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Biosimulation of Normal Pressure Hydrocephalus (NPH) Using COMSOL Multiphysics

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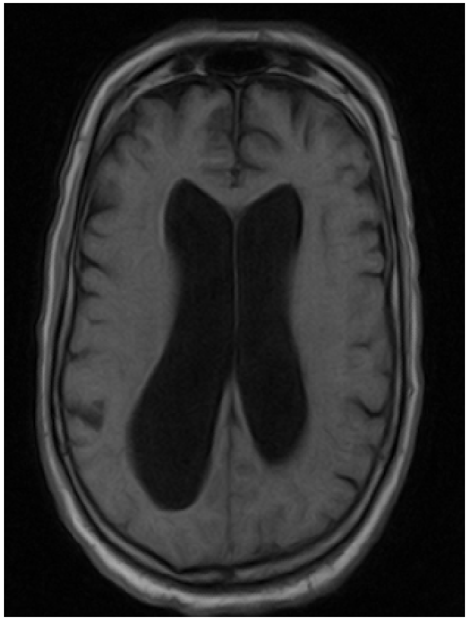


Hes·SO // GENÈVE Haute Ecole Spécialisée de Suisse occidentale

HUG Hôpitaux Universitaires de Genève

ESPCI ParisTech

LSMX LABORATOIRE DE SIMULATION DES MATERIAUX COMPUTATIONAL MATERIALS LABORATORY

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

NPH : computed tomography (CT) scan*

Normal

Sick

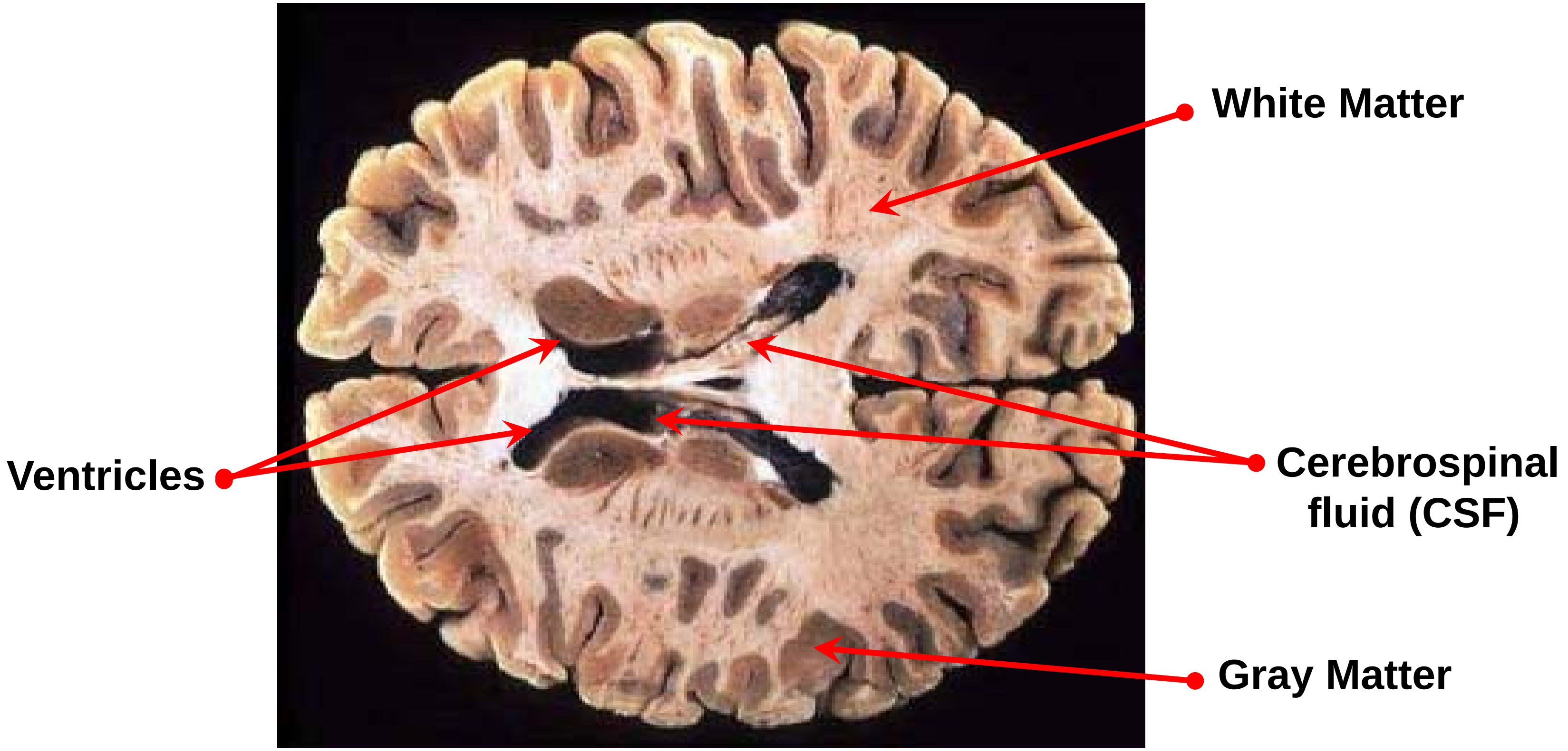
- **Hydrocephalus affects approximately 1 in every 500 children**
- **In children, it appears as head enlargement, headache and visual changes**
- **In older patients, it may cause dementia, walking disorder and urinary incontinence**

Important disease, which is not fully understood!

