Effects of CSF pressure waves on the spinal cord tissue

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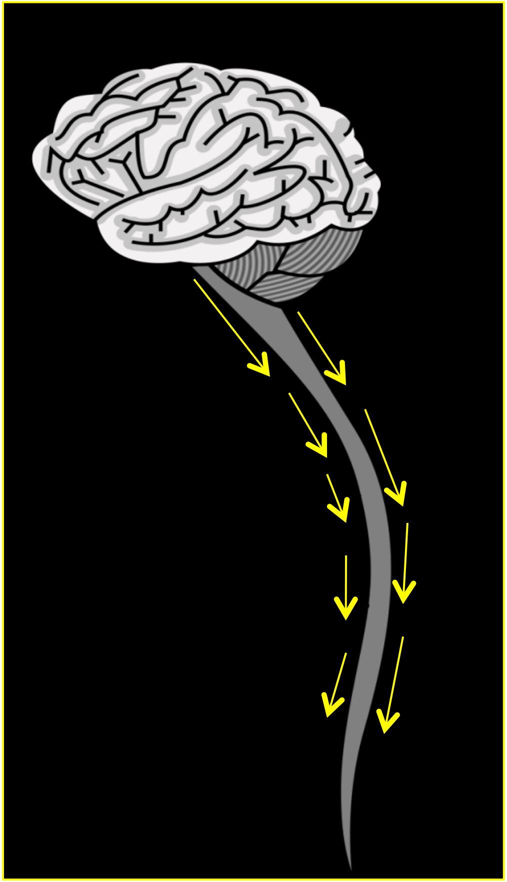
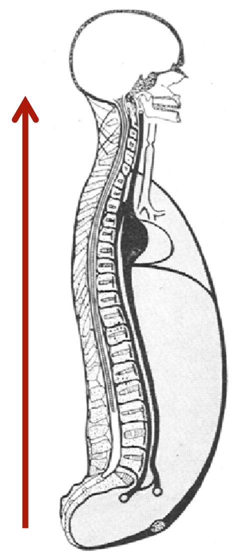
San Diego, May 2013

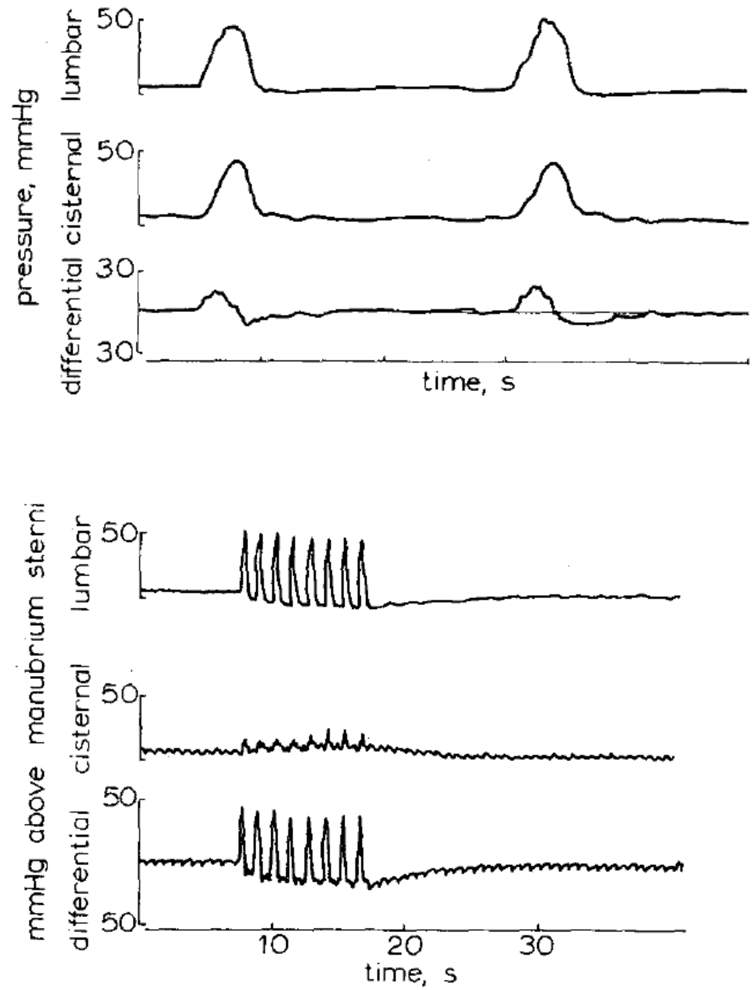


Hyphothetically, pressure waves causes fluid and tissue movement in the cervical spinal cord

- ✓ Current studies on pressure waves
- ✓ Assume porous & elastic spinal cord
- ✓ Comparison with linear elasticity

An obstruction in the subarachnoid space (SAS) attenuates and delays pressure waves





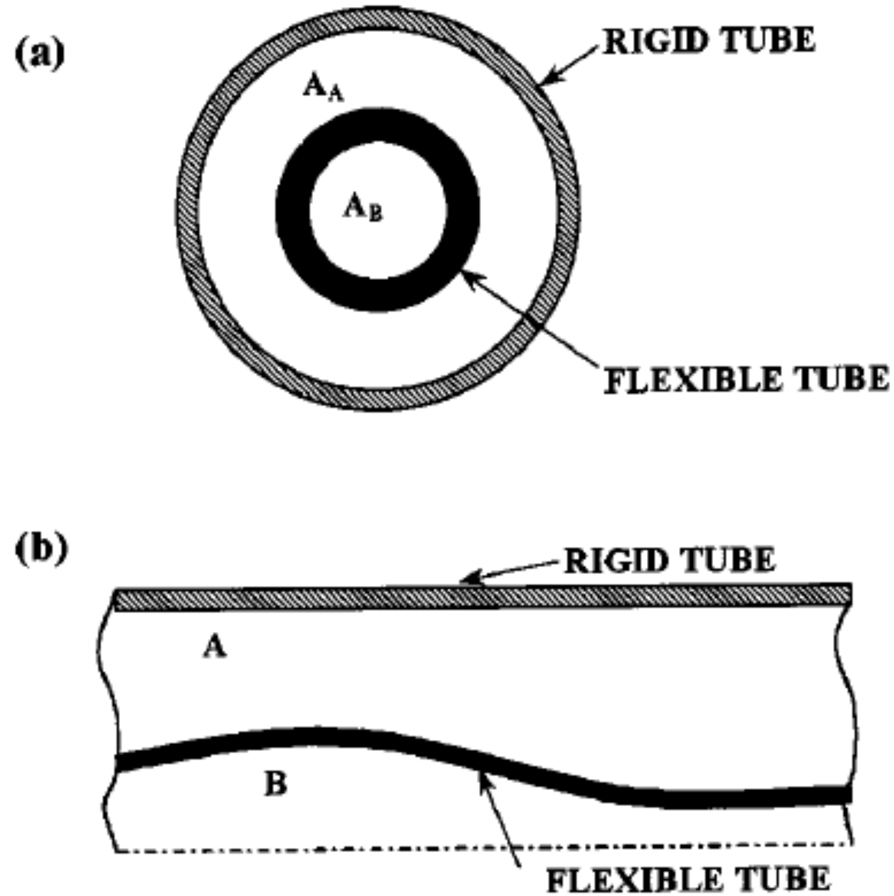
Williams: c ≈ 13 m/s
Kalata (MR): **c ≈ 4.5 m/s**

