Computational fluid dynamics in cerebral aneurysms: our experience

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The goal

The goal of this contribution is to show how mathematical modelling can help to neurosurgeons in decision making process.

The presentation is based on the following papers:

- H. Švihlová, S. Hodis, K.D. Dennis, A. Sejkorová, A.Hejčl, D.Dragomir Daescu, T.Radovnický, J.Hron, M.Sameš: *Wall shear stress is significantly different for large and small MCA aneurysms.* In: Brain Sciences (accepted).
- A. Hejčl, M. Stratilová, H. Švihlová, A. Sejkorová, T. Radovnický, J. Hron, A. Feletti, M. Koblížek, J. Zámečník, V. Beneš, D. Dragomir-Daescu, M. Sameš (Sep.2019): Hemodynamics in ruptured intracranial aneurysms. Book chapter in: Intracranial aneurysms.
- A. Hejčl, H. Švihlová, A. Sejkorová, T. Radovnický, D. Adámek, J. Hron, D. Dragomir-Daescu, J. Málek, M. Sameš (2017): *Computational Fluid Dynamics of a Fatal Ruptured Anterior Communicating Artery Aneurysm.* In: Journal of Neurological Surgery Part A: Central European Neurosurgery 11.
- A. Sejkorová, K. D. Dennis, H. Švihlová, O. Petr, G. Lanzino, A. Hejčl, D. Dragomir-Daescu (2016): *Hemodynamic changes in a middle cerebral artery aneurysm at follow-up times before and after its rupture: a case report and a review of the literature.* In: Neurosurgical Review 40.2, 329-338.

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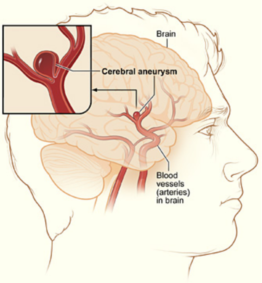
Brain aneurysm

What it is

- the incidence of cerebral aneurysms in a population approximately 5%
- the risk of rupture 1.5-2%
- the risk of death 26-36% in case of rupture
- 20% of those that survive develop a global cognitive deficit
- preventive treatment: risk of severe complications maybe more than 16% of patients, the risk of mortality being 0-3.2%



Risk factors

- Japanese or Finish nationality, women
- hypertension, smoking

Open problems

Doctors are worried

- amount of hemodynamic indicators
- variability in models and techniques
- mesh sensitivity, longitudial studies
- mechanical model
- rigid walls

Engineers are worried

- imaging techniques resolution
- variability in imaging techniques
- boundary conditions
- validation
- studies on "unruptured" and "ruptured" aneurysms

H. Meng and V. M. Tutino and J. Xiang and A. Siddiqui: High WSS or Low WSS? Complex Interactions of Hemodynamics with Intracranial Aneurysm Initiation, Growth, and Rupture: Toward a Unifying Hypothesis. In: American Journal of Neuroradiology 35.7 (2013):1254–1262.

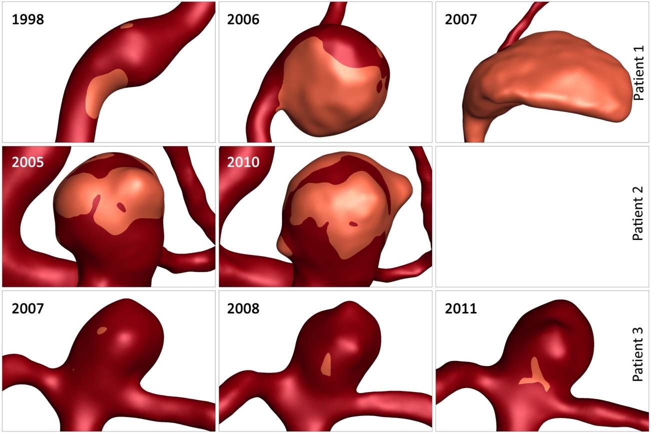
J. Frosen and R. Tulamo and A. Paetau et al.: Saccular intracranial aneurysm: pathology and mechanisms. In: Acta Neuropathology 123.6 (2012):773–786.

