Center for Biomedical Computing

Cerebrospinal fluid flow in the upper cervical canal in patients with the Chiari I malformation

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Outline

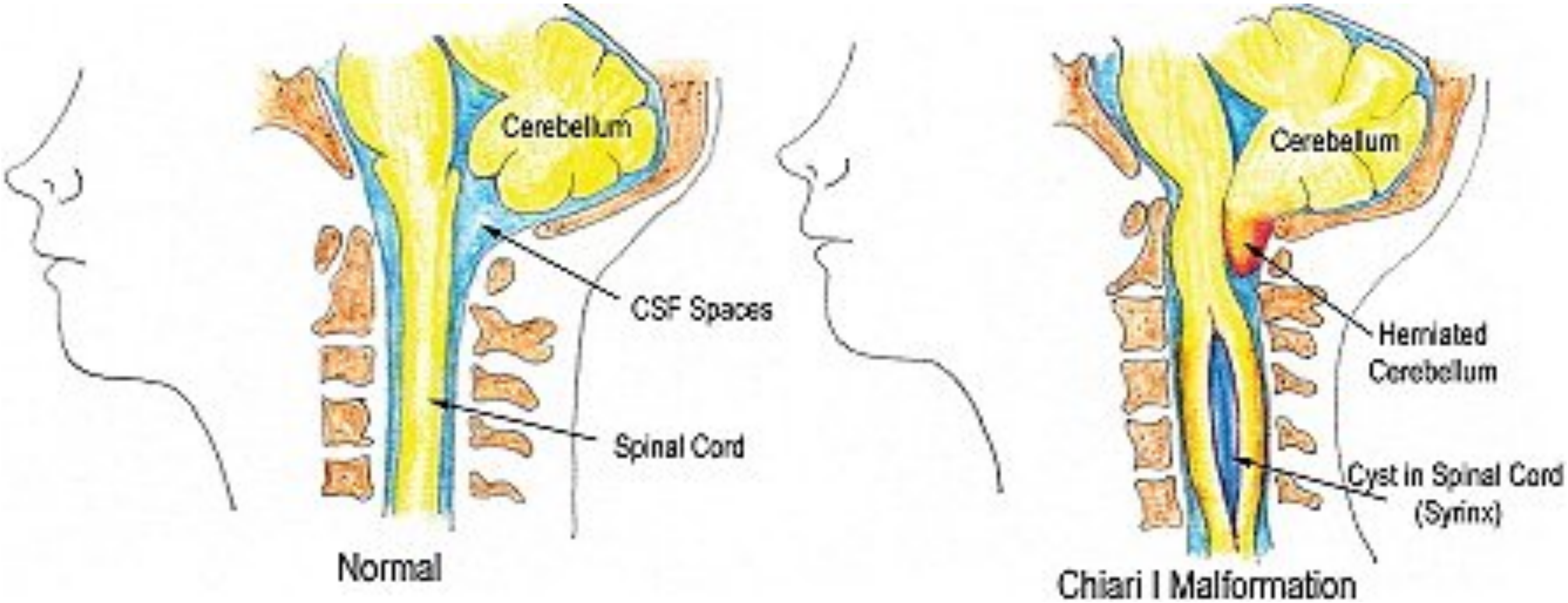
Short medical background

Pressures and velocities in patient specific models

Bernoulli effect (Greitz´s theory)

Porous media models

The Chiari I malformation is a serious condition where the cerebellar tonsils are displaced downwards past the foramen magnum



Obstruction → Abnormal flow

CSF velocities are different in Chiari/syringomyelia patients and normals

- Differences in anatomy characterize the conditions Chiari and syringomyelia
- Velocity differences has been shown differ between Chiari patients and normals in e.g. Haugthon et al, AJNR 2003, Quigley et al, Radiology 2004, Shah et al AJNR 2011
- Working hypothesis:

  Abnormal anatomy -> abnormal flow ->

  abnormal pressure/stress

Related question:

What makes cysts grow?

A CFD study of 13 subjects

Patient characteristics

	Tonsils (mm)	Gender	Age (years)	Syrinx
Volunteer no.				
7	x	NA	NA (adult)	x
9	x	NA	NA (adult)	x
59	x	F	13	x
Chiari I patient no.				
43	12	M	2	x
5	9	M	4	x
26	13	F	5	x
11	6	F	30	x
21	2	F	40	x
58	5	M	10	x
60	5	F	16	x
Postoperative no.				
36	12 (pre-op)	M	54	C1-T10
19	5	F	31	yes
18	x	M	3	x

Table 4.1: *Explanation of the symbols: M=male, F=female, NA = not available, x = not present (syrinx)/ not herniated (tonsils), pre-op = measured prior to surgery, C1-T10 - length of the syrinx.*

Rutkowska, Linge, Haugthon, Mardal, to be submitted to AJNR

Characteristics of the 13 subjects

Model characteristics							
			Deviation from average area				
	Length cm (cm)	Average area (cm³)	C1 (%)	C2 (%)	C3 (%)	C4 (%)	C5 (%)
Volunteer no.							
7	11,0	0,136	63,5	-0,4	-21,0	-20,0	-22,1
9	10,2	0,140	54,0	1,1	-14,2	-16,1	-24,7
59	9,6	0,206	128,0	-0,7	-33,8	-48,3	-45,1
Average	**10,3**	**0,160**	**81,8**	**0,0**	**-23,0**	**-28,1**	**-30,6**