* Momjian S, Bichsel D. Nonlinear poroplastic model of ventricular dilation in hydrocephalus. J Neurosurg 2008; 109(1): 100-7.

Brain physiology

- ✓ **Interstitial fluid (ISF)** Fluid within parenchyma : ***18%***
- ✓ **Cerebrospinal fluid (CSF)** Fluid inside ventricles and subarachnoid space (SAS)
- ✓ **Gray matter** (cell bodies of neurons) : **isotropic** in permeability and elasticity
- ✓ **White matter** (axons of neurons) : **transverse isotropic (TI)** in permeability and elasticity



Objectives

- **Global**

✓ Understand the origins of NPH, notably in terms of CSF flow disturbances

✓ Help medical doctors to better treat NPH by predicting the force distributions along the fibre tracts

✓ Apply the model to other brain diseases (Alzheimer, Edema, …)

- **In this study**

✓ Influence of anisotropy and inhomogeneity in the brain permeability

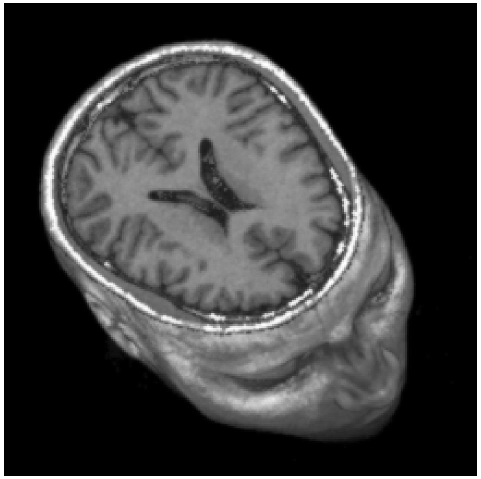
✓ Influence of large deformation

- **Approach**

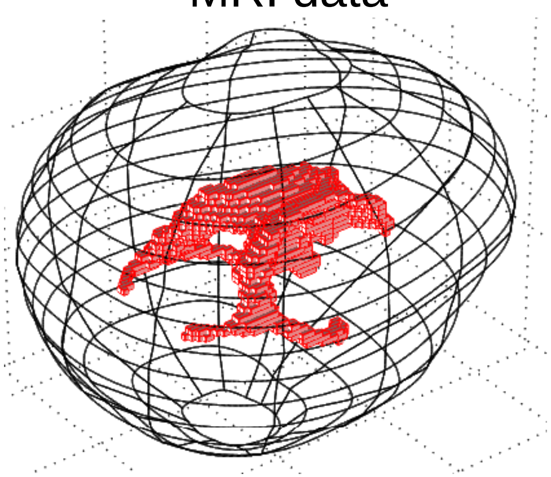
✓ Measurements of input data using MRI and DTI methods

✓ Finite element modeling of the CSF flow in a fully saturated porous medium (brain parenchyma)

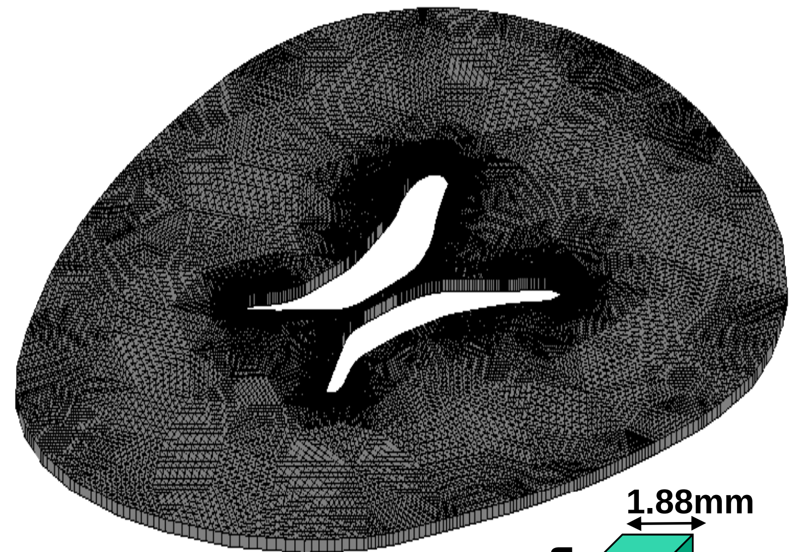
MRI geometry (1.88 x 1.88 x 2 mm^3 voxels)

