

Patient-Specific Hemodynamics in FEniCS

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and

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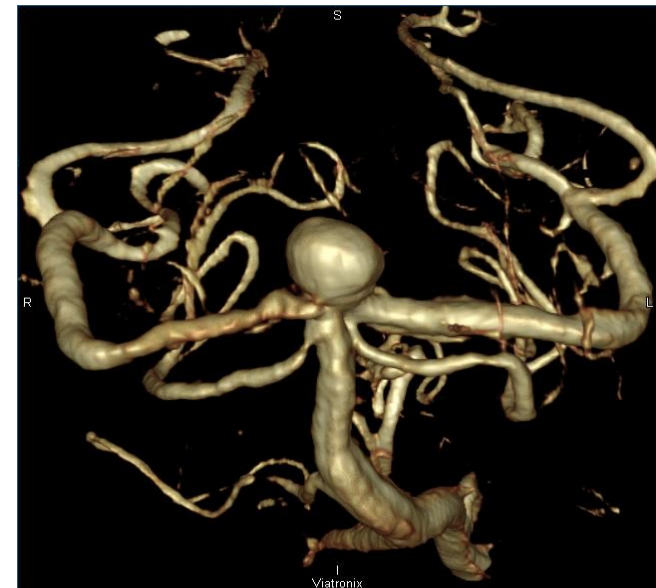
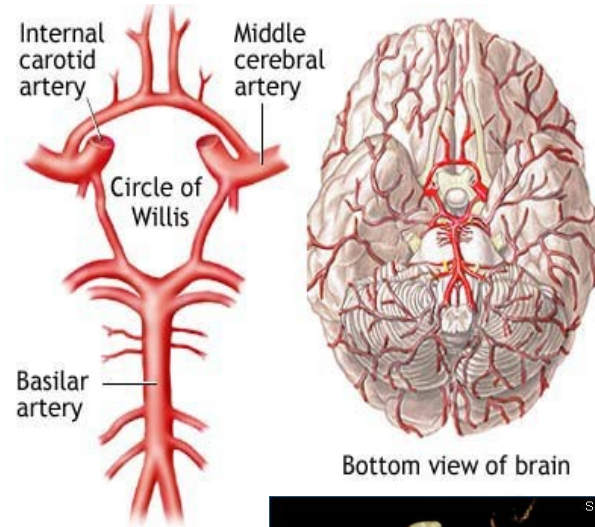
The circle of Willis

The circle of Willis is the brain's main supplier of blood

It connects the carotid and vertebral arteries into a network that ensures the brain with a stable blood supply even if one vessel is occluded

Unfortunately, aneurysms are often found in the circle of Willis (1-6%)

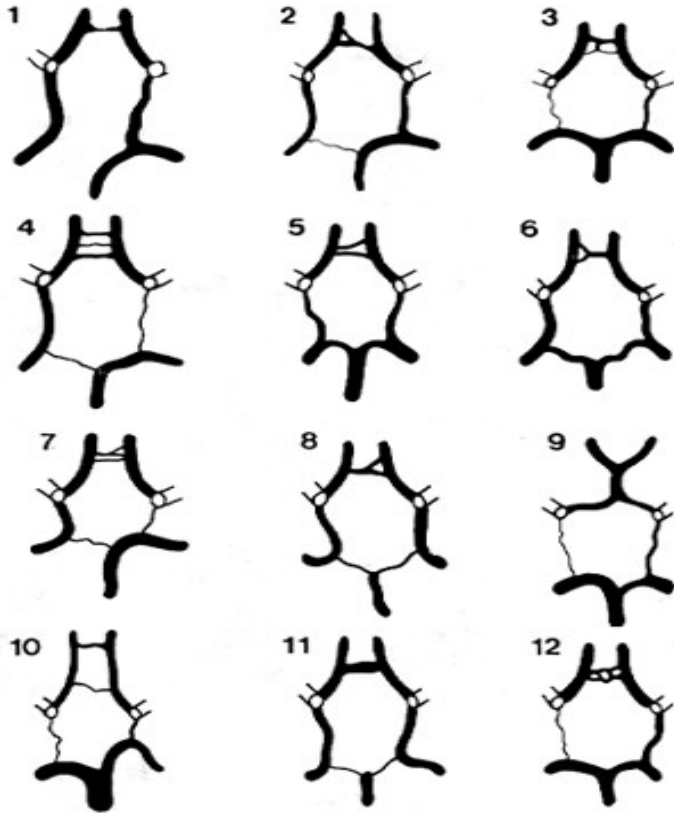
Aneurysms may rupture and cause a stroke
Annual risk is assumed to be ~ 1%



