A Non Newtonian Model for Blood Flow behind a Flow Diverting Stent

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Outline

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  - Flow diverting stents
  - Blood Models
- Our model
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  - Stented Aneurysm
  - CFD Simulations

Results

Viscosity

Velocity profiles

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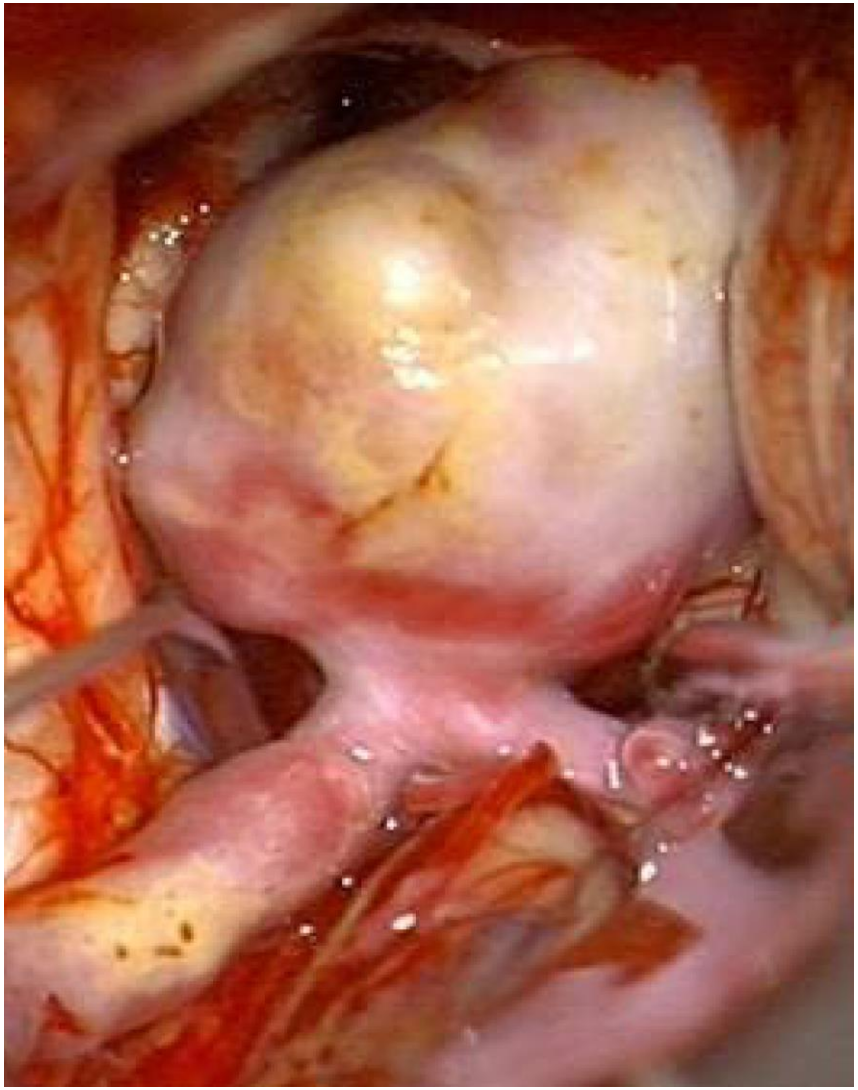
Conclusion and Outlook

Cerebral Aneurysm



- Pathological, blood filled expansion of a blood vessel within the brain
- Risk of rupture

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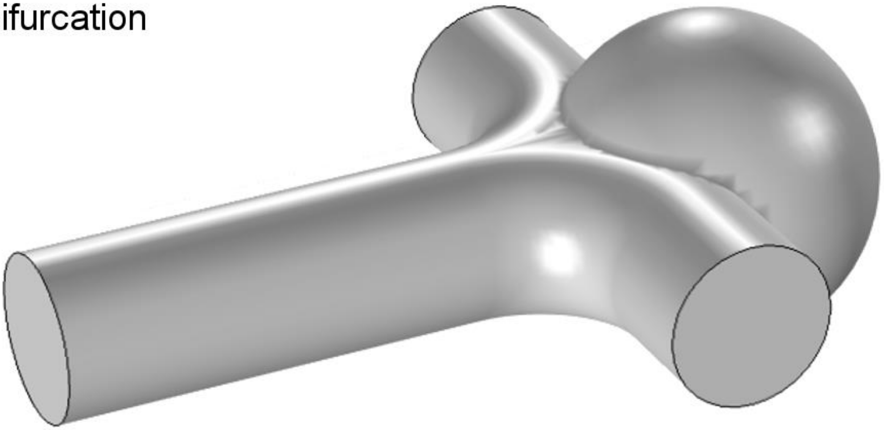
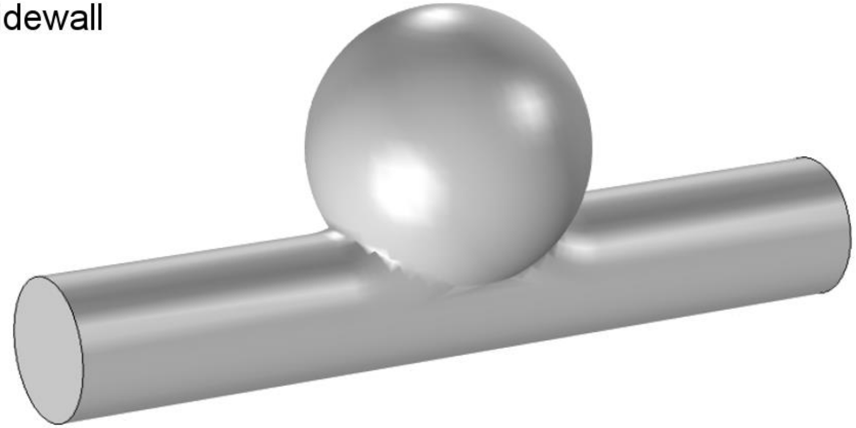
Forms of aneurysms