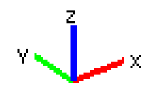


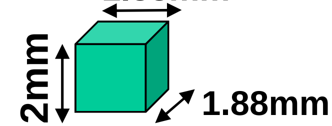
MRI data



3D model of brain







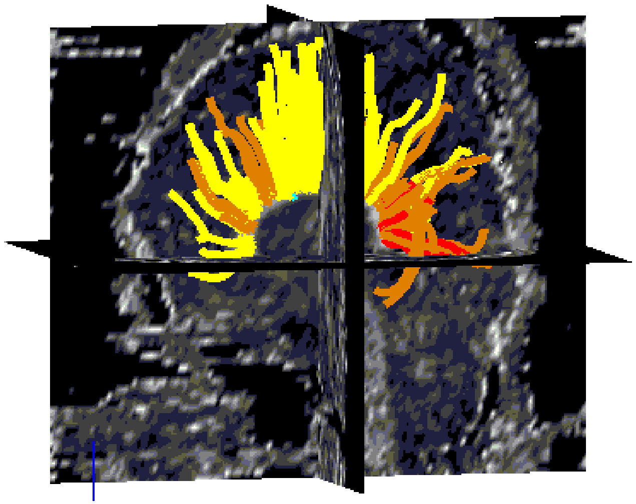
Voxel

63'104 prism elements

64'398 nodes

4 Dofs: ***u,v,w*** (displacements) and ***p*** (CSF pressure)

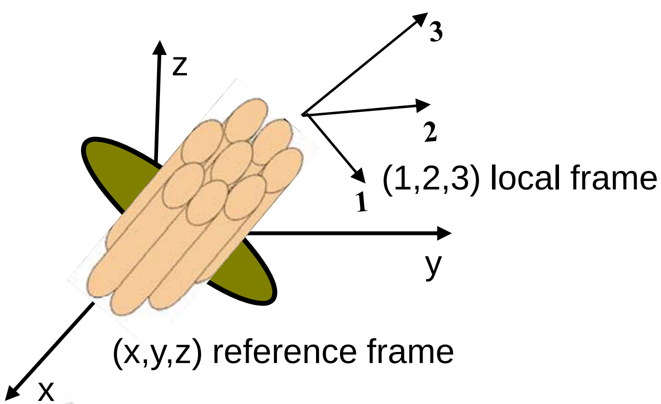
DTI data (1.88 x 1.88 x 2mm³ voxels)



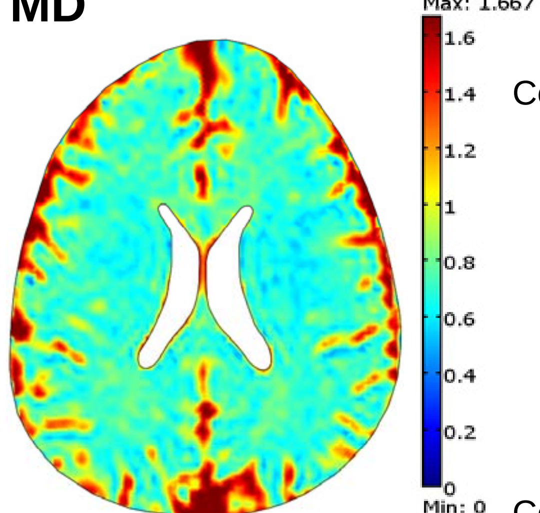
$$\mathbf{D}=\begin{bmatrix} D_{xx} & D_{yx} & D_{zx} \\ & D_{yy} & D_{zy} \\ Symm. & & D_{zz} \end{bmatrix}$$

$$\mathrm{MD}=\bar{\mathrm{D}}=\frac{D_1+D_2+D_3}{3}$$

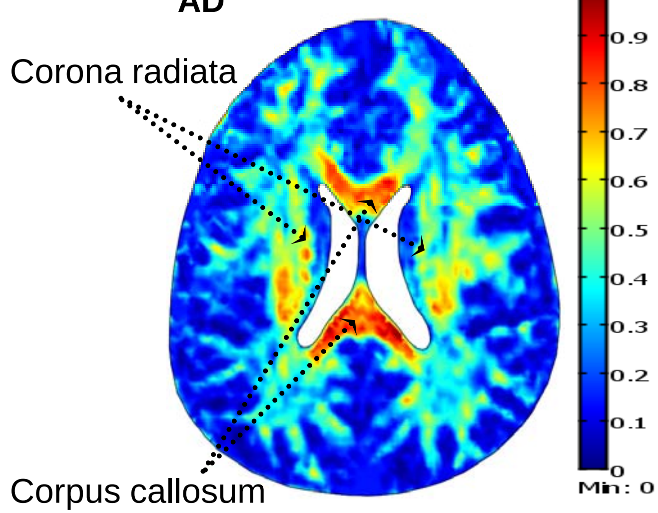
$$\mathrm{F_{AD}}=\sqrt{\frac{3}{2}}\sqrt{\frac{(D_1-\bar{D})^2+(D_2-\bar{D})^2+(D_3-\bar{D})^2}{D_1^2+D_2^2+D_3^2}}\leq 1$$