Lockey et al (1975)

Co-axial tube models have been used to study pressure wave propagation in the subarachnoid space

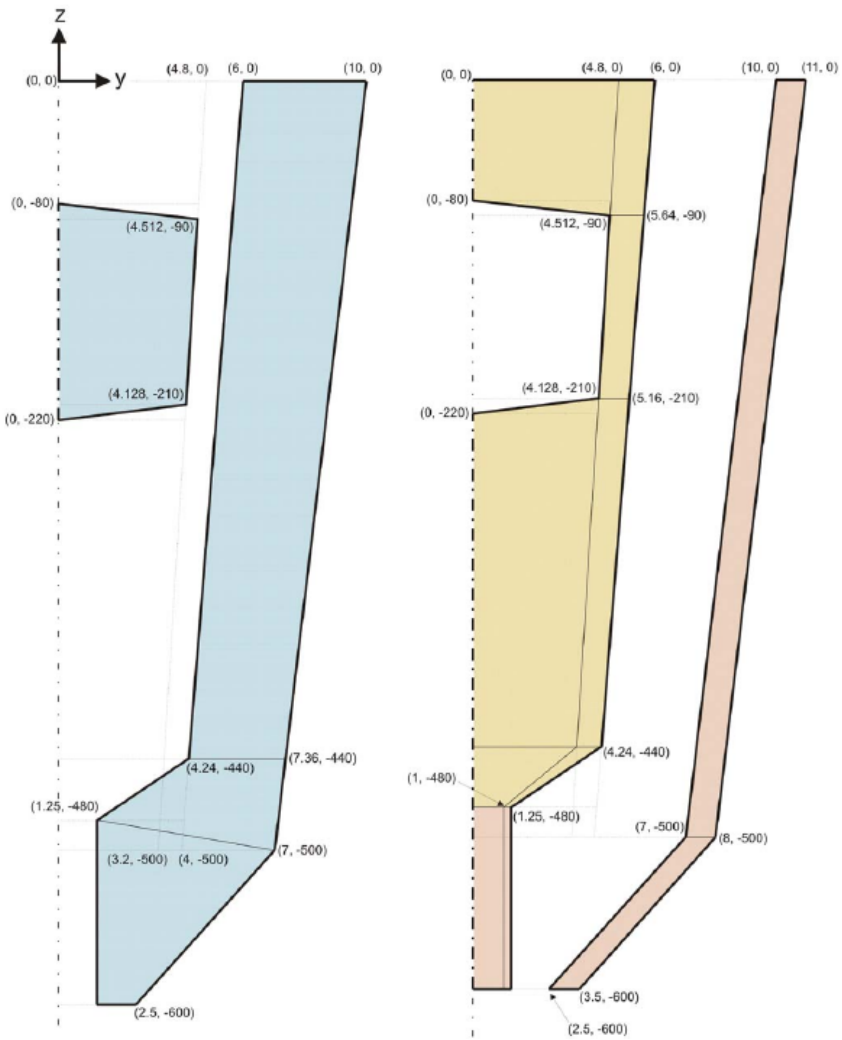
- ✓ Berkouk & Carpenter (2003)
- ✓ Lockey (1975)
- ✓ Cirovic (2009)

Min. wave speed:
c ≈ 2 -13 m/s



Berkouk et al (2003)

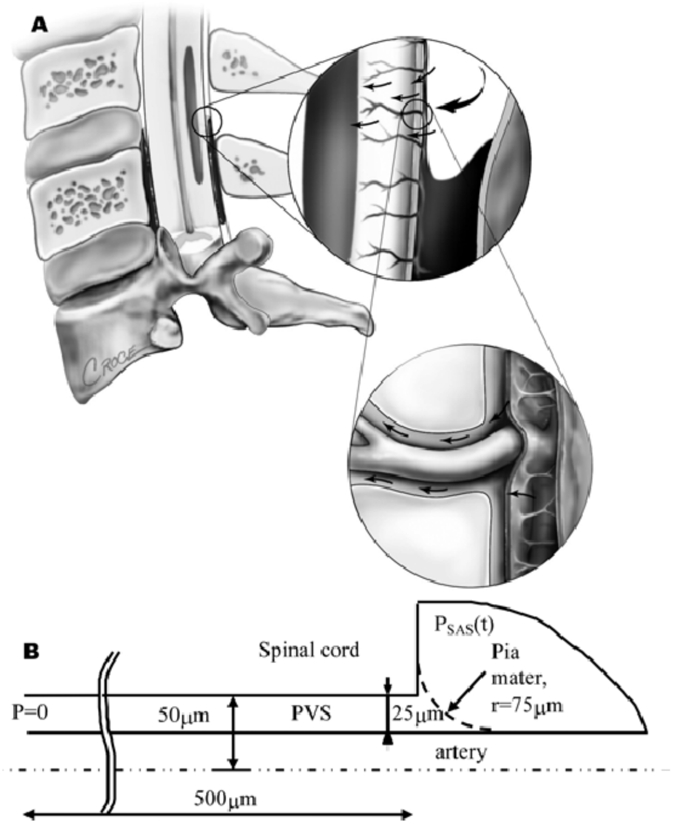
CSF flow and pressure has also been studied in fluid structure interaction of the spinal canal



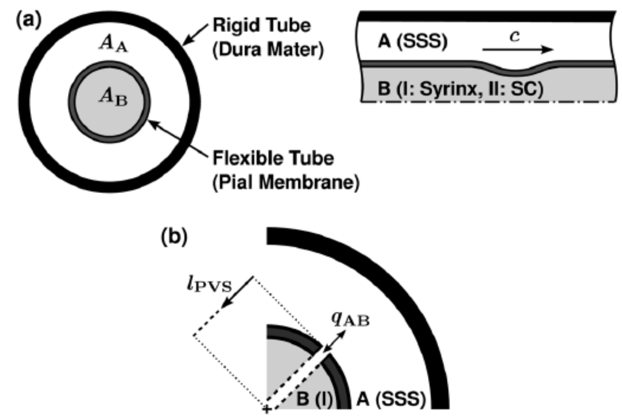
Bertram (2009)

Bertram: c = 12 m/s
Martin: c = 2 - 26 m/s

The SAS and central canal is hydraulically connected through perivascular spaces



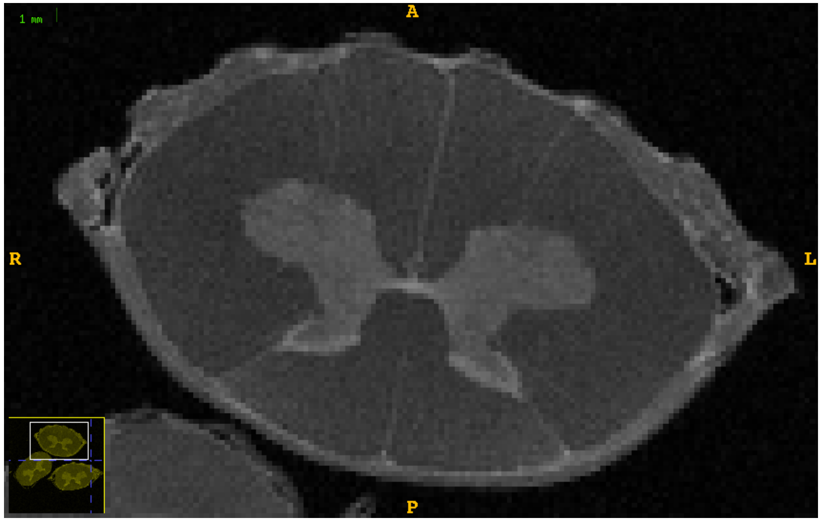
Bilston et al (2009)