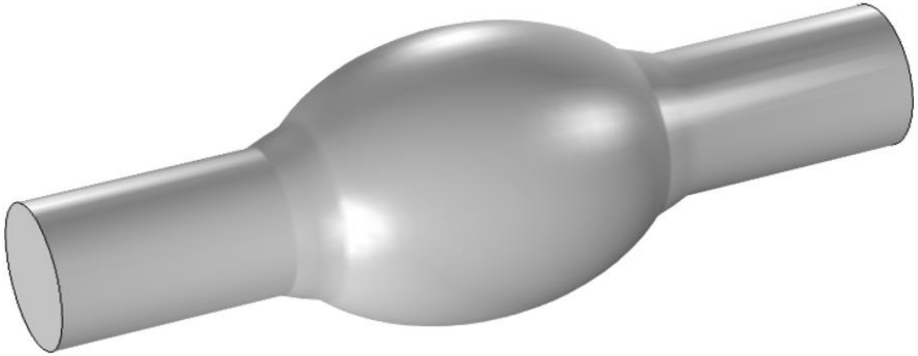
Bifurcation



Sidewall

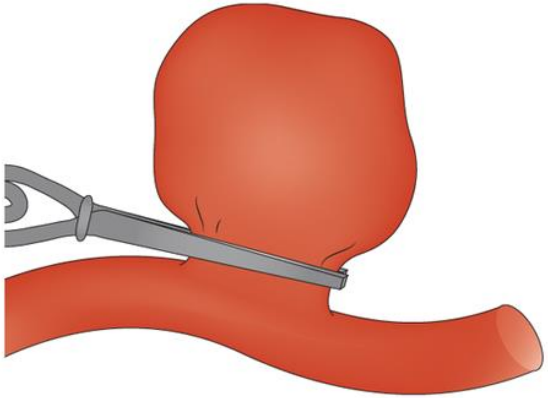


Fusiform

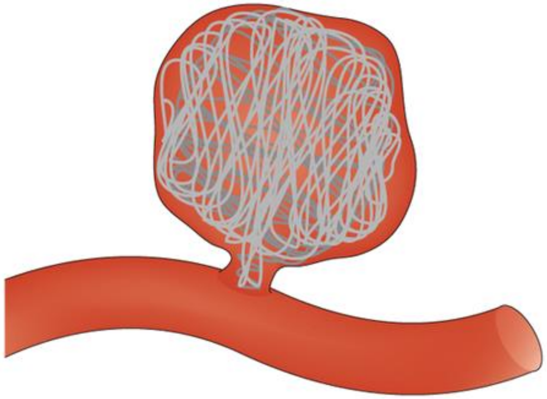


combinations

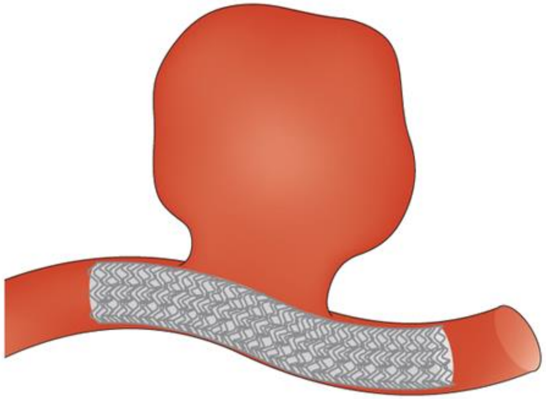
4 different treatments



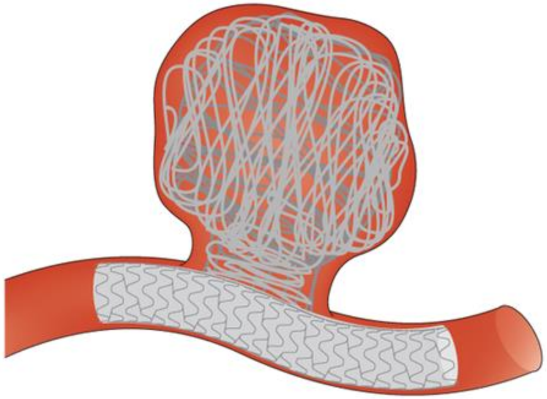
Clipping



Coiling



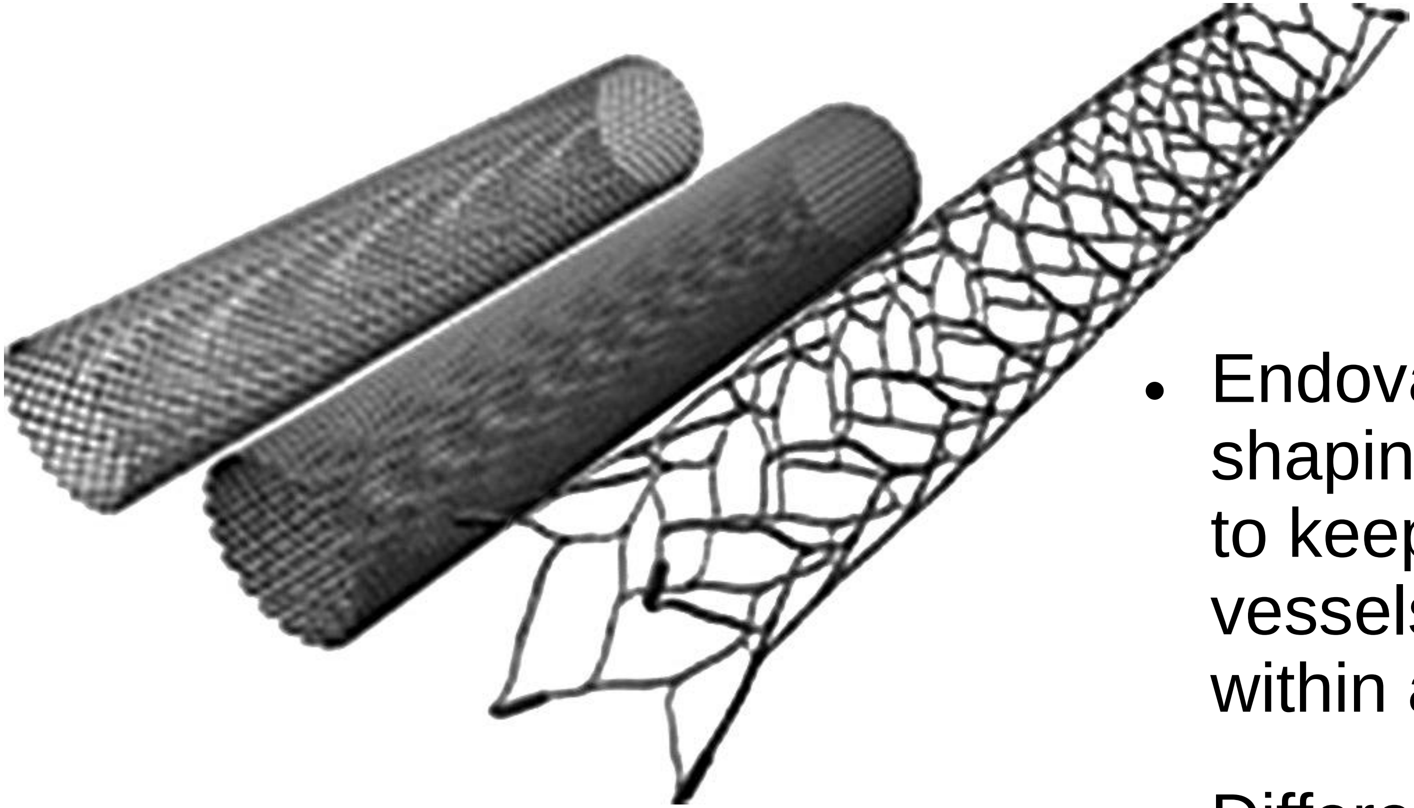
Stenting



Stent assisted coiling

RD. Perrone et al., “Vascular complications in autosomal dominant polycystic kidney disease”, Nature Reviews Nephrology 11, 589–598 (2015)