MD



$\mathrm{F_{AD}}$



Permeability and Diffusion

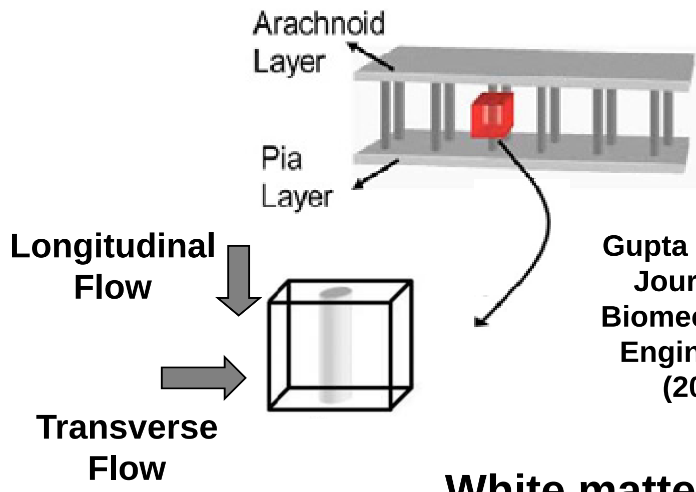
Gray and white matter distinction

White matter $(F_{AD} \geq 0.25)$

Gray matter $(F_{AD} < 0.25)$

Diffusion ratio = [1 - 3]

Permeability ratio = [1 - 100]



Gupta S. et al., Journal of Biomechanical Engineering (2009)

Permeability versus CSF content

Westhuizen - Du Plessis

$$\begin{cases} k_{para} = \dfrac{f_0^{\,2}(\pi + 2.157(1-f_0))}{48(1-f_0)^2} d_w^2, \ [m^2] \\[2ex] k_{perp} = \dfrac{\pi f_0 (1-\sqrt{1-f_0})^2}{24(1-f_0)^{3/2}} d_w^2, \ [m^2] \end{cases}$$

Carman-Kozeny

$$k_{gray} = \frac{f_0^{\,3}}{180(1-f_0)^2} d_g^2, \ [m^2]$$

anisotropy in permeability

White matter

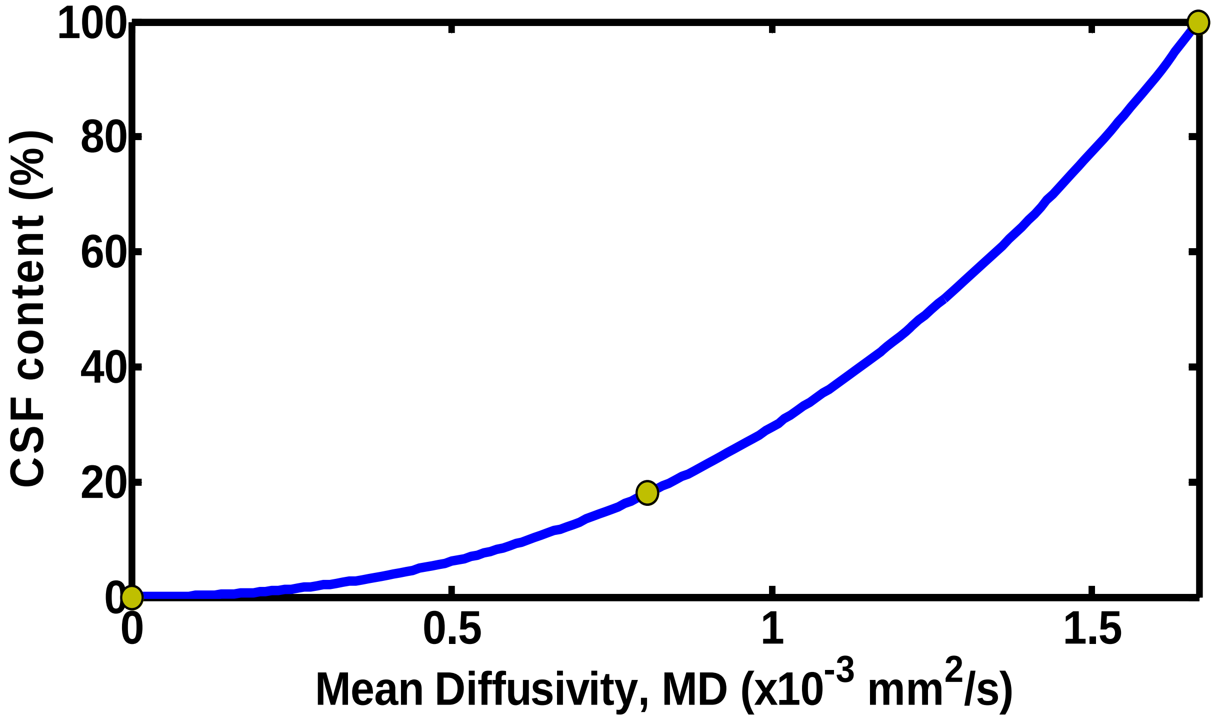
$$\mathbf{k} = \begin{bmatrix} k_{perp} & 0 & 0 \\ 0 & k_{perp} & 0 \\ 0 & 0 & k_{para} \end{bmatrix}$$

