3-D Finite Element Modeling of Brain Edema

Initial Studies on Intracranial Pressure Using Comsol Multiphysics

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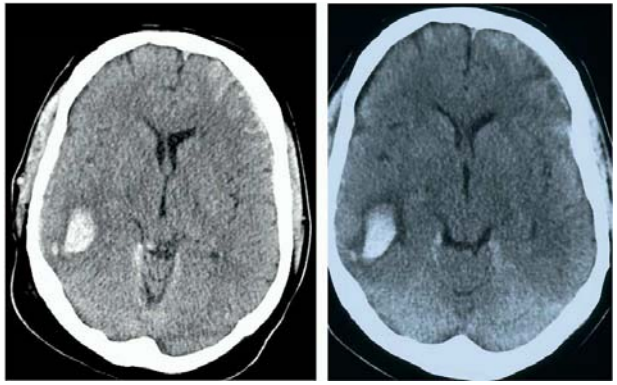
X.G. Li, H.von Holst, J.Ho and S. Kleiven

Division of Neuronic Engineering, School of Technology and Health
KTH - Royal Institute of Technology

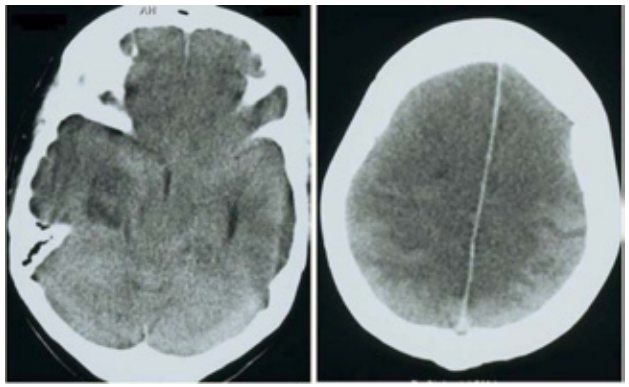
Stockholm, Sweden

Traumatic brain edema

CT image Focal traumatic brain edema



CT Image of Diffuse brain edema



Brain Edema

Excess accumulation of **water** in the intracellular and/or extracellular spaces of the brain tissue.

A. W. Unterberg et al. / Neuroscience 129 (2004) 1021–1029

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Monro-Kellie doctrine

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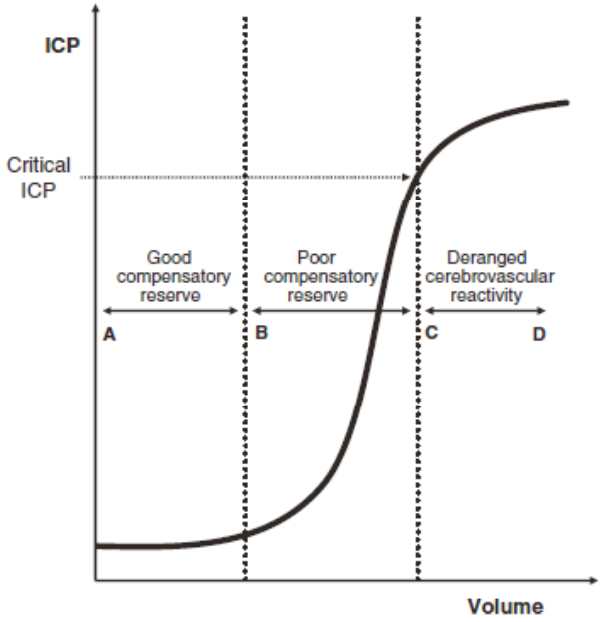
Water content

- Normal brain ≈ 78%
- Edema ≈ 80%

Monro-Kellie doctrine

- Volume increase – increase ICP



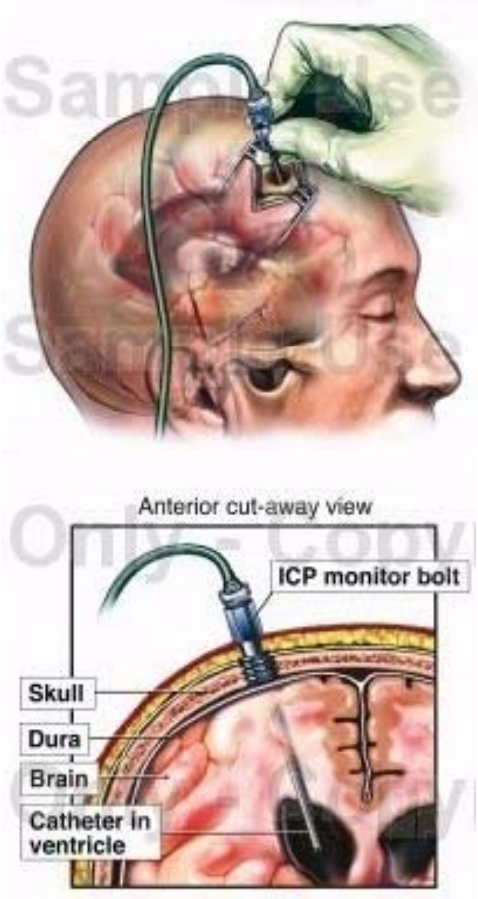
Martin Smith, 2008

Intracranial pressure

- Measured by catheter inserted through skull, into the ventricle.
- Invasive:
  - Continuous, accurate , reliable
  - Infection risk, suffering, cost

Hard to decide whether or not monitor.

Predict.....



http://ebsco.smartimagebase.com/imagescooked/3449W.jpg

Scope of the research

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Aim: 3D Finite element model of brain edema to predict intracranial pressure.

This paper: Study how different boundary conditions affect the pressure distribution.

