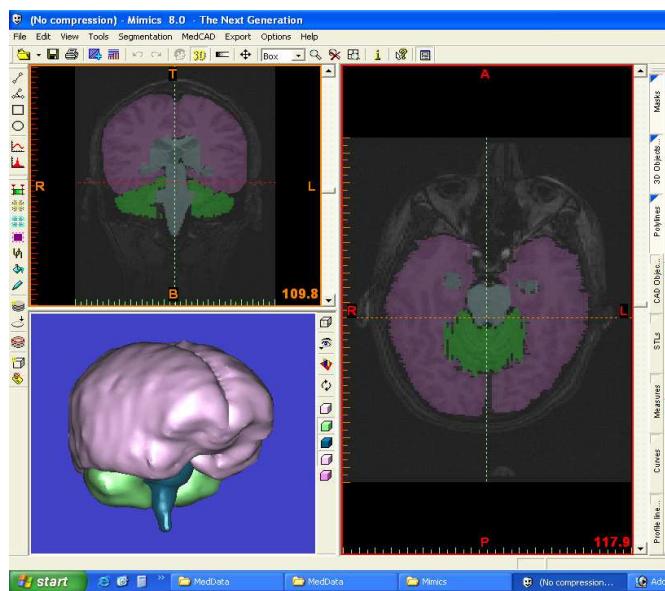


Fields Foundation

Richard D. Penn
and
Andreas Linninger
UIC

The Physics of Hydrocephalus



William of Ockham



the explanation of any [phenomenon](#) should make as few assumptions as possible, eliminating those that make no difference in the observable predictions of the explanatory [hypothesis](#) or [theory](#). The principle is often expressed in Latin as the **lex parsimoniae** ("law of [parsimony](#)" or "law of succinctness"):

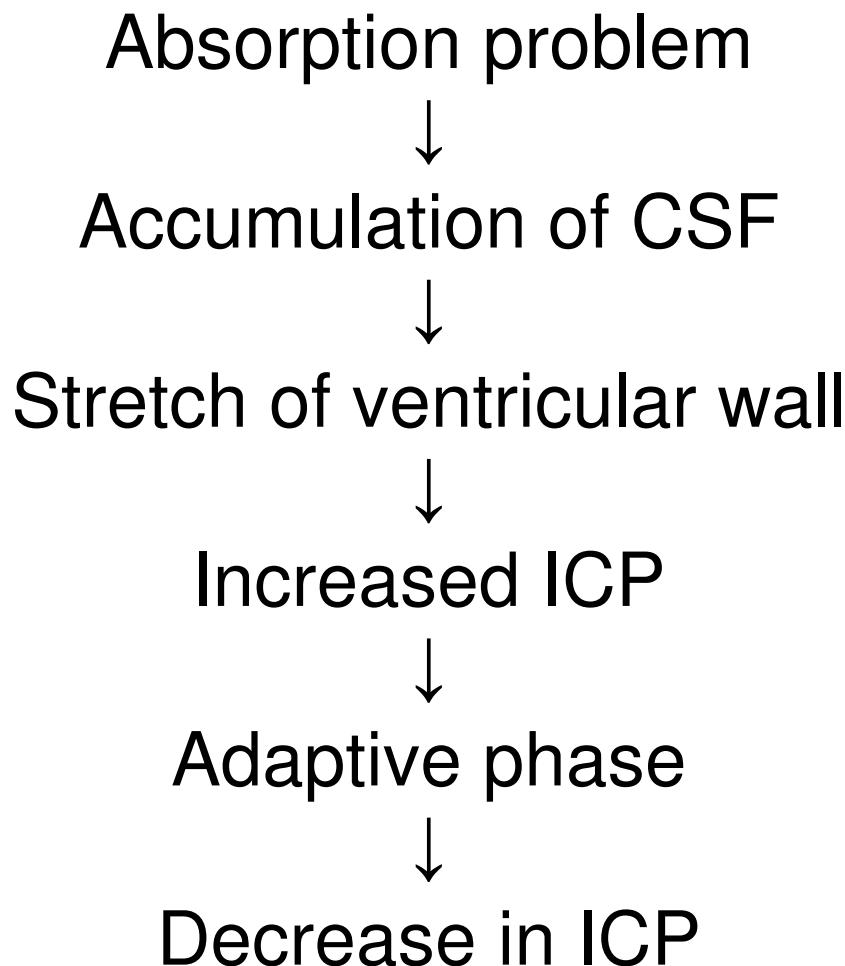
Question

How much of hydrocephalus can be explained by applying the well known physical laws

Methods

- Use MRI measurements to find important parameters e.g. brain and ventricular size, CSF flow patterns, brain water, and brain movements
- Use computer simulations of the physical laws in one to three dimensional models
- Check the results by seeing if predicted values match real patient values

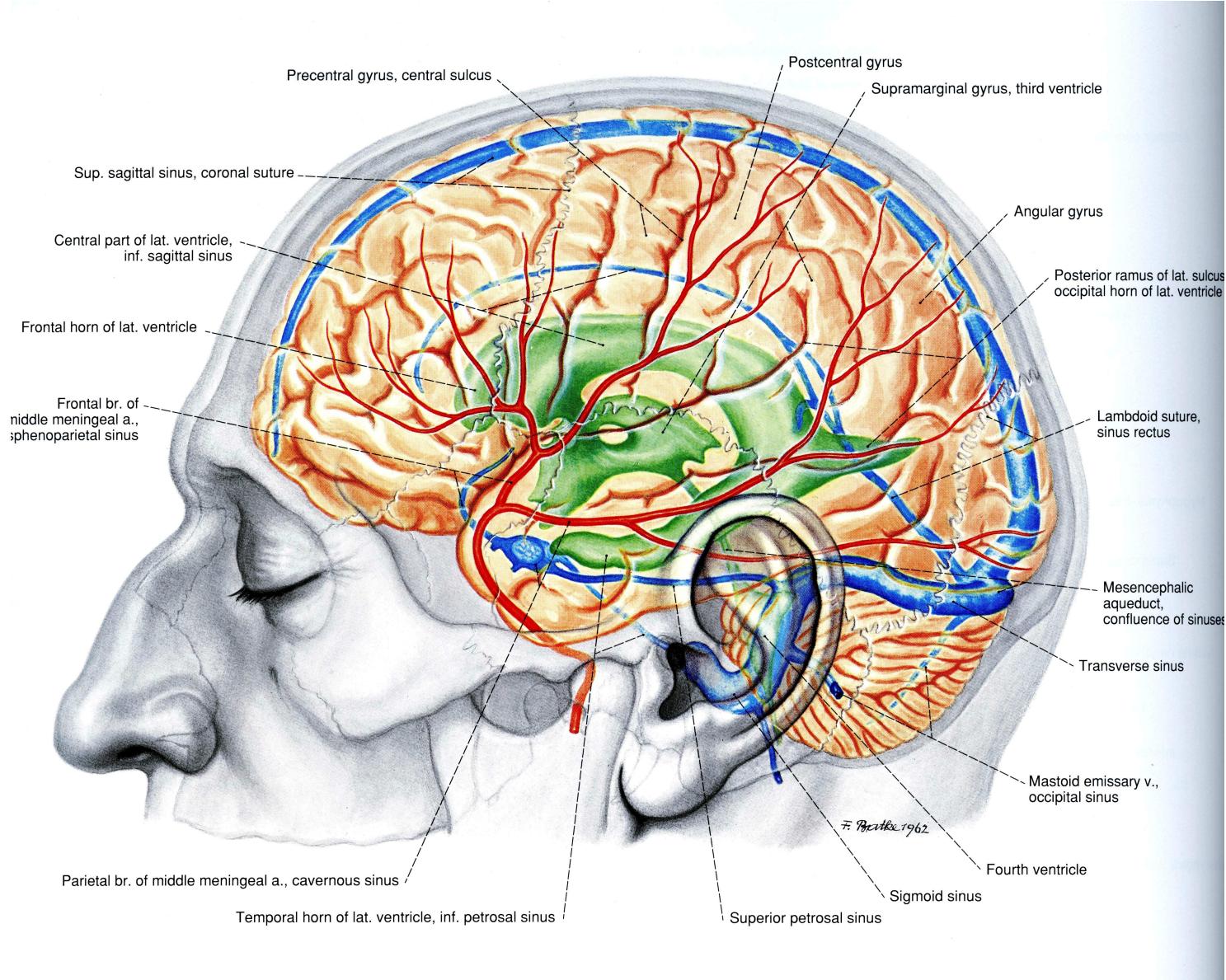
Steps in Hydrocephalus



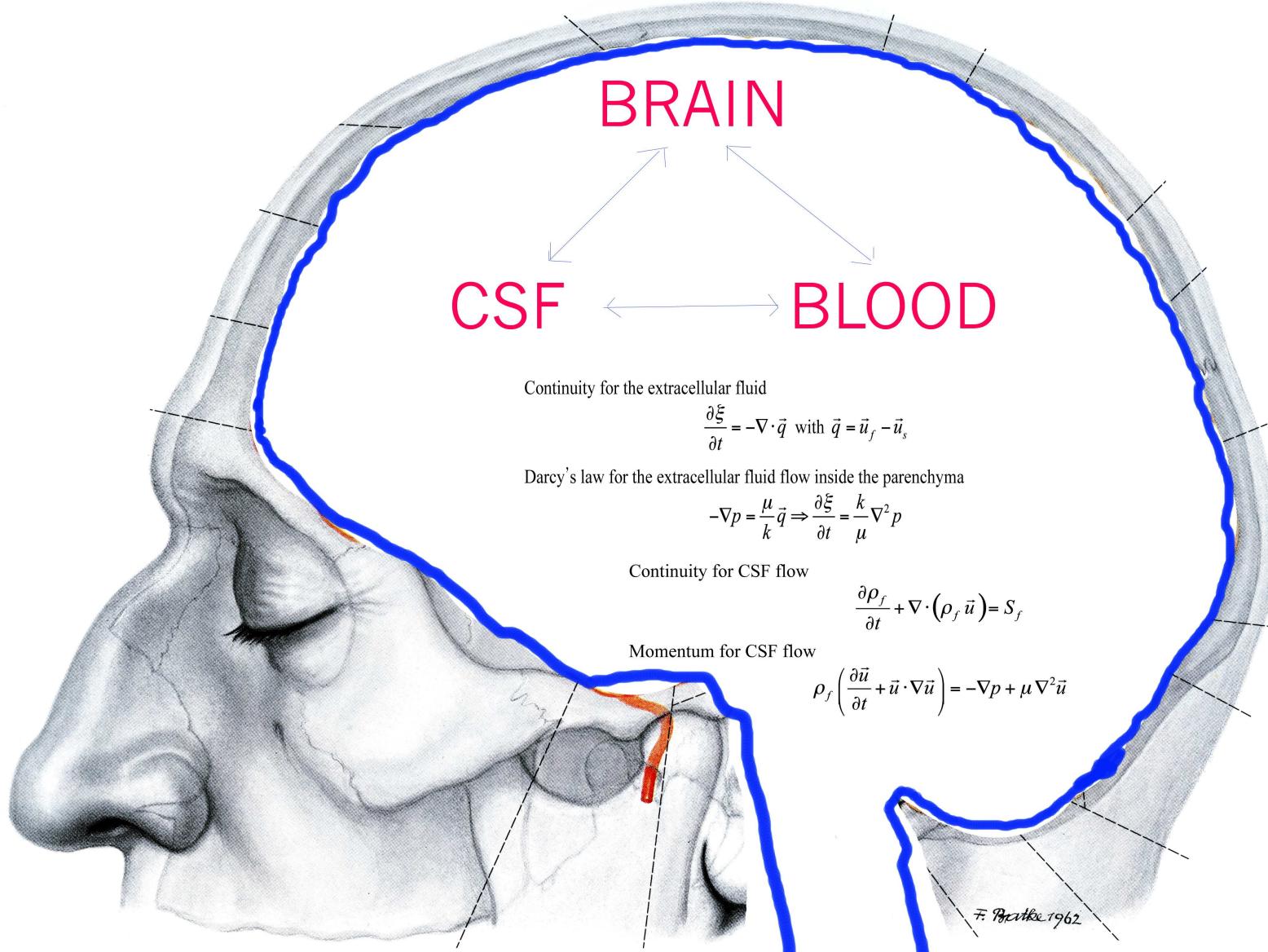
Three Interacting Compartments

- CSF-filled ventricular and subarachnoid system
- Brain parenchyma
- Cerebral blood vessels

