Computational fluid dynamics in cerebral aneurysms: our experience

Aleš Hejčl[a], Helena Švihlová[b], Jaroslav Hron[b], Alena Sejkorová[a]

a, Department of Neurosurgery at Masaryk Hospital, Usti nad Labem
b, Mathematical Institute, Charles University, Prague

MMP Hradec Králové, September 23, 2019

Mathematical Institute: Mathematical Modelling

Mathematical Modelling

Josef Málek	mathematical analysis
Miroslav Bulíček	mathematical analysis
Jaroslav Hron	computations
Michal Pavelka	physics
Milan Pokorný	mathematical analysis
Vít Průša	physics
Tomáš Roubíček	mathematical analysis
Ondřej Souček	geophysics
Karel Tůma	computations

Cerebral arteries affected by an aneurysm - cooperation

Engineering Department, Mayo Clinic, Rochester MN

Dan Dragomir-Daescu	engineer
Kendall Dennis	engineer
Susheil Uthamaraj	engineer

Department of Mathematics, Texas A& M University, Kingsville TX

Simona Hodis	mathematician

Prevence

Prevence




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.

What all of them want

mathematical models

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

numerical part

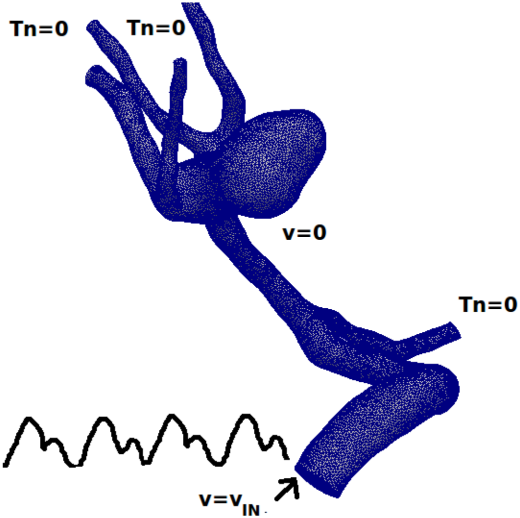
- space and time discretization
- nonlinear system
- large linear system/ preconditioning
- high performance computing/ parallelization

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

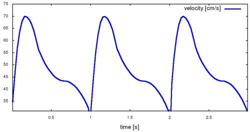
Model



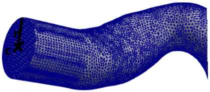
Model

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

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



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



Mesh

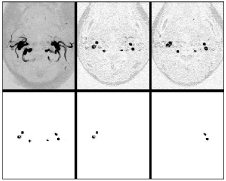
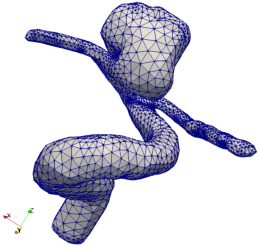
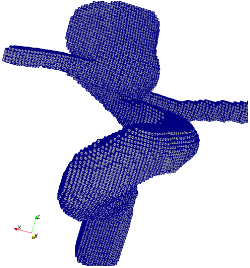
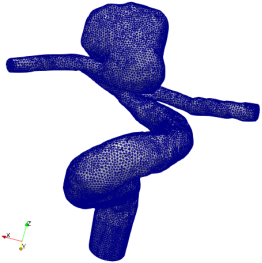


Figure 9: CT image processing.



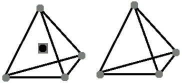




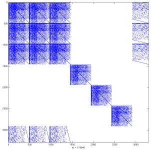
Discretization

- 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.