Overview of the presentation

- Introduction of brain edema and ICP
- **Method**
  - *Geometry of the model*
  - Poroelastic material
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- Results
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The KTH head model

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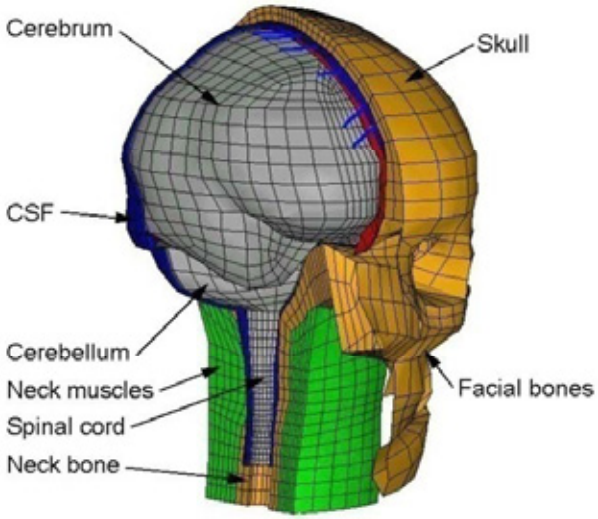

S. Kleiven (Stapp-2007)

Modified for edema simulation

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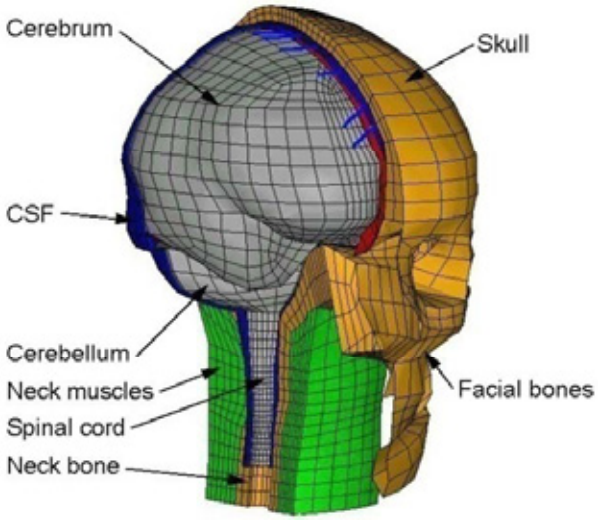
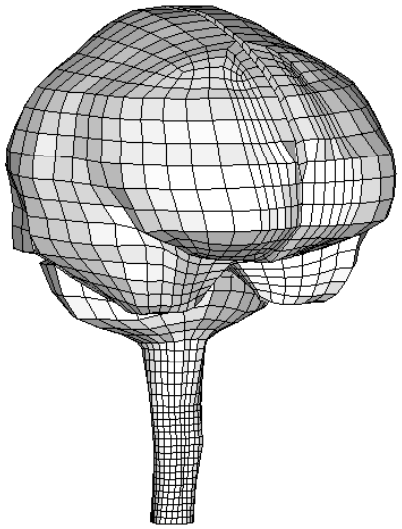


Ls-Dyna



Nastran

Importing problem

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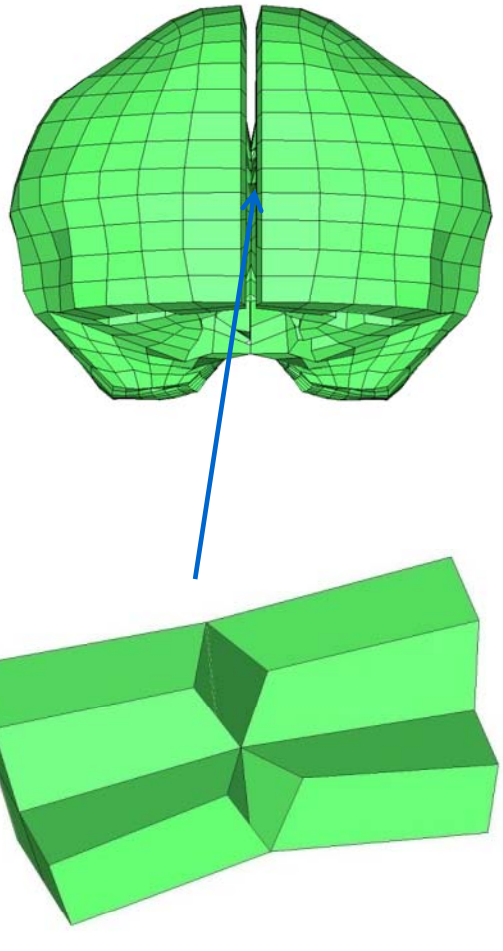
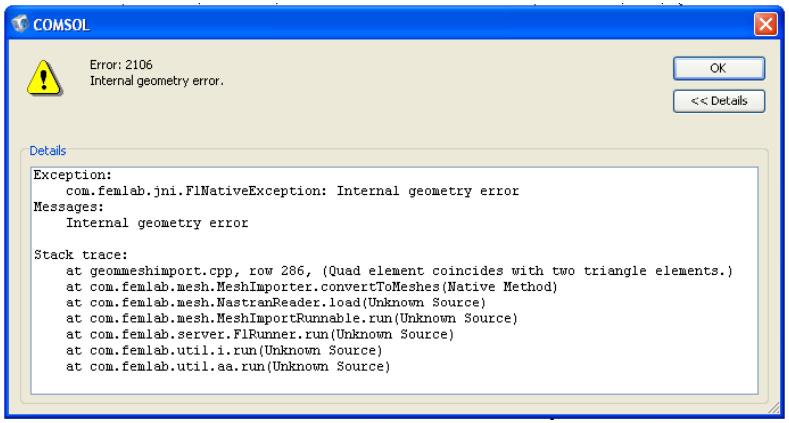
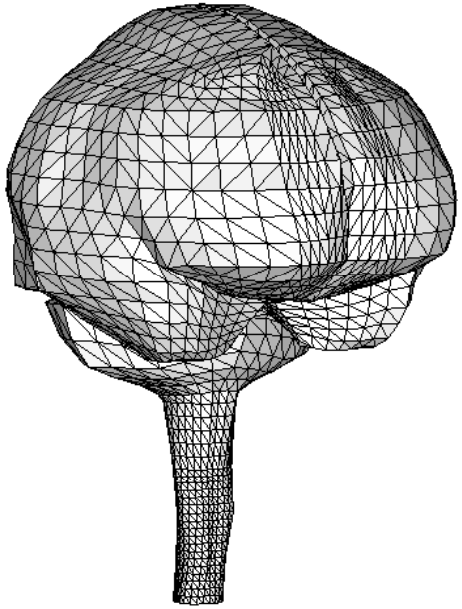
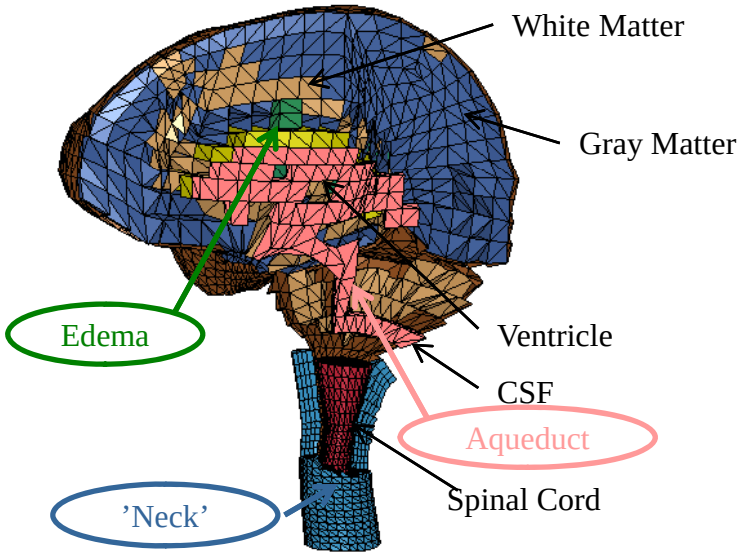