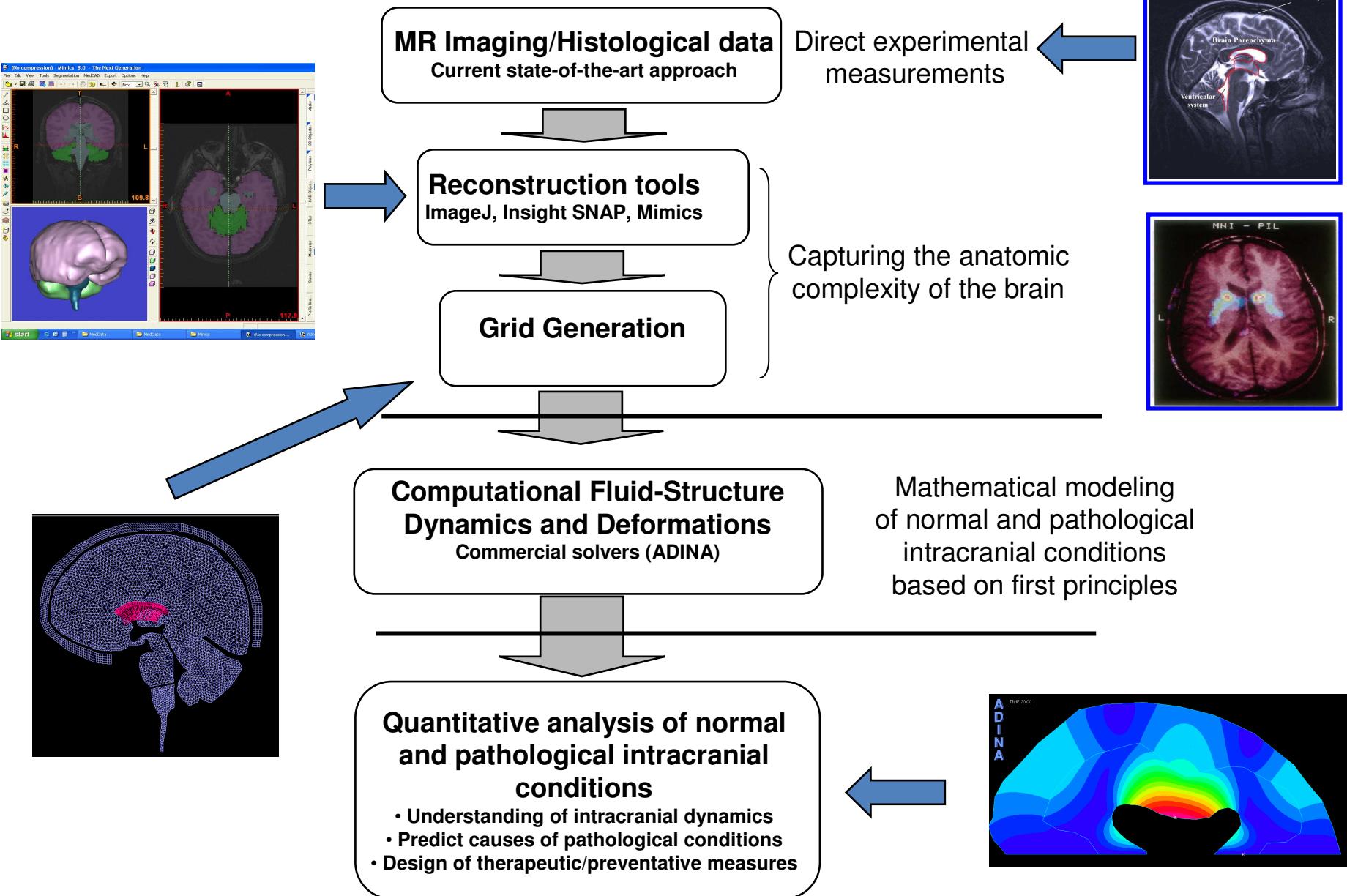
BRAIN BLOOD CSF



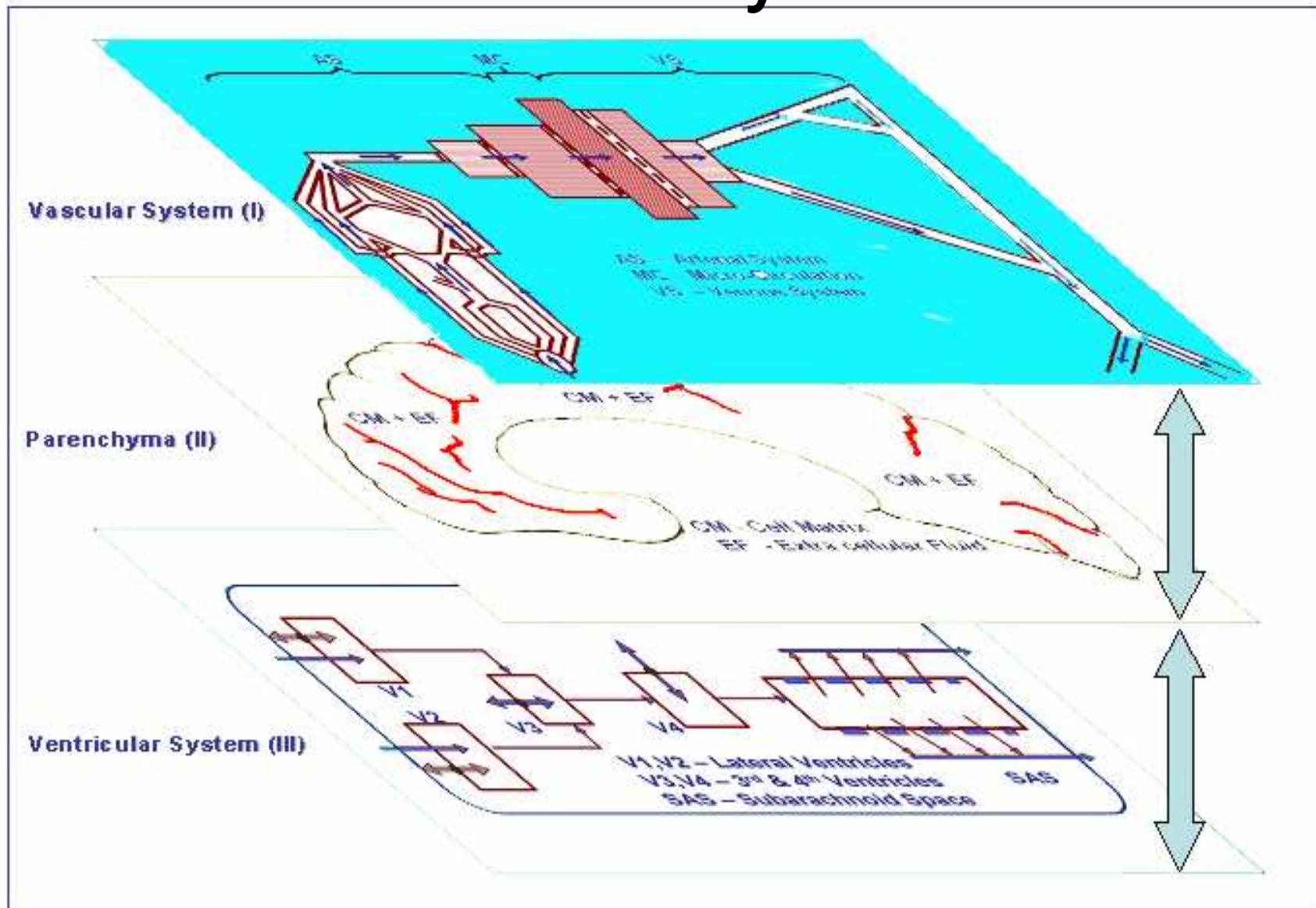
The interactive problem



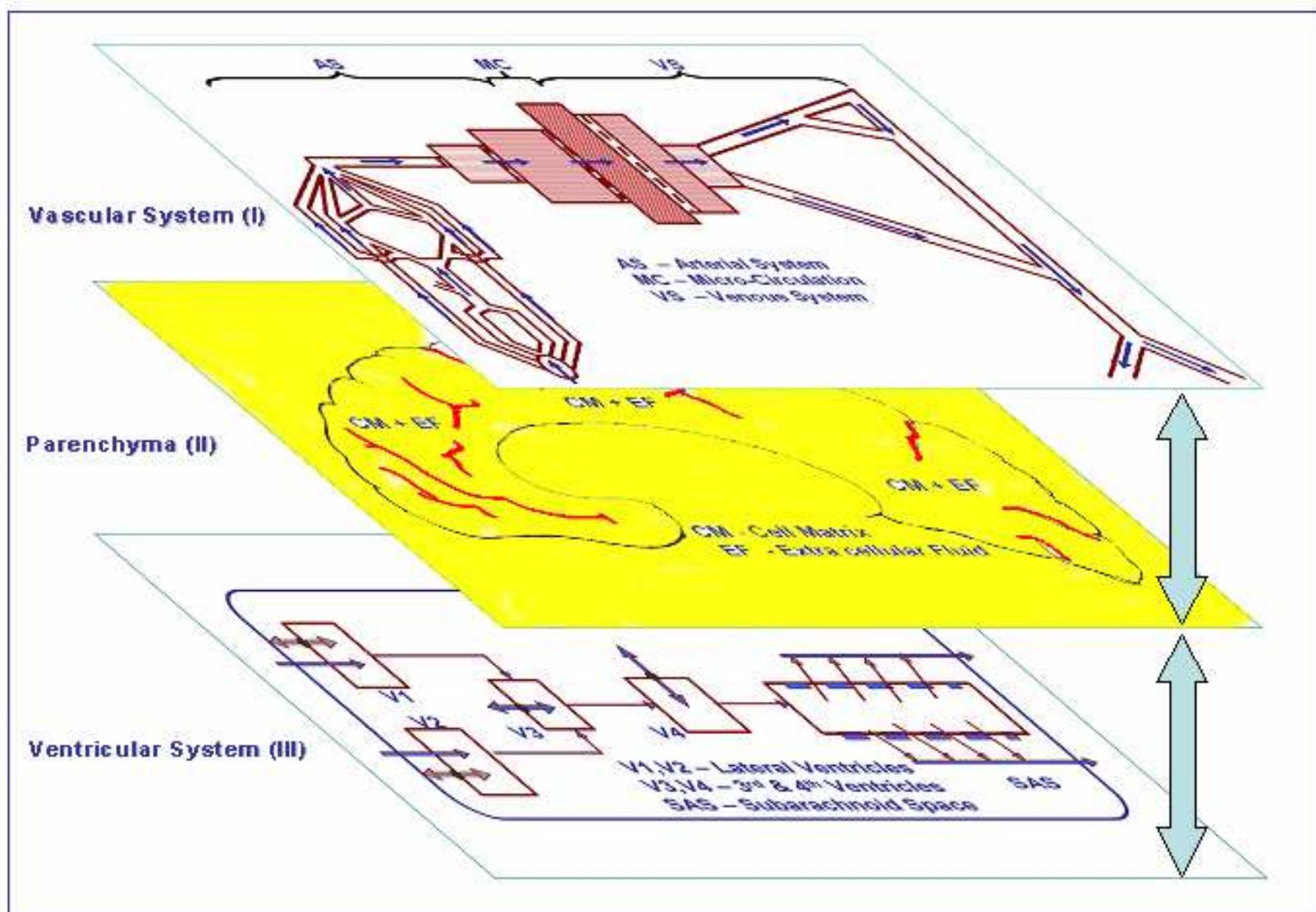
General Methods



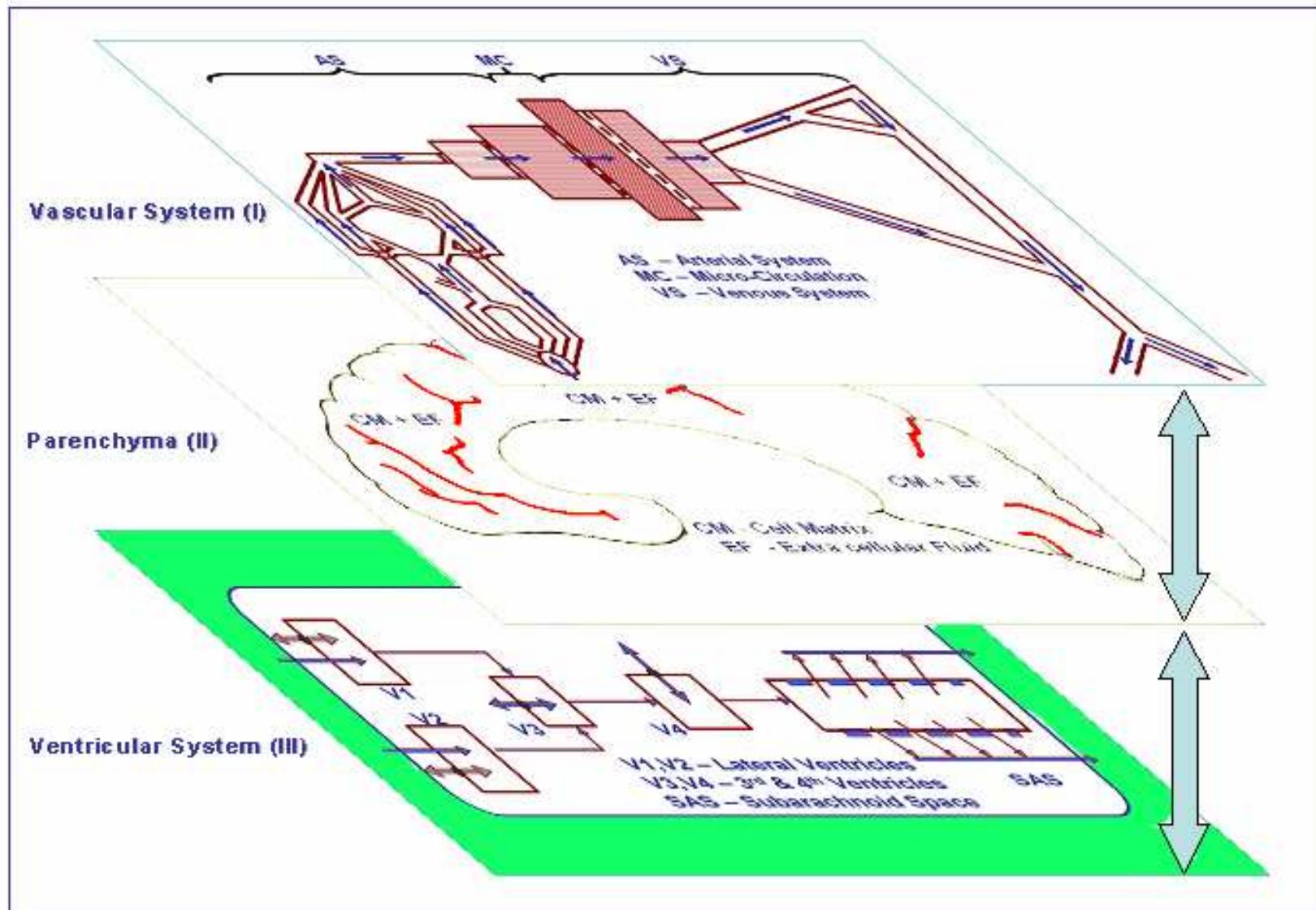
Vascular System



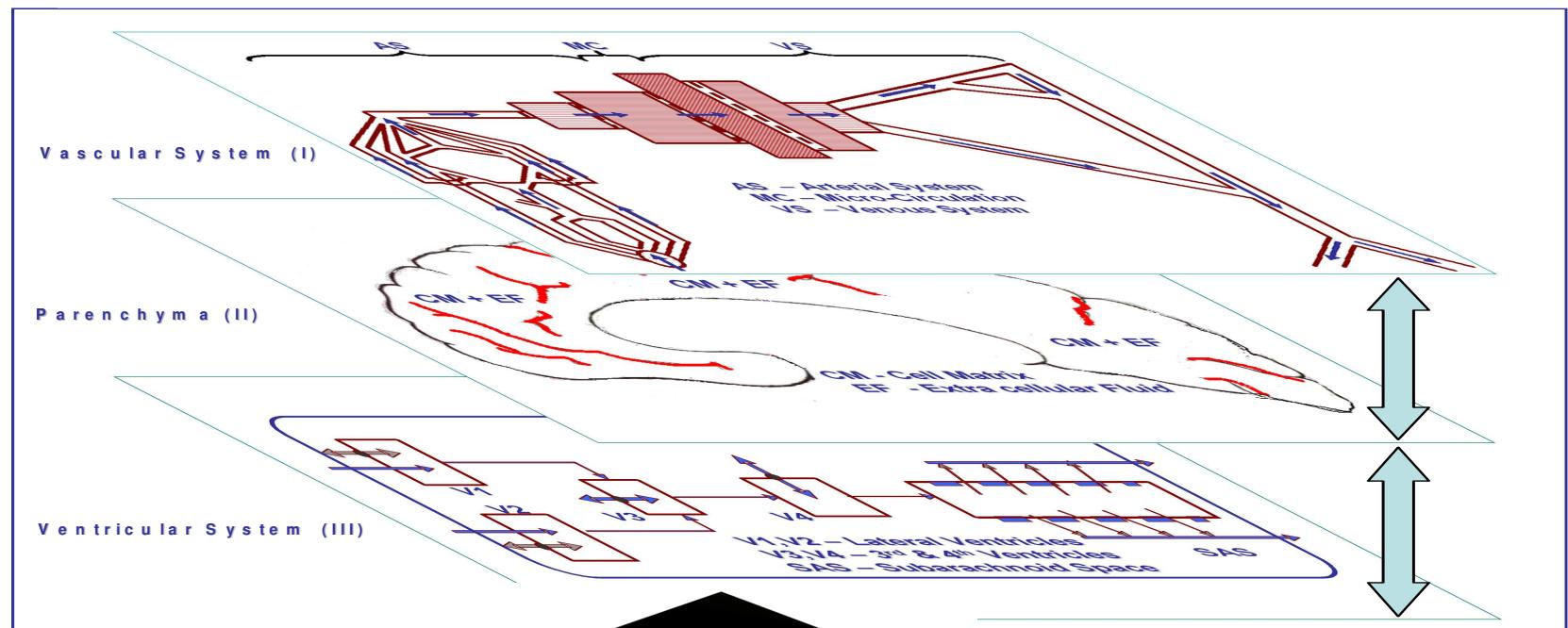
Brain



CSF

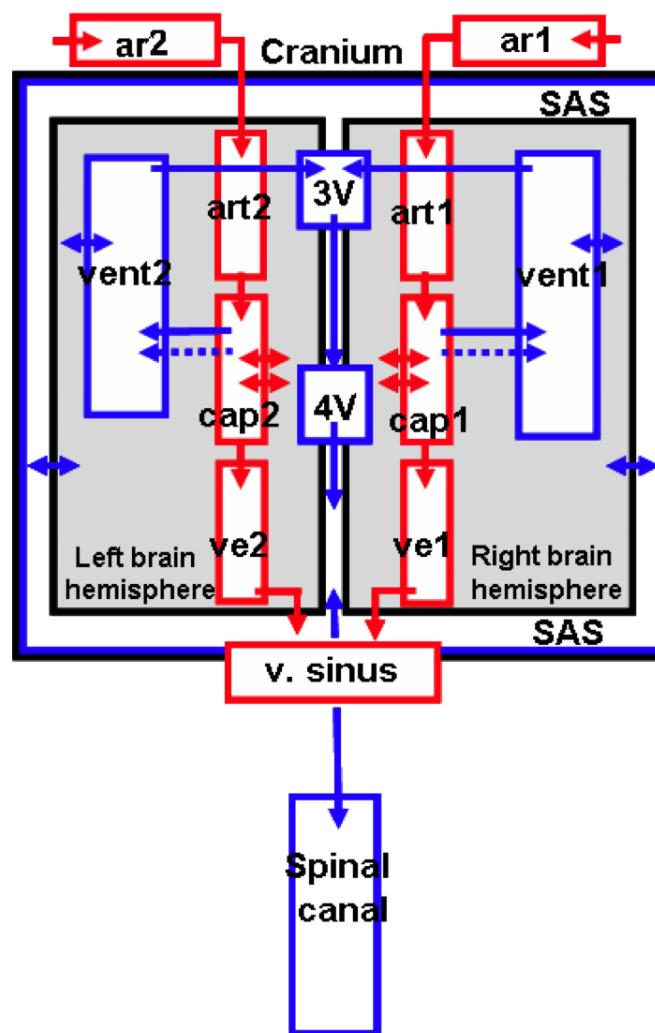


Combined Systems

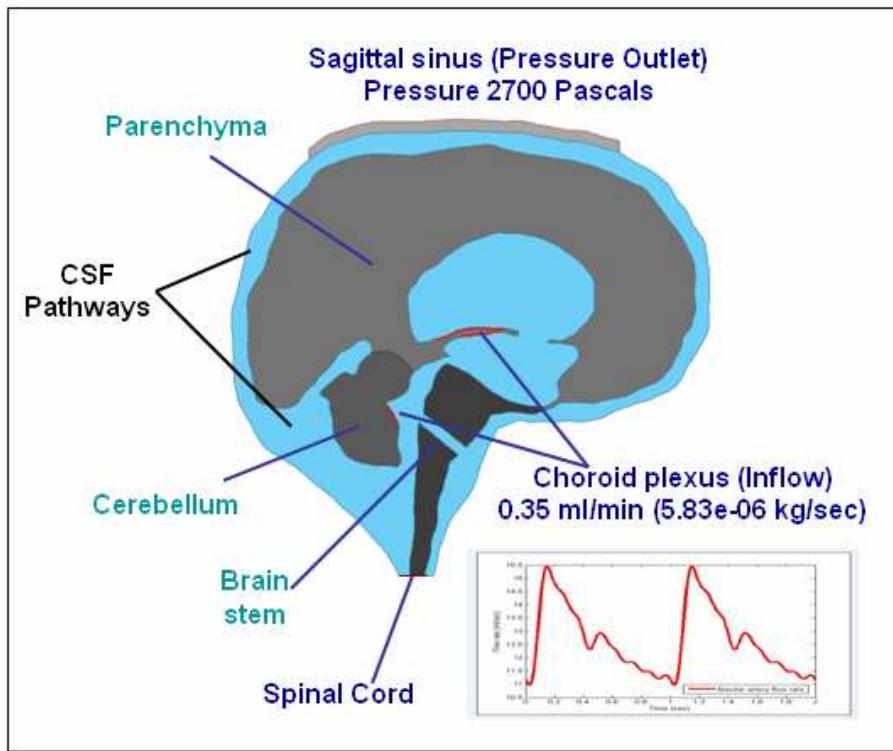


FLOW DYNAMIC PATHWAYS

BLOOD ,BRAIN,CSF



Finite Volume Calculations



Bulk production:

$$a(t) = q_{bulk} + q_{puls}(t)$$

$$q_{bulk} = const;$$

$$q_{puls}(t) = \alpha \left[\sin\left(\omega t - \frac{\pi}{2}\right) - \frac{1}{2} \cos\left(2\omega t - \frac{\pi}{2}\right) \right]$$