Gray matter

$$\mathbf{k} = \begin{bmatrix} k_{gray} & 0 & 0 \\ 0 & k_{gray} & 0 \\ 0 & 0 & k_{gray} \end{bmatrix}$$

Permeability and Diffusion

CSF content (%) versus Mean Diffusivity (MD)

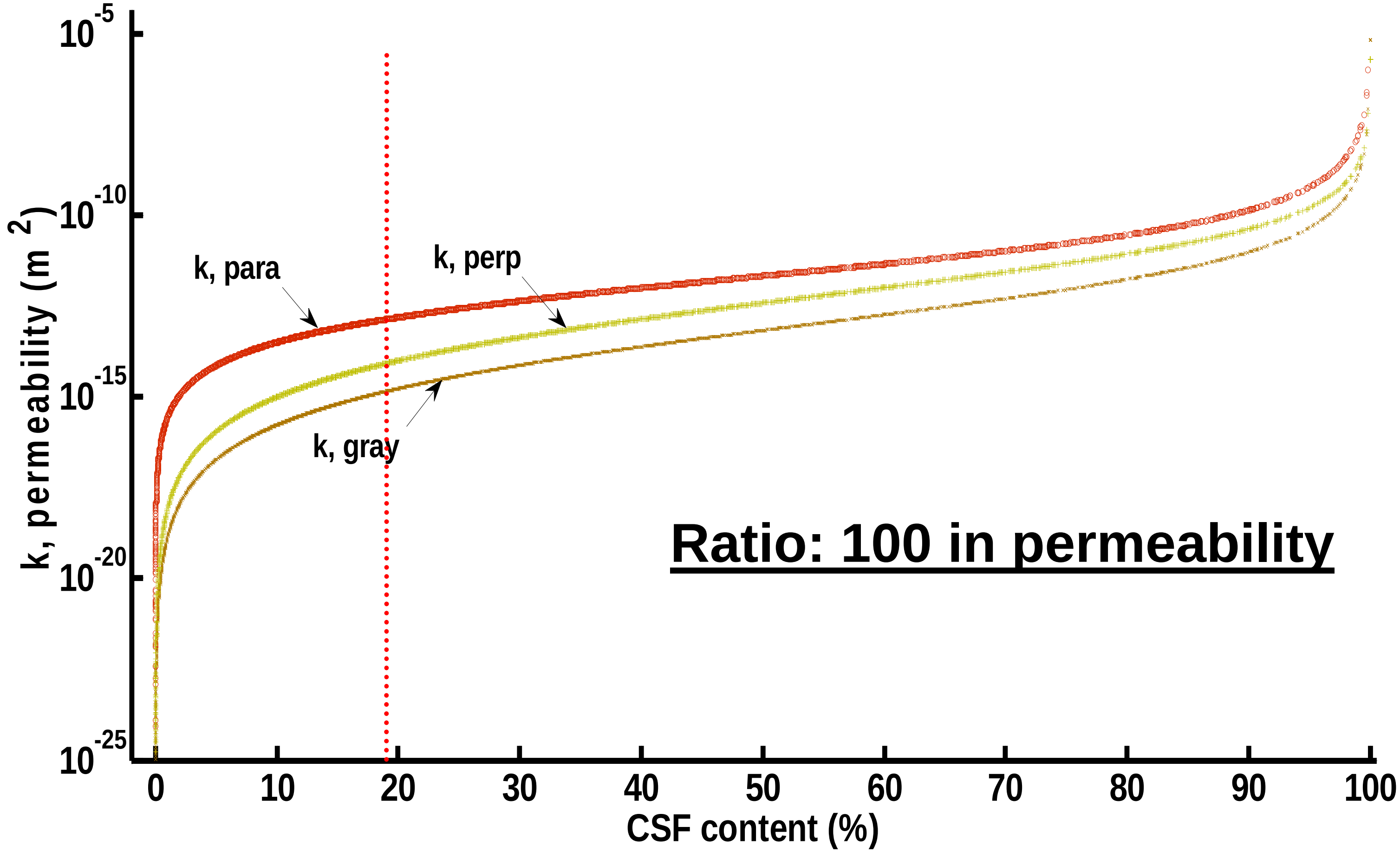


	Min.	Ave.	Max.
MD	0	0.8	1.667
CSF	0	18	100

$$f_0 = 9.633(\mathrm{MD})^3 + 19.94(\mathrm{MD})^2$$

Permeability and Diffusion

Permeability coefficients for gray and white matter versus CSF content (%)