Modified for edema simulation



Aqueduct : connect third with fourth ventricle

Edema: two elements from white matter

'Neck': with spinal cord as reservoir

Elements: 58,732

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Poroelastic property of brain tissue

- Structure mechanics module

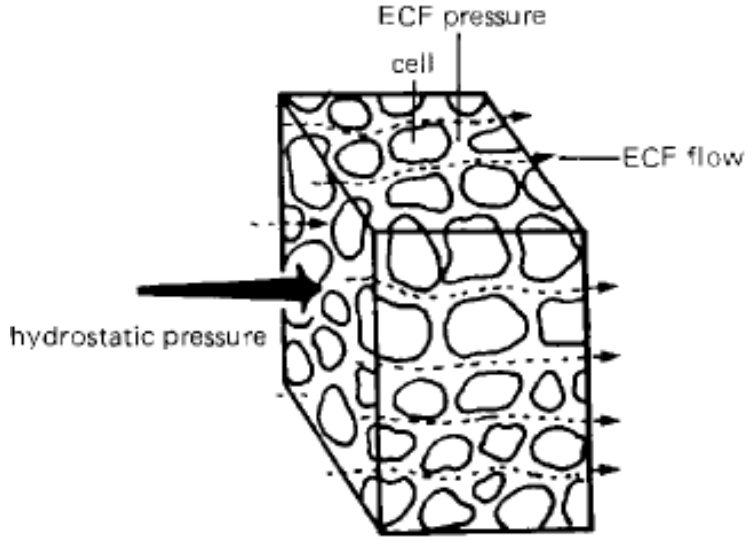
$$-G\nabla^2\mathbf{u}-\frac{G}{(1-2v)}\nabla(\nabla\cdot\mathbf{u})=-\alpha\nabla p$$

- Darcy's law

$$\frac{1}{M}\frac{\partial p}{\partial t}-\nabla\cdot\frac{\mathbf{k}}{\eta}\cdot(\nabla p)=-\alpha\frac{\partial}{\partial t}(\nabla\cdot\mathbf{u})+Qs$$

Increasing pressure p

Edema



T.Nagashima,1990

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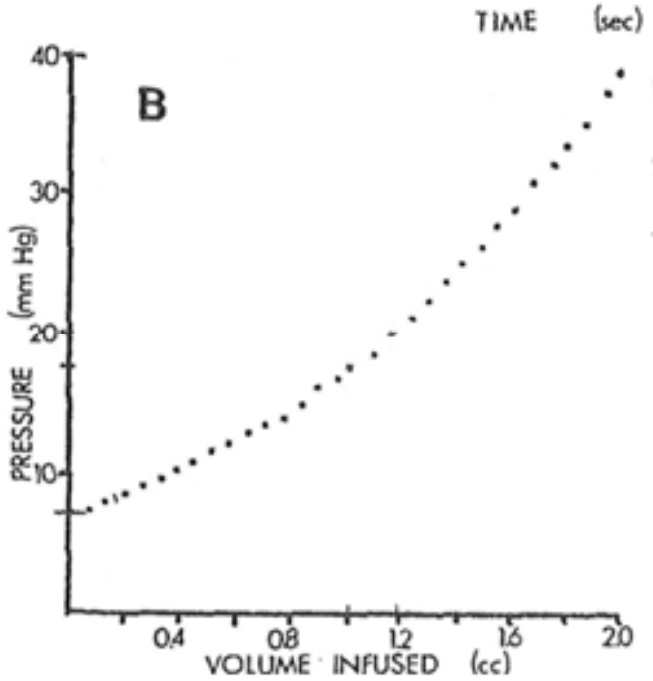
Infusion experiments

Infusion experiments at subarachnoid space of dog's brain at a constant rate.