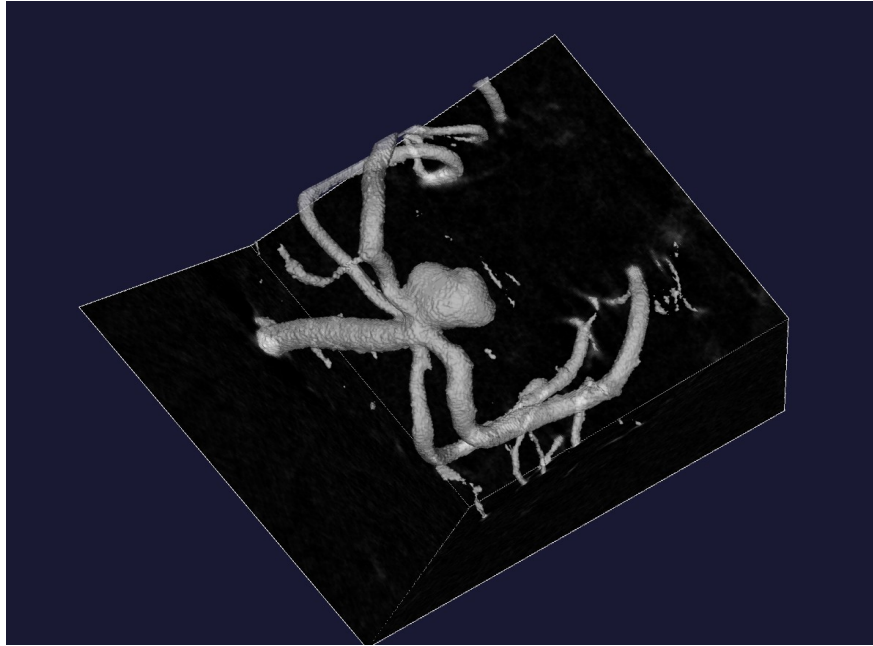
What causes aneurysm development and rupture?

Differences in anatomy ->
differences in flow

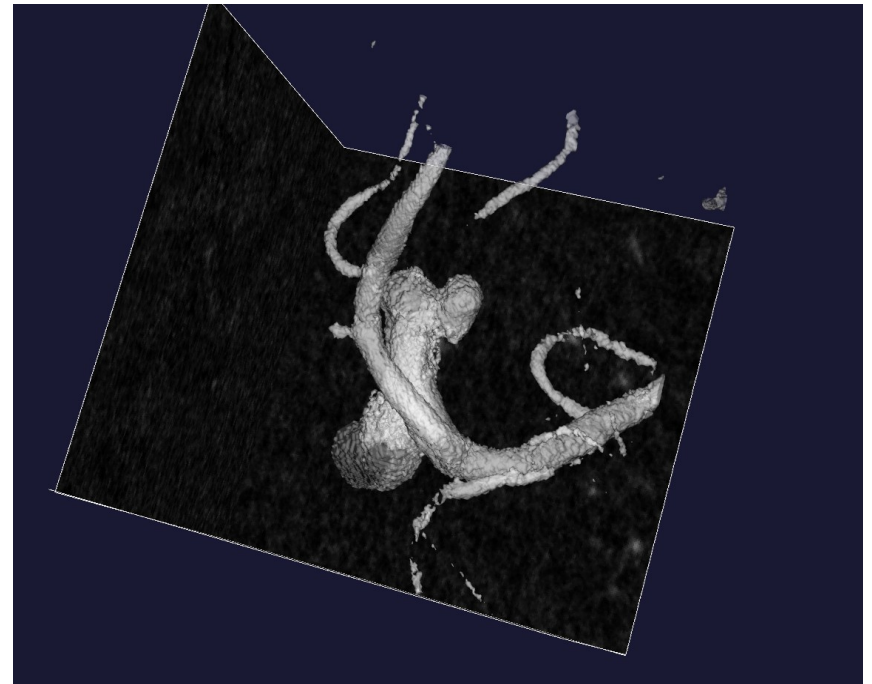
Great variations in anatomy
Eg only 50% have a well-
balanced circle



Clinical Problem: which aneurysms are at risk of rupture?