Chiari I patient no.							
43	5,5	0,104	30,0	7,1	-7,5	-14,9	-14,7
5	8,1	0,159	56,0	16,8	-20,0	-34,1	-18,7
26	6,2	0,157	51,3	2,8	-16,4	-18,7	-19,0
11	9,4	0,232	38,6	7,5	-21,6	-18,3	-6,2
21	9,0	0,260	37,6	20,6	-5,0	-25,0	-28,1
58	8,8	0,146	80,2	-7,7	-24,6	-26,1	-21,8
60	9,2	0,176	56,9	-4,7	-19,7	-17,3	-15,3
Average	**8,0**	**0,176**	**50,1**	**6,1**	**-16,4**	**-22,1**	**-17,7**

Postoperative patient							
36	7,7	0,145	72,3	11,8	-26,0	-28,0	-31,0
19	9,8	0,189	66,2	-7,6	-21,4	-22,4	-14,7
18	5,6	0,970	38,7	-16,4	-17,5	-13,1	8,4
Average	**7,7**	**0,435**	**59,1**	**-4,1**	**-21,6**	**-21,2**	**-12,4**

Numerical model used in the study

- We assume laminar Newtonian flow, rigid and impermeable walls
- We use a finite element implementation of the incremental pressure correction scheme (a projection method) with semi-implicit handling of convection, and implicit Euler
- Boundary conditions are p(top) – p(bottom) = A sin(2*pi*t), where A = 24.3 Pa (since they are unknown)
- Poiseuille flow predicts 42% higher velocities in the Chiari I patients

Software: FEniCS + VMTK

```
# Tentative velocity step
U = 0.5*(u0 + u)
F1 = (1/k)*inner(u - u0, v)*dx \
   + inner(grad(u0)*u0, v)*dx \
   + inner(sigma(U, p0, nu), epsilon(v))*dx \
   + inner(p0*n, v)*ds \
   - beta*nu*inner(grad(U).T*n, v)*ds \
   - inner(f, v)*dx
a1 = lhs(F1)
L1 = rhs(F1)

# Pressure correction
a2 = inner(grad(p), grad(q))*dx
L2 = inner(grad(p0), grad(q))*dx \
   - (1.0/k)*div(u1)*q*dx

# Velocity correction
a3 = inner(u, v)*dx
L3 = inner(u1, v)*dx - k*inner(grad(p1 - p0), v)*dx
```

VMTK is used for segmentation and mesh generation

FEniCS is a finite element library
(book *Automated Solution of Differential Equations by the Finite Element Method* in press at Springer, Eds: Logg, Mardal, Wells)

Illustration of the simulations (healthy and postop.)

