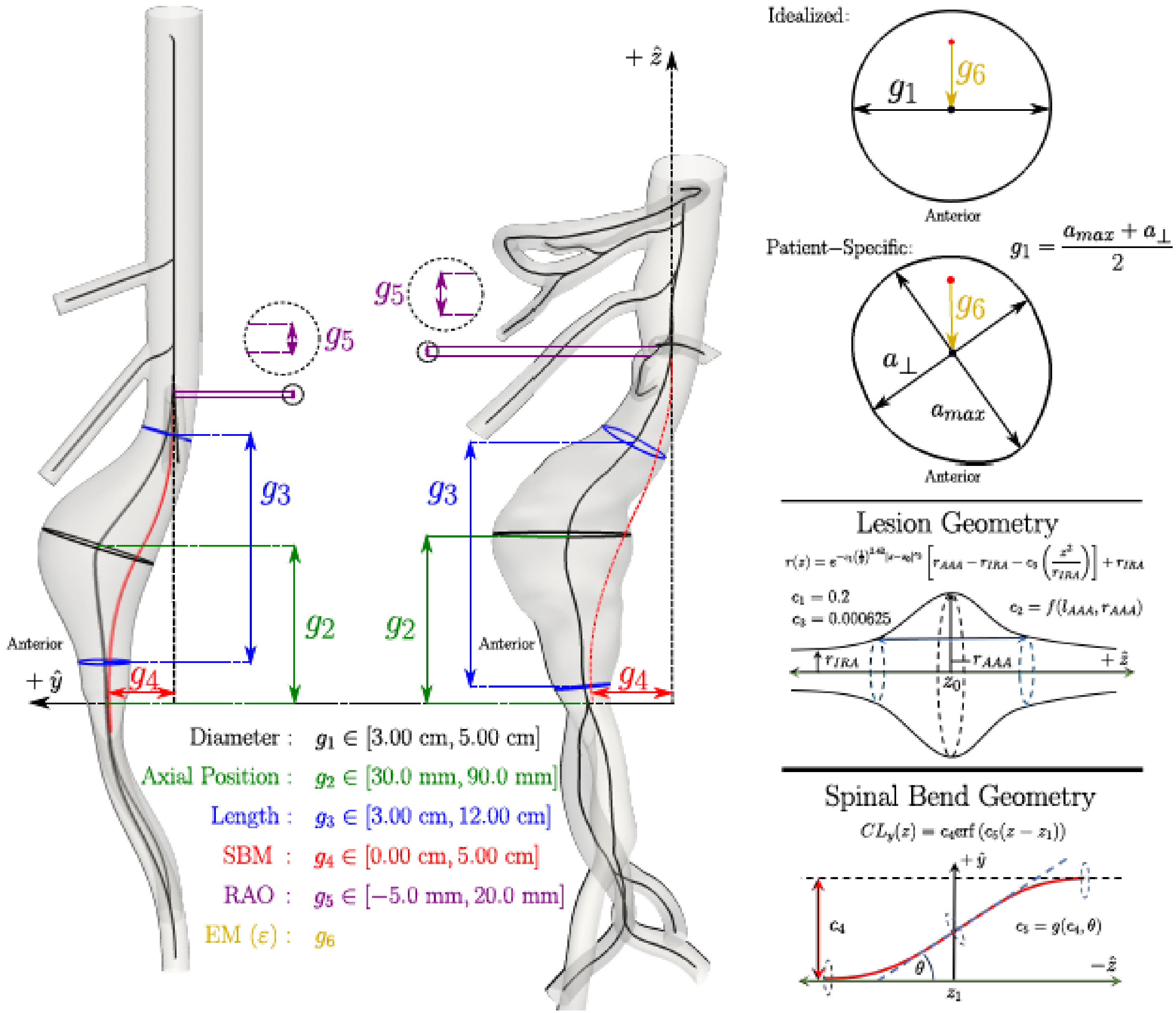
Di Achille et al. (2016)

HPC Resources Utilized

- Yale Center for Research Computing
  - Omega HPC Cluster (HP ProLiant blades) – 3 10^6 CPU/hrs
  - Grace HPC Cluster (IBM/Lenovo NeXtScale) – 0.5 10^6 CPU/hrs

- XSEDE Consortium
  - TACC LoneStar (Dell/Cray) – 0.35 10^6 CPU/hrs
  - TACC Stampede (Dell/Mellanox) – 0.3 10^6 CPU/hrs
  - SDSC Comet (Dell) – 0.1 10^6 CPU/hrs
  - LSU SuperMic (Dell) – 0.1 10^6 CPU/hrs

XSEDE
Extreme Science and Engineering Discovery Environment


Idealized:
g_1
g_6
Anterior
Patient–Specific:
$g_1 = \frac{a_{max} + a_\perp}{2}$
$a_\perp$
a_{max}
Anterior
$+\hat{z}$
g_5
g_3
g_2
g_4
Anterior
$+\hat{y}$
Diameter : $g_1 \in [3.00 \text{ cm}, 5.00 \text{ cm}]$
Axial Position : $g_2 \in [30.0 \text{ mm}, 90.0 \text{ mm}]$
Length : $g_3 \in [3.00 \text{ cm}, 12.00 \text{ cm}]$
SBM : $g_4 \in [0.00 \text{ cm}, 5.00 \text{ cm}]$
RAO : $g_5 \in [-5.0 \text{ mm}, 20.0 \text{ mm}]$
EM (ε) : g_6
Lesion Geometry
$c_1 = 0.2$
$c_3 = 0.000625$
$c_2 = f(l_{AAA}, r_{AAA})$
r_{IRA}
r_{AAA}
z_0
$+\hat{z}$
Spinal Bend Geometry
$CL_y(z) = c_4 \text{erf}(c_5(z - z_1))$
$+\hat{y}$
c_4
$c_5 = g(c_4, \theta)$
θ
z_1
$-\hat{z}$

Acknowledgments

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Current & Former Students / Fellows

S. Baek, C. Cyron, **P. Di Achille**, S. Kyriacou, **S. Sankaran**, P. Seshaiyer, A. Valentin, L. Virag, J. Wilson

Key References:

Wilson JS et al. (2013) *J Biomech Engr;*
Di Achille P et al. (2014) *Pro R Soc A;*
Virag L et al. (2015) *Annl Biomed Engr;*
Di Achille P et al. (2016) *IJNMBBE*

Funding: American Heart Association, US National Institutes of Health (NHLBI)

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Additional Resources

- Visualization Hardware
  - UT Maverick (HP/Nvidia)
  - Visualization Nodes on Stampede
  - High-End Workstations in Continuum Biomechanics Lab
- Data Transfer/Storage
  - Globus, GridFTP
  - TACC Ranch (500 GB)
  - Local Storage in Continuum Biomechanics Lab (~20 TB)