CSF reabsorption in Sagittal Sinus:

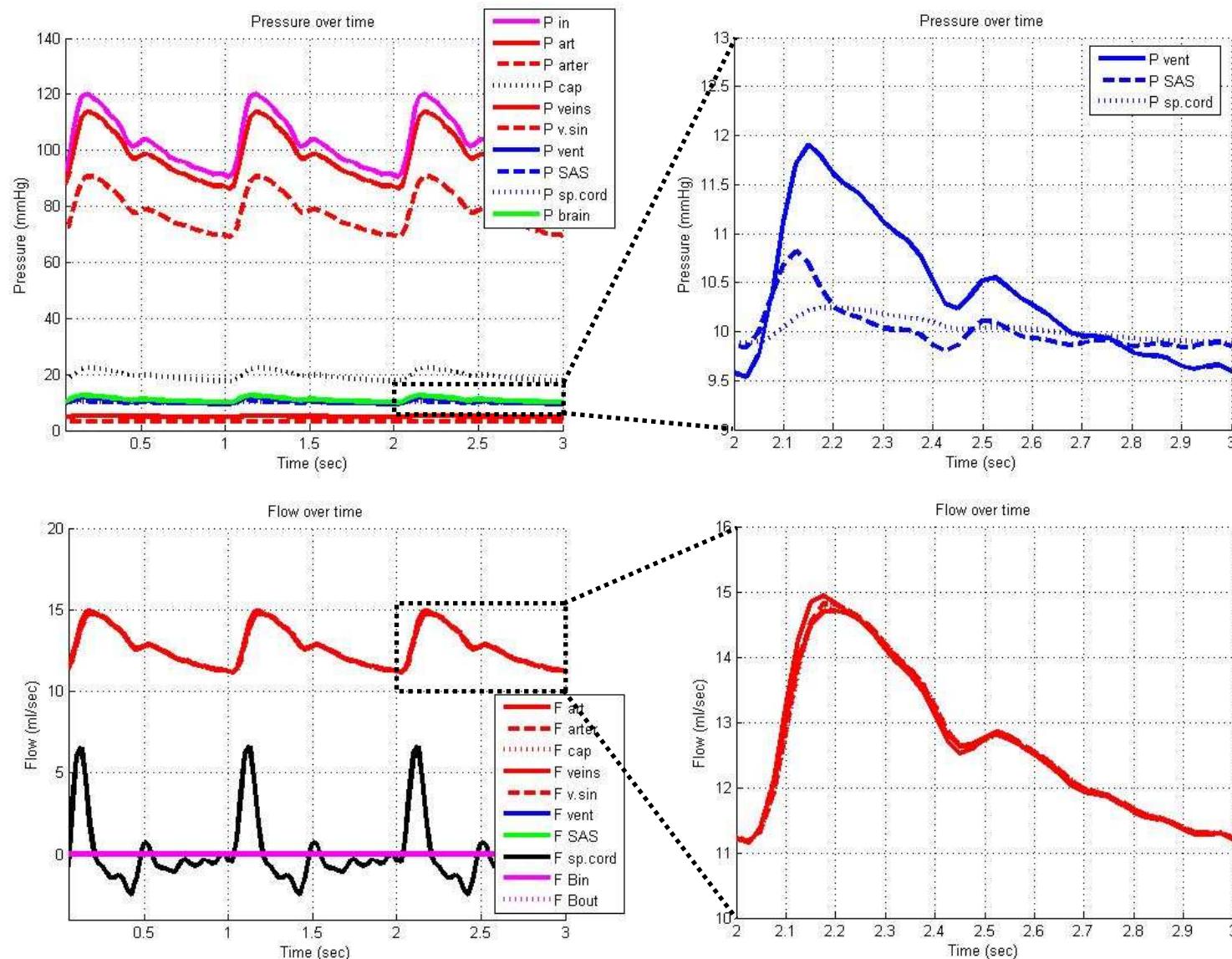
$$q(\vec{x})|_{@Sag.S.} = \kappa \cdot (p(\vec{x})|_{@Sag.S.} - p_v)$$

Oscillatory volumetric flow in Spinal cord:

$$q|_{@Spin.C.}(t) = \alpha \left[\sin\left(\omega t - \frac{\pi}{2}\right) - \frac{1}{2} \cos\left(2\omega t - \frac{\pi}{2}\right) \right]$$

A. Linninger, C. Tsakiris, D. Zhu, M. Xenos, P. Roycewicz, Z. Danziger and R. Penn. Pulsatile cerebrospinal fluid dynamics in the human brain. *IEEE Transactions on Biomedical Engineering*, 52 (4): 557-565, 2005.

Normal Intracranial Dynamics

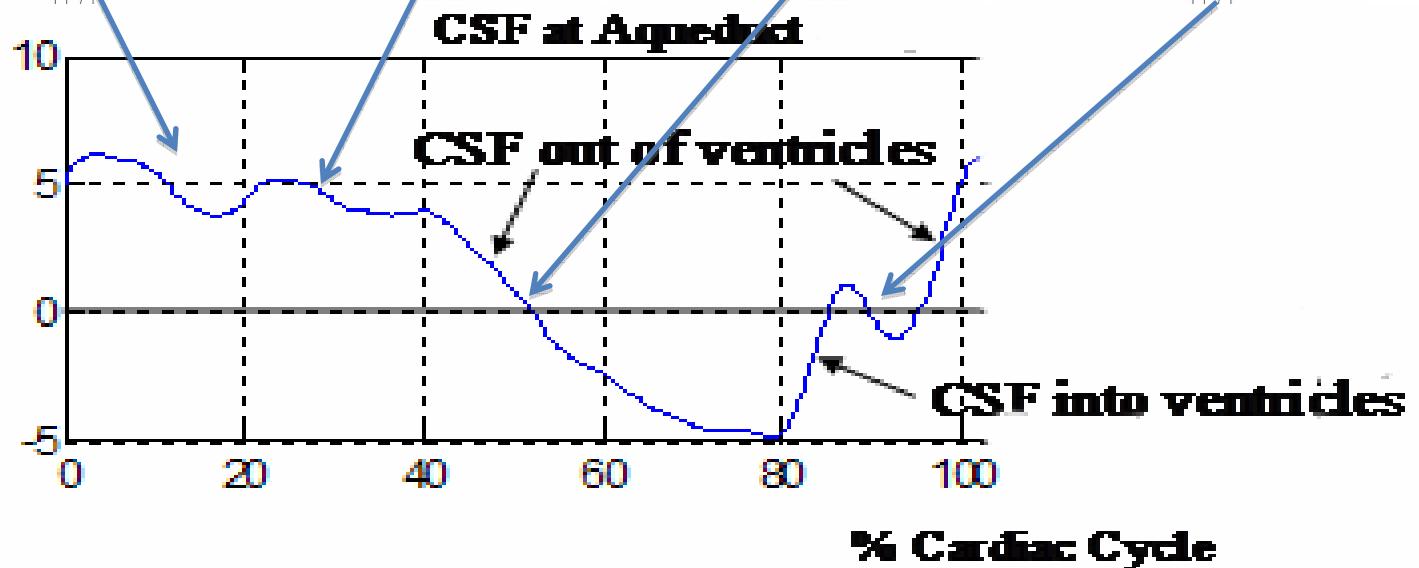
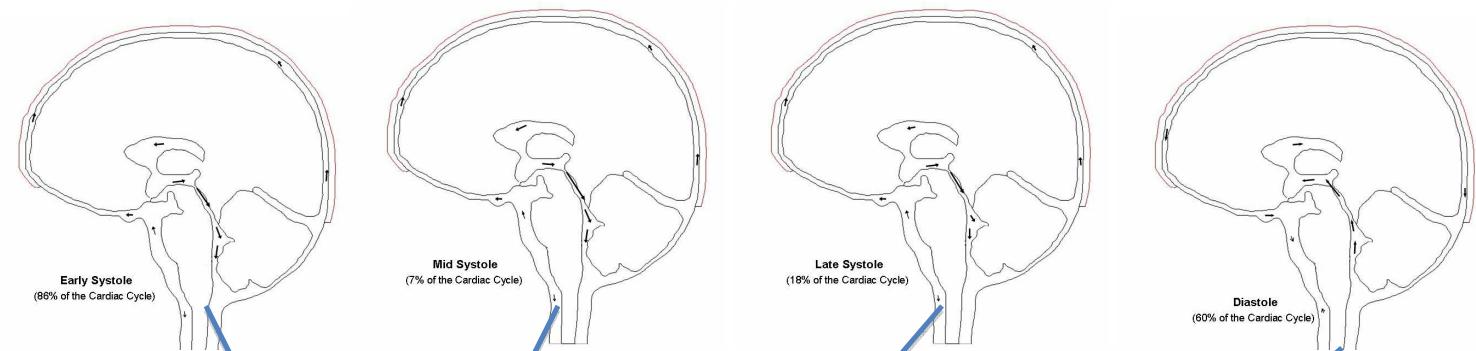
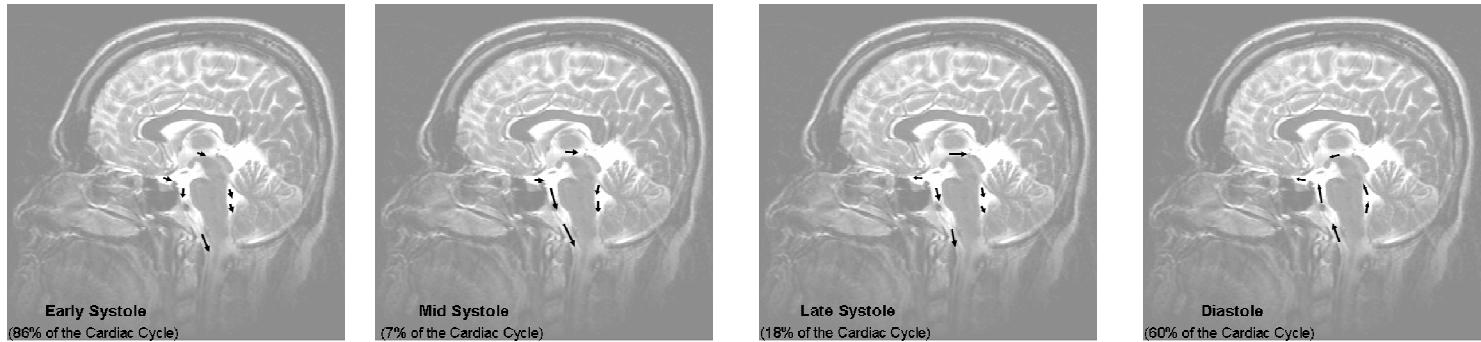