Hemodynamic parameters

- 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)

1. Cooperation and open problems

2. Model and numerical implementation

3. **Current projects**
   - Ruptured aneurysms
   - Growing aneurysms - change in the hemodynamic parameters
   - Size influence
   - Correlation between histology and CFD

Cerebral arteries affected by an aneurysm

Our projects

- 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
- 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
- Correlation of the CFD parameters with the histological changes in the walls of aneurysm sacs

A. Hejčl, H. Švihlová, A. Sejkorová, T. Radovnický, D. Adámek, J. Hron, D. Dragomir-Daescu, J. Málek, M. Sameš: Computational Fluid Dynamics of a Fatal Ruptured Anterior Communicating Artery Aneurysm. In: Journal of Neurological Surgery Part A: Central European Neurosurgery 11 (2017).

A. Sejkorová, K. D. Dennis, H. Švihlová, O. Petr, G. Lanzino, A. Hejčl, D. Dragomir-Daescu: 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 (2016):329-338.

Ruptured aneurysms - the case report

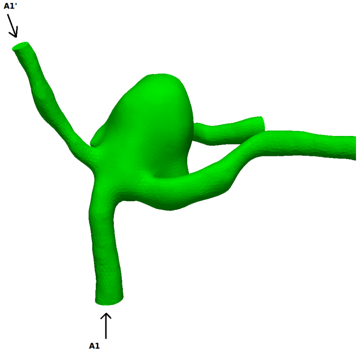


Figure: The geometry with two inflow vessels - A1 and A1'.

Ruptured aneurysms - the case report

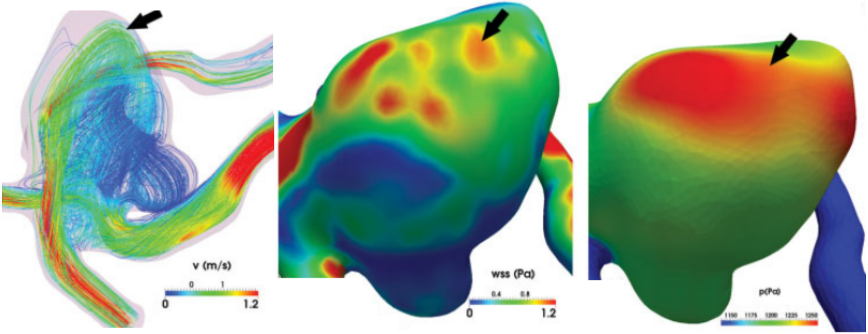
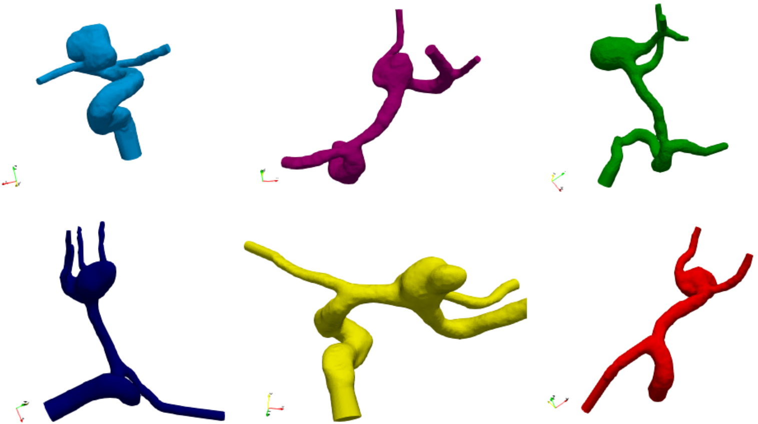


Figure: Correlation of hemodynamic parameters to the site of the rupture for the ACom aneurysm.