S. Hodis and S. Uthamaraj and A. L. Smith and K. D. Dennis and D. F. Kallmes and D. Dragomir-Daescu: Grid convergence errors in hemodynamic solution of patient-specific cerebral aneurysms. In: Journal of Biomechanics 45.16 (2012):2907–2913.

Unruptured and ruptured aneurysms

- *Unruptured* aneurysms are aneurysms detected by imaging techniques. They can be stable for whole patient's life, they can grow, even rupture.

- *Ruptured* aneurysms are aneurysms imagined after the rupture. They can (and they do!) change their size and shape.



What engineers and doctors want

mathematical models

- proper blood model
- proper vessel wall model
- fluid-structure interaction
- coupling the artery with the whole blood system

numerical part

- space and time discretization
- nonlinear system
- large linear system/ preconditioning
- high performance computing/ parallelization

testing and validation

- benchmarking
- in vitro tests
- MRI comparison and validation
- error estimation in each step
- real time meshing/adaptivity

up-to-date knowledge in all areas

One parameter wanted

- there is still a discussion about hemodynamic parameters responsible for the birth, growth and rupture of the aneurysms
  - high pressure
  - pressure gradient
  - maximum velocity
  - high/low WSS
  - low WSS area
  - high OSI oscilatory shear index
  - high RRT relative residence time
- recently, it is assumed that both low and high wall shear stress can lead to rupture

Y. Miura et al. Low Wall Shear Stress Is Independently Associated With the Rupture Status of Middle Cerebral Artery Aneurysms. In: Stroke 44.2 (2012): 519–521.

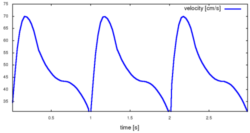
J. R. Cebral and F. Mut and J. Weir and C. Putman. Quantitative Characterization of the Hemodynamic Environment in Ruptured and Unruptured Brain Aneurysms. In: American Journal of Neuroradiology 32.1 (2011): 145–151.

E. Metaxa et al. High Wall Shear Stress and Positive Wall Shear Stress Gradient Trigger the Initiation of Intracranial Aneurysms. In: ASME 2009 Summer Bioengineering Conference, Parts A and B. ASME International. (2009)

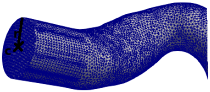
Model

$$
\begin{aligned}
\frac{\partial \mathbf{v}}{\partial t} + (\nabla \mathbf{v})\mathbf{v} &= \operatorname{div} \mathbf{T} && \text{in } (0,T) \times \Omega, \\
\mathbf{T} &= -p\mathbf{I} + \nu_* \left(\nabla \mathbf{v} + (\nabla \mathbf{v})^T\right) && \text{in } (0,T) \times \Omega, \\
\operatorname{div} \mathbf{v} &= 0 && \text{in } (0,T) \times \Omega, \\
\mathbf{v} &= \mathbf{v}_{in} && \text{on } (0,T) \times \Gamma_{in}, \\
\mathbf{v} &= \mathbf{0} && \text{on } (0,T) \times \Gamma_{wall}, \\
\mathbf{T}\mathbf{n} &= \mathbf{0} && \text{on } (0,T) \times \Gamma_{out}, \\
\mathbf{v}(t=0) &= \mathbf{0} && \text{in } \overline{\Omega}.
\end{aligned}
$$

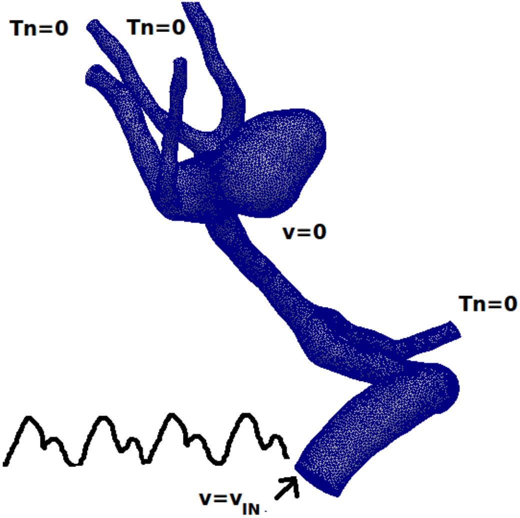
$$Re = \frac{VL}{\nu} = \frac{8 \cdot 10^{-1} m/s \cdot 10^{-3} m}{4 \cdot 10^{-6} m^2/s} = 200$$