Infusion rate = *3.87cc/min*
Infusion time = *30 seconds*

F.H.Sklar et al. (1977)

Poroelastic FE Model

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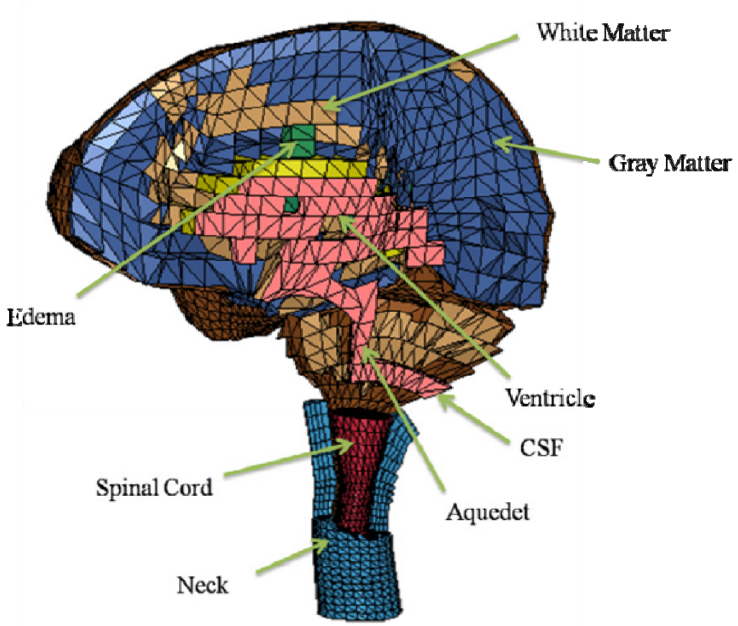
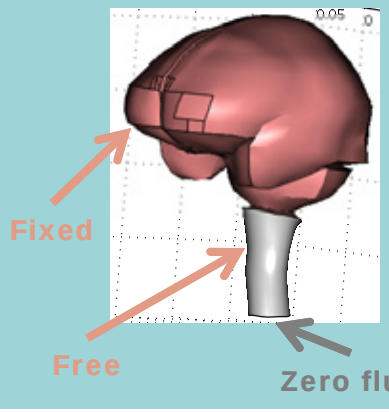
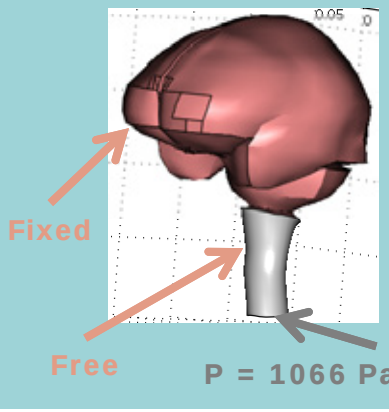
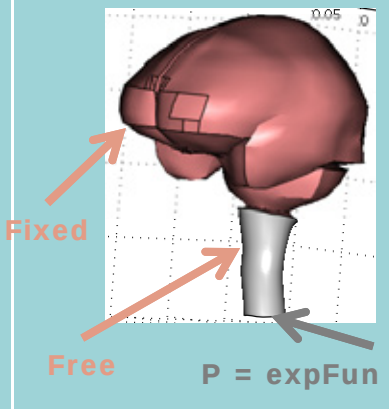


Scaling

Time : 30 -> 3000 seconds

Infused volume: According to the V_{dog} - V_{model}, give same relative volume change.

Boundary Conditions

Boundary conditions			
Solid phase: Same	Skull (Outer surface of the CSF): Fixed 'Neck': Free to expand		
Fluid phase: 3 different BCs	1. Zero flux	2. Constant pressure:	3. Exponential pressure
		Pressure as resistance to fluid outflow	

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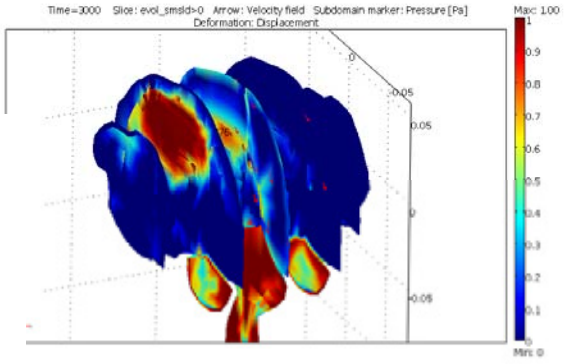
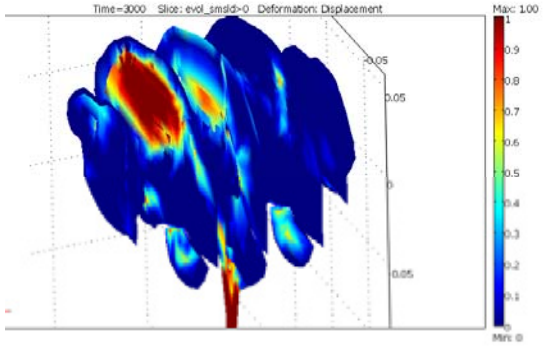
Clinical observations