Cine MRI - In vivo CSF flow measurements

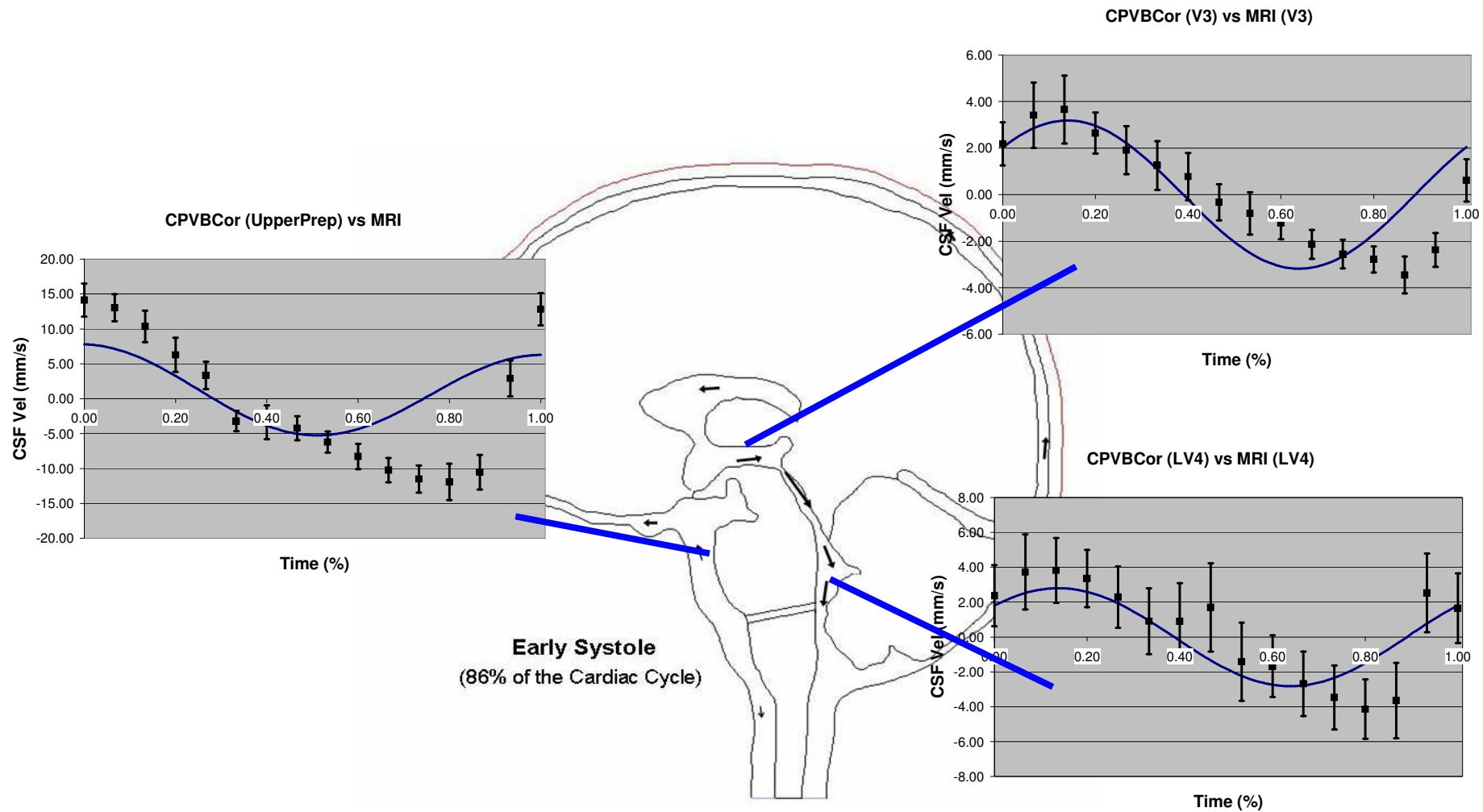


3Tesla GE Signa system
(GE Medical Systems, Milwaukee,
WI)
© U of C

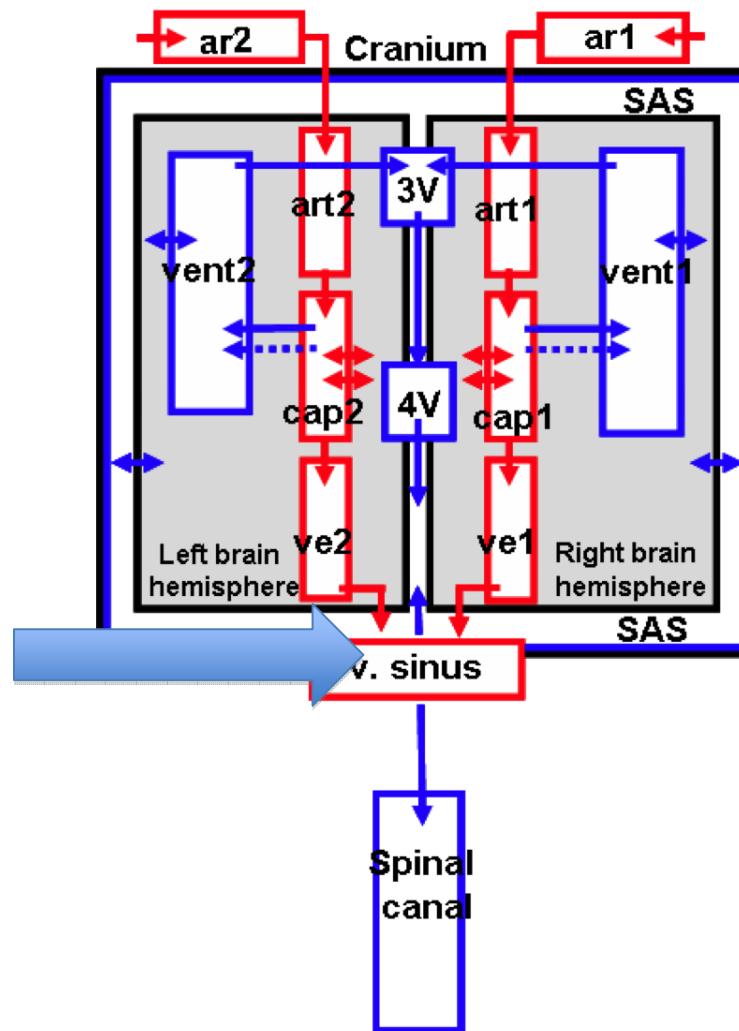
D. Zhu, M. Xenos, A. Linniger and R. Penn. Dynamics of Lateral Ventricle and Cerebrospinal Fluid in Normal and Hydrocephalic Brain. *Journal of Magnetic Resonance Imaging*, 24 (4): 756-770, 2006.



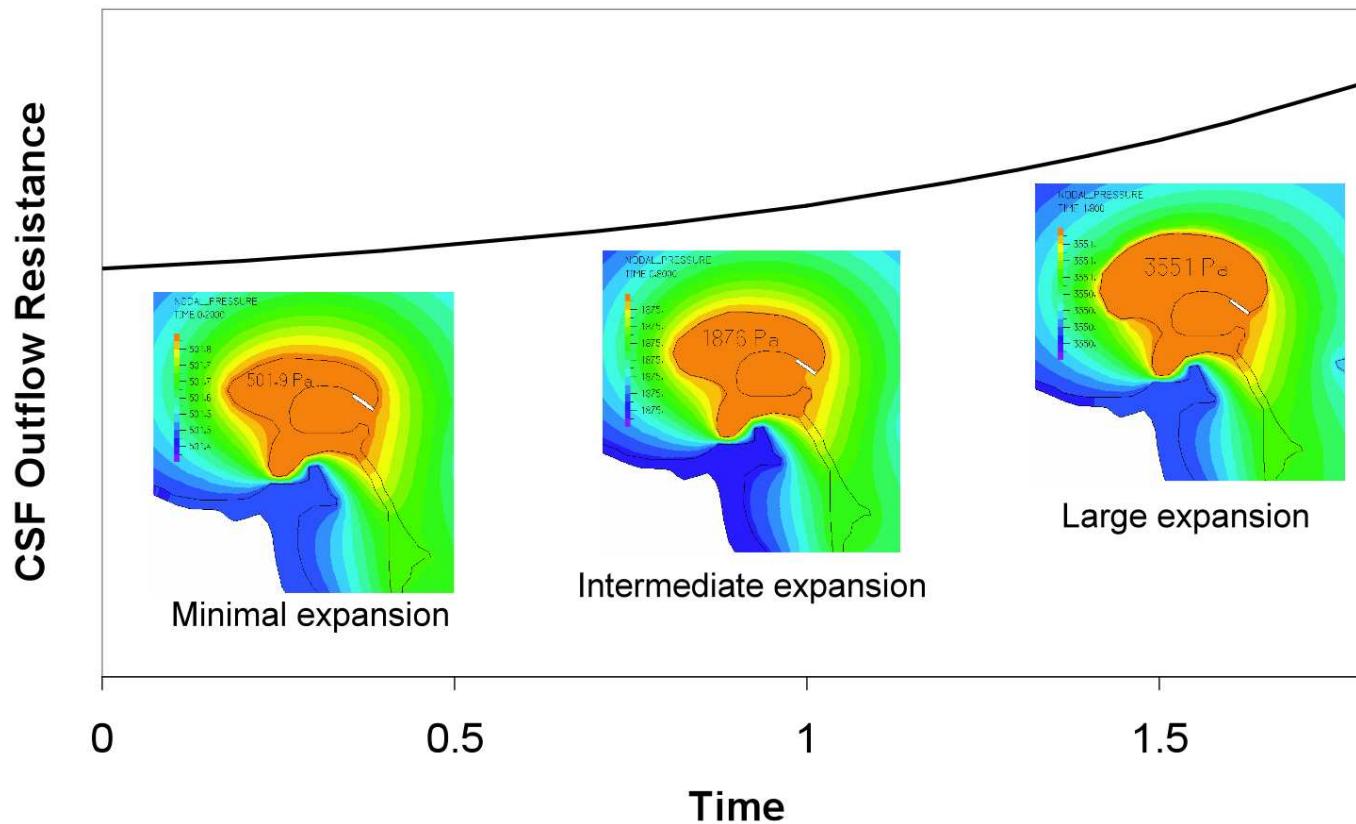
Validation of the simulations with CINE-phase-MRI