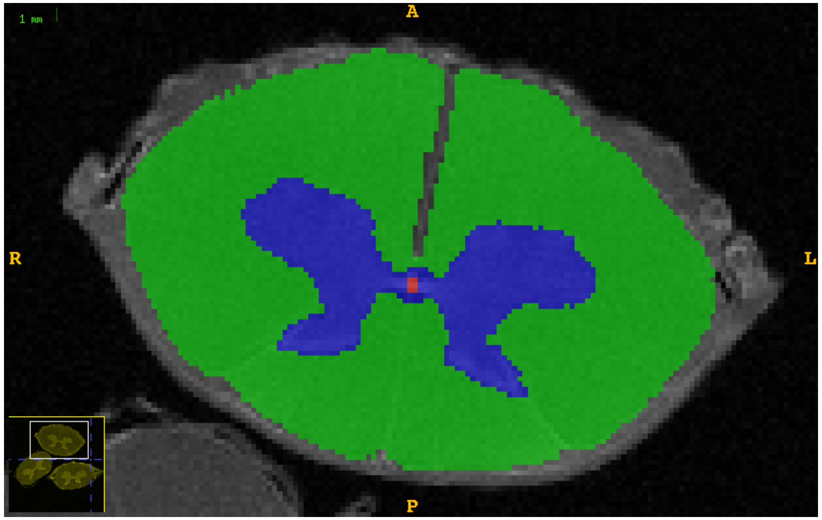


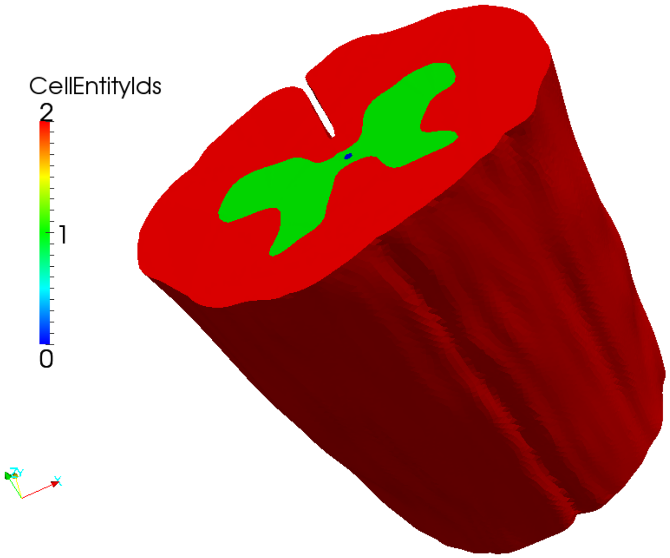
Elliott et al (2011, 2012)

c = 5.6 m/s

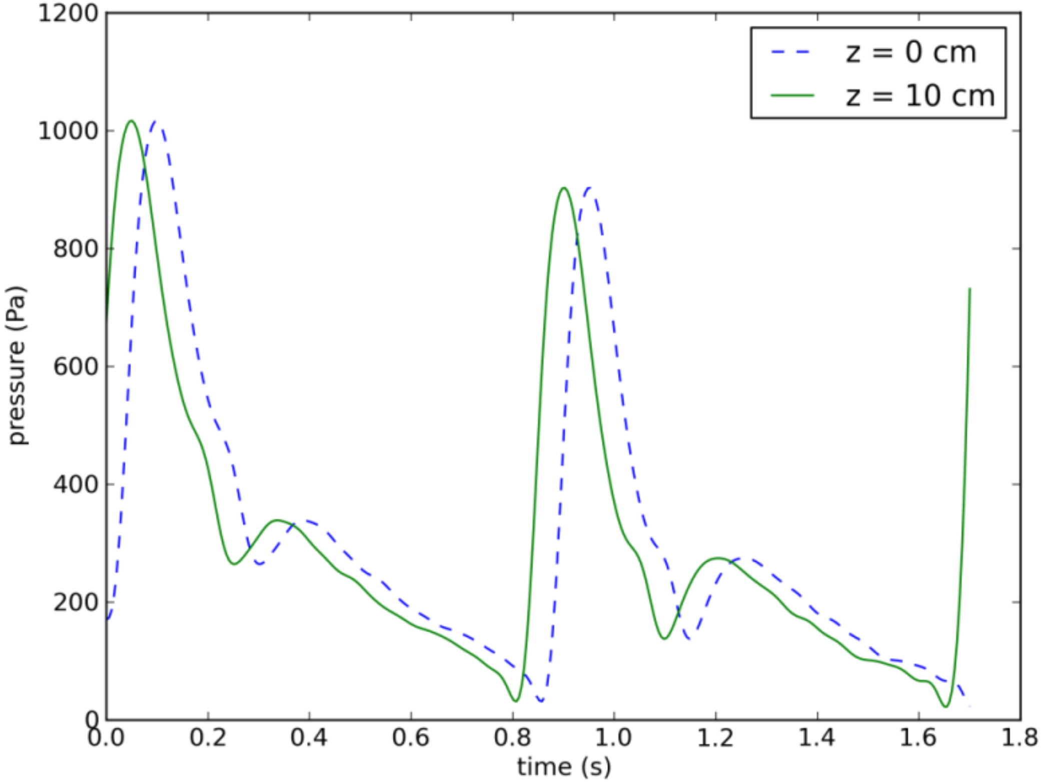
Geometric model of spinal cord based on DTI images of sheep spinal cord

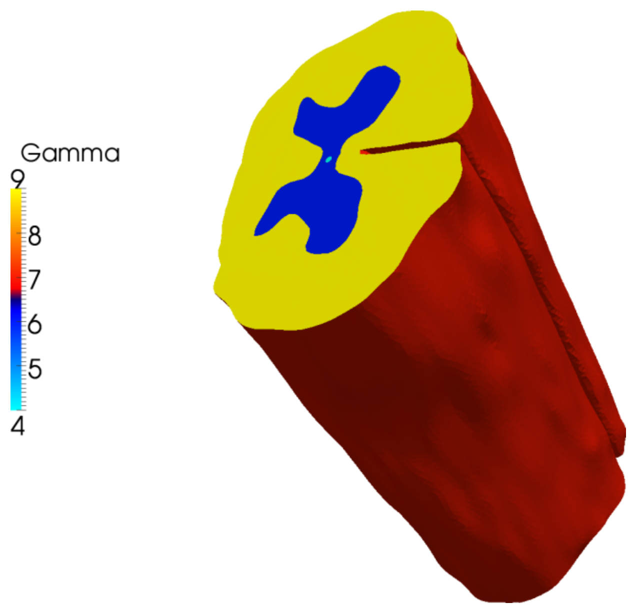






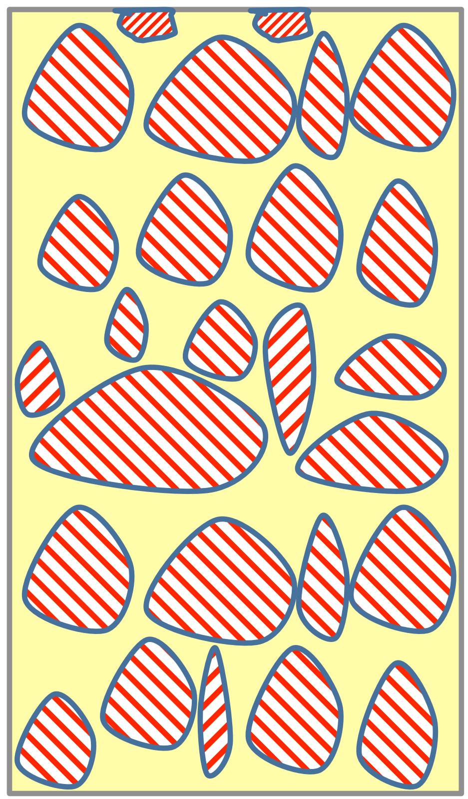
A traveling wave based on intracranial pressure measurements is applied along the walls of the model