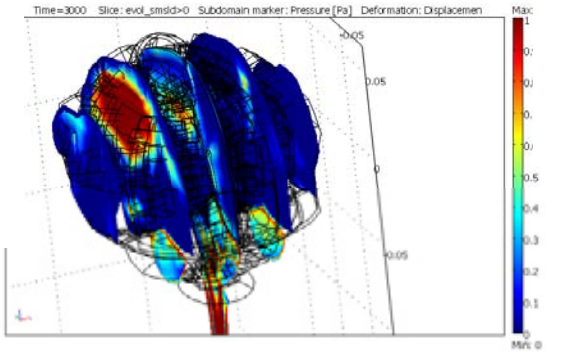
Zero flux



Constant Pressure



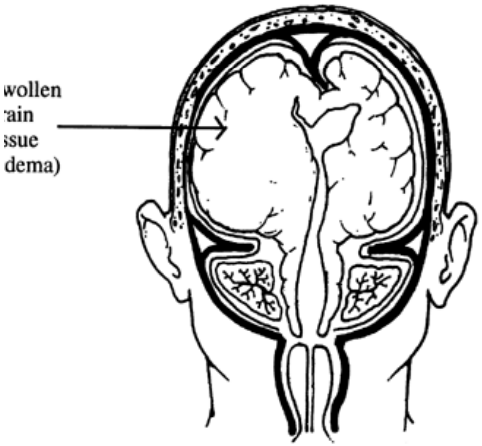
Exponential pressure



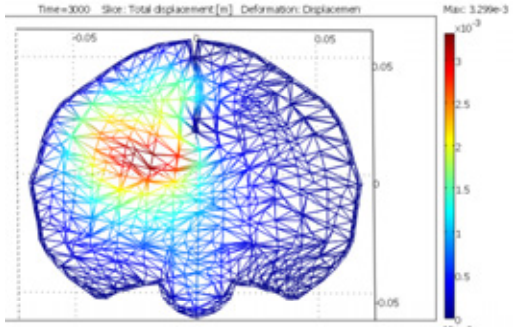
Edema swelling,
Ventricle squeezed,

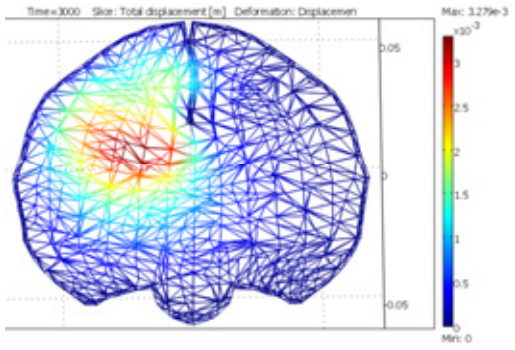
CSF squeezed due to rigid skull .

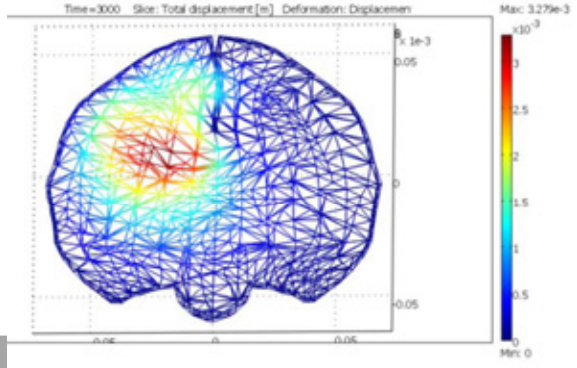
Spinal cord expand.