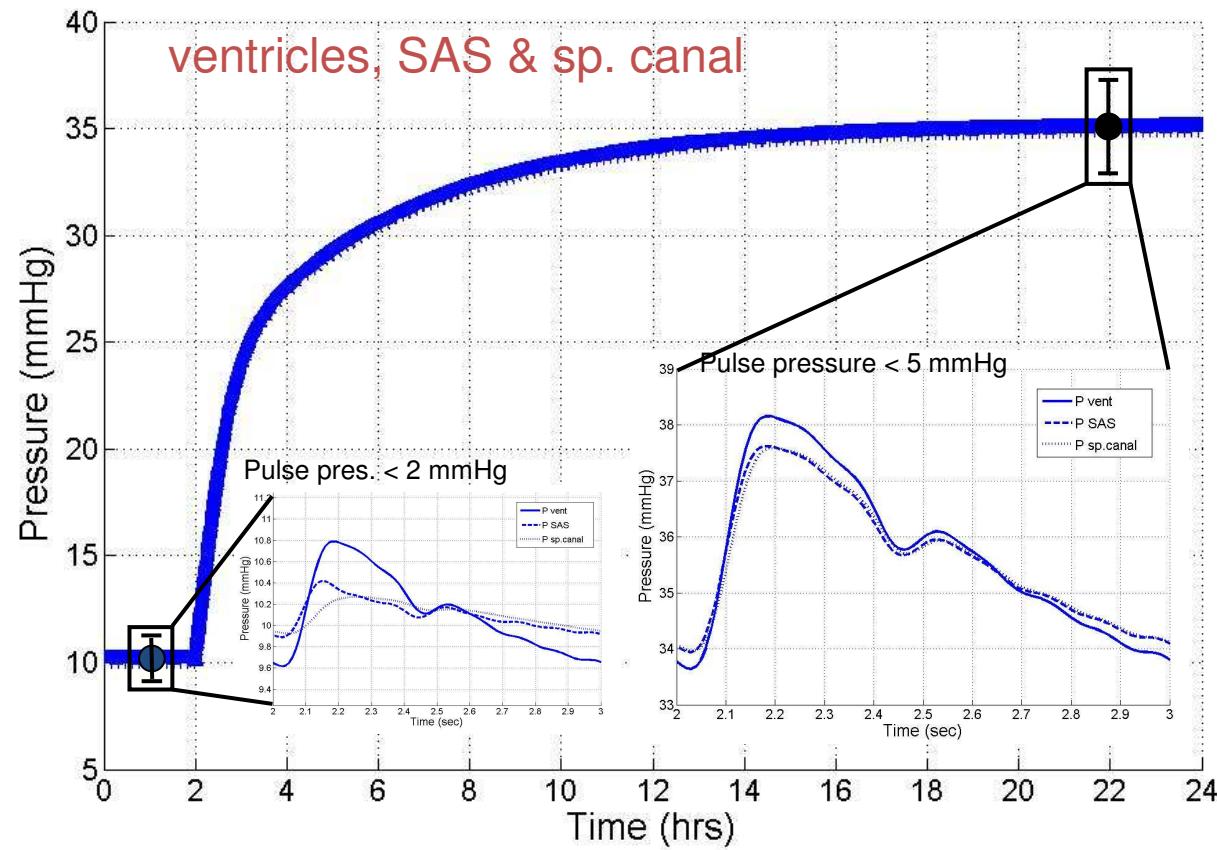
BLOCK of CSF



The Development of Hydrocephalus Increasing Outflow Resistance

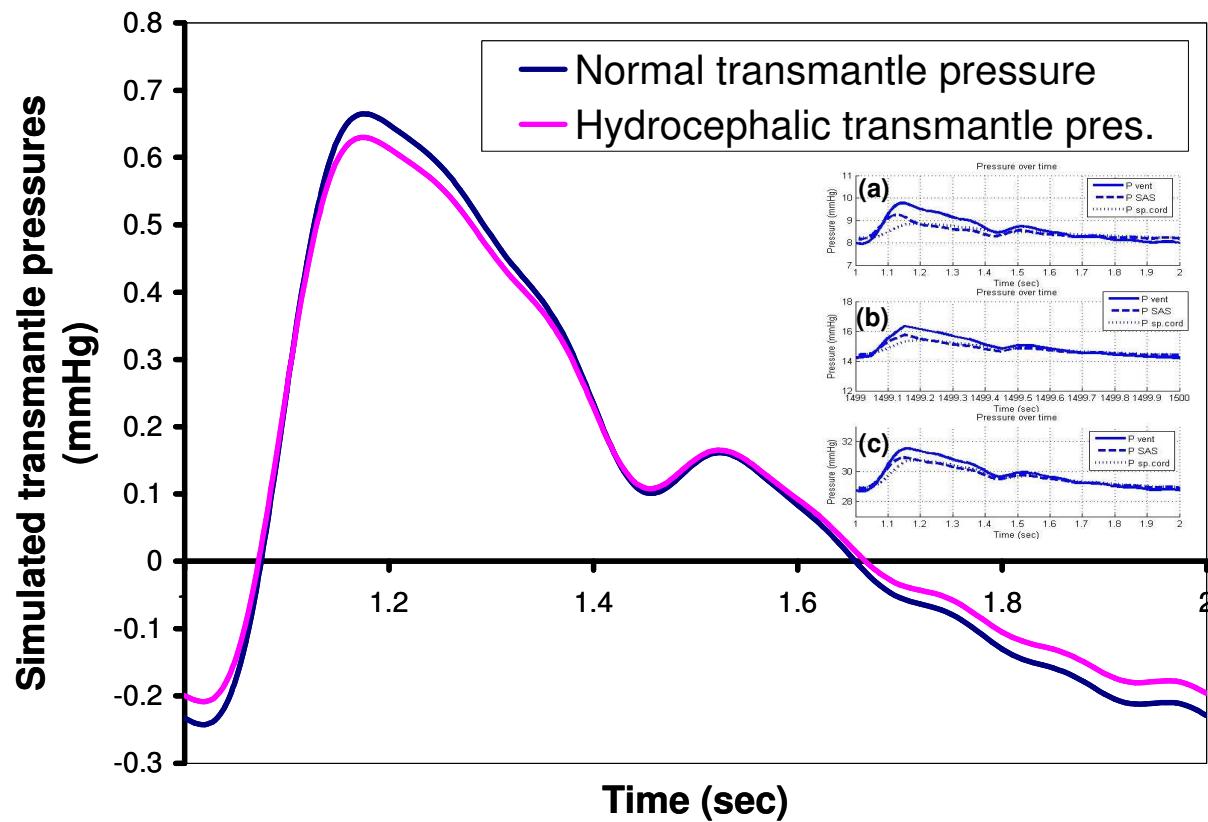


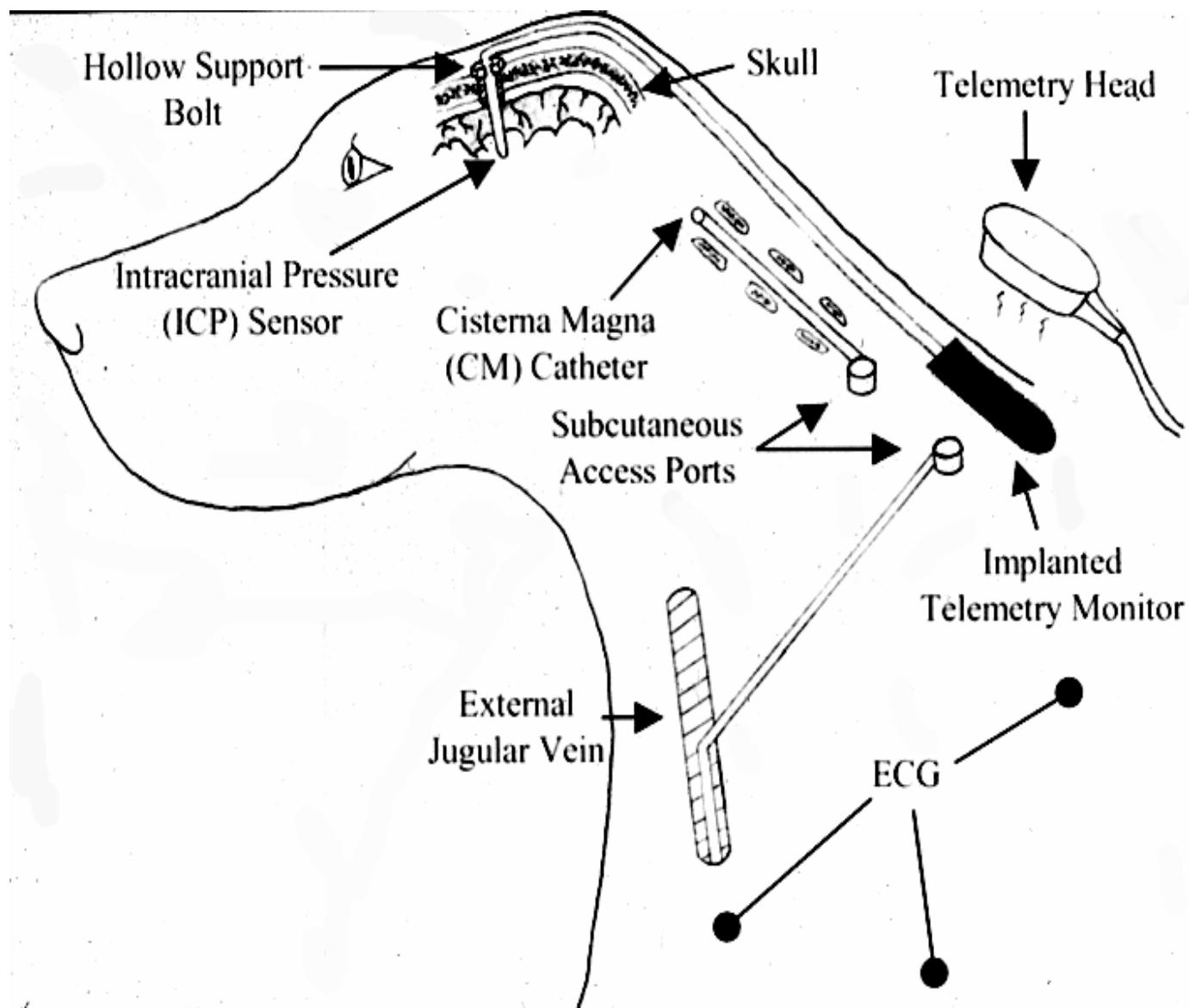
Development of Hydrocephalus over time



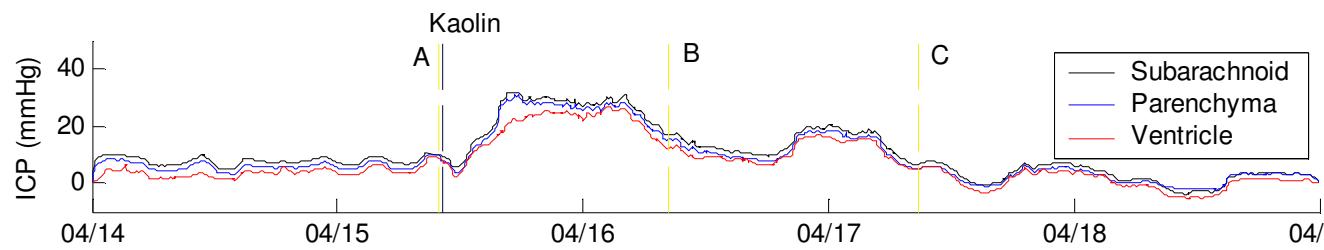
A. Linniger, M. Xenos, B. Sweetman, S. Ponkshe, X. Guo, and R. Penn. A mathematical model of blood, cerebrospinal fluid and brain dynamics. *Journal of Mathematical Biology*, 59(6): 729-759, 2009.

The model predicts that TRANSMANTLE PRESSURE DIFFERENCES ARE SMALL IN NORMALS AND HYDROCEPHALUS





Real Time Waveforms



A
Prior to kaolin

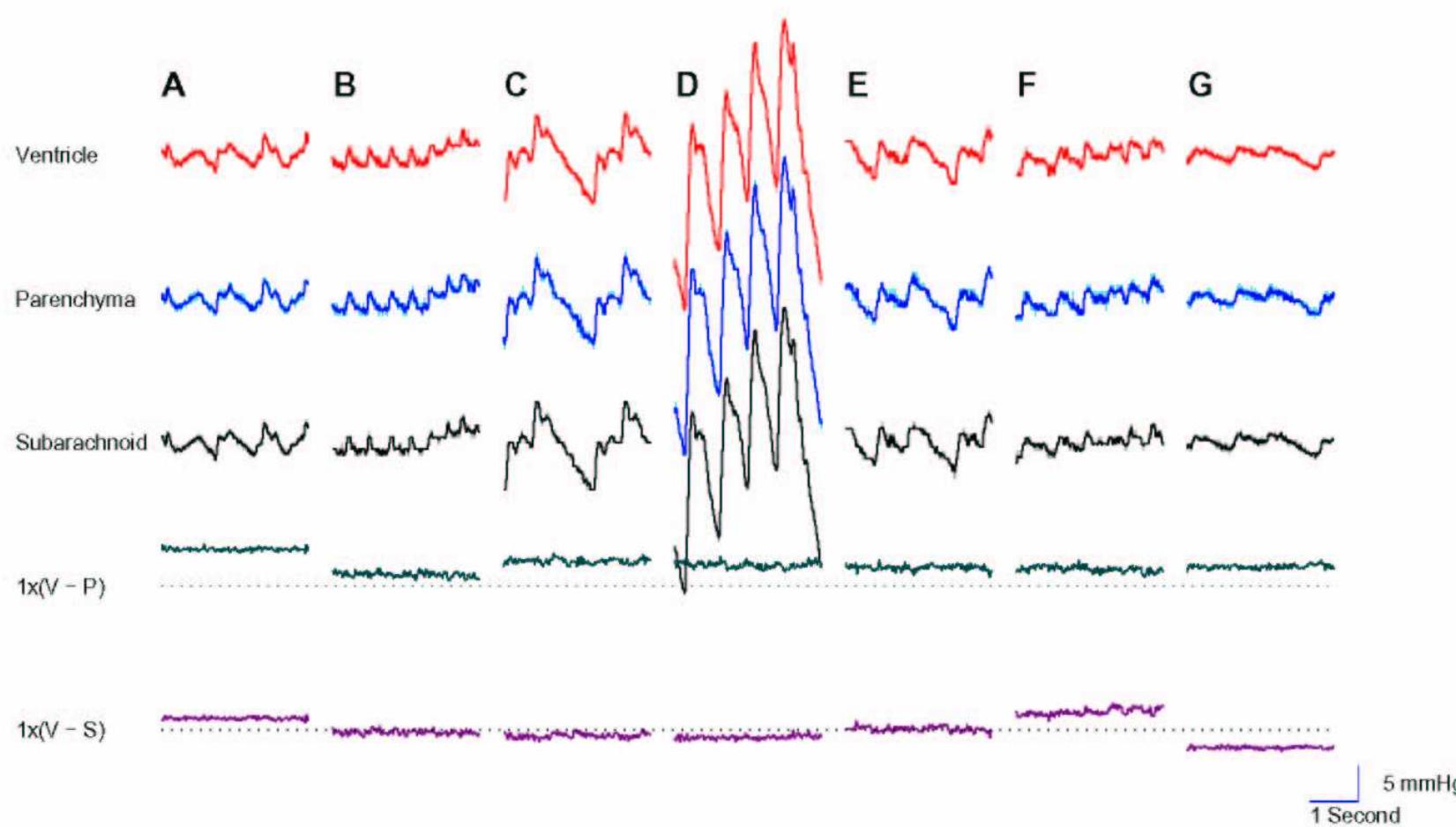
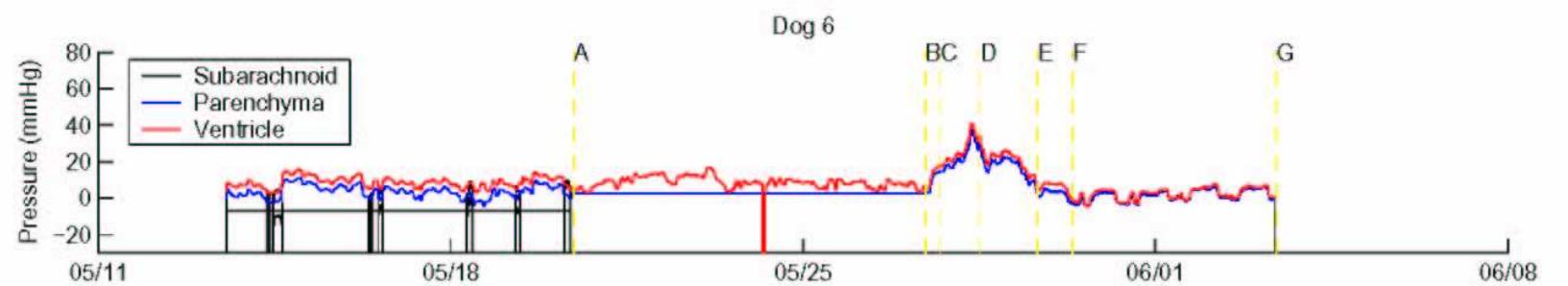
B
~1 day post kaolin

C
~2 days post kaolin

0 mmHg

5 mmHg

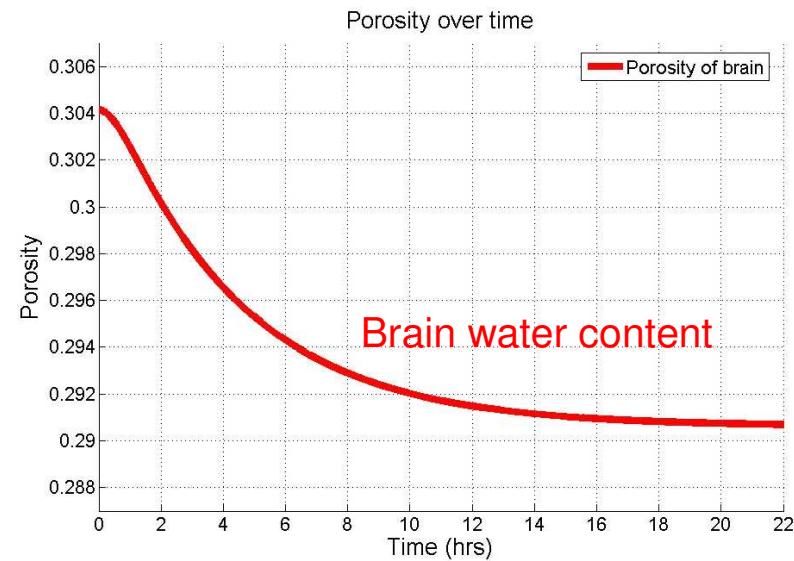
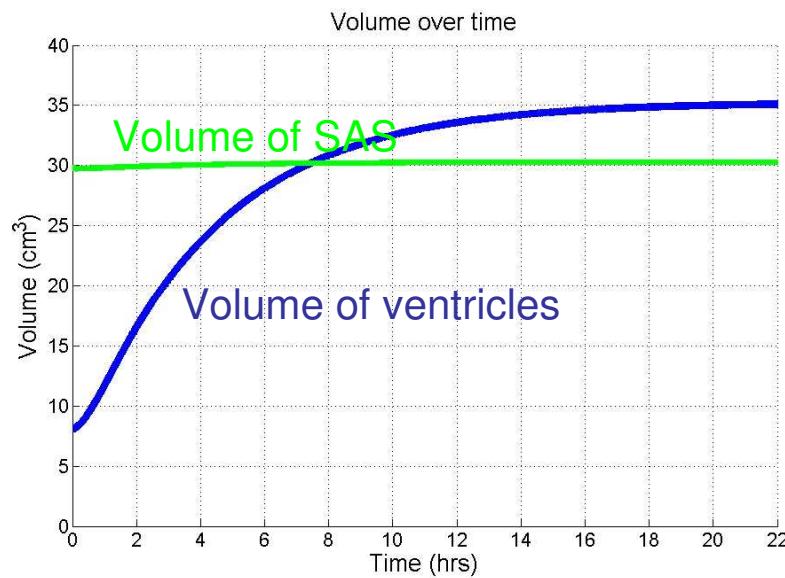
1 Second



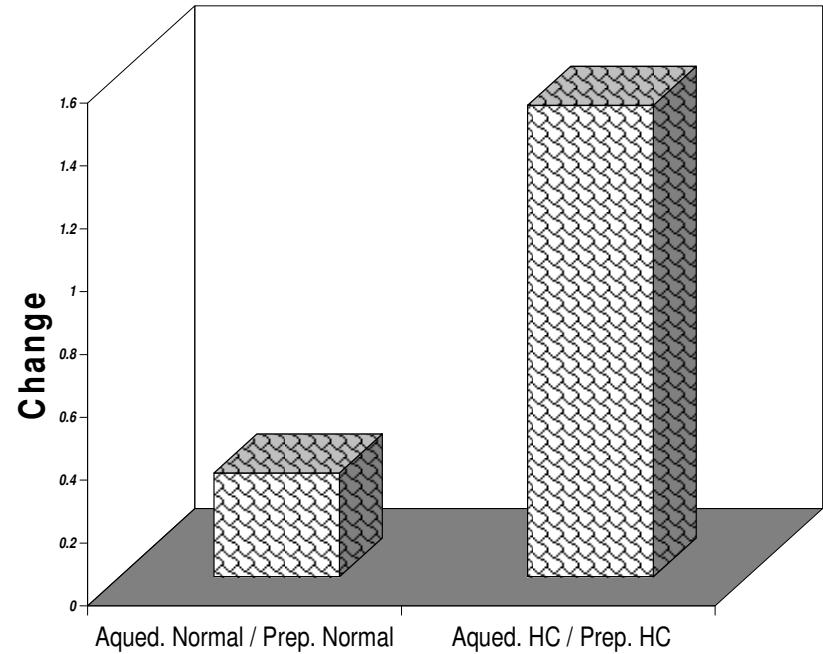
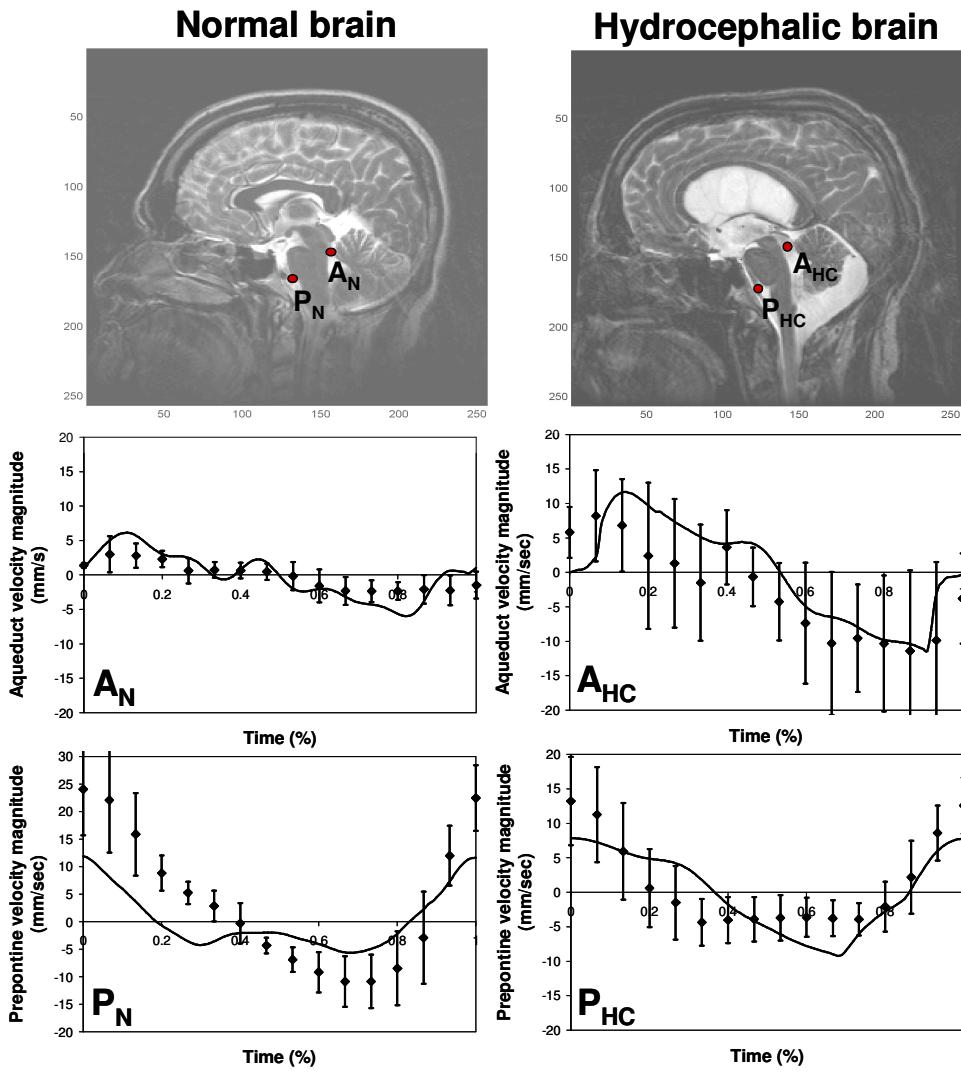
No measurable pressure gradients