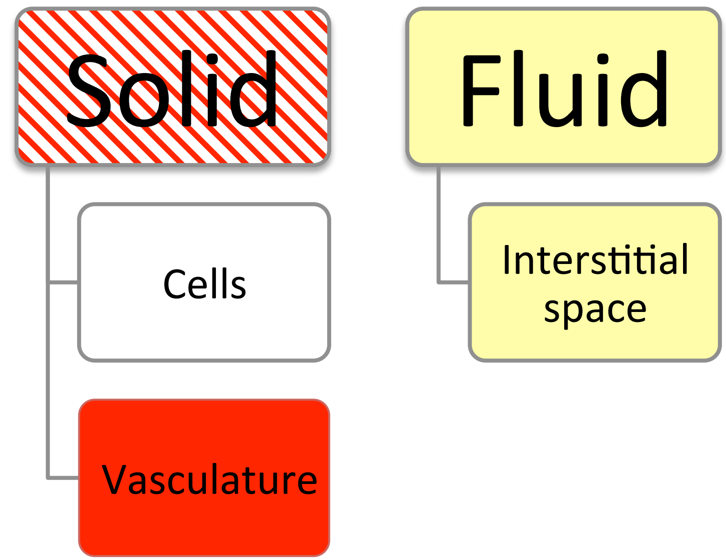




c ≈ 2 m/sec

The spinal cord tissue is modeled as a poro-elastic medium

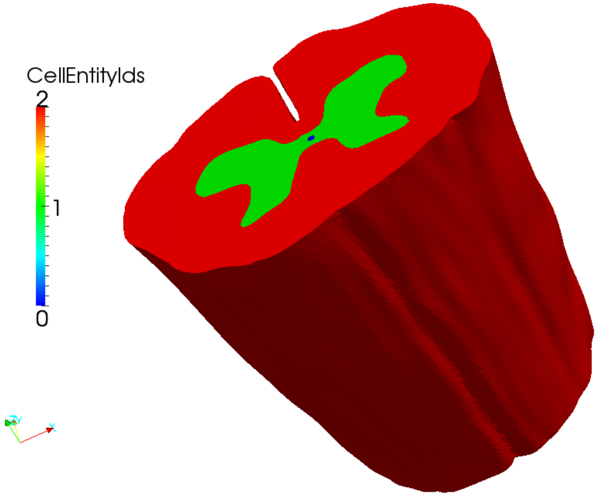




The Biot equations for incompressible solid and fluid phase

Volume balance:

$$\nabla \cdot \left(\frac{\partial \mathbf{u}}{\partial t} - \frac{\mathbf{K}}{\mu_w} \nabla p \right) = 0 \quad \text{in} \quad \Omega$$



Momentum balance:

$$\nabla \cdot (\boldsymbol{\sigma} - p\mathbf{I}) = 0 \quad \text{in} \quad \Omega$$

$$\mathbf{v}_f = \frac{\partial \mathbf{u}}{\partial t} - \frac{\mathbf{K}}{\mu_w} \nabla p$$

Stress tensor:

$$\boldsymbol{\sigma} = 2\mu\boldsymbol{\epsilon} + \lambda(\text{tr}\boldsymbol{\epsilon})\mathbf{I}$$

$$\mathbf{v}_D = -\frac{\mathbf{K}}{\mu_w} \nabla p$$

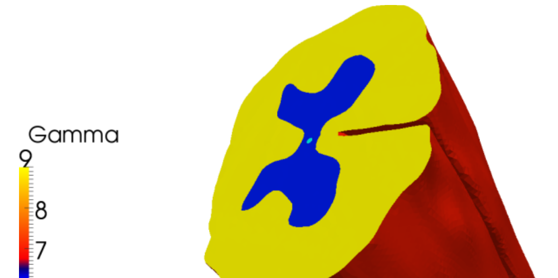
Strain tensor:

$$\boldsymbol{\epsilon} = \frac{1}{2}(\nabla \mathbf{u} + \nabla^T \mathbf{u})$$

We apply the traveling wave as a boundary condition along the walls of the geometry

Volume balance:

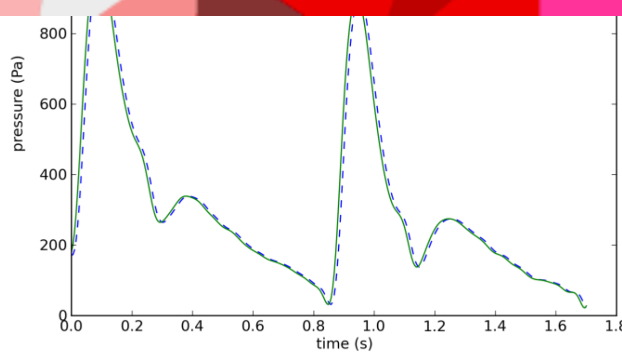
$$p = p_0(z + ct) \qquad \text{on} \quad \Gamma_7$$