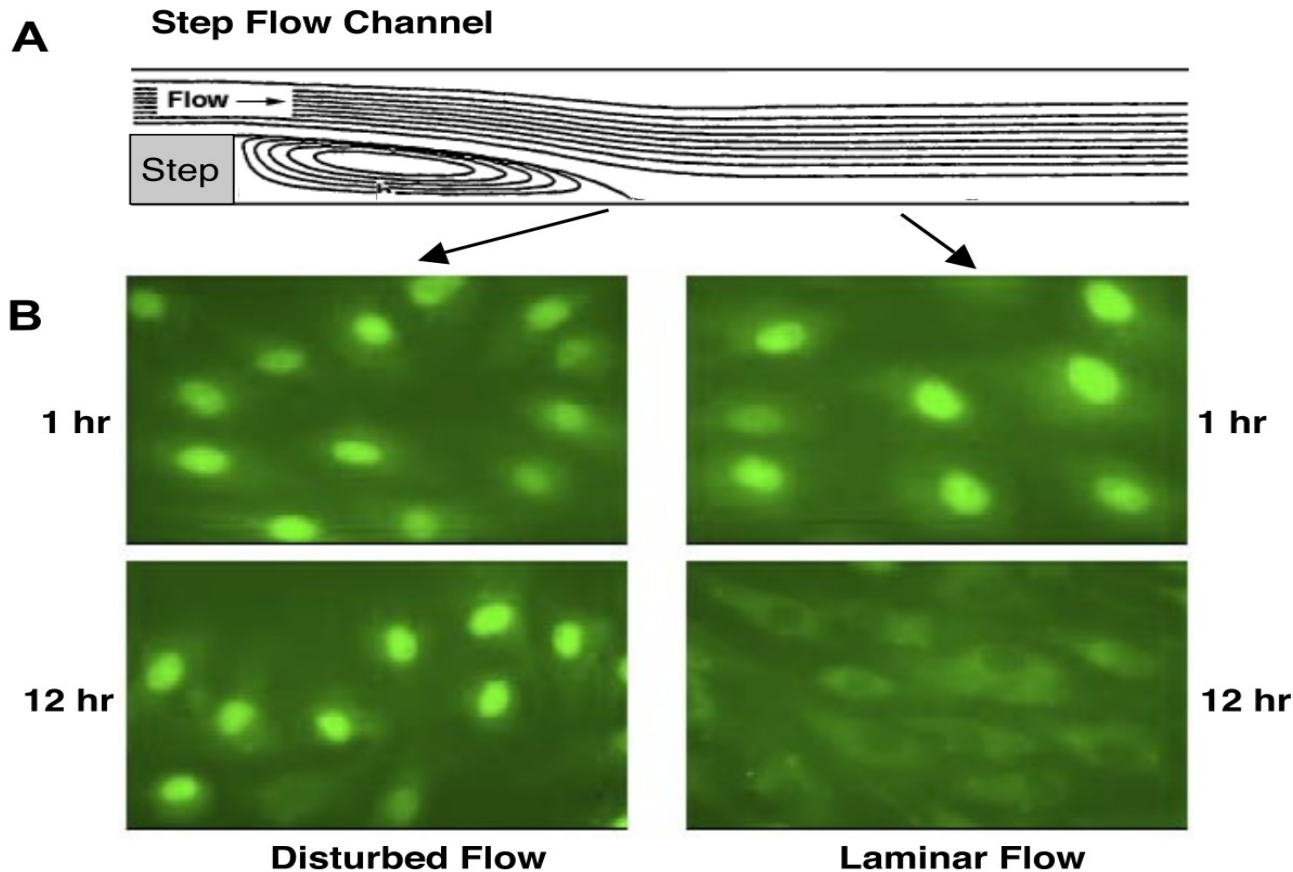
The biggest?



→
The one at the most (statistically) dangerous location?