- Acute
 - Chronic
 - Rapid
 - Slow
- No abnormal oscillations

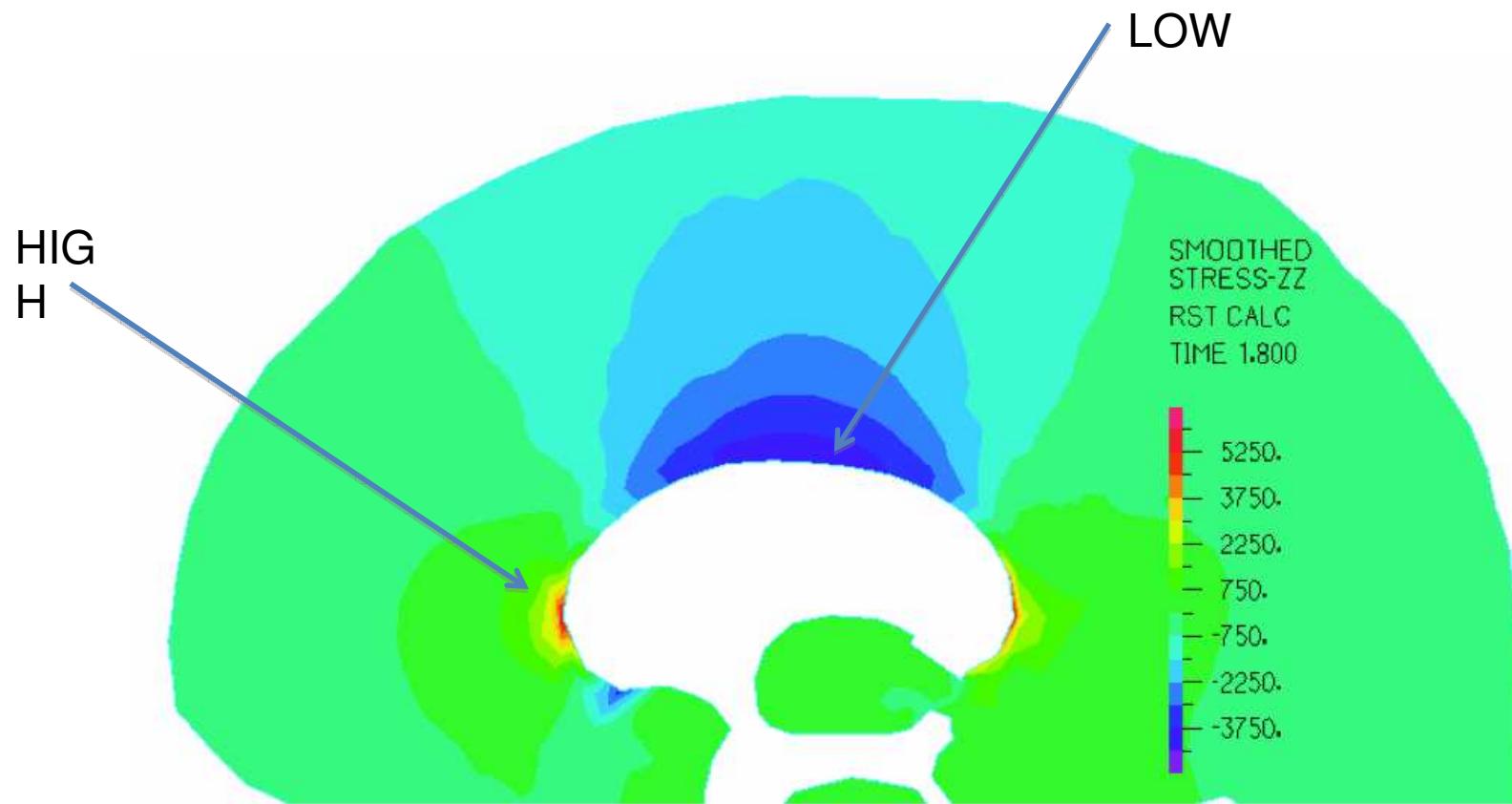
Fluid Movement as Hydrocephalus Develops



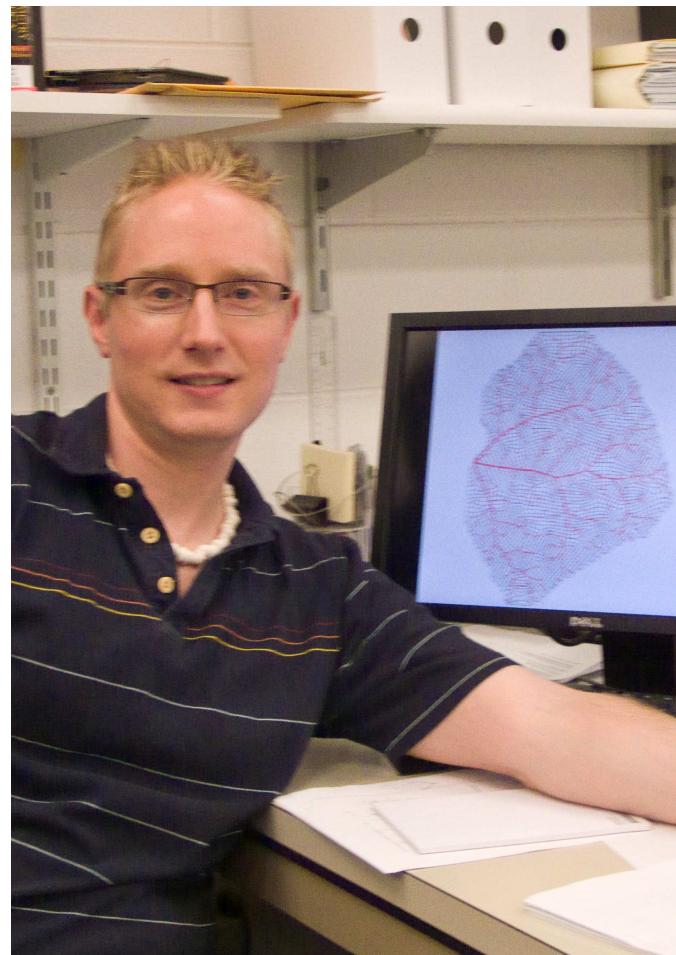
RATIO OF A.S. FLOW TO PREPONTINE FLOW INCREASES IN HYDROCEPHALUS



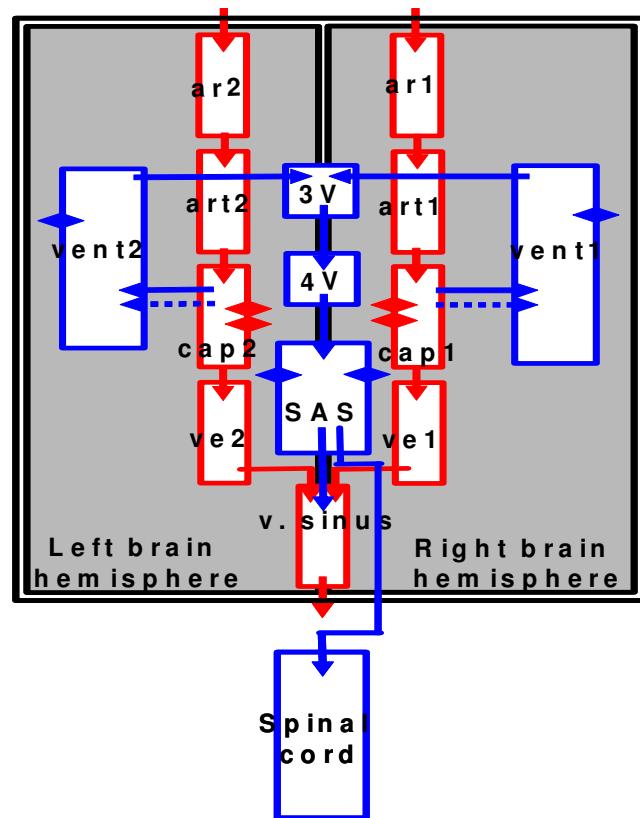
Model of stress fields in hydrocephalus



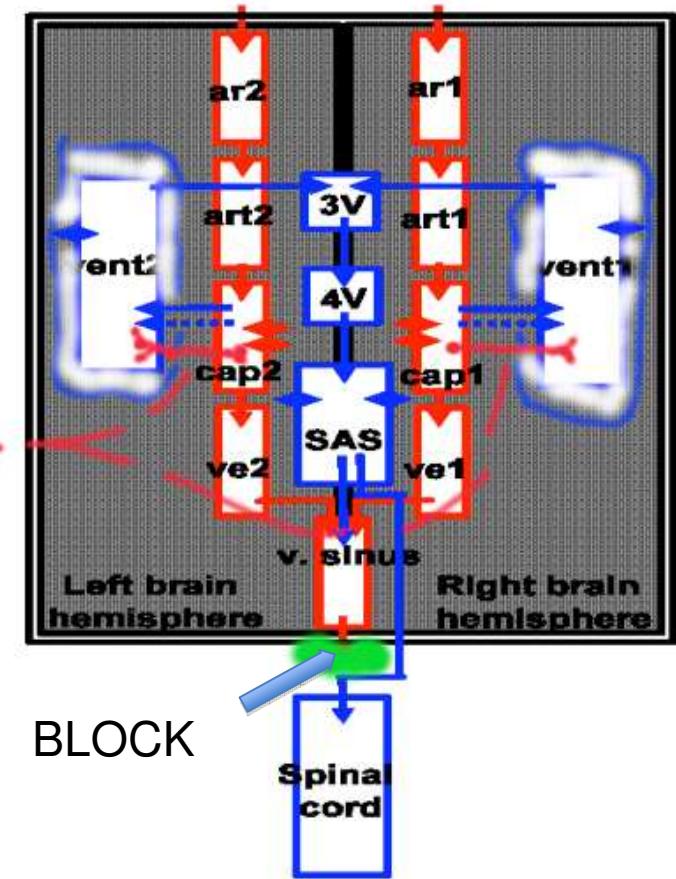
Brian Sweetman



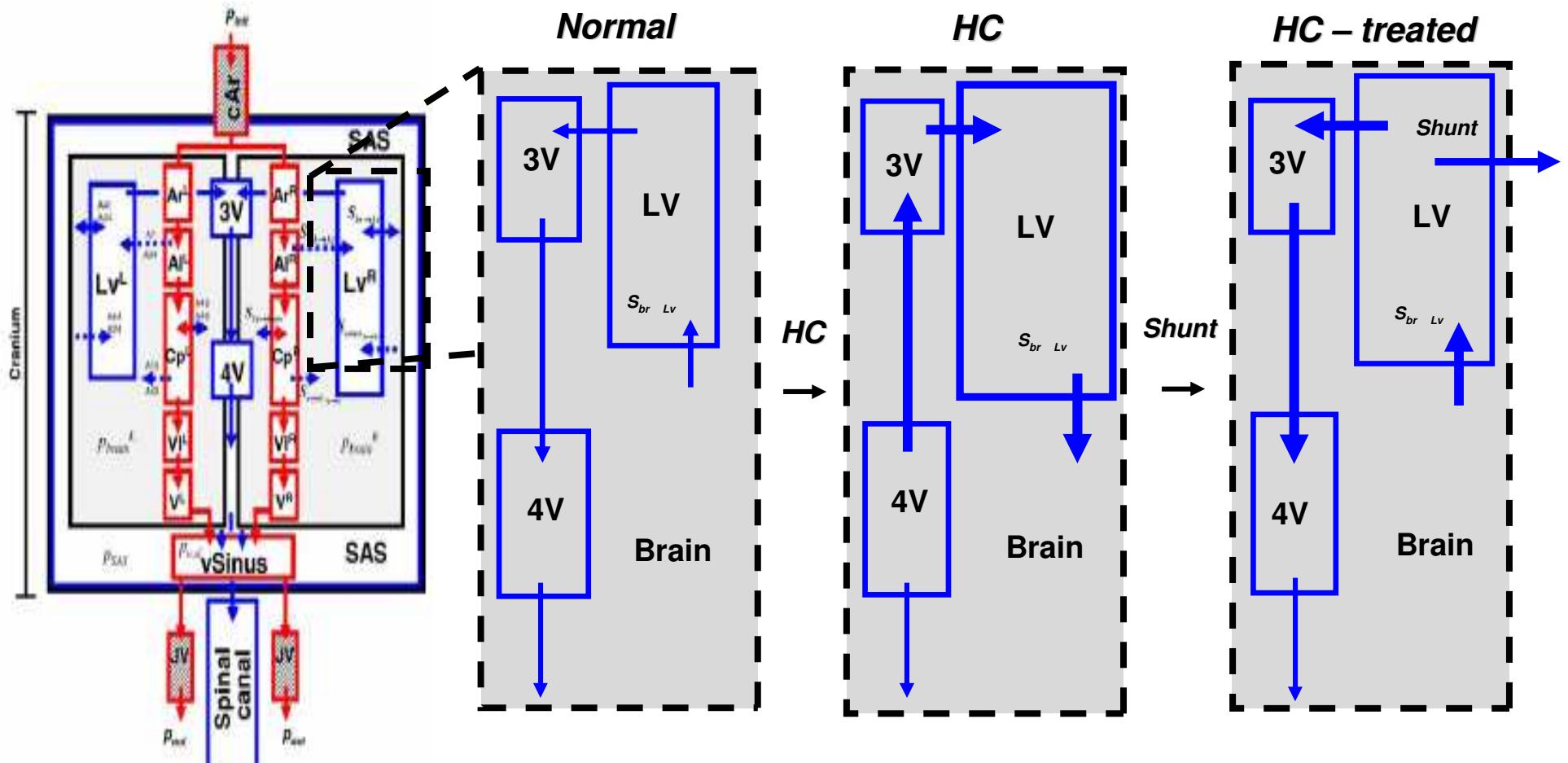
If a diminished reabsorption is responsible for ventricular enlargement then a flow reversal is predicted