Flow diverting stents



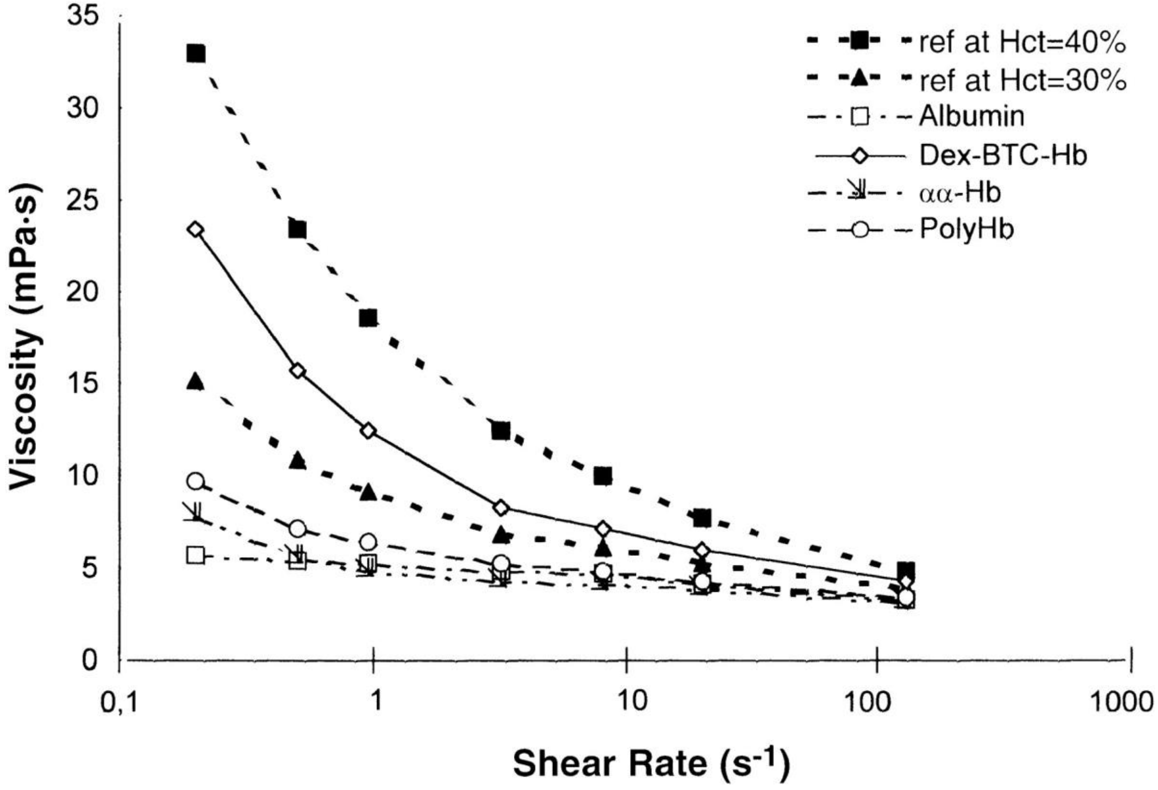
- Endovascular craft shaping the blood flow to keep it within parent vessels and stop it within aneurysm
- Different grids and permeabilities

K. Masahiro et al., “The study of flow diversion effects on aneurysm using multiple enterprise stents and two flow diverters”, Asian Journal of Neurosurgery 7(4), 159–165 (2012)

Viscosity of blood

Viscosity depending on:

- Hematocrit
- Temperature
- Shear rate
- ...

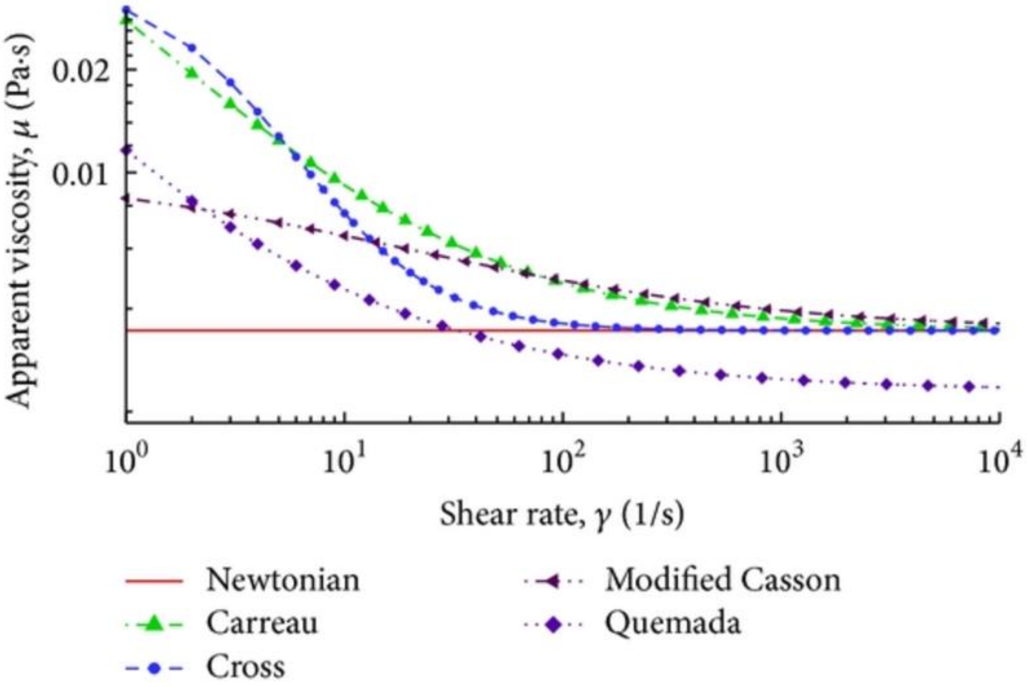


A. Caron et al., “Cardiovascular and hemorheological effects of three modified human hemoglobin solutions in hemodiluted rabbits”, Journal of Applied Physiology 86(2), 541–548 (1999)

Different blood models

Different Models:

- Power Law
- Carreau Yasuda
- Casson
- Walburn-Schneck
- …



MG. Rabby et al., “Pulsatile Non-Newtonian Laminar Blood Flows through Arterial Double Stenoses”, Journal of Fluids 2014, (2014)