These are examples of two common risk indicators, unfortunately none of them very precise

The endothelium layer remodel itself according to the flow conditions

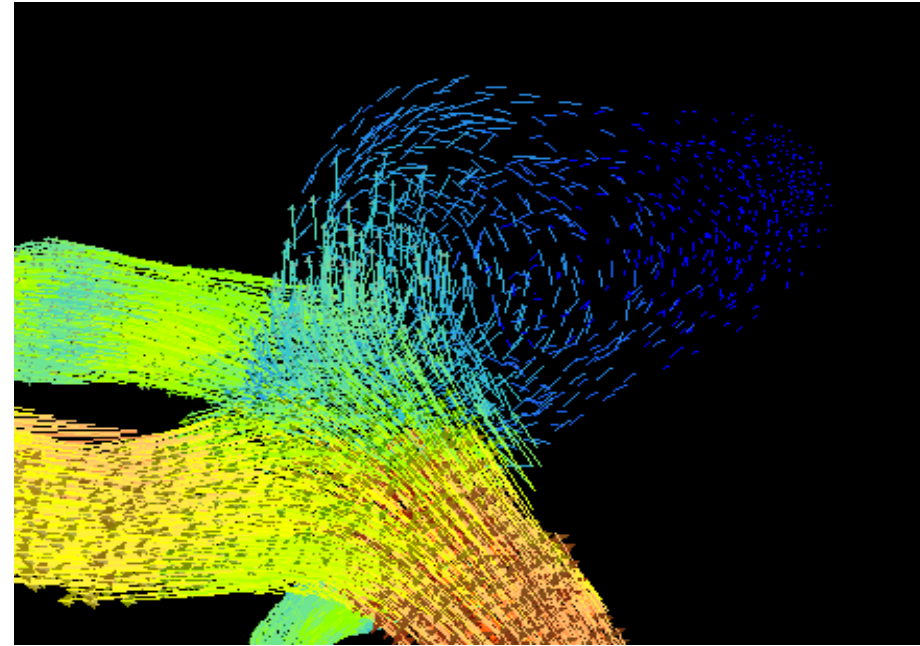


Chien, Am J Physiol Heart Circ Physiol, 2006

Can we provide better risk indicators?

Stress computations based on fluid flow or fluid-structure interaction seem as a promising tool

Patient-specific anatomies can be obtained with a reasonable accuracy



Popular computational risk indicators are low shear stress, high shear stress, oscillatory shear stress, and pressure

These indicators have been linked to remodeling of the vessel wall via the endothelium

Validation and testing in a patient specific case

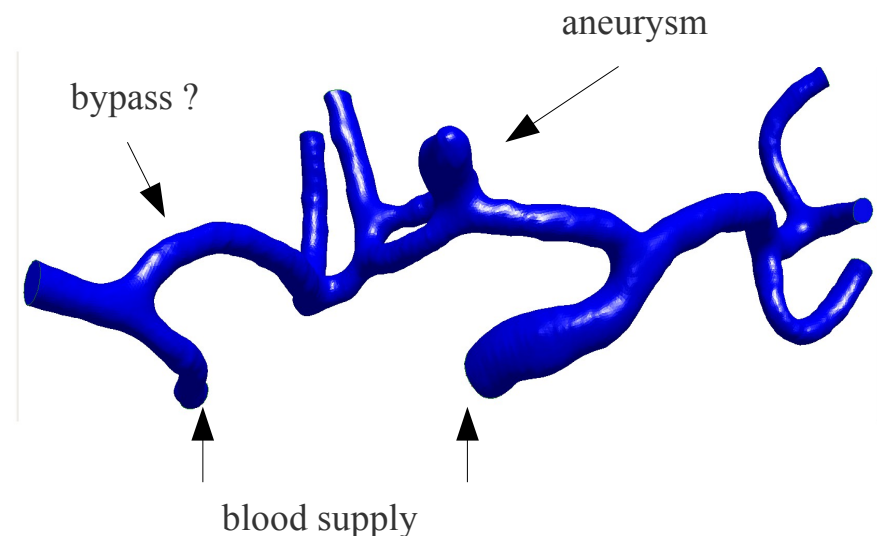
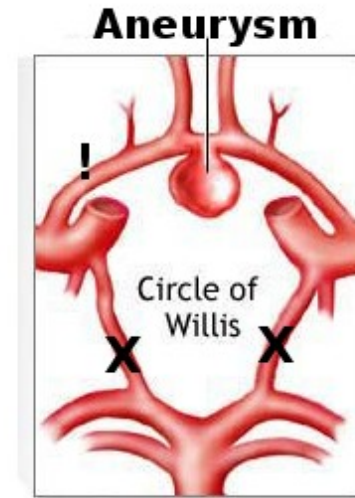
She has limited blood supply to the left part of the brain.