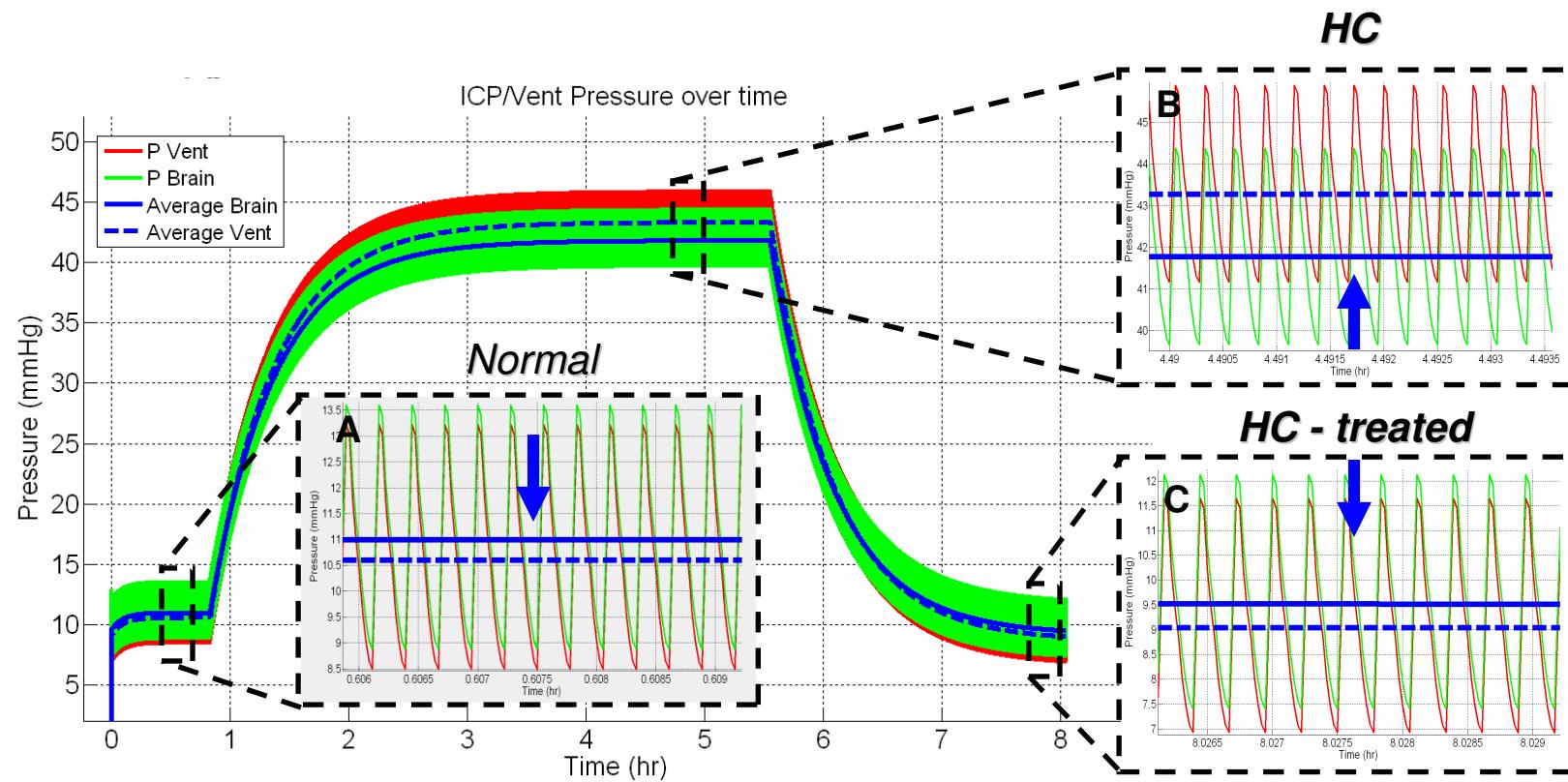


FLOW
REVERS
AL

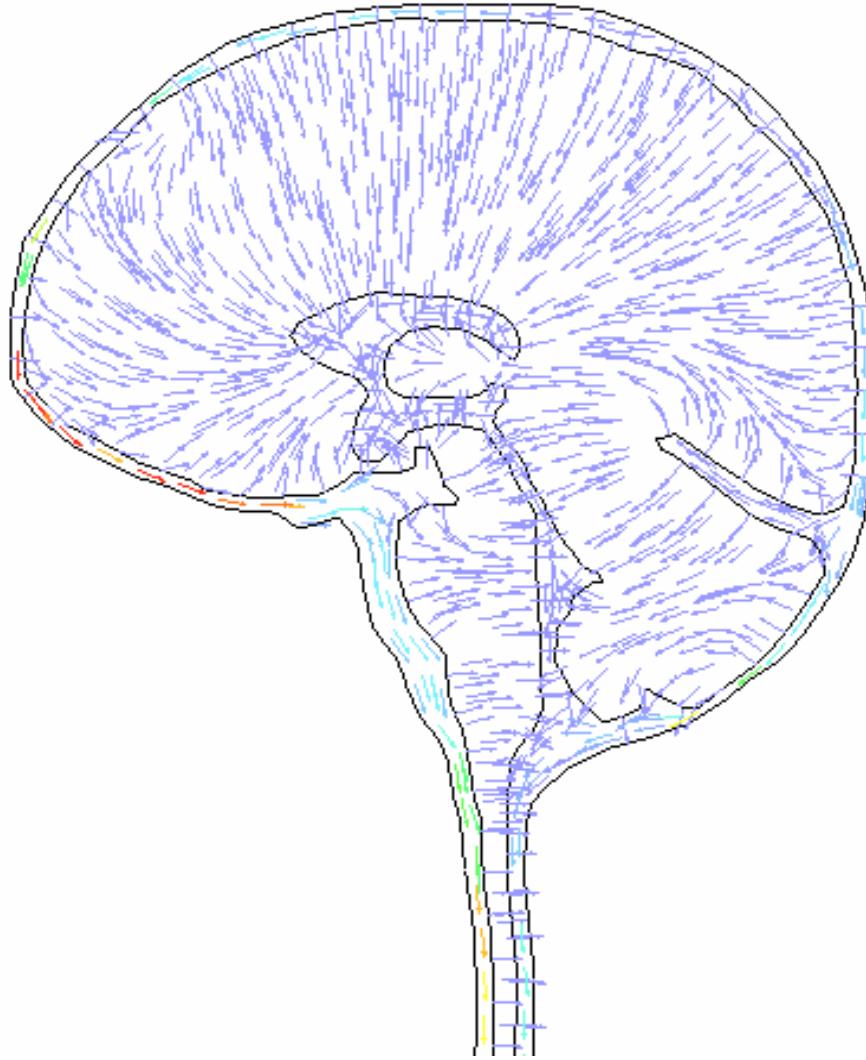


Flow Direction and Hydrocephalus

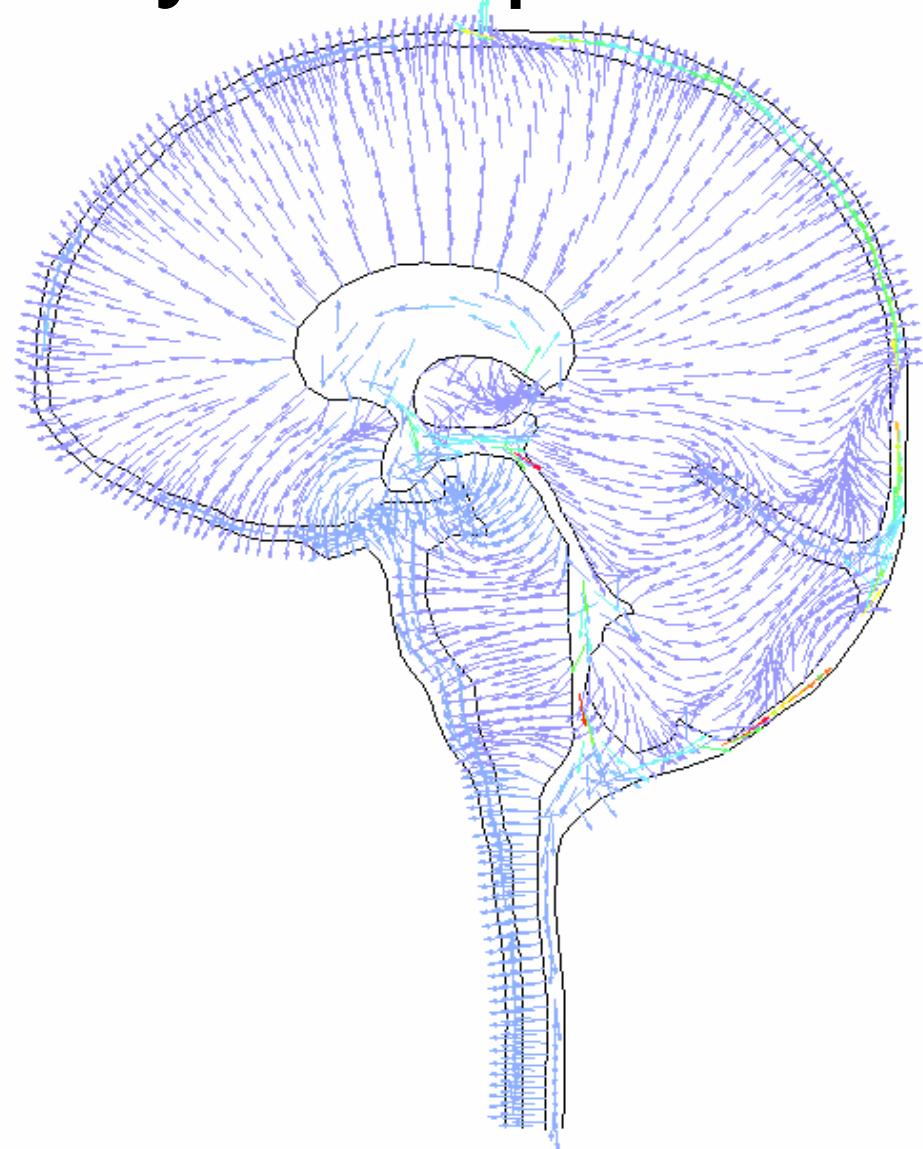




Normal



Hydrocephalus



Cine-MRI Flow at Aqueduct in Normal Pressure Hydrocephalus Pre and Post Shunting

	Net Flow (ml/min)		LV volume (mL)	
	Pre	Pos	Pre	Post
1 – NPH	-8.8	-1.5	130	98
2 – NPH	-5.6	0.76	172	120
3 * NPH	1.2	3.07	123	123

Normal (n=8) 1.14 ± 0.599

Child's Nerv Syst (1999) 15:461–467
© Springer-Verlag 1999 ORIGINAL PAPER

Dong-Seok Kim

Joong-Uhn Choi

Ryoong Huh

Pyeung-Ho Yun

Dong-Ik Kim

Quantitative assessment of cerebrospinal fluid hydrodynamics using a phase-contrast cine MR image in hydrocephalus

11 NPH Patients

Pre

Post

“Stroke volume” ($\mu\text{l}/\text{cycle}$) **-63.2 ± 49.0** **16.3 ± 52.4**

Cine-MRI Venticular Wall Movement Pre and Post Shunting

	Wall displacement (mm)		LV volume (mL)	
	Pre	Post	Pre	Post
1 – NPH	0.27	0.30	130	98
2 – NPH	0.24	0.21	172	120
3 * NPH	0.25	0.26	123	123
Normal (n=8)	0.168 ± .038			

A theoretical study of the effect of intraventricular pulsations on the pathogenesis of hydrocephalus

K.P. Wilkie^a, C.S. Drapaca^b and S. Sivaloganathan^{a, c, ,}

^a Department of Applied Mathematics, University of Waterloo, Waterloo, ON, Canada N2J 3G1

^b Department of Engineering Science and Mechanics, The Pennsylvania State University, University Park, PA 16802, USA

^c Centre for Mathematical Medicine, Fields Institute for Mathematical Sciences, Toronto, ON, Canada M5T 3J1

Applied Mathematics and Computation

Volume 215, Issue 9, 1 January 2010, Pages 3181-319

“cranial vault is a rigid container, as in adult hydrocephalus, very small displacements are predicted.”

“models predicted peak-to-peak displacements of about 100 nm at the ventricle wall”

Physical laws can explain

- CSF flow fields
- Lack of measurable transmural pressure gradient
- Development of hydrocephalus starting from the normal state with the only change being an increase in outflow resistance
- Reversal of flow with hydrocephalus
- Pressure / volume relationships

Can the study of the physics of hydrocephalus help patients?

- Shunts frequently fail
- Shunts cause slit ventricle syndrome
- Shunts vary in design and function and how can one choose the best one
- Can a “smart shunt” be designed to follow the needed flow dynamics