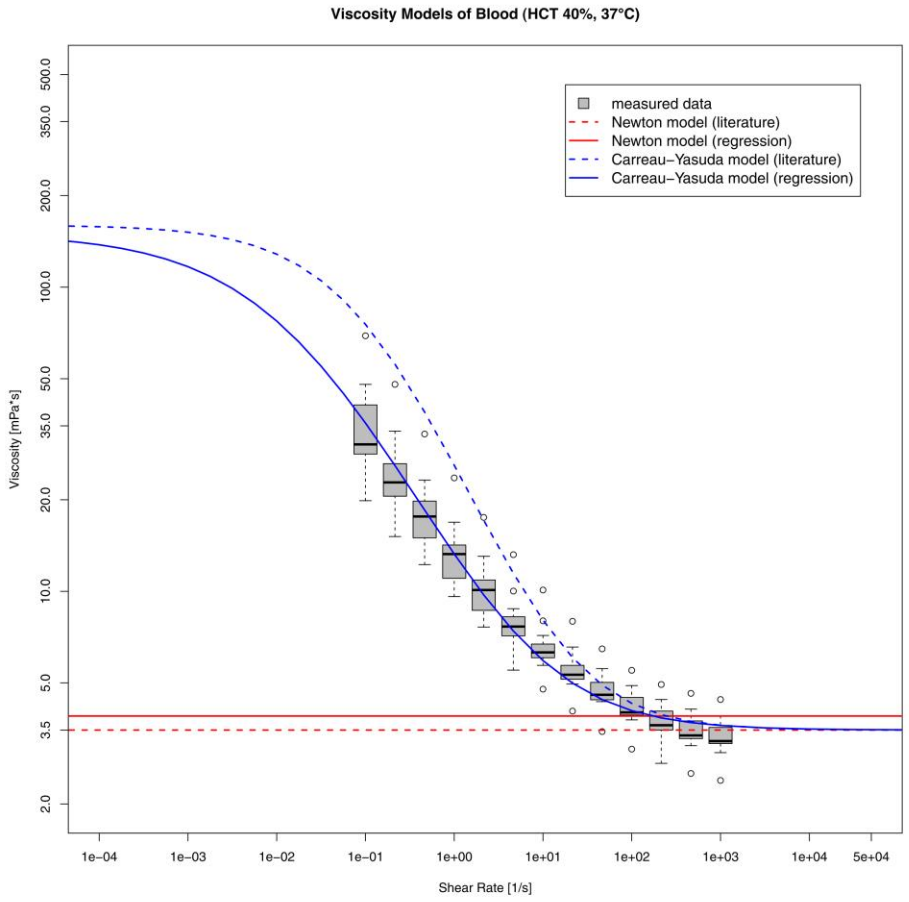
Blood viscosity measurements

Double gap cylinder viscosimeter

- Whole blood samples
- Fixed hematocrit 40%
- Peltier controlled temp. 37°C
- Rising shear rates

Original image from H. Barnes, “Viscosity Measurement”, Thermopedia, 2011; http://www.thermopedia.com/content/1244

Our blood model



Carreau Yasuda

Parameters found by weighted non linear least square regression

$$\mu = \mu_\infty + (\mu_\infty + \mu_0)\left(1 + (\lambda + \dot{\gamma})^a\right)^{\frac{n-1}{a}}$$

	Newtonian	Carreau Yasuda
$a[1]$	—	0.500
$\lambda[\mathrm{s}^{-1}]$	—	46.530
$\mu_0[\mathrm{mPa\,s}]$	—	150.000
$\mu_\infty[\mathrm{mPa\,s}]$	3.892	3.500
$n[1]$	—	0.342