$$\mathbf{v}_{in} = 2\frac{r^2 - |CX|^2}{r^2} V(t)$$



Model



Mesh

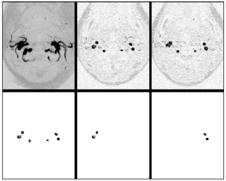
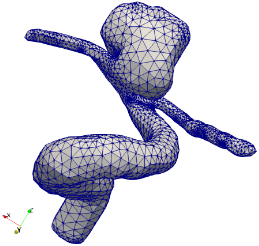
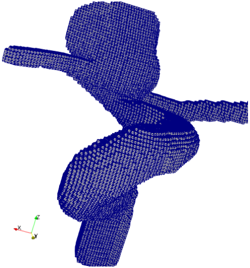
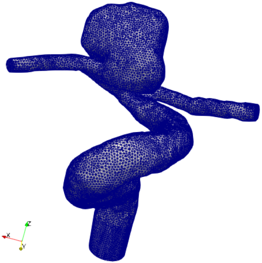


Figure 9: CT image processing.



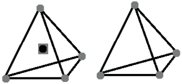




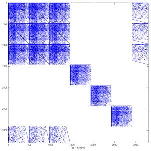
Discretization

- In time: Crank-Nicholson scheme (2^{nd} order), time step 0.01-0.001s
- In 3D space: FEM P_1^+/P_1 (MINI) on tetrahedrons

$$\mathbf{V}_h = \{\mathbf{v}_h \in [C(\Omega_h)]^3 : \ \mathbf{v}_h\,|_K \in [P_1^+(K)]^3 \quad \forall K \in \mathbf{T}_h\}$$
$$P_h = \{p_h \in C(\Omega_h) : \ p_h\,|_K \in P_1(K) \quad \forall K \in \mathbf{T}_h\}$$
$$\left[P_1^+(K)\right]^3 = [P_1(K) \oplus B_4(K)]^3$$



  - solving the discrete nonlinear system (Newton method, Fstrin software)
  - solving large linear system (direct sparse methods, PETSc)



Core problem: Solve large, sparse, non-symmetric, indefinite linear system of equations.

Limitations

newtonian fluid

- diameter of the vessel about 3 mm
- velocity about 0.5 $\frac{\mathrm{m}}{\mathrm{s}}$
- diameter of the red blood cell 8 μm
- even Newton-like plasma can exhibit normal stress differences
- Newtonian model underestimates blebs in comparison with Carreau viscosity model
- Newtonian model underestimates the viscosity and overestimate WSS in regions of a peak values

numerical part

- rigid walls
- chemical and thermal properties are neglected
- coupling to the rest of the circulatory system
- MRI comparison and validation
- patient-specific geometries extraction

L. Dintenfass (1985): *Blood Viscosity,* Springer.

J. Xiang, M. Tremmel, J. Kolega, E. I. Levy, S. K. Natarajan, H. Meng (2011): *Newtonian viscosity model could overestimate wall shear stress in intracranial aneurysm domes and underestimate rupture risk.* In: Journal of NeuroInterventional Surgery 4.5:351–357.

J. E. Hippelheuser, A. Lauric, D. Cohen, A. M. Malek (2014): *Realistic non-Newtonian viscosity modelling highlights hemodynamic differences between intracranial aneurysms with and without surface blebs.* In: Journal of Biomechanics 47.15:3695–3703.