At the same time a growing aneurysm was discovered.

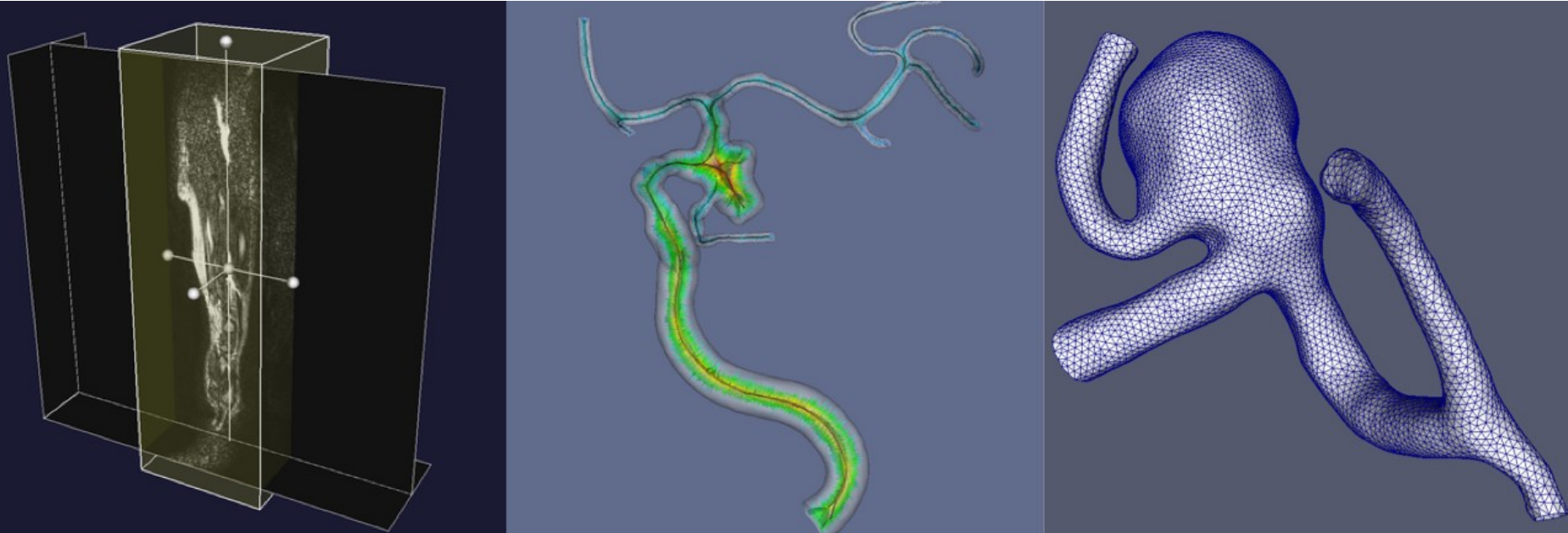
Problem that is to be evaluated

Can we compute a flow that is similar to the measured flow?

Would a bypass be beneficial ?



Software tools: VMTK – the vascular modeling toolkit



VMTK is a tool for 3D reconstruction, geometric analysis, mesh generation and surface data analysis for image-based modelling of blood vessels

Main developer: Luca Antiga, Bergamo, Italy

Development by Tangui (Kalkulo/Simula)

Generation of Dolfin mesh, boundary indicators, FSI mesh, resolution steering etc.