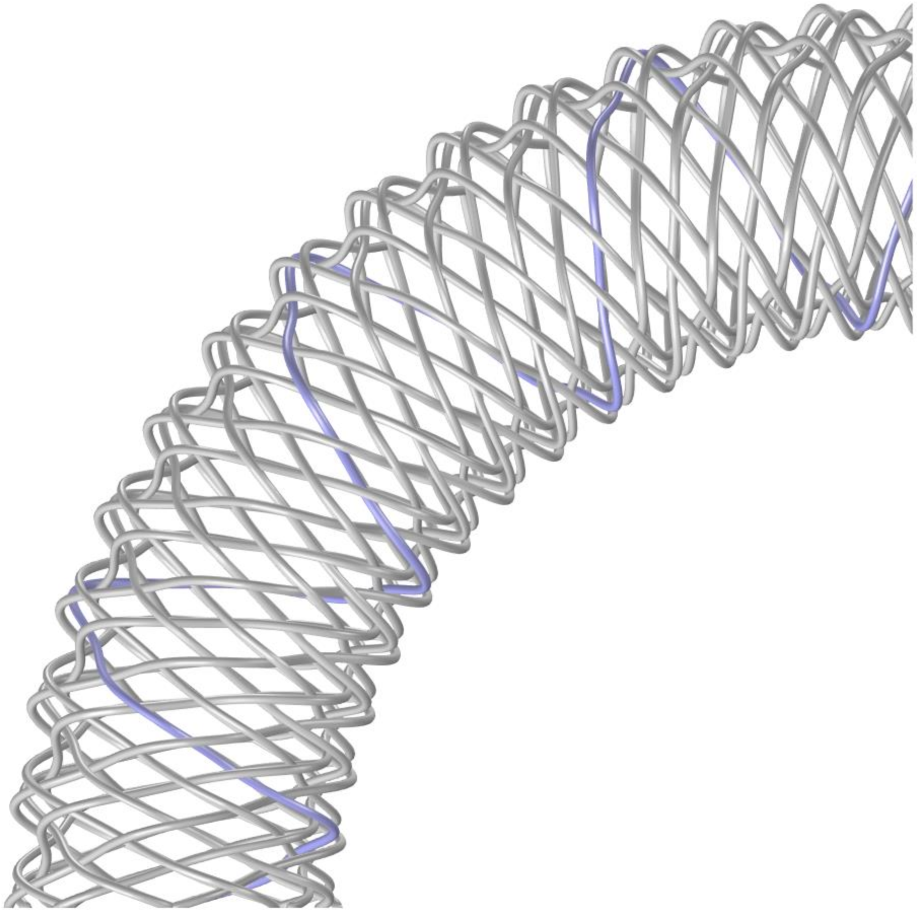
Model of an aneurysm

Sidewall aneurysm

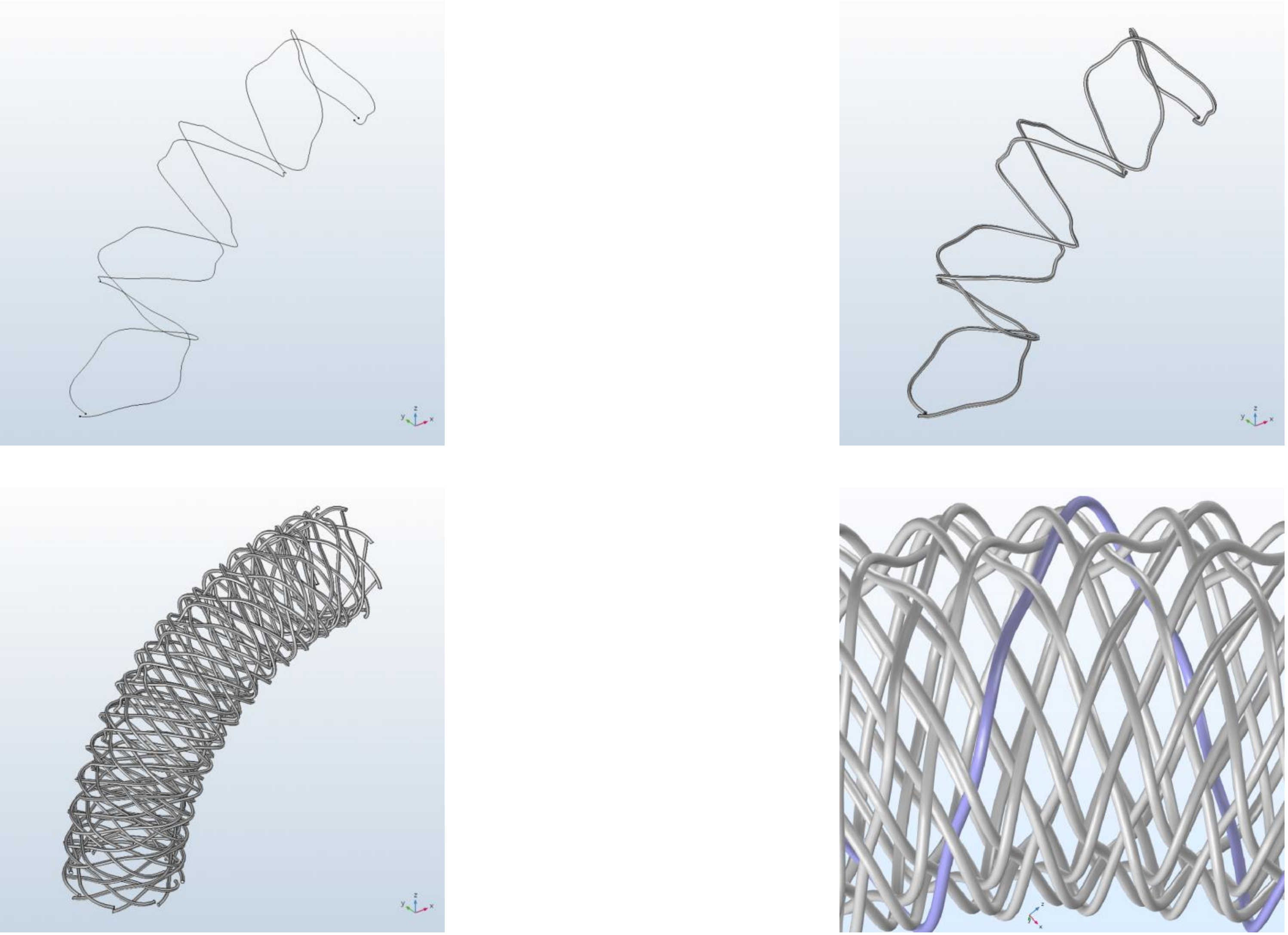
- Balloon like bulge at the side of the vessel
- Vessel diameter: 2.14mm
- Neck length: 4.41mm
- Dome height: 4.09mm

Model of a flow diverter

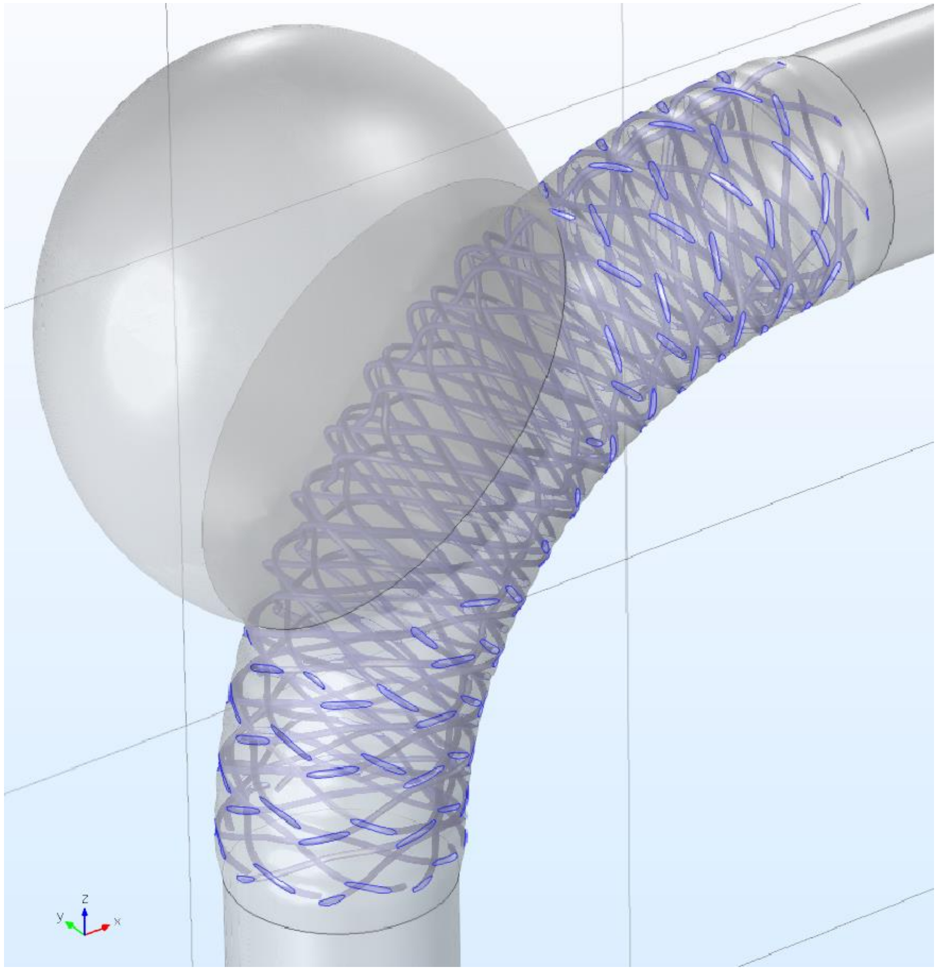
- Complex knitting
- 16 wires
- Wire diameter: 70µm
- Permeability: ~55%



Steps of modeling the flow diverter geometry



Model of a stented cerebral aneurysm



Stented Aneurysm

- Sidewall aneurysm
- Added dilatation by stent
- Stent subtracted from flow bearing area
- Aneurysm neck above the stent

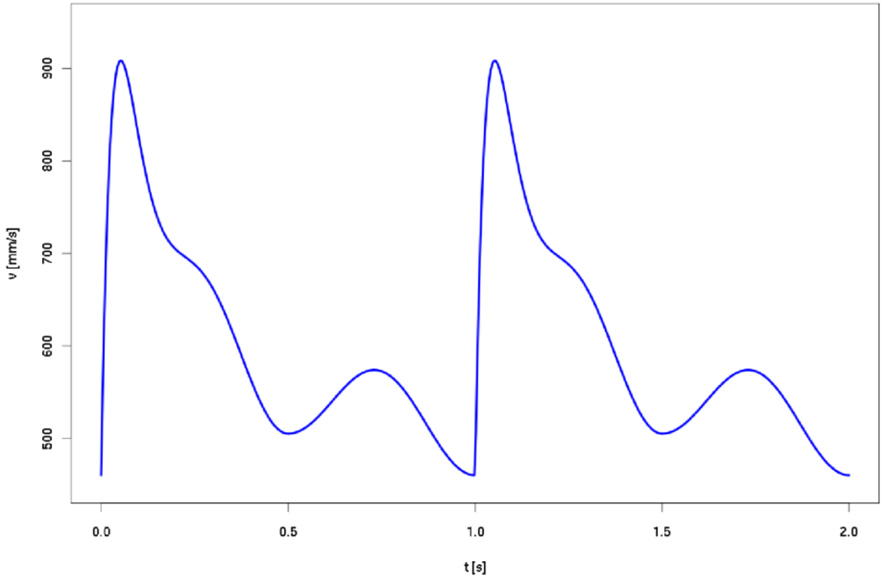
Incompressible Navier-Stokes Equation

$$\overbrace{\rho\left(\frac{\partial\vec{u}}{\partial t}+\vec{u}\cdot\vec{\nabla}\vec{u}\right)}^{\text{Inertia}} = \overbrace{-\vec{\nabla}p+\mu\nabla^2\vec{u}}^{\text{Divergence of stresses}} + \underbrace{\vec{f}}_{\text{Other body forces}}$$