Cerebral arteries affected by an aneurysm

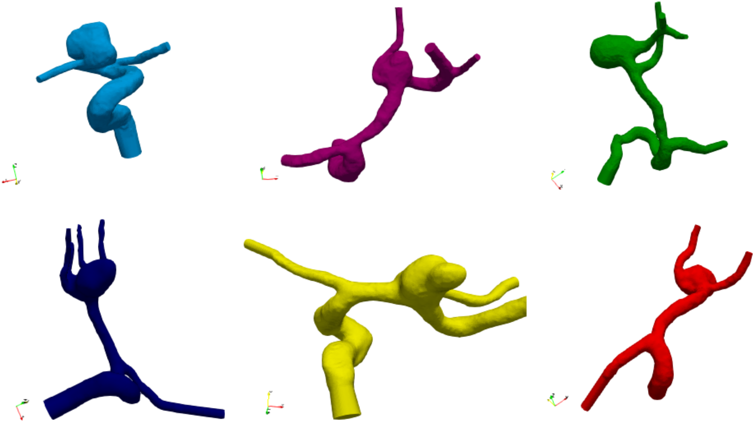
Our projects

- Followed and ruptured aneurysms
  - 20 aneurysms at the same location with different sizes, 10 of them ruptured
  - hemodynamic factors are significantly different for big and small aneurysms without noticing the rupture status
  - Ruptured aneurysms
    - 7 ruptured aneurysms with the known place of rupture
    - the inflow jet, high normal pressure and high WSS correlate with the place of rupture in the case report
  - Growing aneurysms - change in the hemodynamic parameters
- Correlation of the CFD parameters with the histological changes in the walls of aneurysm sacs
- Correlation of the CFD parameters with the histological changes in the walls of carotid stenoses
  - blood flow model including the chemical properties of the blood

Ruptured aneurysms

- **data:** Usti nad Labem
  - 7 ruptured aneurysms, 1 ACom, 5 MCA, 1 carotid
  - size from 8.83mm to 12.60mm
- **segmentation and meshing:** ITK SNAP, iso2mesh
  - meshes about 1milion tetrahedra, mesh dependency test on three meshes, average edge length for the finest meshes 0.25mm
- **computation:** Fstrin
  - FE, no-slip, parabolic profile, dt=0.001, TAV 0.66m/s on inlet
- **postprocessing:** ParaView

Ruptured aneurysms



Ruptured aneurysms

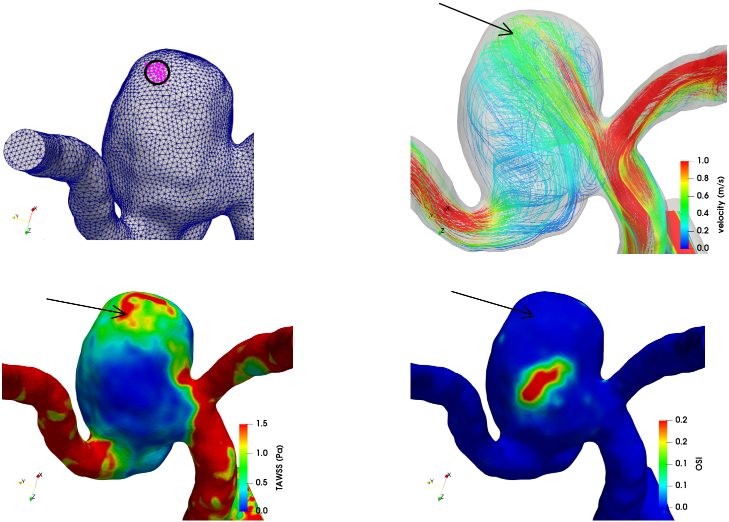


Figure: Correlation of hemodynamic parameters to the site of the rupture.

Ruptured aneurysms

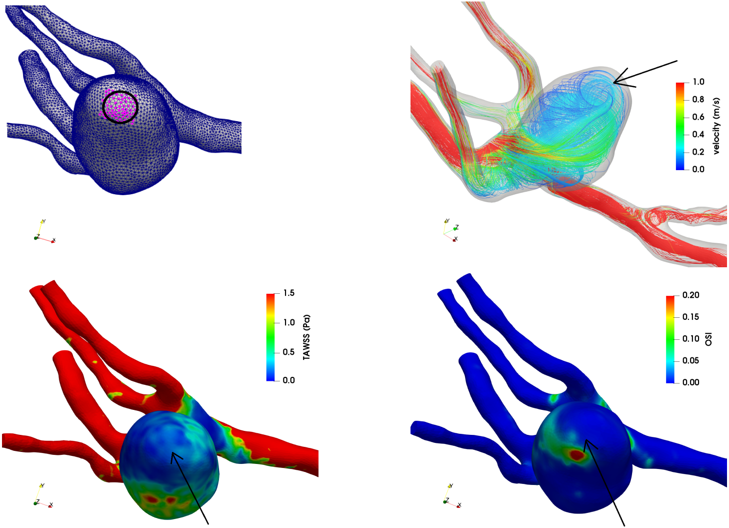


Figure: Correlation of hemodynamic parameters to the site of the rupture.