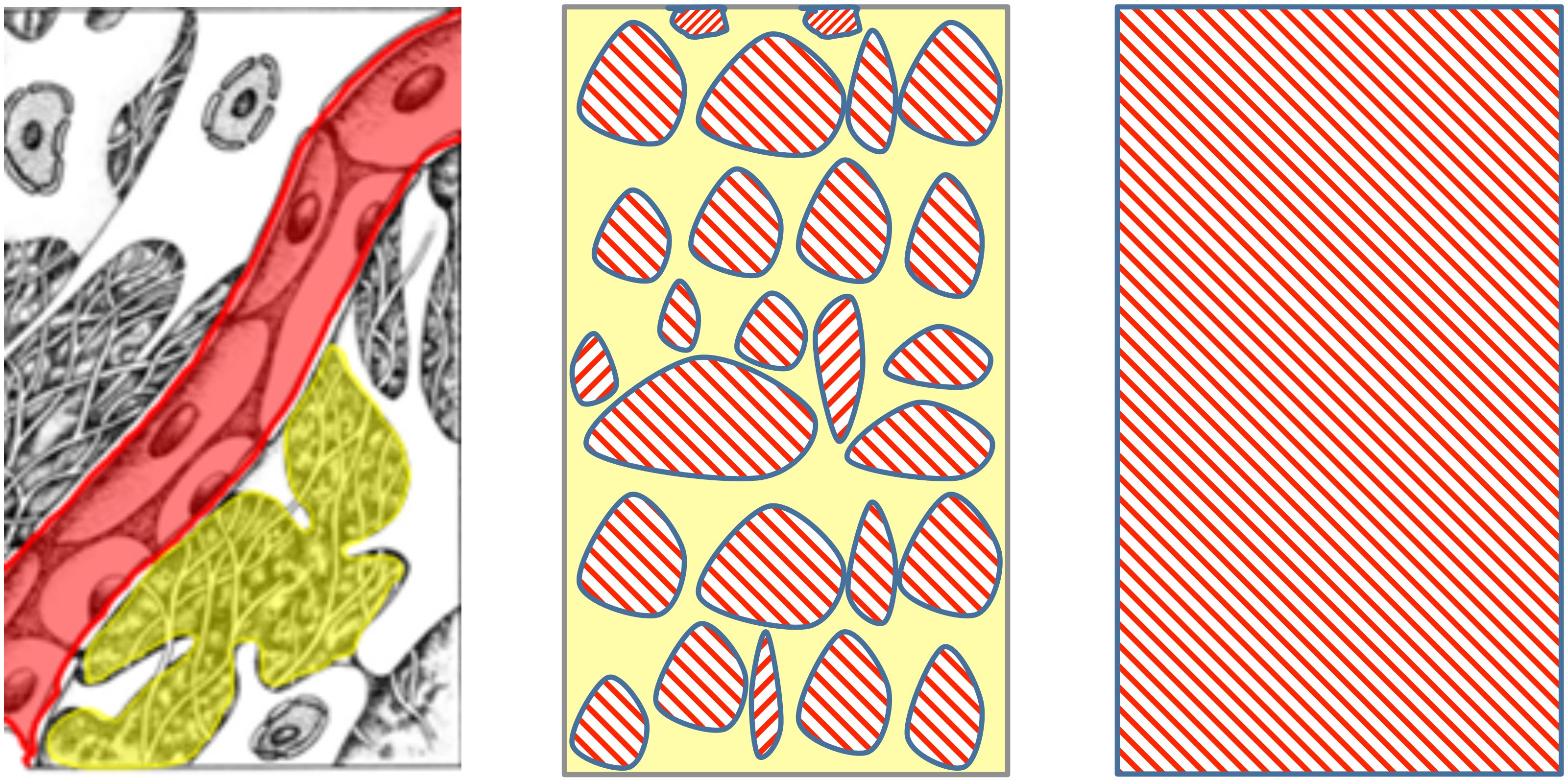
FEniCS project

$$\mathbf{u} = 0 \qquad \text{on} \quad \Gamma_4$$

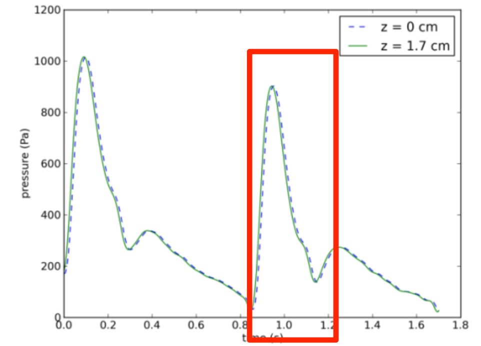
$$u_z = u_\theta = 0 \qquad \text{on} \quad \Gamma_{6,9}$$



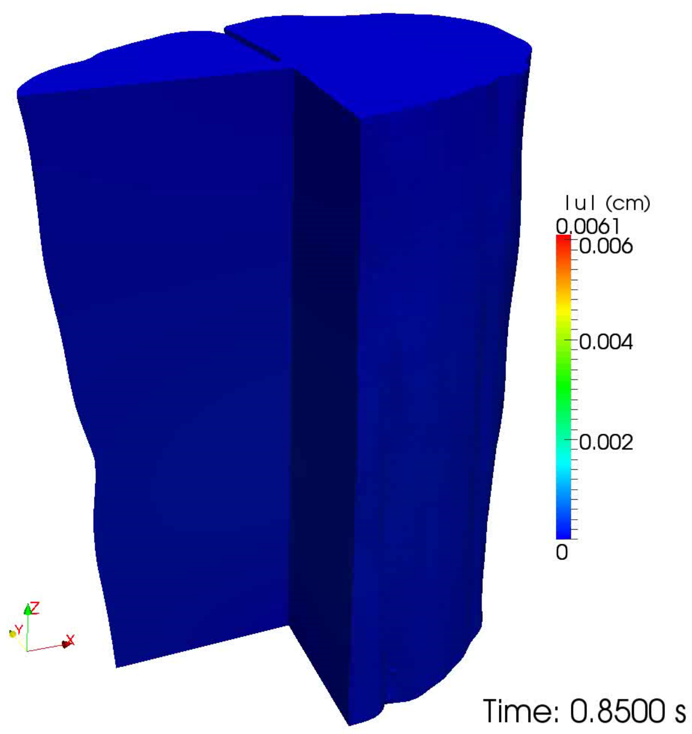
It is common to assume the spinal cord to behave as a single solid phase



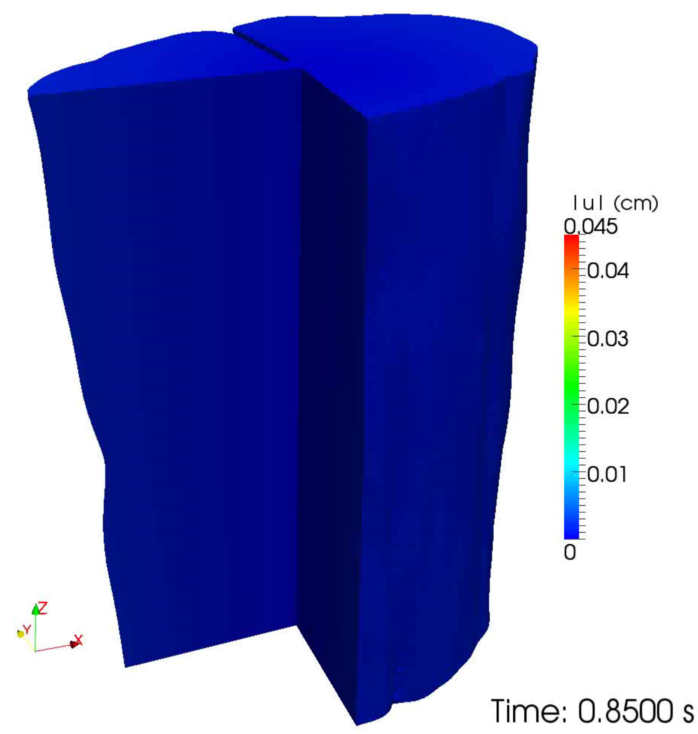
Comparison with linear elasticity: Is it important to include the fluid phase in the model