Boundary conditions:

- Inlet: laminar inflow with flow profile
- Outlet: laminar outflow with no pressure
- Vessel walls: no slip boundaries

Pulsatile blood flow



Inflow velocity profile

- Derived from various human artery Doppler sonograms

$$v(t) = v_{min} + (v_{max} - v_{min}) \cdot \frac{1}{10} \cdot \left(42 \cdot (\sin(2\pi t) + |\sin(2\pi t)|) \cdot e^{-20 \cdot (t - \mathrm{rnd}(t-0.5))} + 3 \cdot \sin(2\pi t)^2 + |\sin(2\pi t)| \cdot \sin(2\pi t) + \left|\sin(\pi t)^2\right|\right)$$

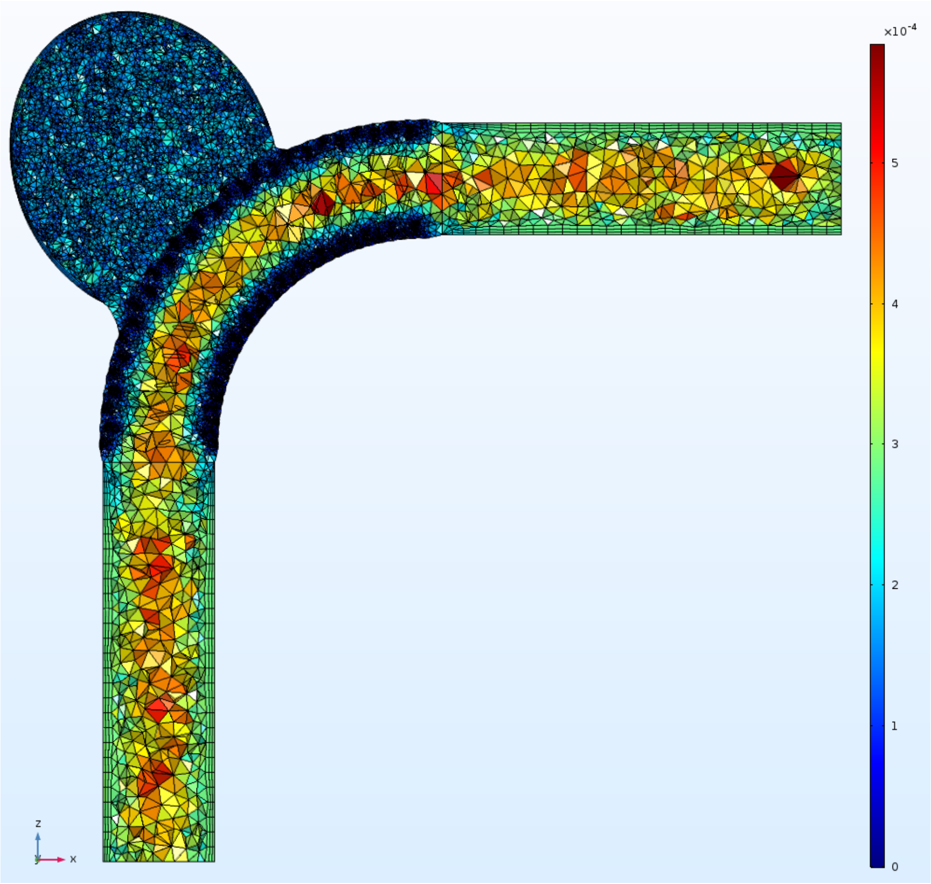
Mesh

Statistics:

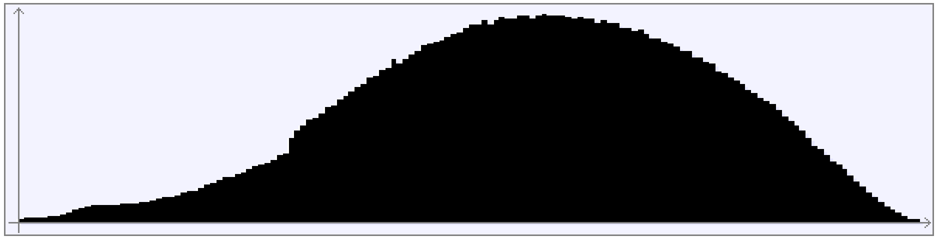
- Elements: 1,405,924
- Mesh volume: 141.1mm³

- Avg. Growth rate: 2.041
- Max. Growth rate: 26.690

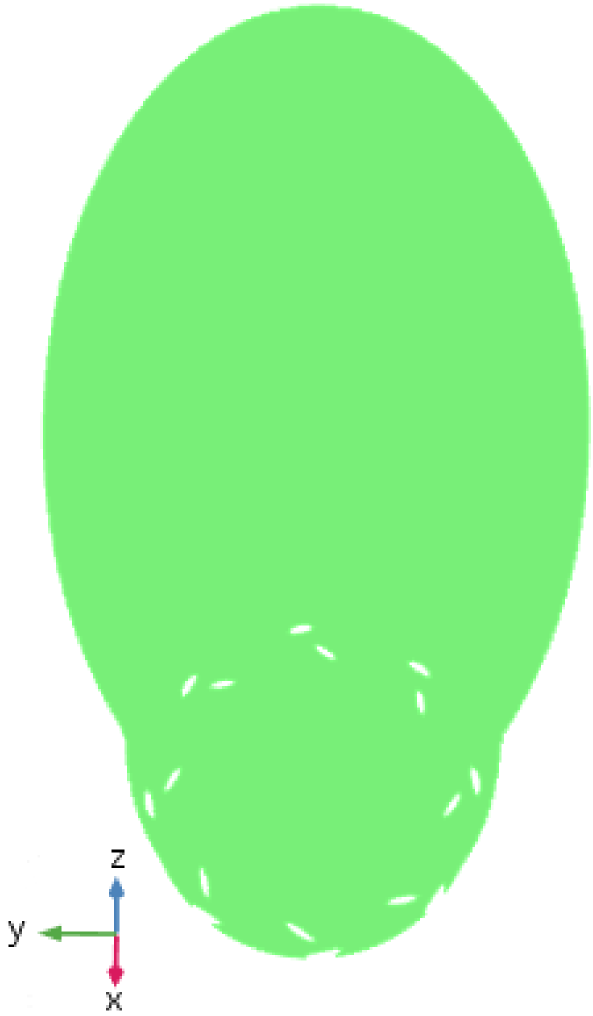
- Min. Quality: 8.75E-6
- Avg. Quality: 0.5757



Quality histogram:



Use symmetry?



not symmetric!