Ruptured aneurysms

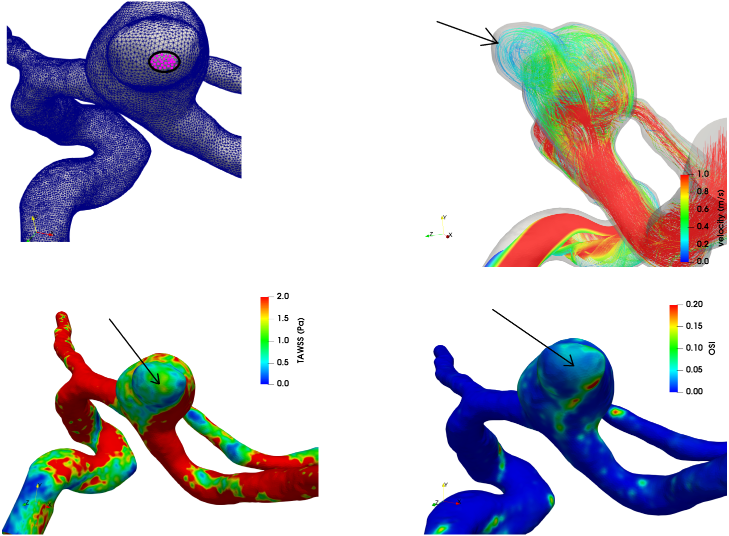
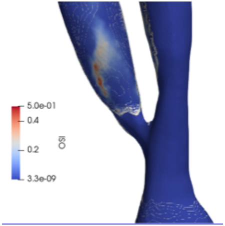
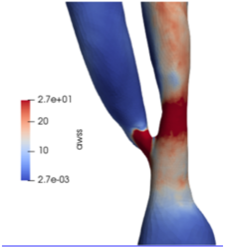


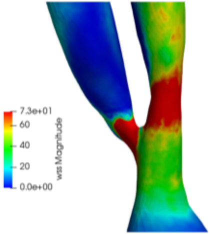
Figure: Correlation of hemodynamic parameters to the site of the rupture.

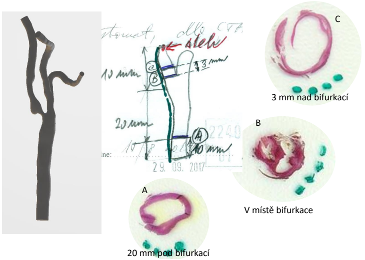
Carotid stenosis

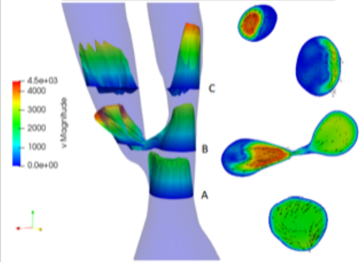
Look for correlation between histology and CFD results





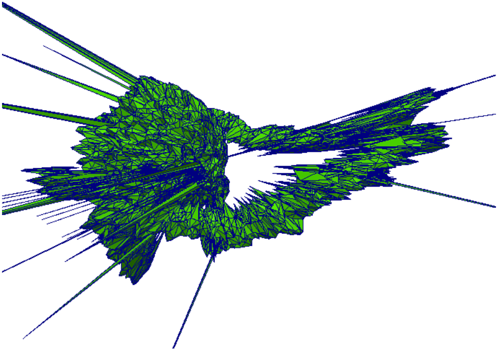






Conclusion

- We introduced the state-of art in brain aneurysm treatment and its connection to the mathematical modelling.
- Brain aneurysms are challenging for neurosurgeons, neuroradiologists, mathematicians, physicists and engineers.
- The problem covers many areas including image processing, mesh generation, modelling and numerical problems, validation.



Thank you for your attention.