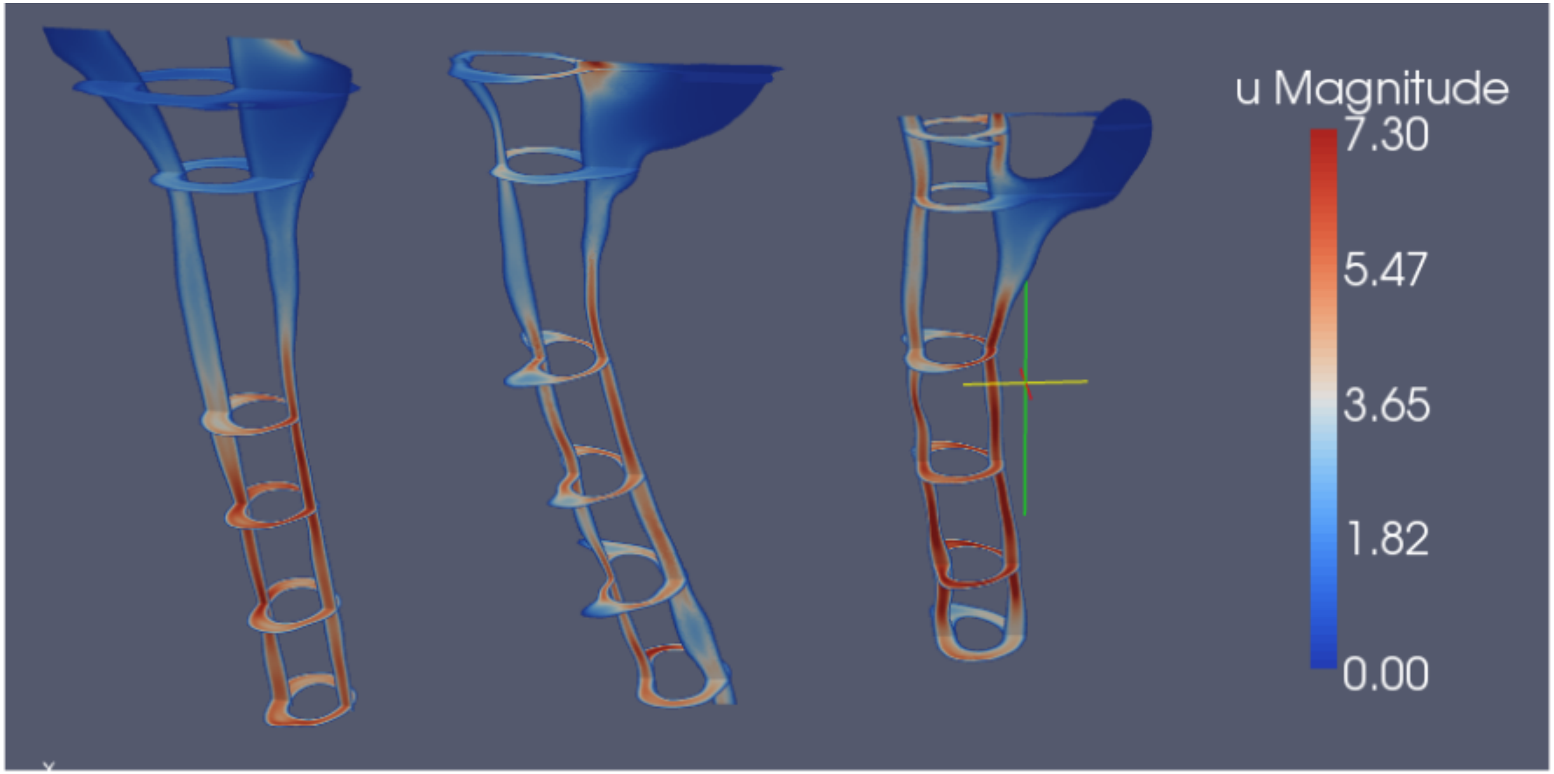


Figure 4.11: *Peak systolic velocity magnitudes in one volunteer (left) and two postoperative patients with signs of tonsils at foramen magnum. The displayed velocity magnitude-range has been rescaled in order to improve visualization.*

Illustrations of simulations (Chiari I patients)

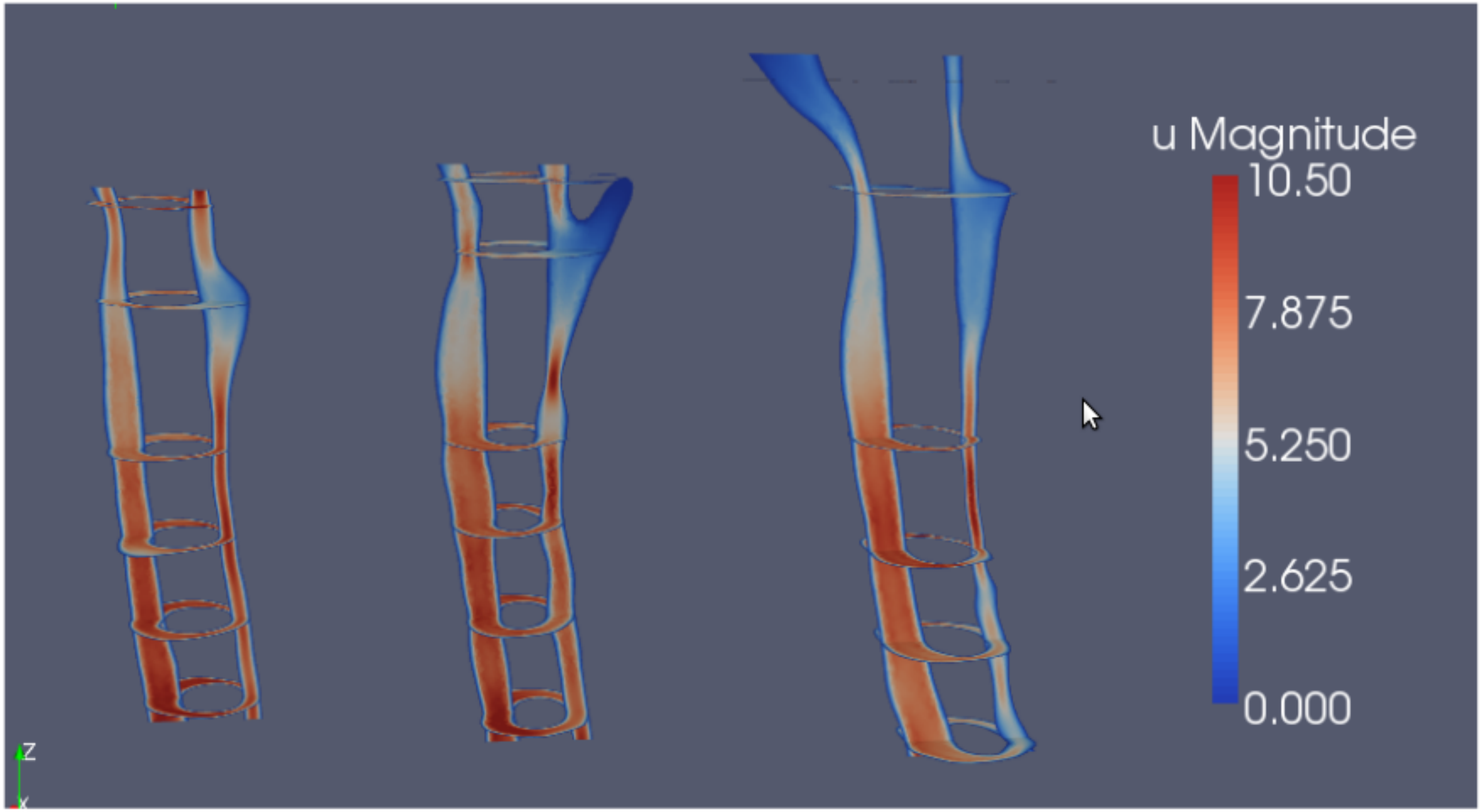
- 

Figure 4.10: *Peak systolic velocity magnitudes in three Chiari patients. The displayed velocity magnitude-range has been rescaled in order to improve visualization.*

Bidirectional flow was most clearly seen in Chiari patients and this corresponds well with clinical observations