FEniCS: Chorin solver for Navier-Stokes equations

```
# Tentative velocity step
a0 = dot(v, u)*dx + k*nu*dot(grad(v), grad(u))*dx
L0 = dot(v, u0)*dx + k*dot(v, f)*dx - k*dot(v, mult(grad(u0), u0))*dx

# Poisson problem for the pressure
a1 = 1.0e-6*p*q*dx + dot(grad(q), grad(p))*dx
L1 = -(1.0/k)*q*div(us)*dx

# Velocity update
a2 = dot(v, u)*dx
L2 = dot(v, us)*dx - k*dot(v, grad(pl))*dx

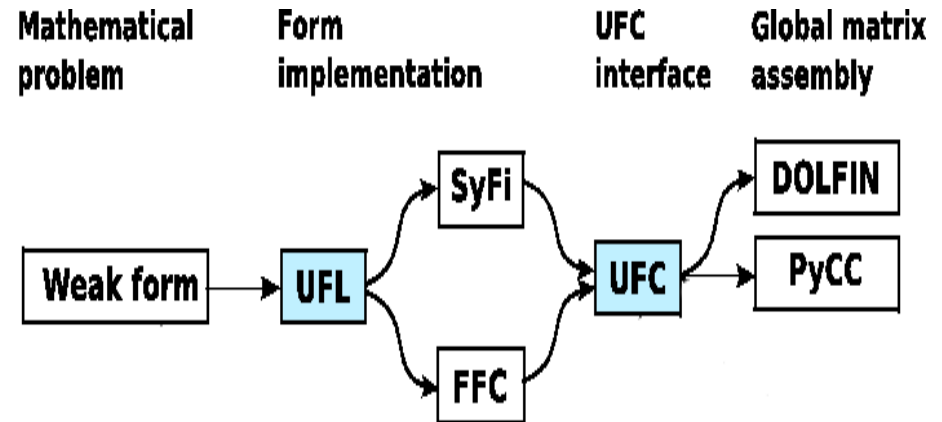
# Assemble matrices
A0 = assemble(a0, mesh)
A1 = assemble(a1, mesh)
A2 = assemble(a2, mesh)

while t < problem.T:

    # Propagate values to next time step
    t += dt
    u0.assign(u1)

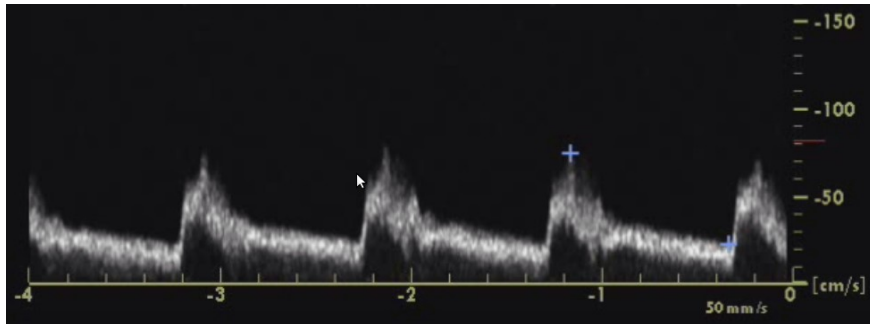
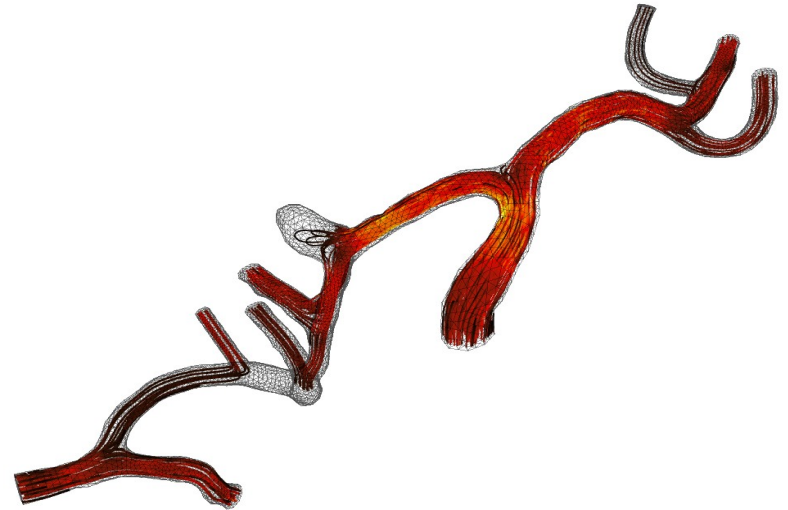
    # Compute tentative velocity
    b = assemble(L0, mesh)
    [bc.apply(A0, b, a0) for bc in problem.bcv]
    solve(A0, us.vector(), b, gmres, ilu)

    # Compute p1
    b = assemble(L1, mesh)
    print len(problem.bcp)
    if len(problem.bcp) == 0: normalize(b)
    [bc.apply(A1, b, a1) for bc in problem.bcp]
    solve(A1, pl.vector(), b, gmres, amg)
    if len(problem.bcp) == 0: normalize(pl.vector())
```