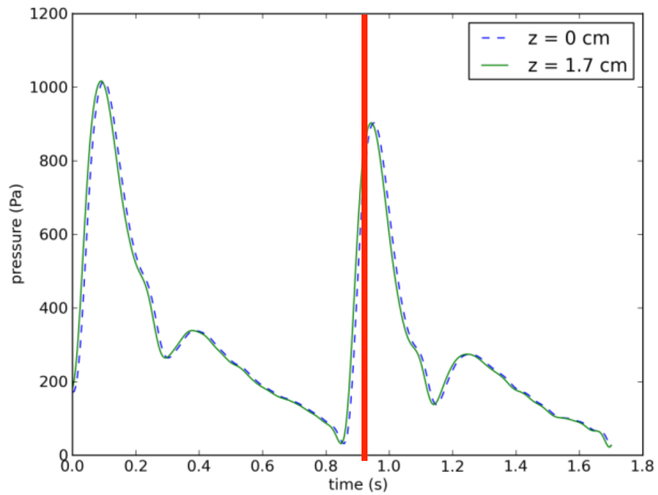
Poro-elasticity

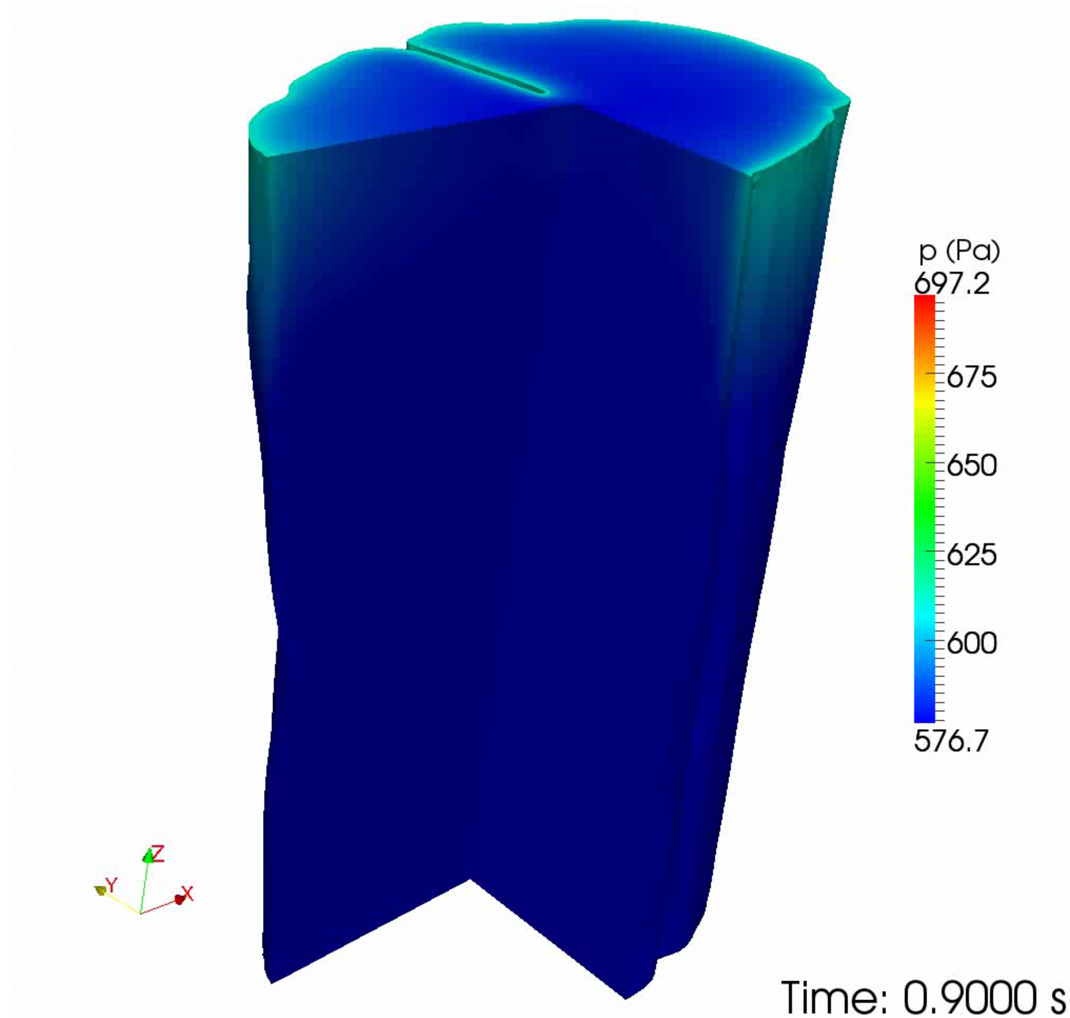


Linear elasticity

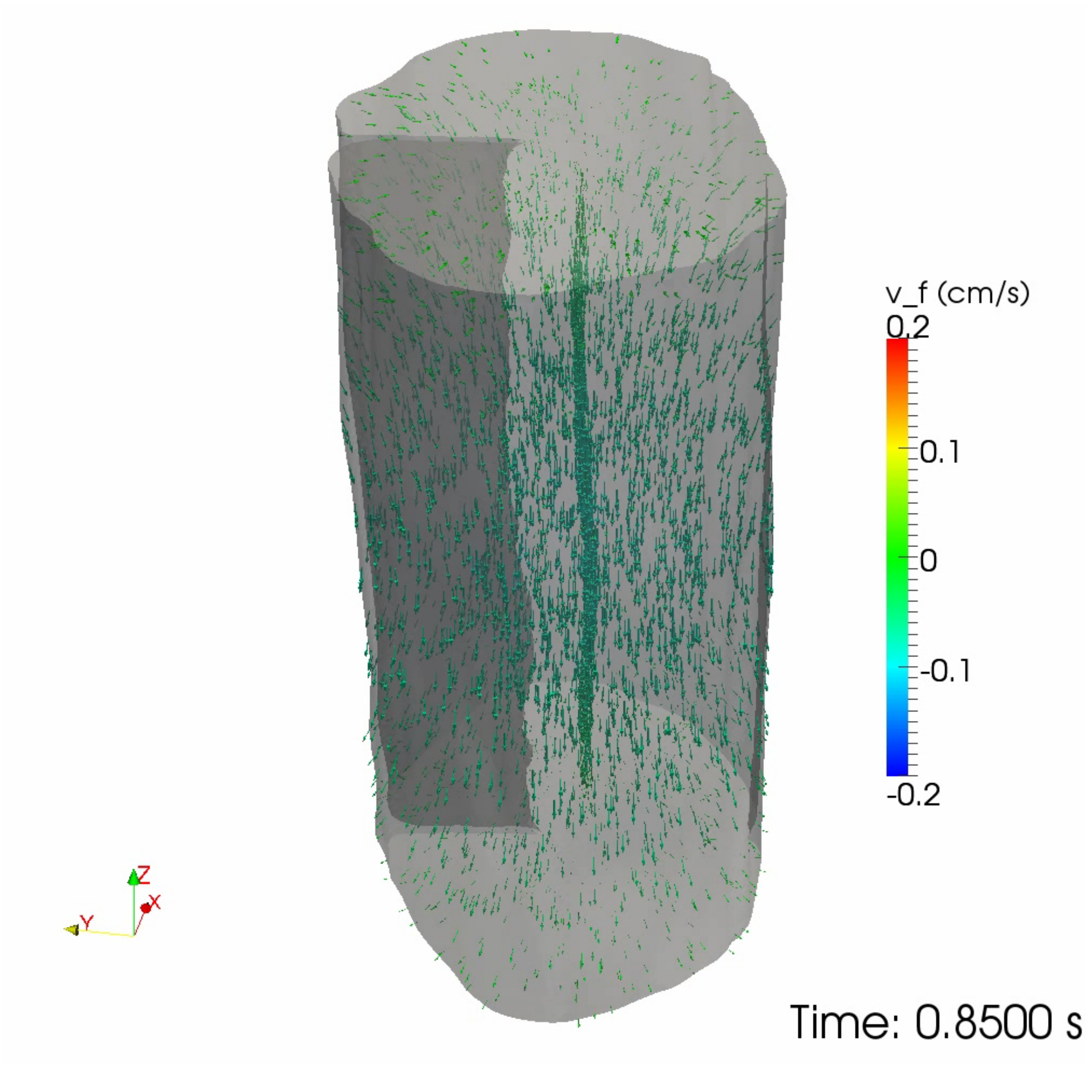


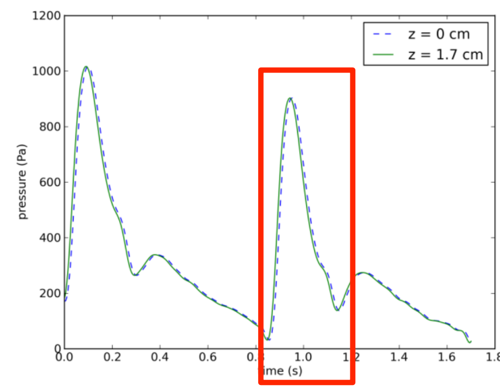
Pressure gradients occur since the pressure wave arrives at different times along the spinal cord



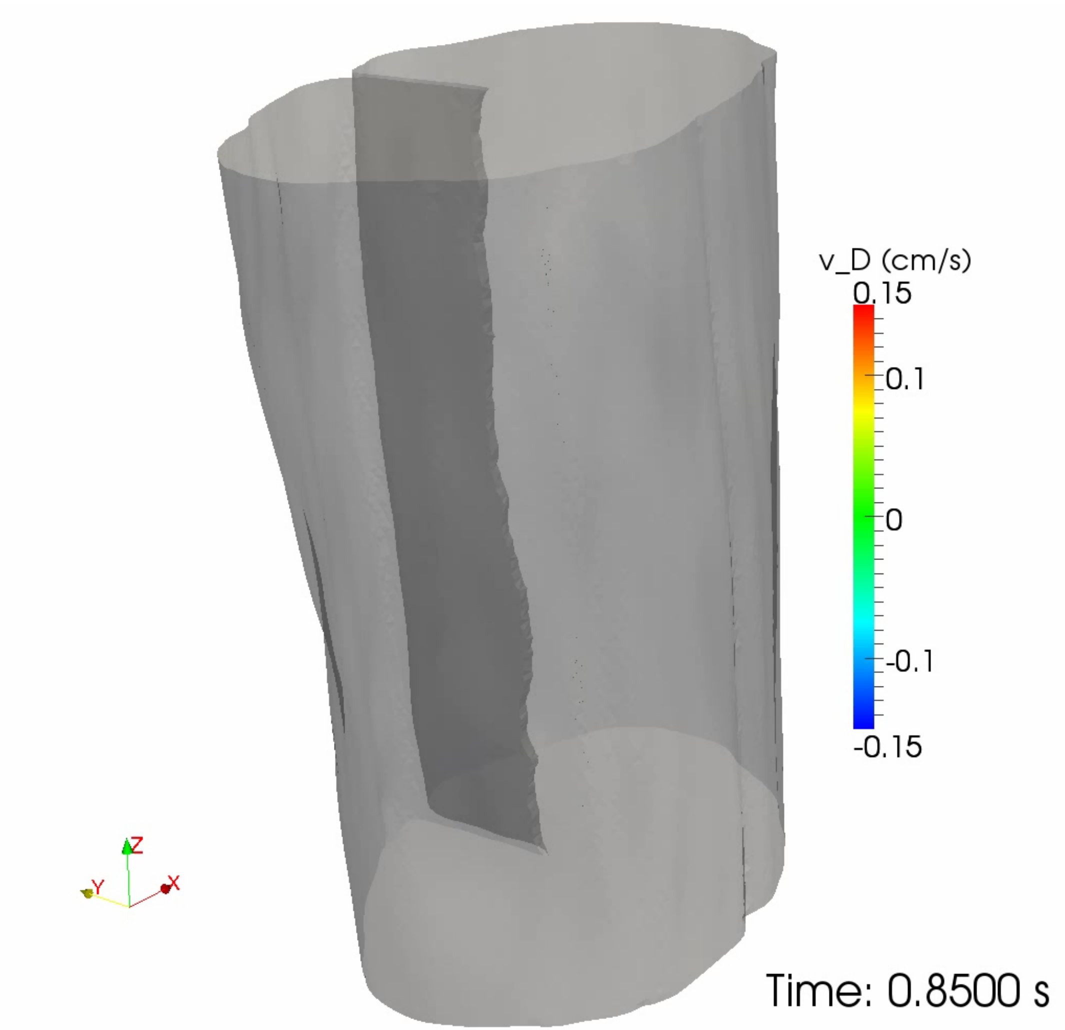


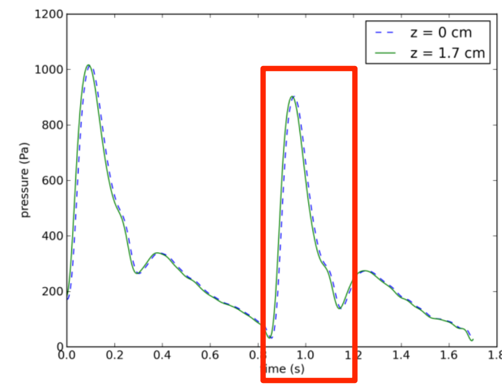
Movement of solid cord tissue produces interstitial fluid flow