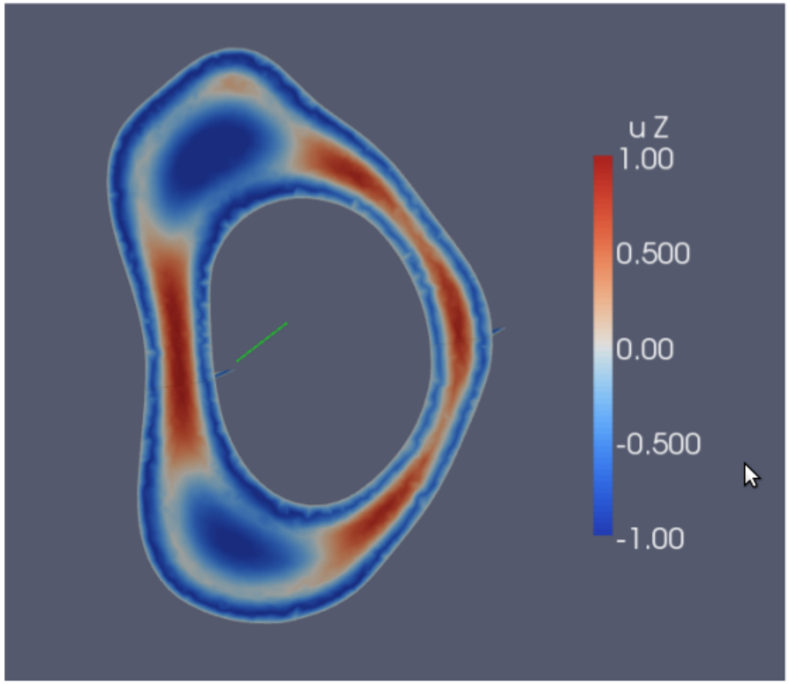


Figure 4.18: *Synchronous bidirectional flow at $t = 0.25$ s at the level of C3 in a Chiari patient.*

Quigley et al, Radiology, 2004, made the same observations using MR

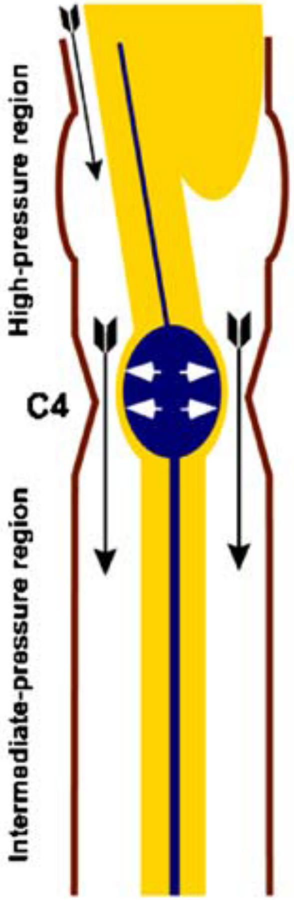
The velocities differ quite a bit between the three groups!

Flow characteristics				
	Max v systole (cm/s)	Max v diastole (cm/s)	Max bidir flow difference (cm/s)	Bidirectional flow duration (s)
Volunteer no.				
7	6,8	6,5	3,8	0,20
9	7,5	7,4	3,2	0,22
59	7,9	7,5	5,3	0,18
Average volunteers	**7,4**	**7,1**	**4,1**	**0,20**
Chiari I patient no.				
43	12,1	10,9	7,2	0,24
5	11,9	11,8	7,6	0,30
26	11,5	11,4	7,5	0,22
11	11,4	8,8	6,0	0,38
21	9,4	8	5,4	0,24
58	7,7	7,6	4,9	0,20
60	7,5	6,9	4,5	0,24
Average patients	**10,2**	**9,3**	**6,2**	**0,26**
Postoperative patient				
36	10	9,9	5,5	0,22
19	8,3	7,8	4,4	0,22
18	15,6	15,7	7,3	0,18
Average postoperative:	**11,3**	**11,1**	**5,7**	**0,21**

Table 4.9: *Flow characteristics in all the studied models after simulations with equal pressure gradient for all patients.*

38% higher velocities in Chiari patients

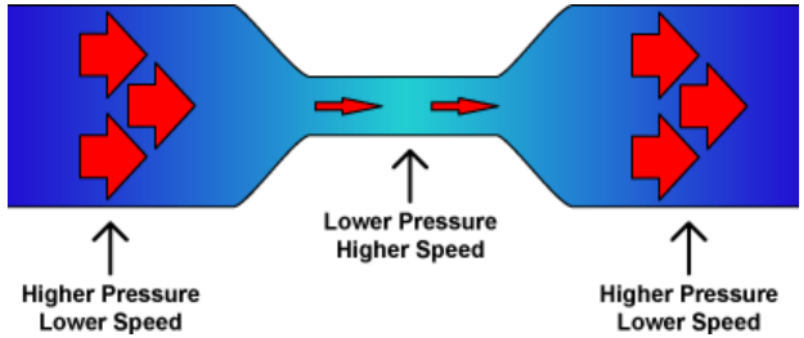
Obstruction of the CSF space causes a pressure drop which leads to cyst formation (Greitz)



Greitz (2006)

Bernoulli's law:

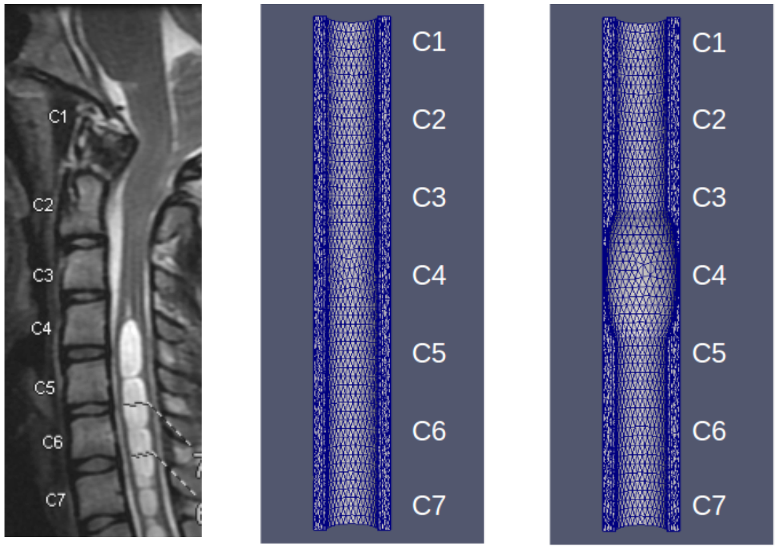
$$p_1 + \frac{1}{2}\rho u_1^2 = p_2 + \frac{1}{2}\rho u_2^2$$



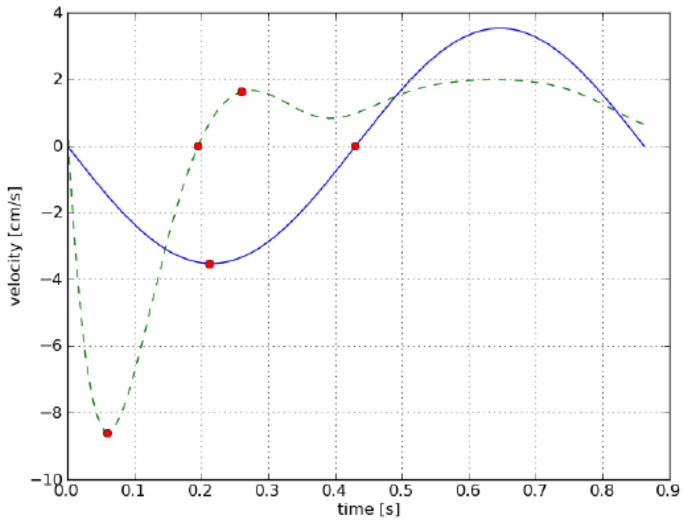
Assumptions:

- No viscous forces
- Steady flow

Testing Greitz´s theory computationally



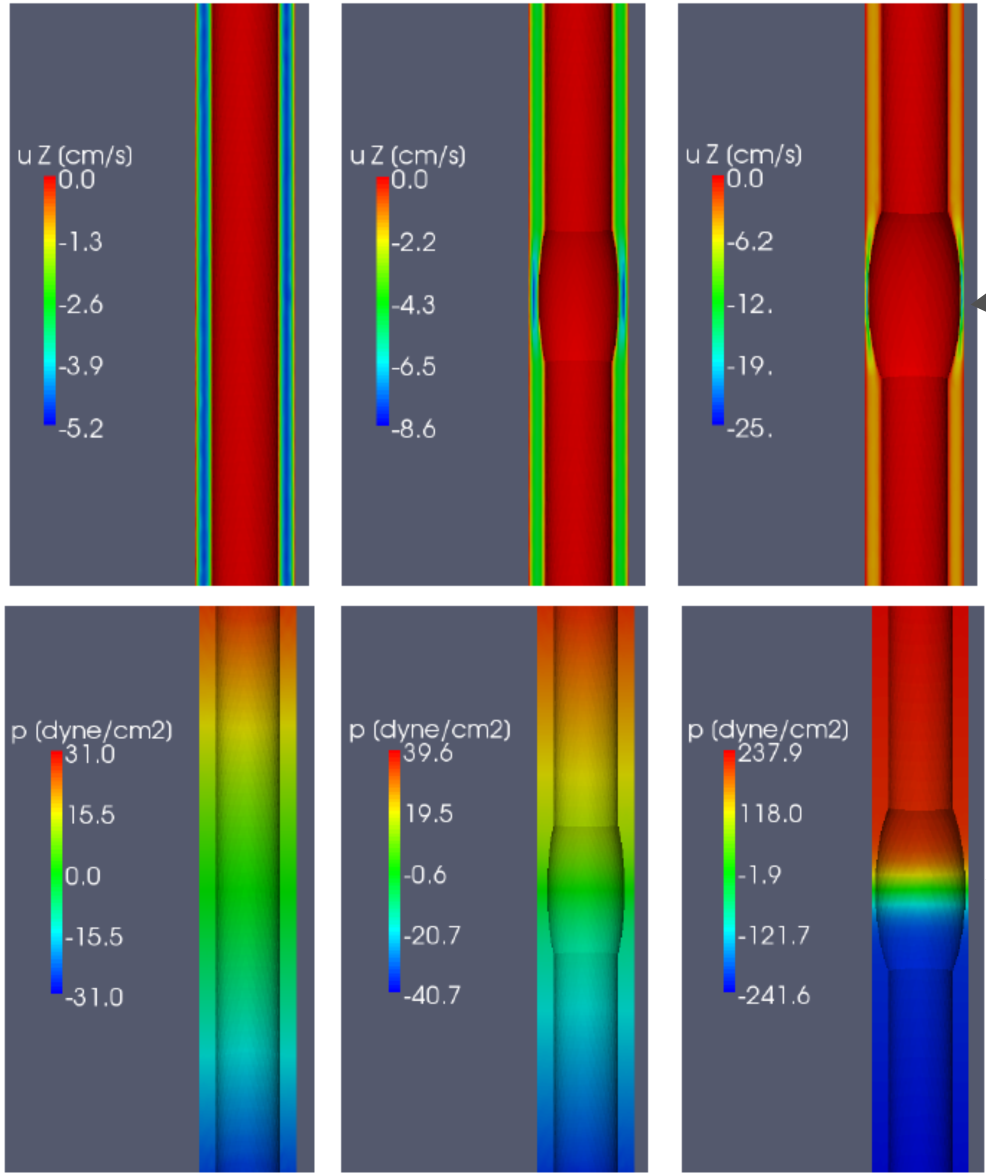
Geometries



Flow boundary conditions

Støverud, Mardal, Langtangen, Haugthon, Mekit11

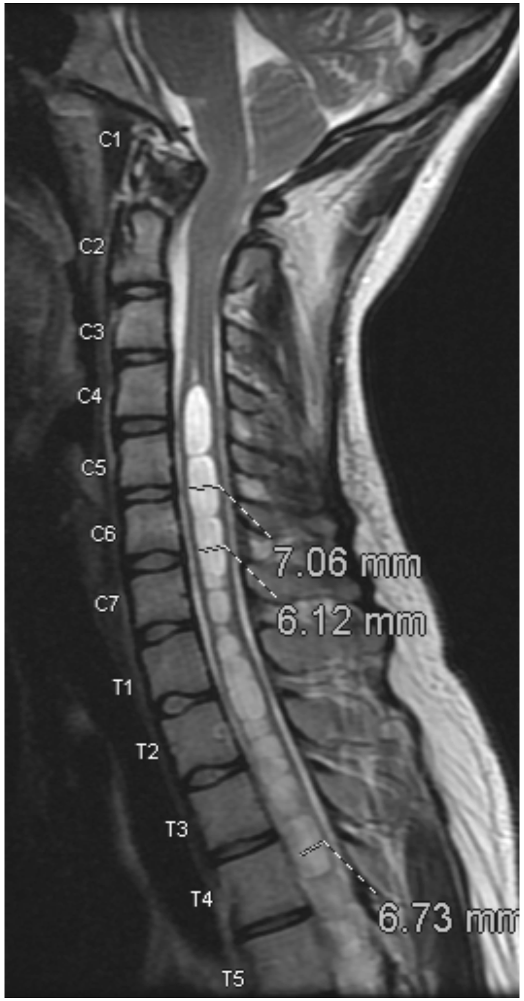
Obstructions of the CSF space give increased velocities and steeper pressure gradients



Five fold of velocity

Steeper pressure gradient

Why do 50% of Chiari patients develop syringomyelia?



How do oscillatory CSF flow in the subarachnoid space affect the spinal cord?

Pressure fluctuations do not travel far!

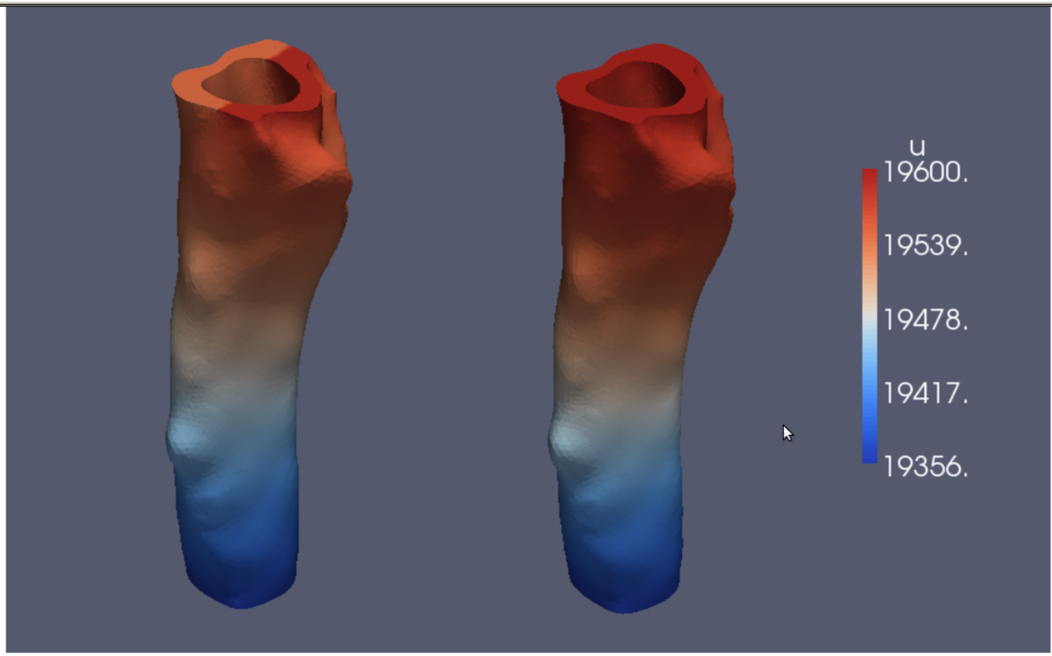
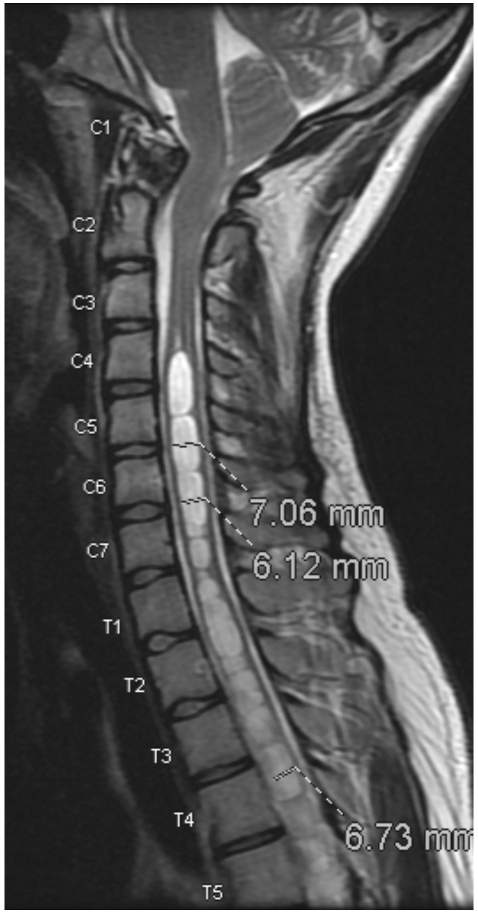