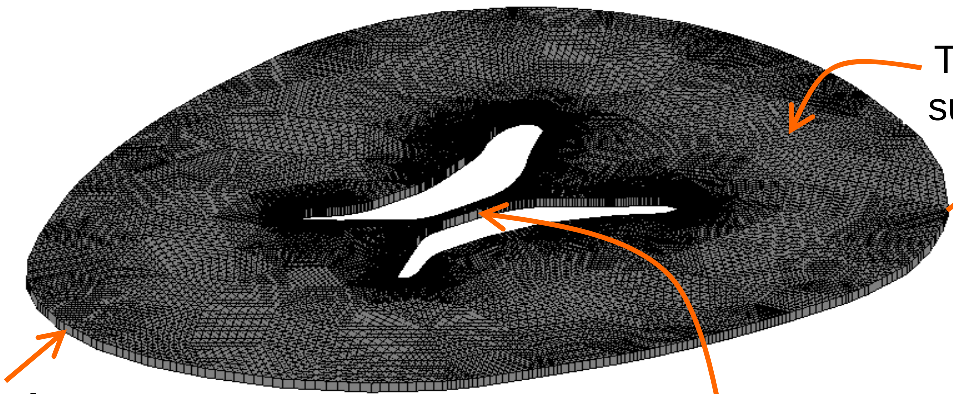
FE modeling

Biot's equations

Steady-state

No sink/source terms

$$
\begin{cases}
div(\boldsymbol{\sigma}) + \vec{\nabla} p = \vec{0} \\
\nabla \cdot (\mathbf{k} \vec{\nabla} p) = 0
\end{cases}
$$