The pressure wave drives movement of fluid in the central canal of the spinal cord



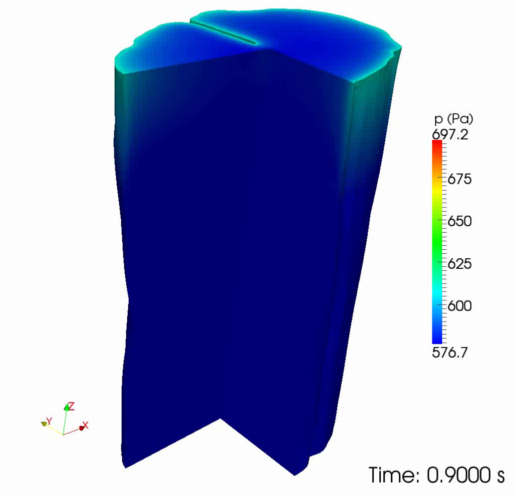


In conclusion, pressure waves affect the tissue and fluid movement within the spinal cord

Pressure waves ⇨ Displacement

Velocity central canal **>>** Velocity tissue

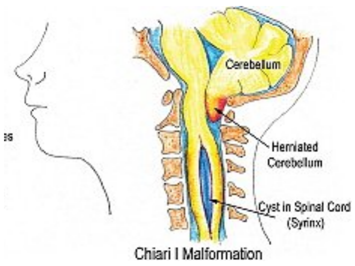
Poro-elasticity **≠** Linear elasticity



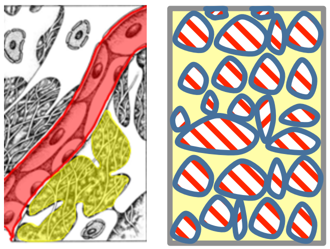
Role in the pathogenesis of syrinx need more study