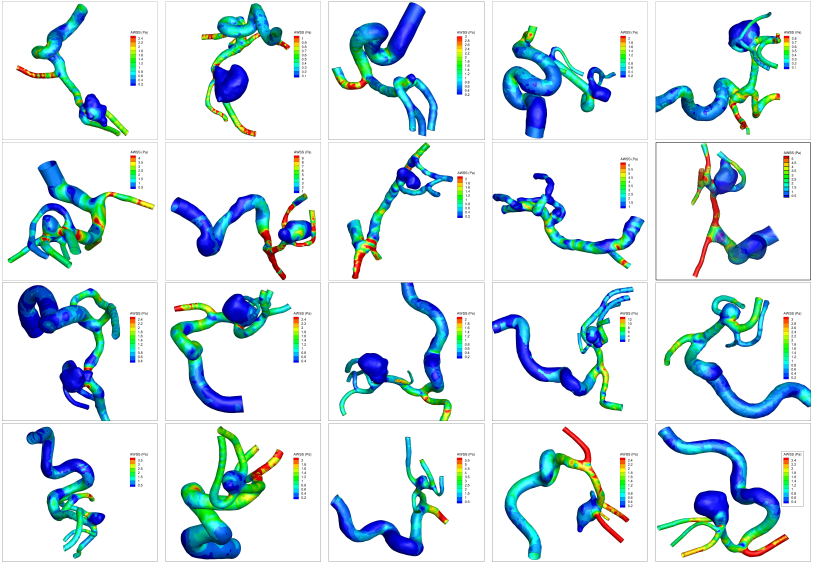
Ruptured aneurysms - other six cases



Followed aneurysms - size influence

- **data:** Usti nad Labem and Mayo Clinic
  - 20 MCA aneurysms, 10 ruptured vs. 10 unruptured
  - 13 small aneurysms(size$<$10mm) vs. 7 big(size from 10.98mm to 17.45mm)
- **segmentation and meshing:** Mimics, ICEM CFD
  - meshes about 5milions cells, average edge length 0.25mm
- **computation:** Ansys Fluent 16.1
  - FV, Womersley profile, $WN = 3.7$, dt=0.001, $CN < 20$
- **postprocessing:** Tecplot, Matlab
  - Mann-Whitney test, P$<$0.05 for significant difference

Followed aneurysms - size influence

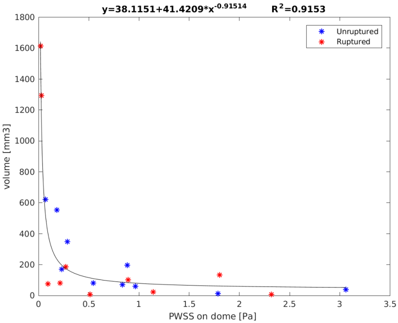


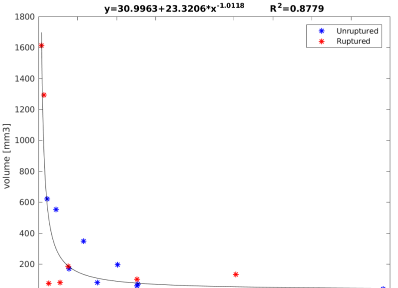
Followed aneurysms - size influence

Parameter	small/big	rupt/unrupt
Aneurysm neck diameter [mm]	0.0026	0.0452
Aspect ratio	0.0155	0.9096
Aneurysm volume [mm3]	0.0004	0.7913
Aneurysm surface [mm2]	0.0004	0.9097
Nonsphericity index	0.0089	0.1859
mean PWSS dome [Pa]	0.0112	0.6232
mean PWSS parent artery [Pa]	0.1538	0.5708
mean TAWSS dome [Pa]	0.0071	0.5708
mean TAWSS parent artery [Pa]	0.0684	0.6776
peak LSA [%]	0.0140	0.3075
aver LSA [%]	0.0476	0.0890
TAWSS ratio	0.0324	0.1212
max OSI dome	0.1322	0.2123
mean OSI dome	0.1320	0.0820
relative residence time	0.0089	0.5708

Table: Statistically significant diferences for two groups: small(13) and big(7) aneurysms and for ruptured(10) and unruptured(10) aneurysms. P values for Mann-Whitney test.

Dependence of volume on WSS





Conclusion

- Brain aneurysms are challenging for neurosurgeons, neuroradiologists, mathematicians, physicists and engineers.
- The problem covers many areas including image processing, mesh generation, model creations and validations, ..