Patient specific Simulations

- CT-scan, Doppler measurements
- Generated a surface mesh (VMTK)
- Generated a volume mesh (VMTK)
- Computational fluid dynamics (FENICS)



Intracranial Doppler measurements

Incompressible Navier-Stokes equations with rigid, impermeable walls solved with Fluent

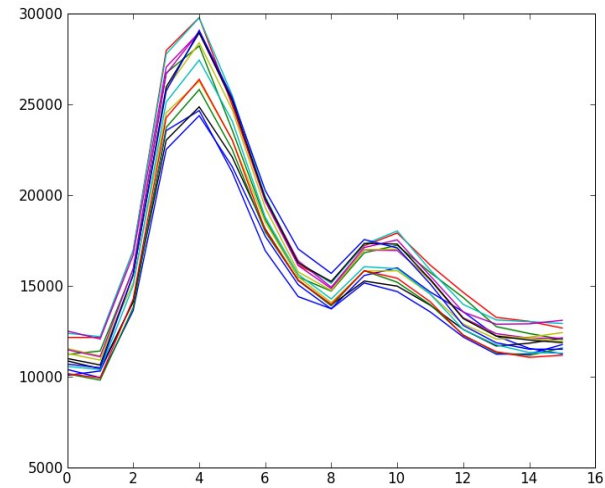
Our validation failed, boundary conditions are highly patient-specific (Resistance coeff. differ by factor 5)

Validation through canine models

Experiments done by Charles Strother and co-workers

Novel MR techniques to measure the flow at a resolution $\sim (0.5 \text{ mm})^3$

Flow seems very different in simulations and measurements when using standard boundary conditions



Uncertainties...

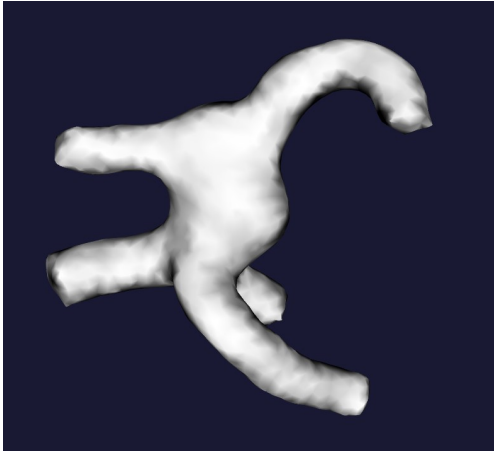


Figure 1. During segmentation.

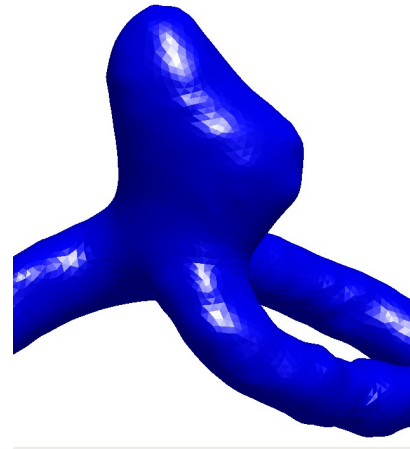


Figure 2. Removed a blood vein.



The anatomy is uncertain

Velocity measurements and corresponding boundary conditions are even more uncertain!

Conclusions and future work

More advanced models like FSI, non-linear rheology, turbulence etc may be required, currently our validation has failed

The accuracy in the input data seem to be a major bottleneck

FEniCS, with its scripting capabilities, is an ideal platform for patient studies

We have a (small) database of (human) aneurysms and additional data from canine experiments