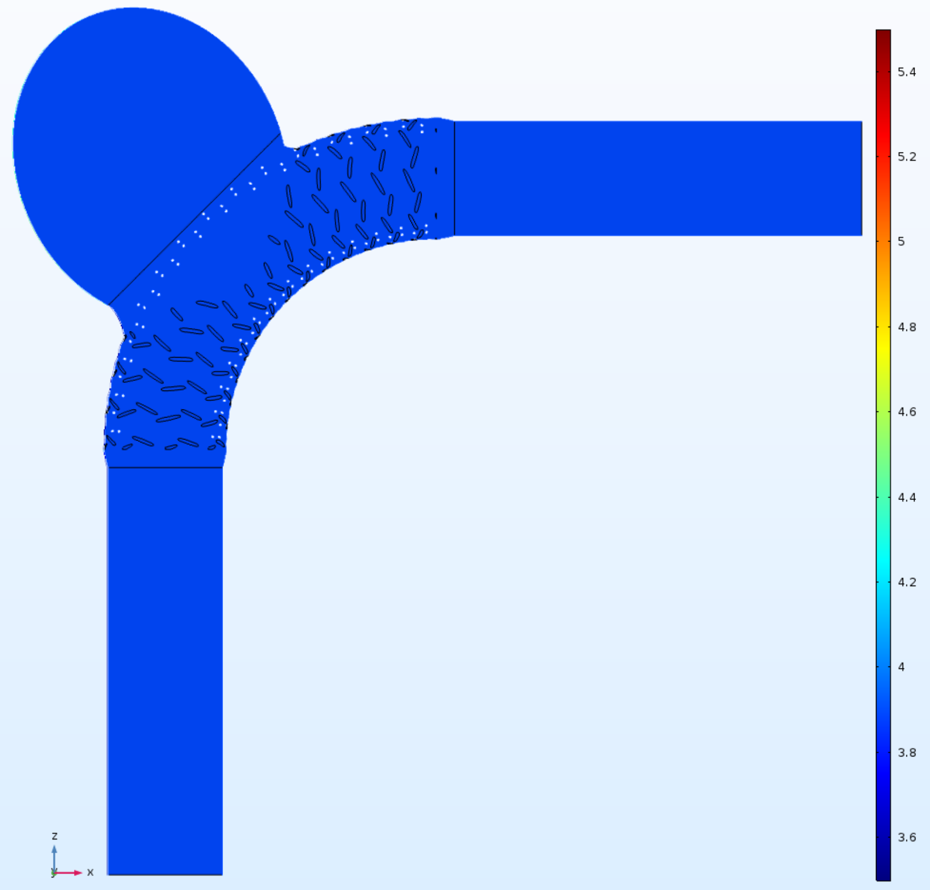
Simulation

Material sweep
(i7 Quadcore, 32GB RAM)

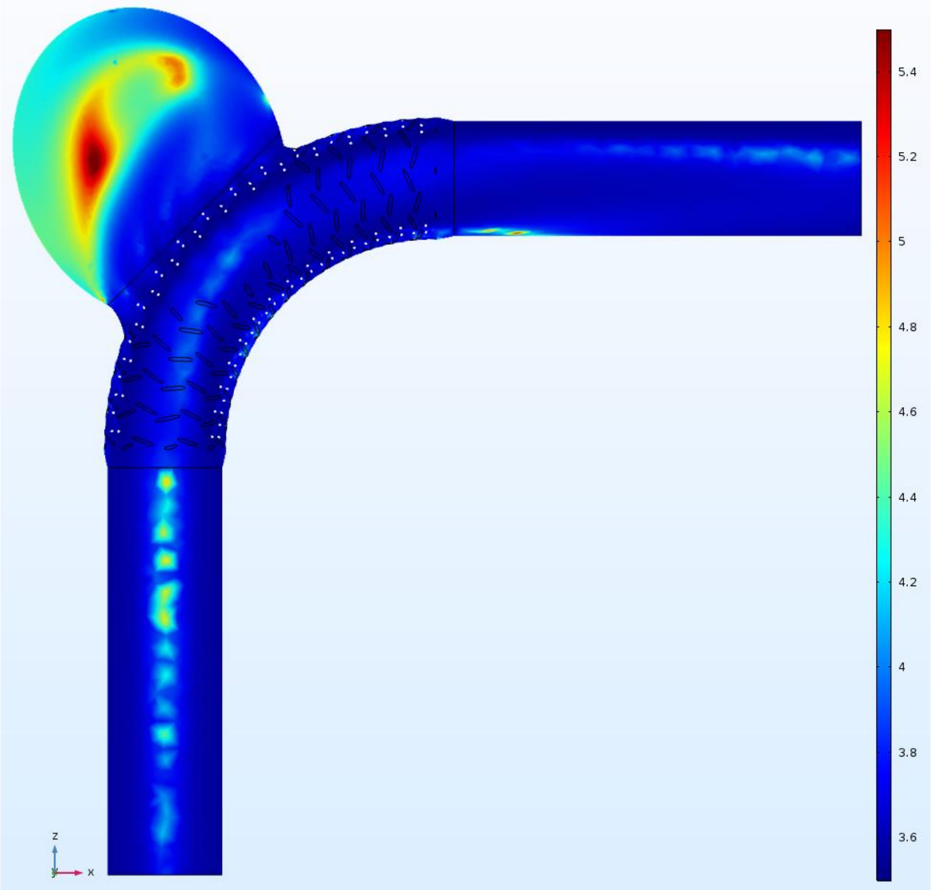
Stationary study:	Transient study (2s):
2:42:50	42:19:25