Center for Biomedical Computing

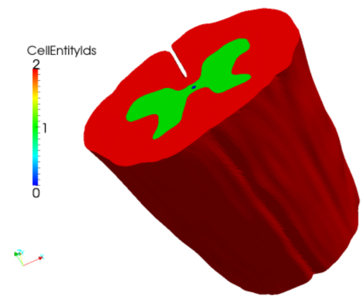
In this presentation we use a poroelastic model to simulate how pressure waves spread in the spinal canal



Abnormal Pressure

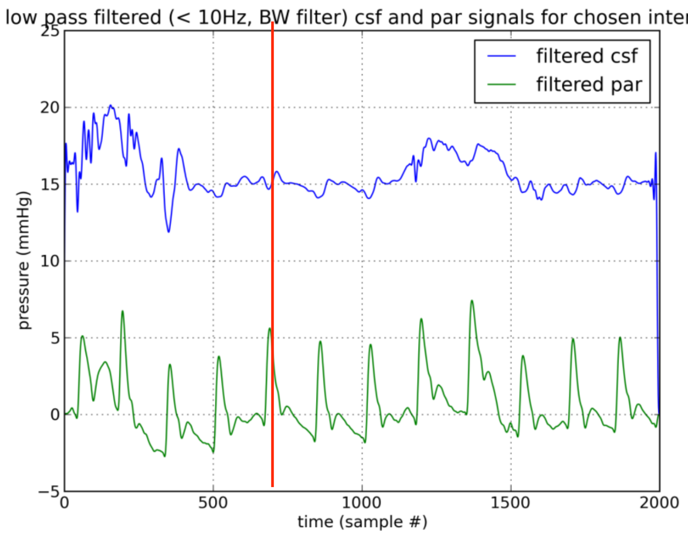


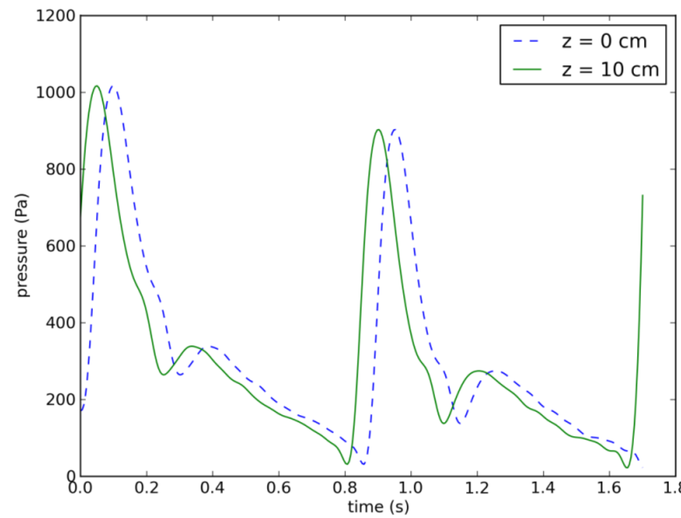
Poroelasticity

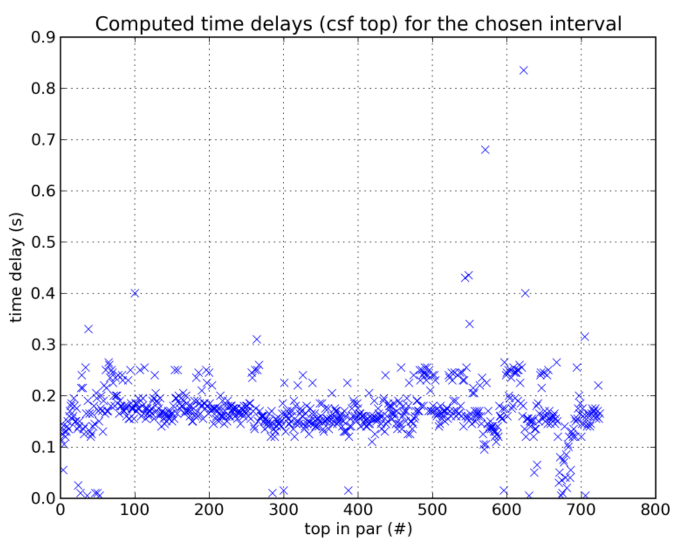


Comparison with linear elasticity

We use continuous pressure measurement from the cranial and lumbal region to define a traveling wave

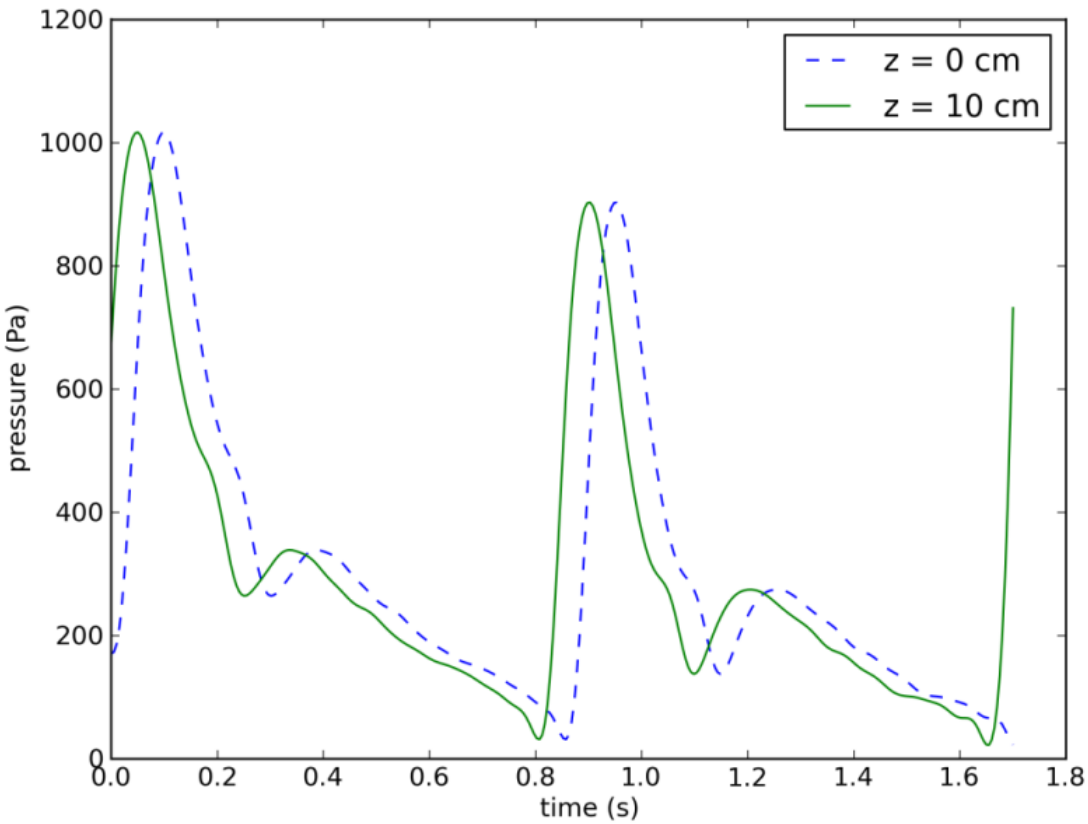






$$p_0(z,t) = p_0(z+ct)$$

The effects of pulsatile CSF pressure on the spinal cord tissue



$$p_0(z,t) = p_0(z+ct)$$