Figure 3.16: *Pressure distribution with uneven pressure gradient (left) and even gradient (right) set at the top of the model.*



The pressure fluctuation is in this case 20% and it clearly does not travel far. No difference at C2.

Coupled viscous and porous flow simulations

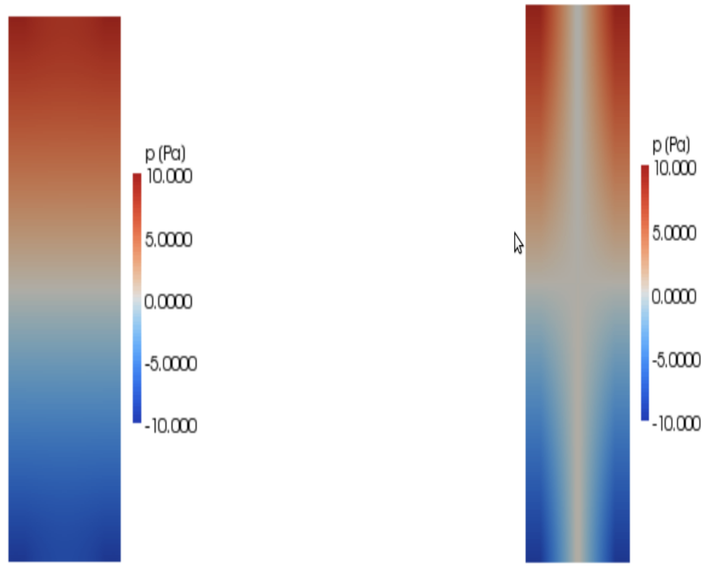
We model the cord as a porous media (Darcy´s law) coupled incompressible viscous flow in SAS

Boundary conditions are
sine function in the SAS + BJS cond and
nu K = 1.4*10^-15 m^2

2D simulations, using inc. pressure corr. scheme.
(dark grey is Darcy domain)

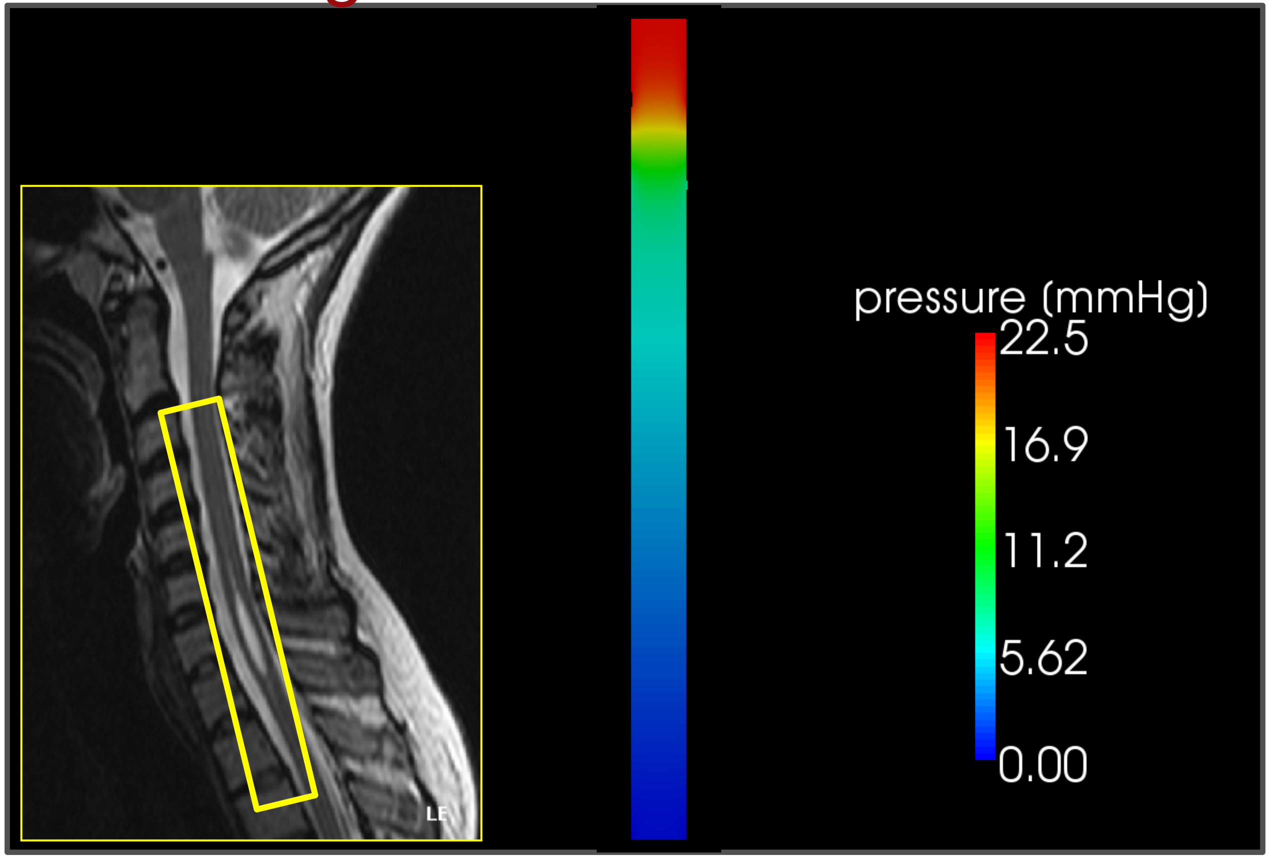
Drøsdal, Haugthon, Mardal, Støverud, CFD2011