Viscosity profiles

Newtonian



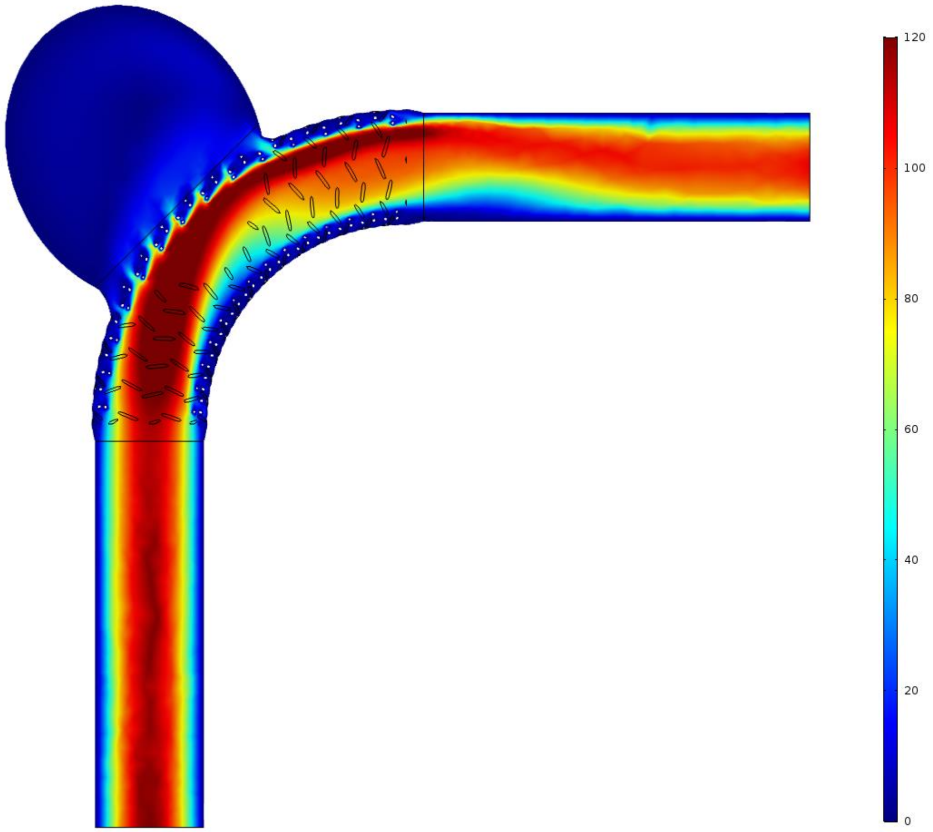
Carreau-Yasuda



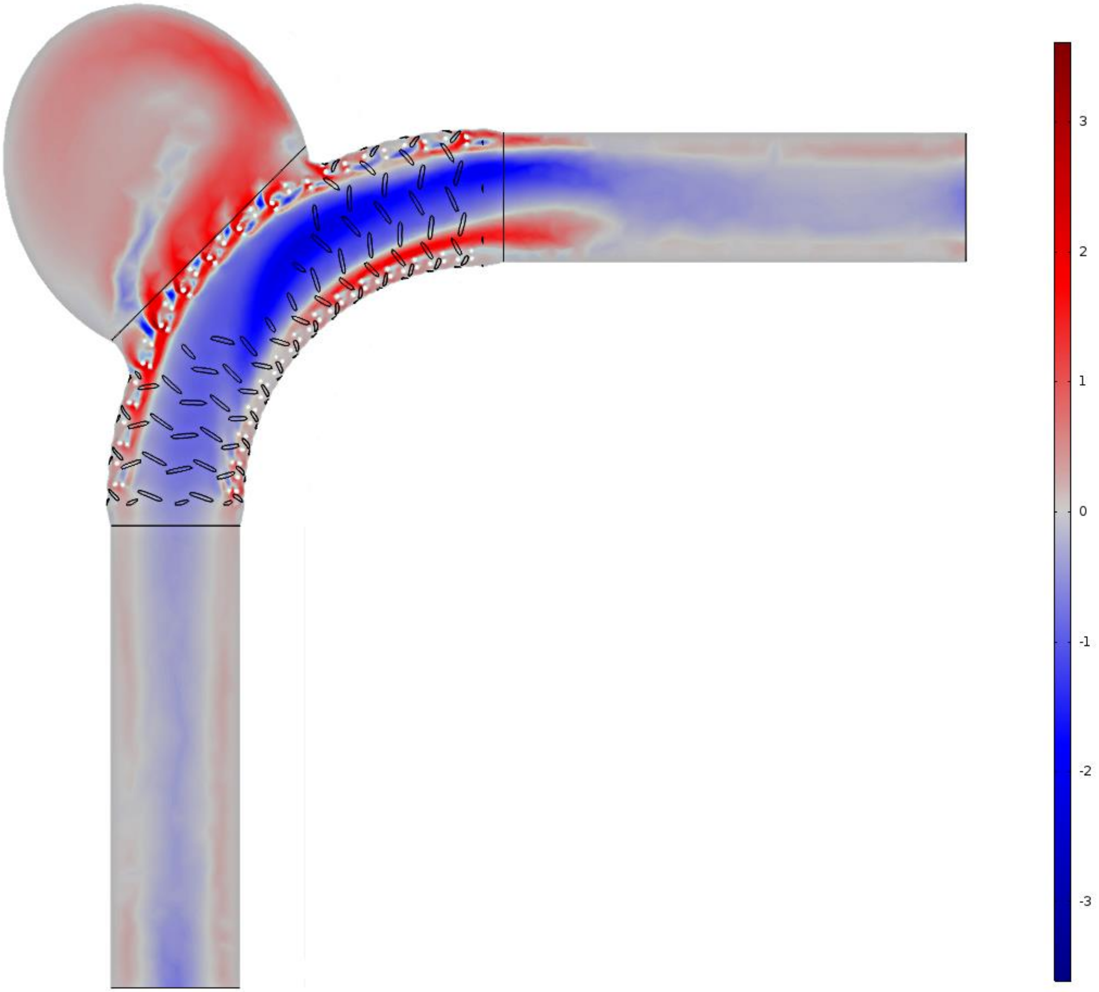
Blood flow profiles I

Newtonian

Carreau-Yasuda



Blood flow profiles II



- Carreau Yasuda minus Newtonian
- Newtonian model shows underestimation of the velocity by up to 6% within the aneurysm sack

Comparison of the results

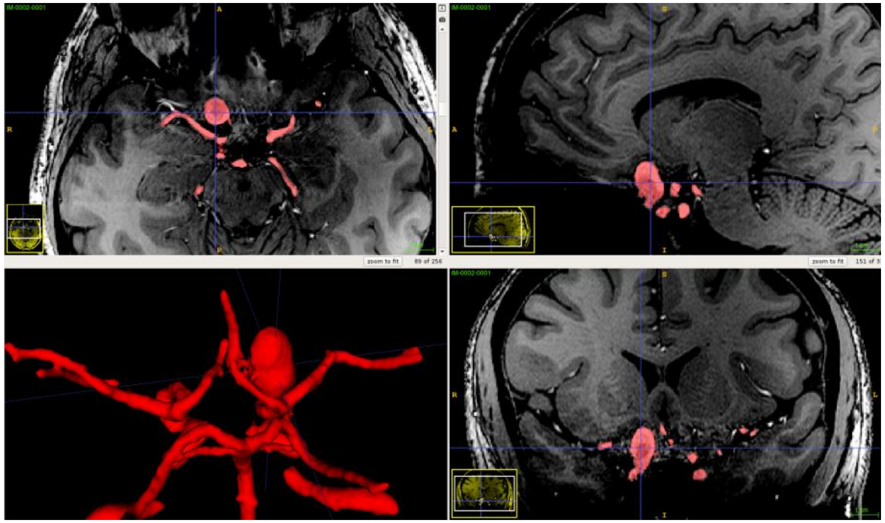
within the aneurysm sack
(above the neck plane)

	Newtonian		**Carreau - Yasuda**		**Difference**
min. shear rate	6.81	s^{-1}	5.30	s^{-1}	---
max. shear rate	2,174.9	s^{-1}	2,178.2	s^{-1}	---
Min. viscosity	3.89	mPa s	3.57	mPa s	---
Max. viscosity	3.89	mPa s	7.10	mPa s	---
Avg. velocity	4.71	$cm\ s^{-1}$	5.03	$cm\ s^{-1}$	+6.8%
Max. velocity	42.94	$cm\ s^{-1}$	43.98	$cm\ s^{-1}$	+2.4%
Tot. inflow	809.51	$mm^3\ s^{-1}$	842.92	$mm^3\ s^{-1}$	+4.1%

Conclusion

- Against first intuition, the Newtonian model overestimates the effect of the flow diverting stent
- The Newtonian model seems not to be sufficient for flow calculations past endovascular devices.

Outlook



Better blood model

- More measurements
- at even lower shear rates

Better aneurysm model

- In vivo imaging
- of stented aneurysms

Thank you!

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