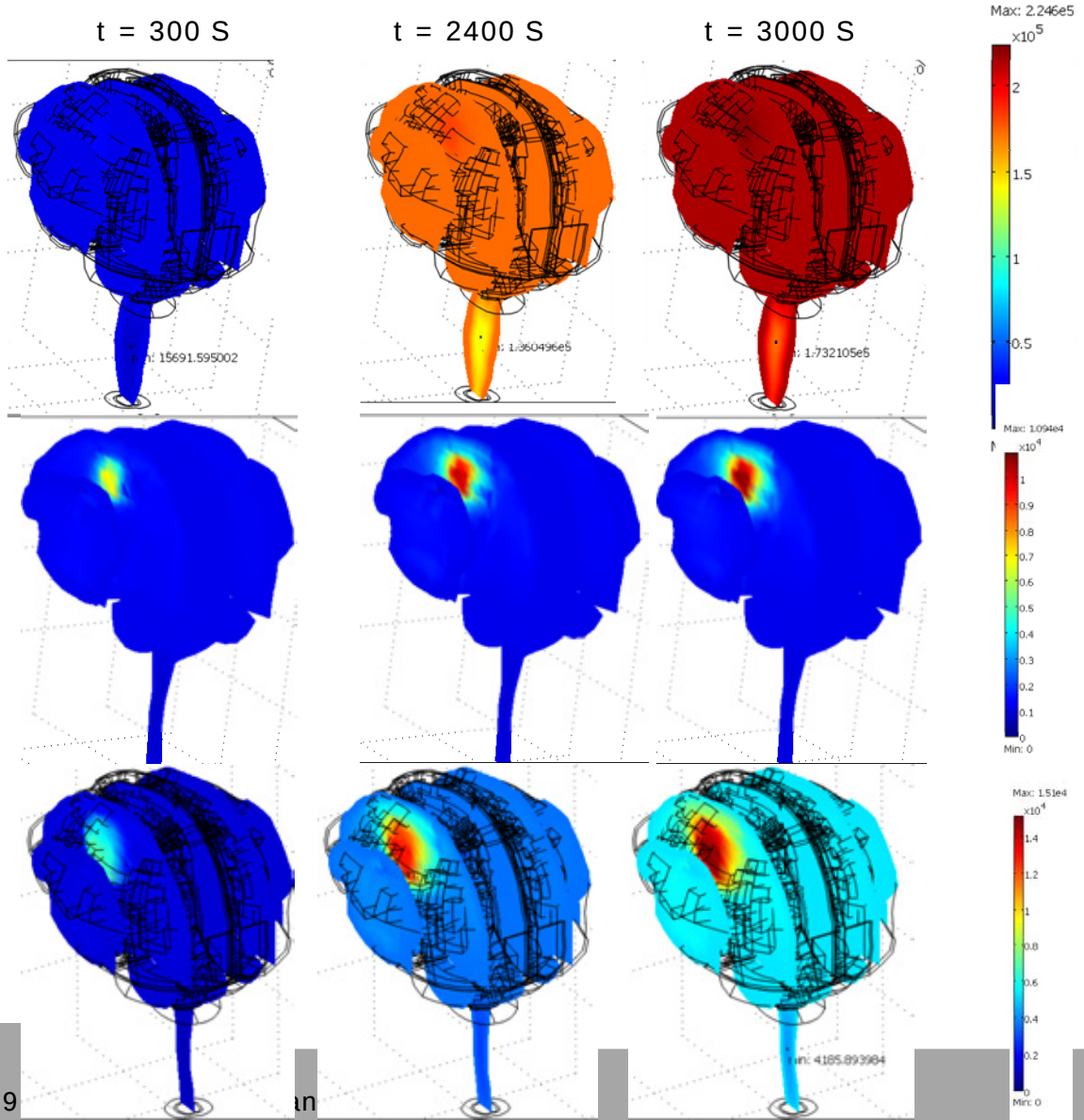
Midline shift







Pressure Distribution



Zero flux

Constant Pressure

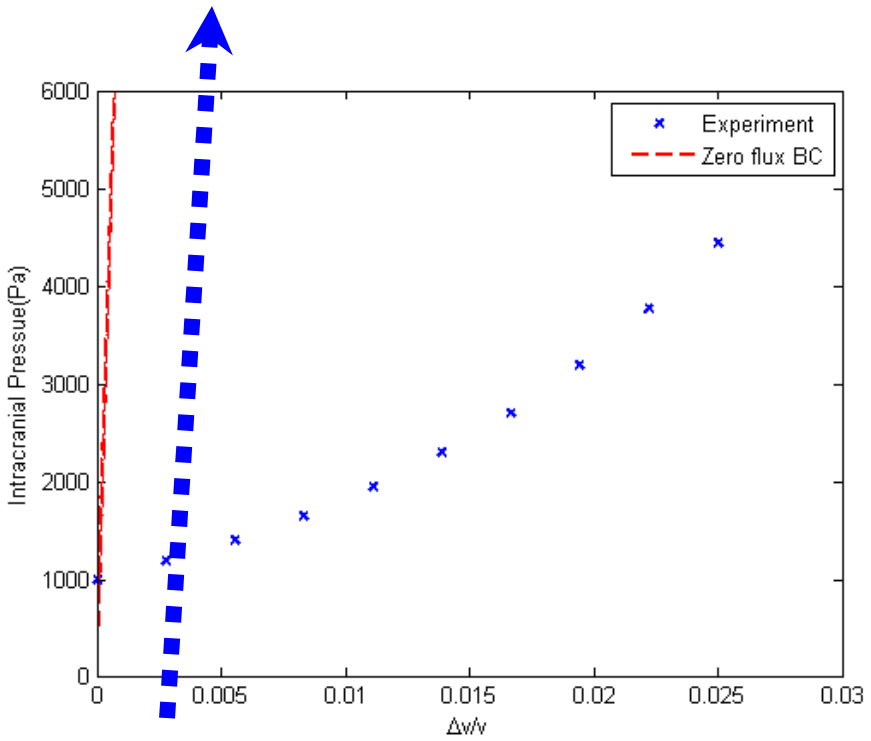
Exponential pressure

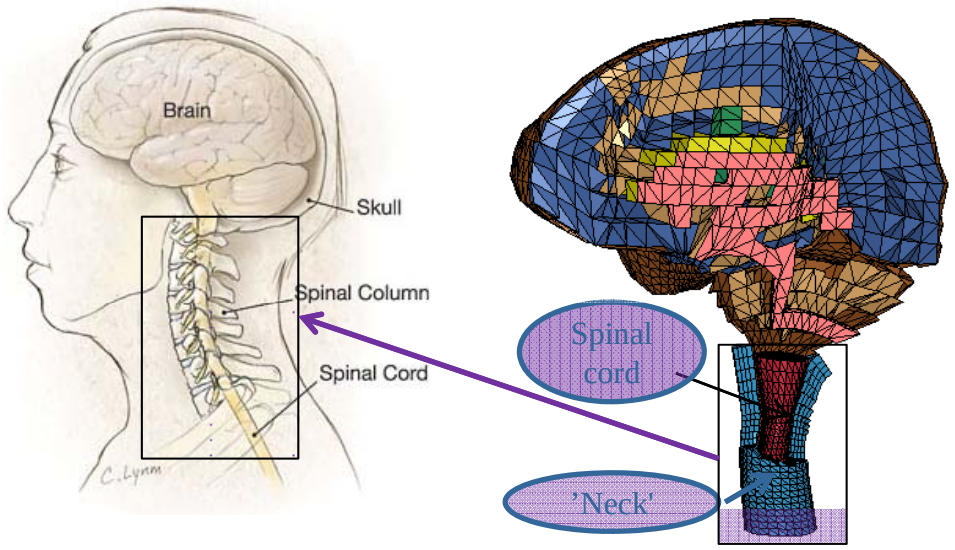
Homogeneous pressure except edema:

–Nearly incompressibility for both the brain tissue and the CSF

–High permeability in ventricle, aqueduct, CSF

Zero flux



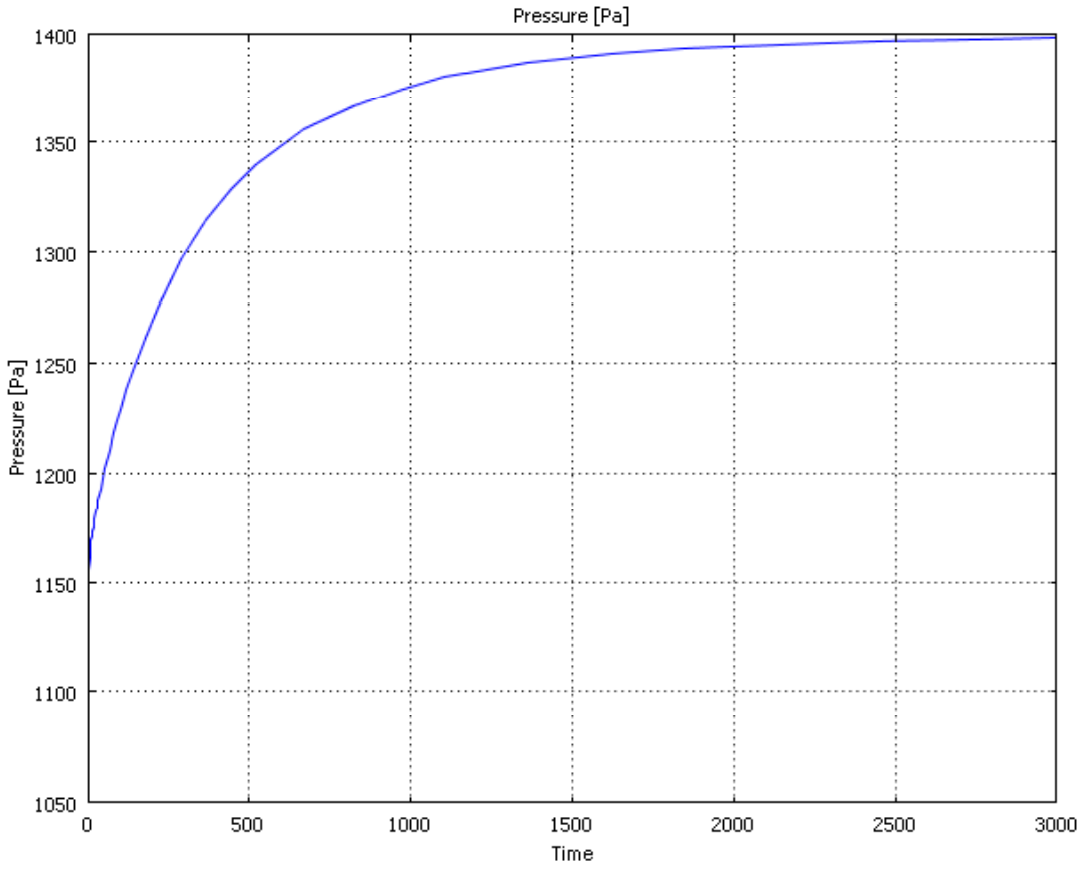


Linearly increasing up to very high pressure (220 kPa)

CSF **generation** and **absorption** added may improve the result for this boundary condition.

http://www.medem.com/medem/images/jamaarchives/jama_brain_brainspinalcordnerve_lev20_neckinjuries_jpp_01.jpg

Constant pressure BC



ICP increase slowly and reach to a steady state, due to high permeability of CSF, water infused will flow out from the end surface of spinal cord.

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Constant pressure BC

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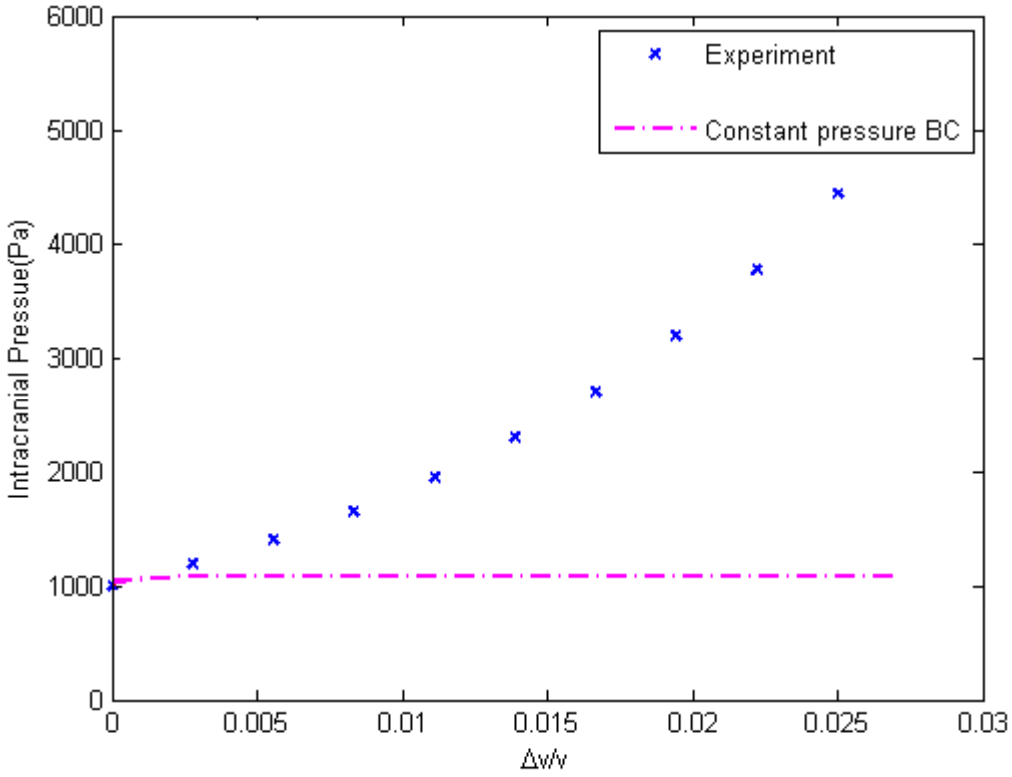
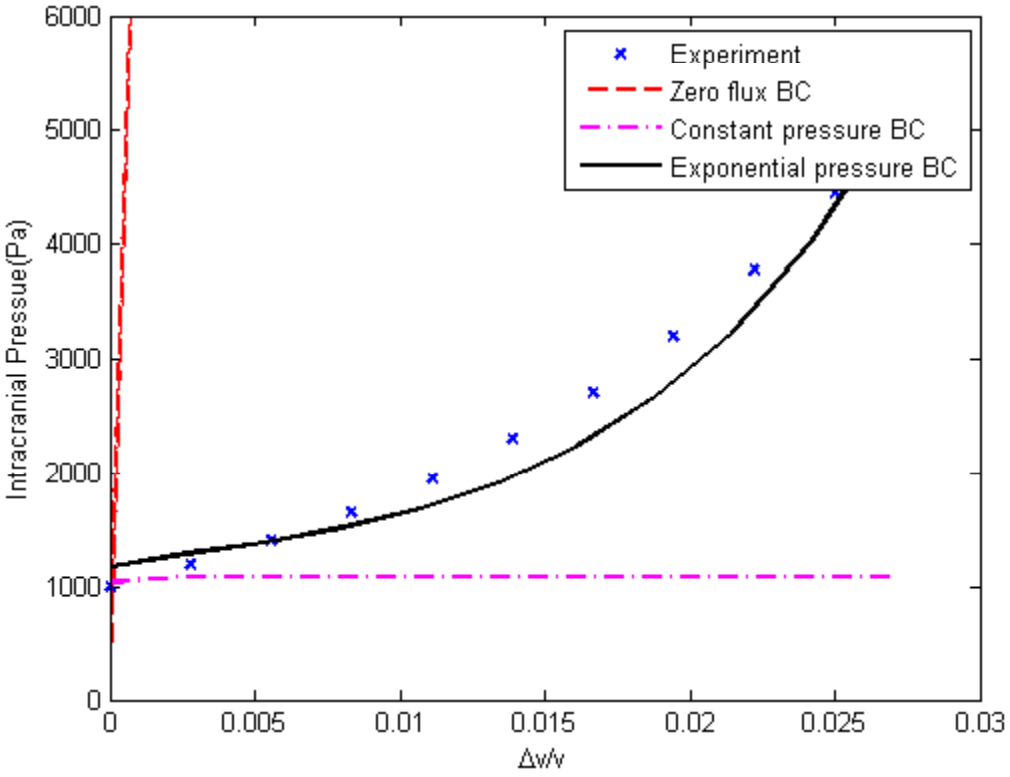