The central canal has a huge impact on the pressure distribution



Left picture shows pressure without central canal, while right picture shows pressure with central canal

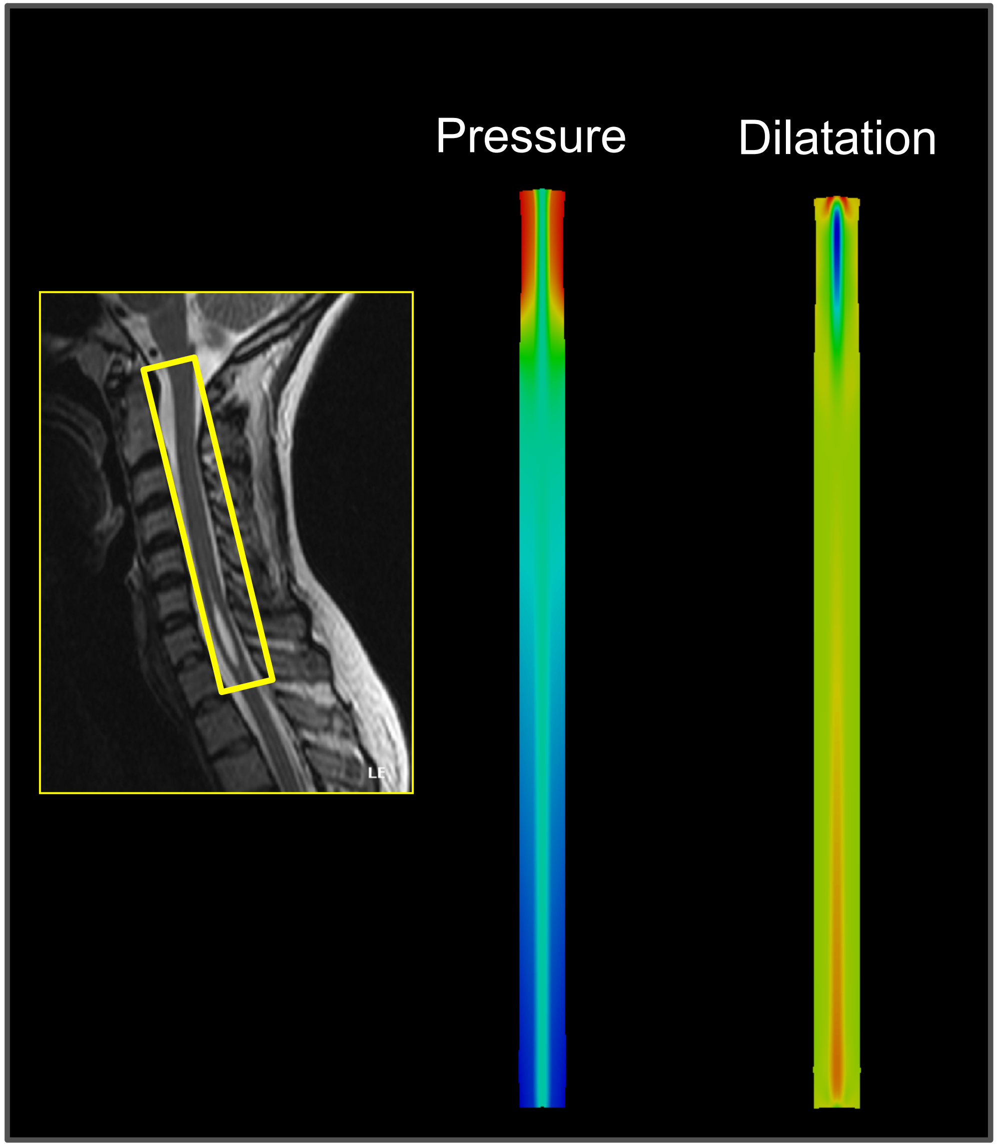
We created an idealized model of a poroelastic spinal cord with central canal and prescribe the pressure in the surrounding CSF



Using Biot equations with material parameters taken from Smith, Humphrey, Microvasc. Research 2007

Støverud, Mardal, Haugthon, Langtangen NRJ 2011

We model the spinal cord as poro-elastic medium and prescribe the pressure in the surrounding CSF



Fluid accumulates in regions of high permeability

Conclusions

Abnomal anatomy seem to generated abnormal flow, pressure and stress in Chiari patients

The distance between the Chiari malformation and the cysts are difficult to explain, but porous/elastic models with central canal could explain it

Papers can be found on my homepage:

www.simula.no/people/kent-and/bibliography