Top and bottom surfaces of slice

$$u_z = 0$$

$$\frac{\partial p}{\partial \vec{n}} = 0$$

Brain surface

$$\vec{u} = \vec{0}$$

$$p = 0$$

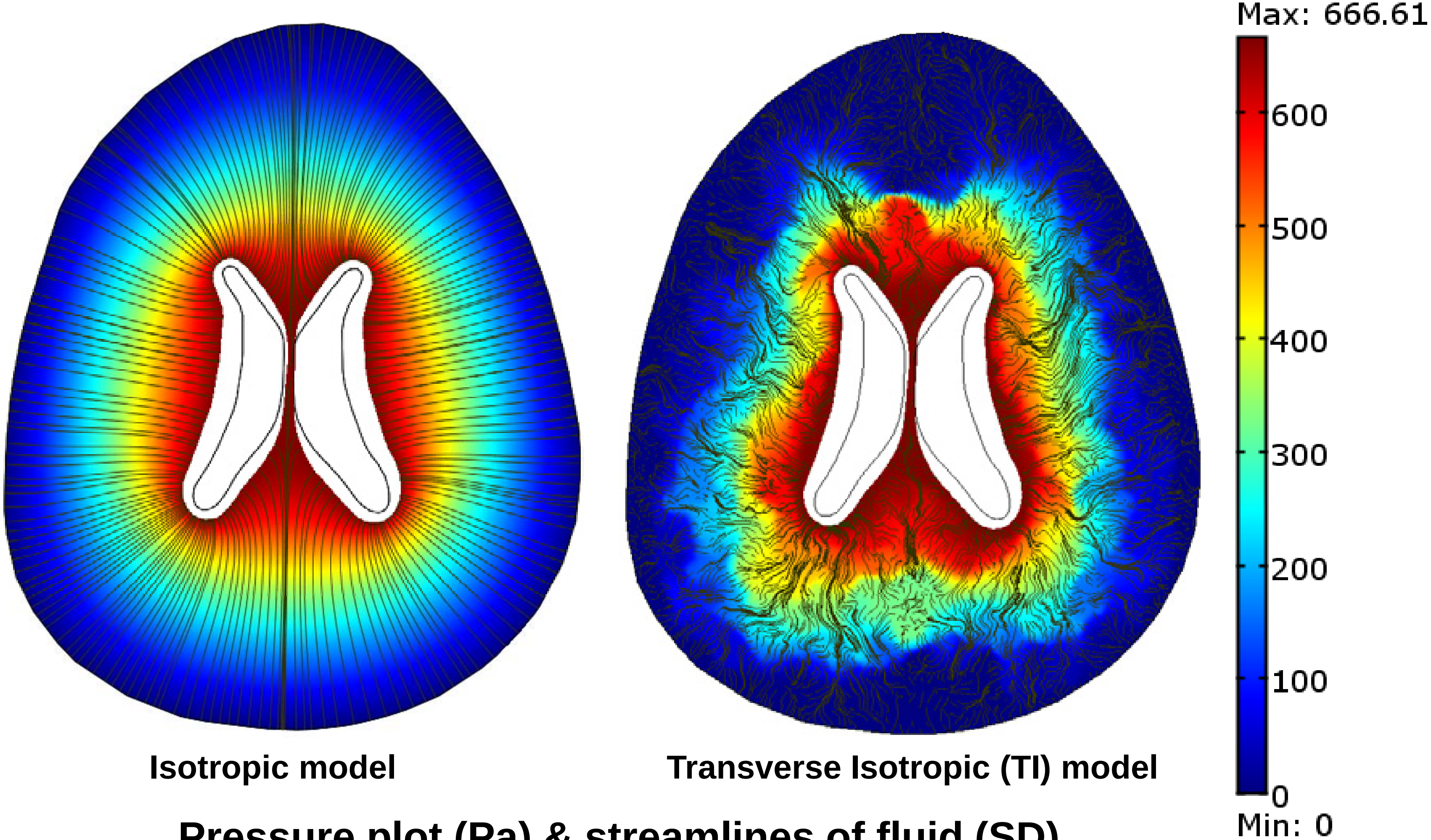
Ventricles

$$\sigma \cdot \vec{n} = -p\vec{n}$$

$$p = 5 \text{ mm Hg}$$

Imposed CSF pressure gradient of 666.61 Pa

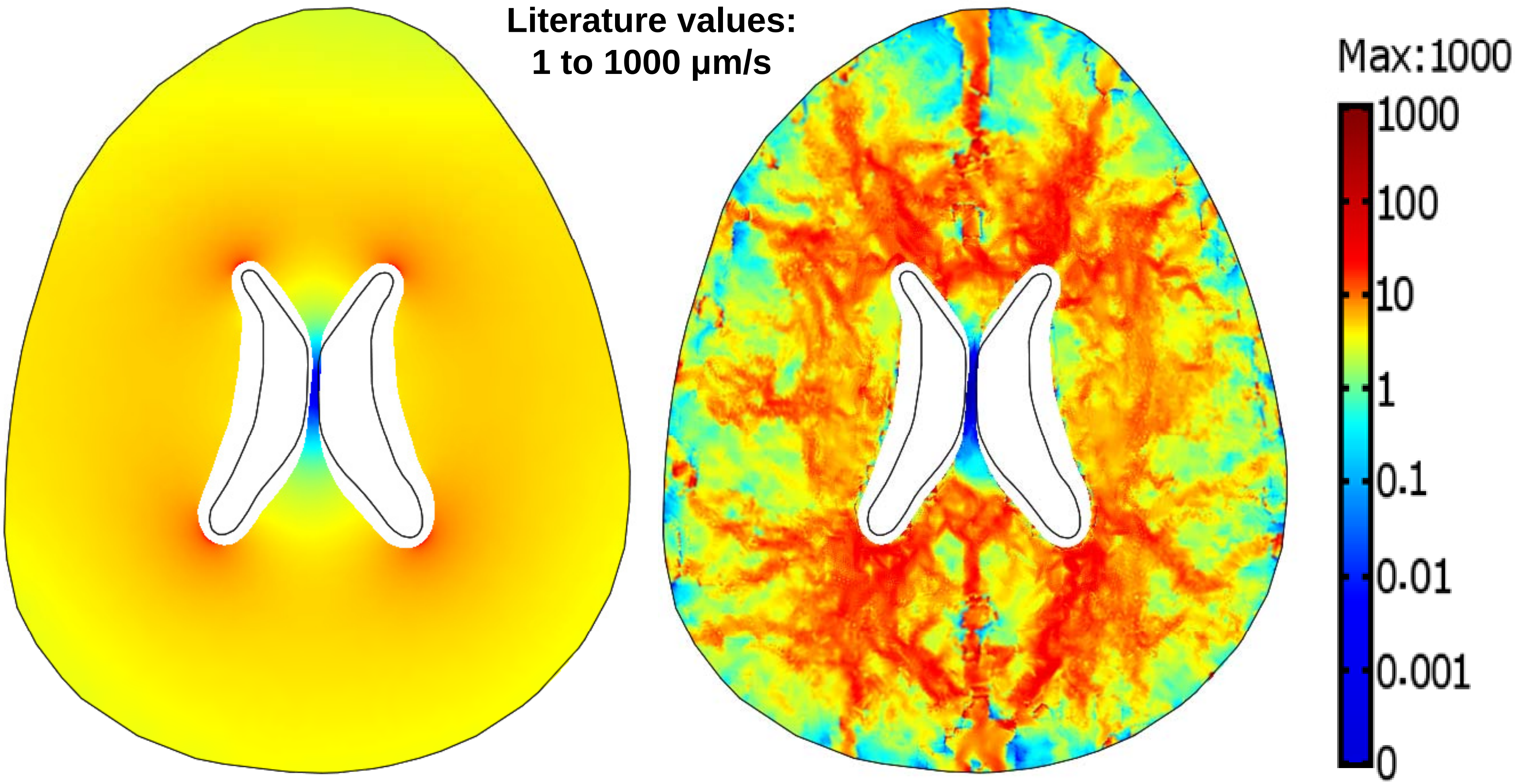
Results: Pressure & fluid streamlines



Pressure plot (Pa) & streamlines of fluid (SD)