Exponential Pressure BC Result



Corresponds well with experiment,
may reflect the realistic non-linear compliance and resistance from the spinal cord.

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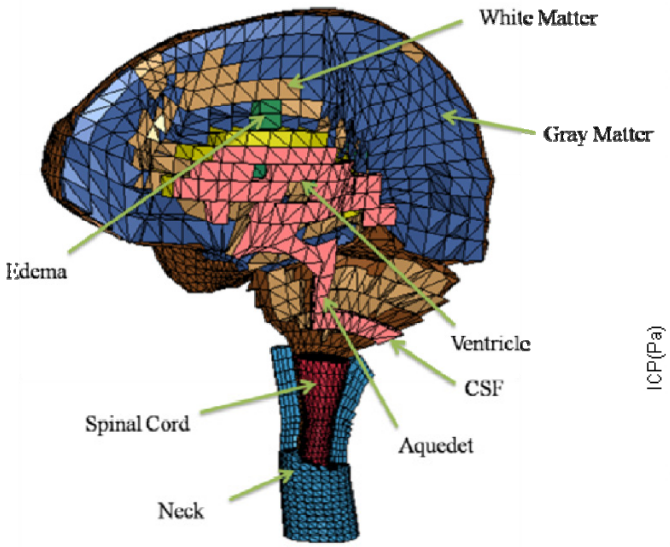
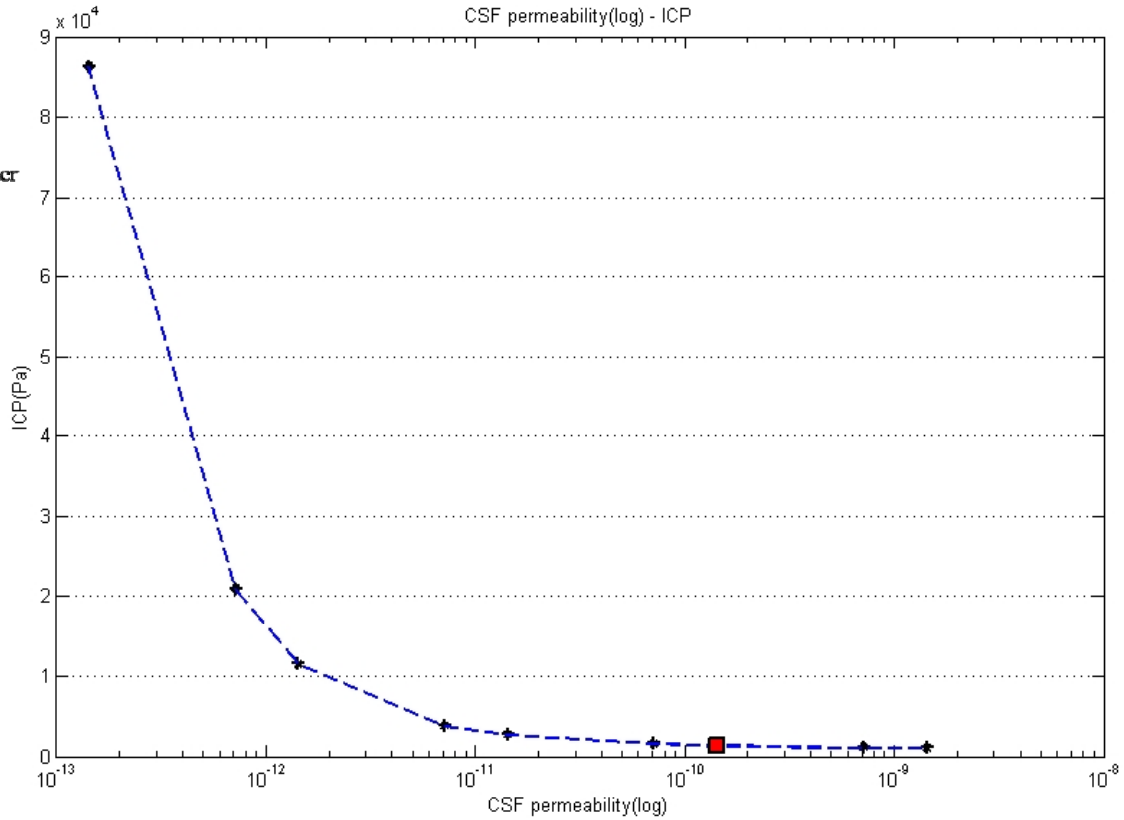
Parametric studies on CSF permeability





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Conclusion

- The water-source edema model corresponds well with the clinical observations in edema development, such as midline shift, brain swelling.
- Boundary conditions at the end of spinal cord significantly affect the pressure distribution.
- More factors need to be taken into conderation in order to reflect the realistic nonlinear pressure-volume curve.

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Future work

- Add CSF generation and absorption in the model.
- CSF should be modelled as fluid instead of poroelastic material.
- Pore water is added with a constant accumulation rate in edema, water accumulation mechanism complex.
- ……

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Thank you!

Comments and questions are welcomed.

Xiaogai.Li@sth.kth.se

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Parametric studies on Infusion rate