Results: fluid velocity

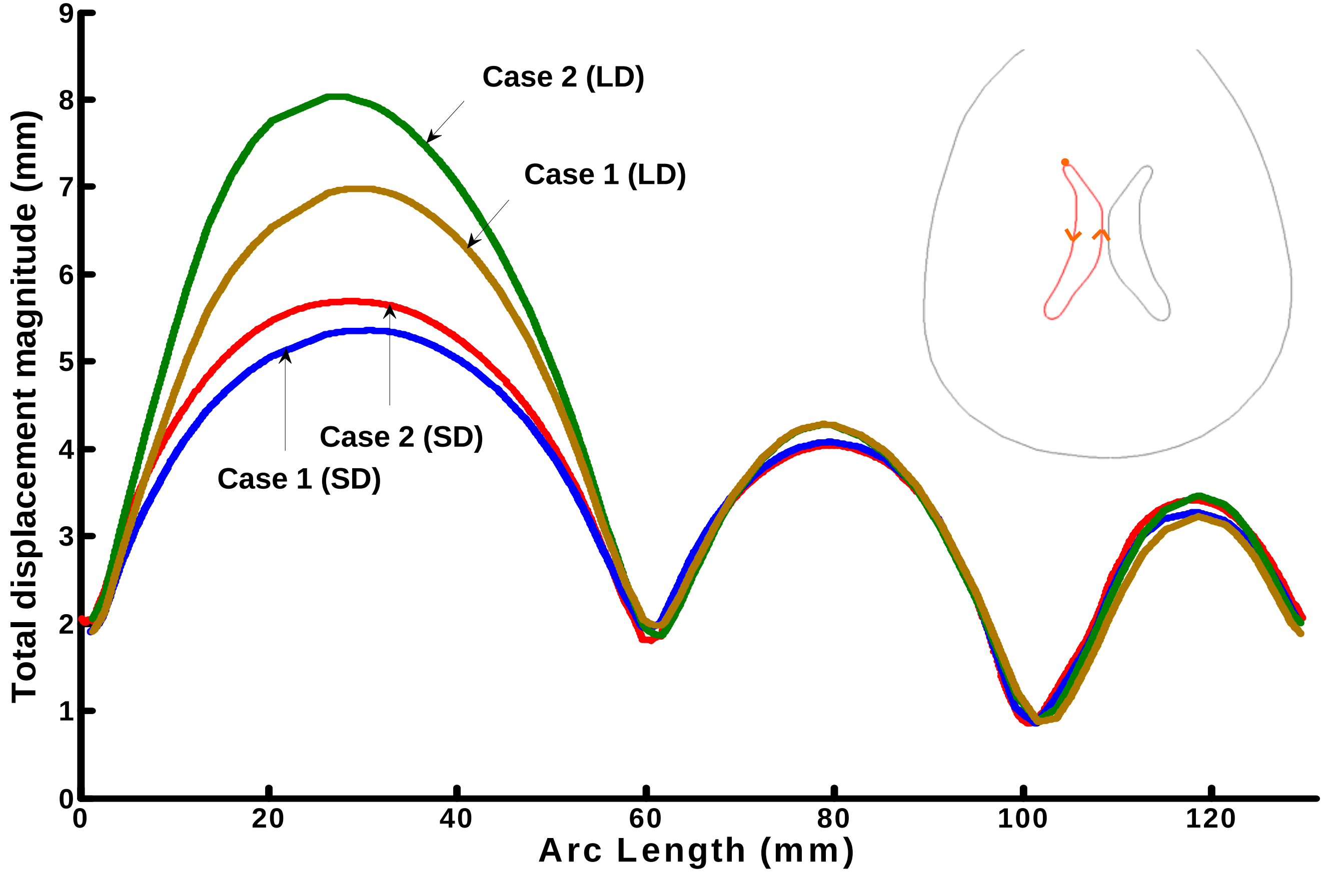
Literature values:
1 to 1000 µm/s



Isotropic model **Transverse Isotropic (TI) model**

Fluid velocity magnitude (µm/s) (SD)

Results: displacement magnitude



Isotropic	SD = 5.37	→	+ 6 %	→	TI	SD = 5.69
	LD = 6.96	→	+ 15 %	→		LD = 8.03

Conclusion

- ✓ A large effect of anisotropy and inhomogeneity in permeability is demonstrated
- ✓ Using large deformation theory yields a larger increase in dilation
- ✓ The CSF velocity field becomes much more inhomogeneous, as measured in the literature (1 to 1000 μm/s)
- ✓ With space dependent CSF content and TI permeability, our model is much more realistic
- ✓ Next step is to study anisotropy in elasticity using magnetic resonance elastography (MRE)

Thank you for your attention