Shunt Treatment

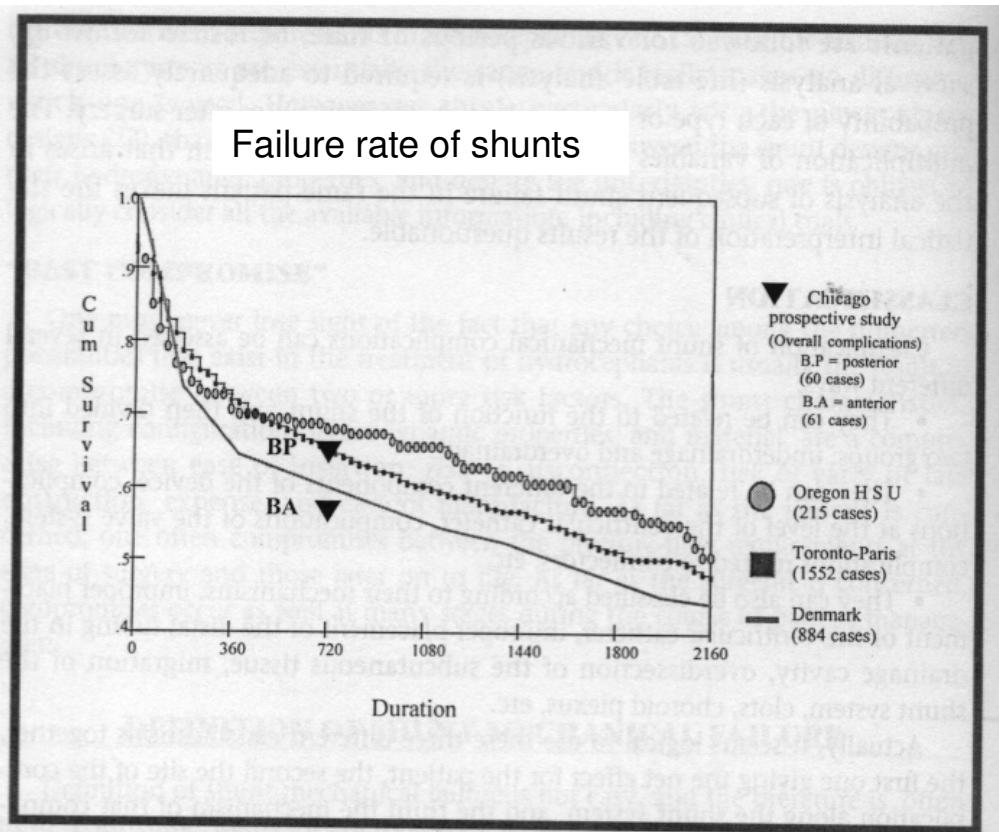
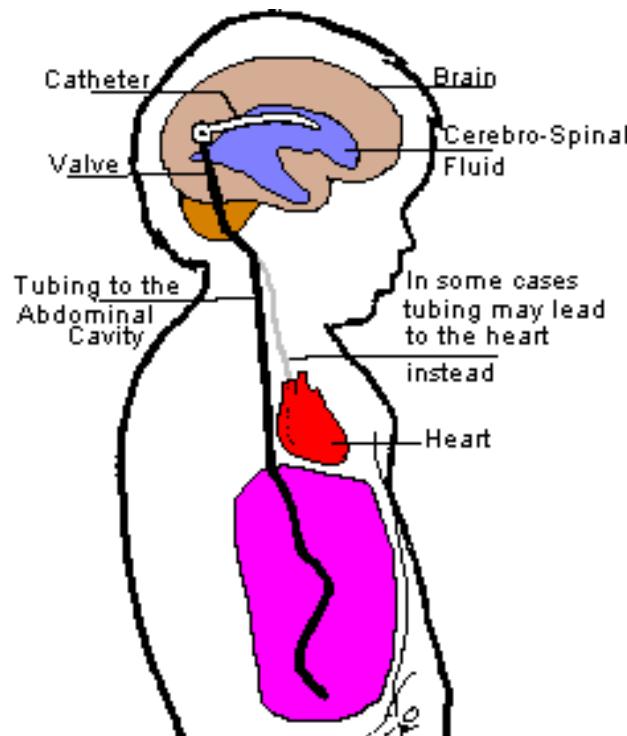
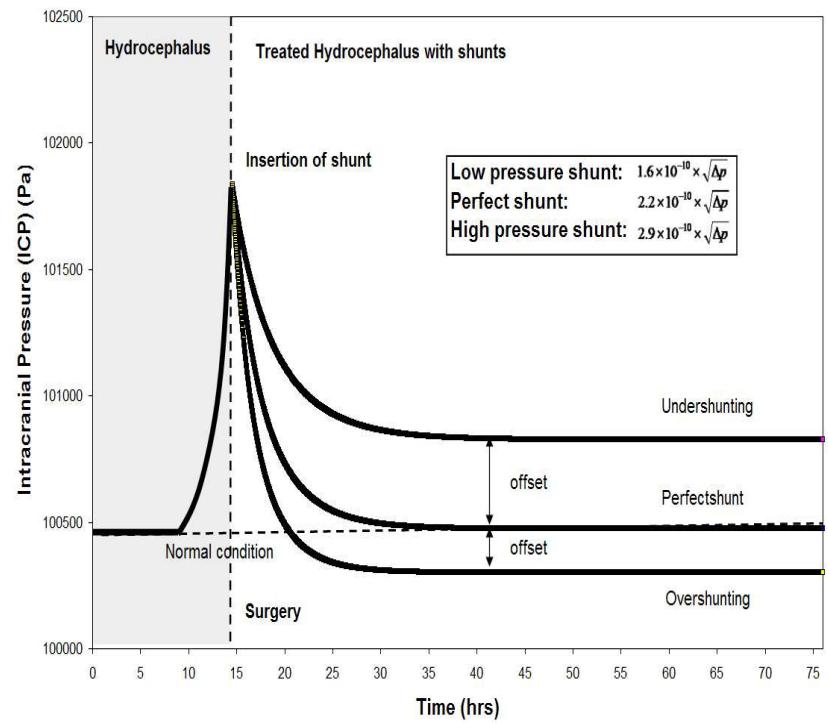
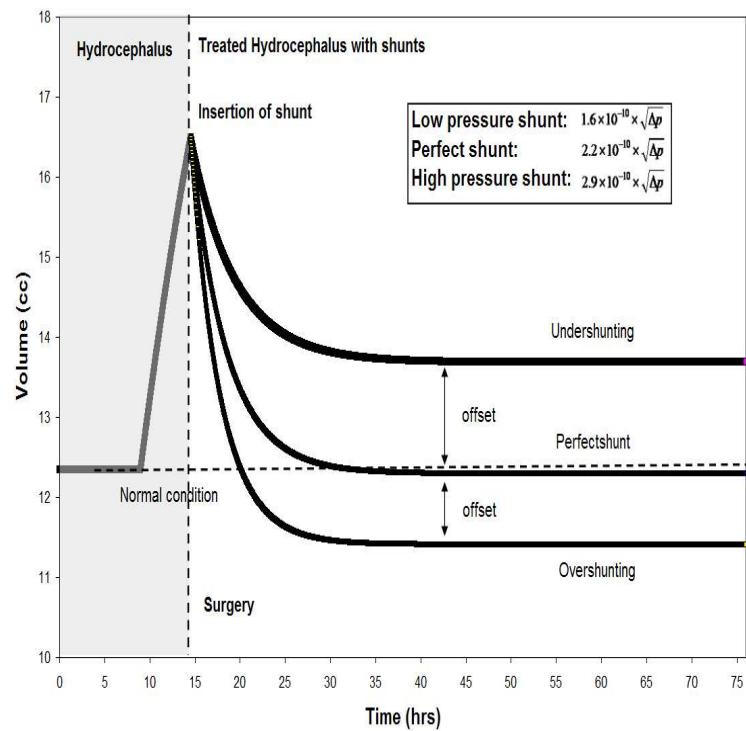


FIGURE 5-1

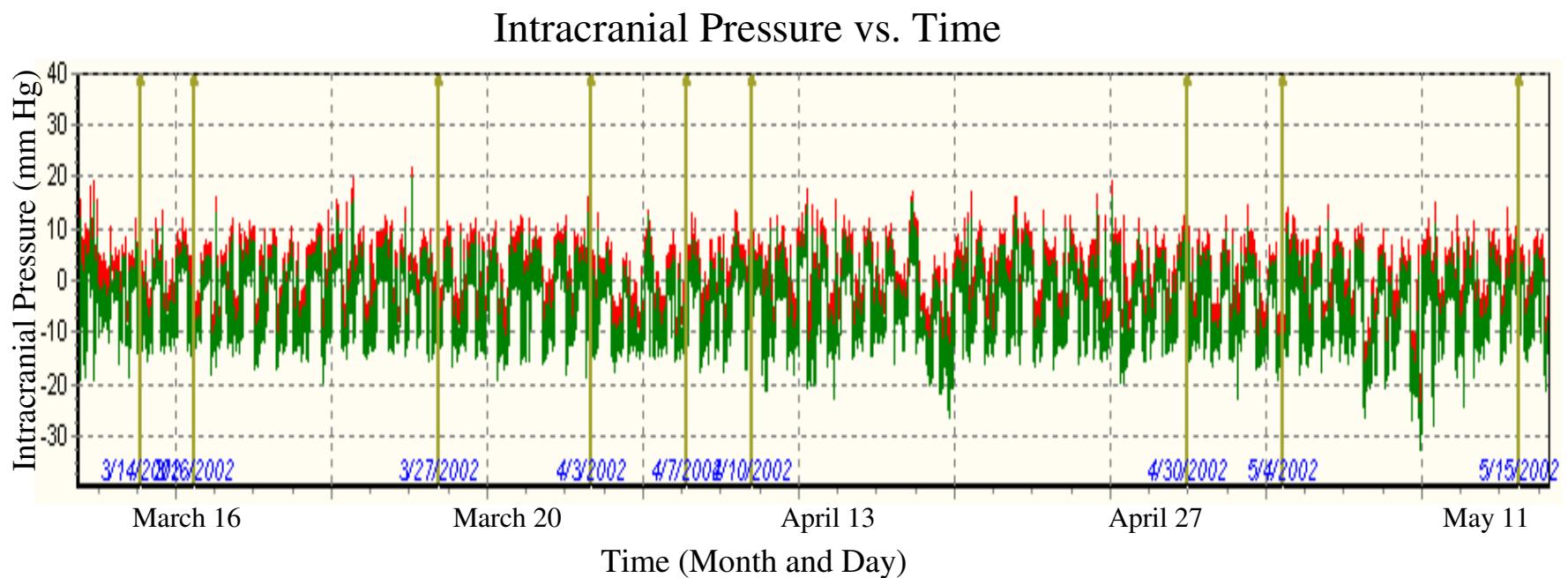
Survival function of four pediatric series of patients treated with "conventional" shunts. The time interval for analysis was one month over a period of six years. The cumulative proportion of shunts not revised (that "survived") is represented by the Y axis. The X axis is the length of follow-up (in days) after the first shunt insertion.

Ref: The Shunt Book, Drake, 1995

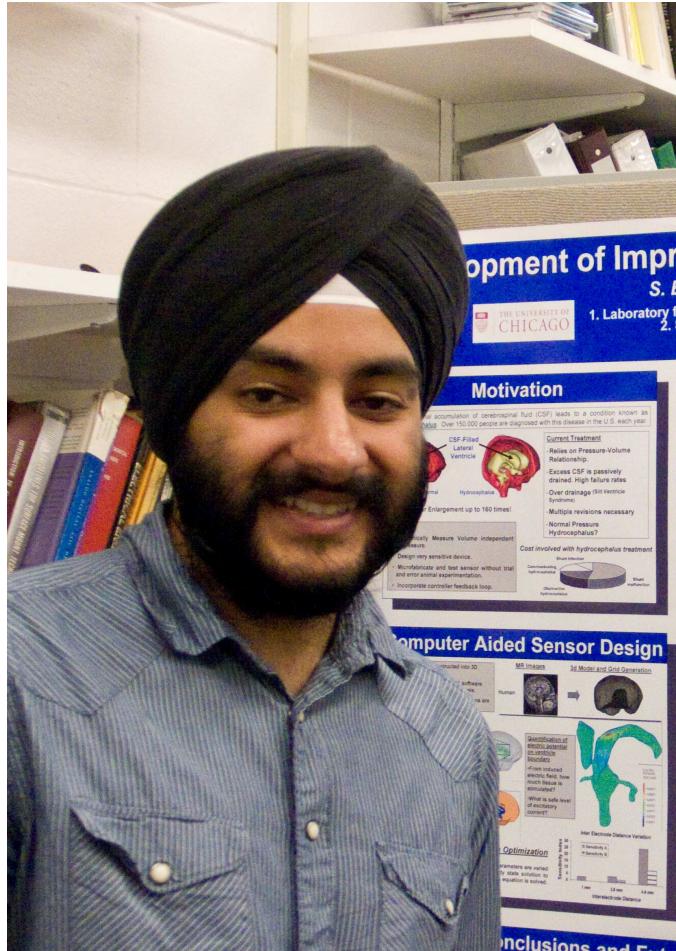
Response to Shunting



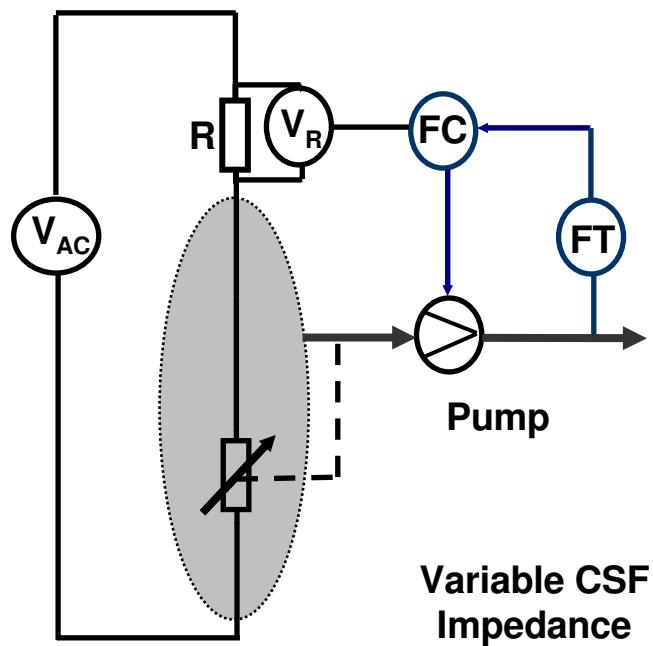
Lack of correlation between symptoms and ICP



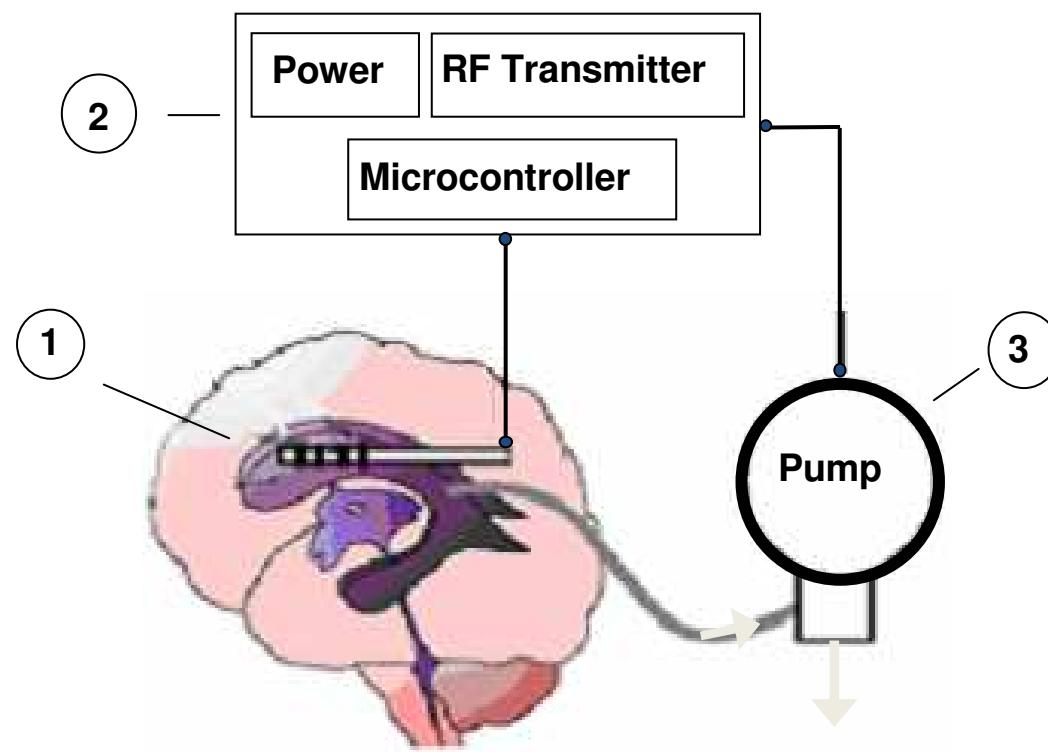
Sukhi Basati



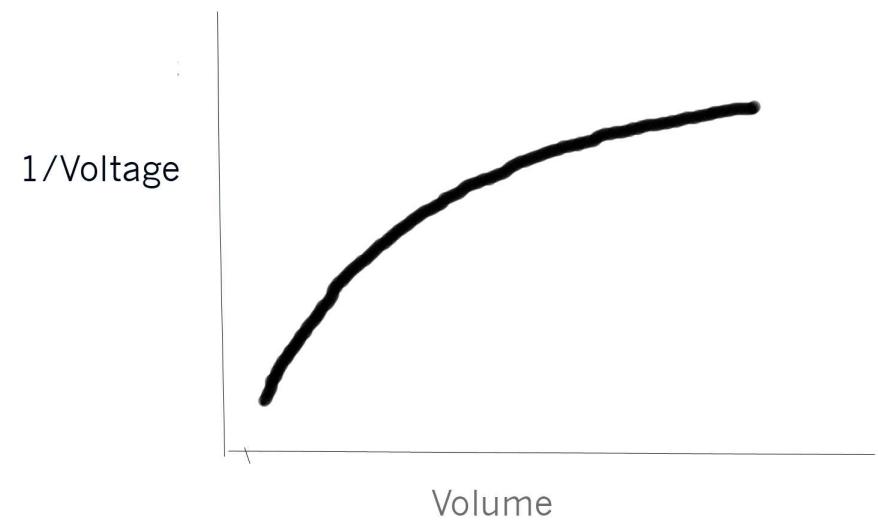
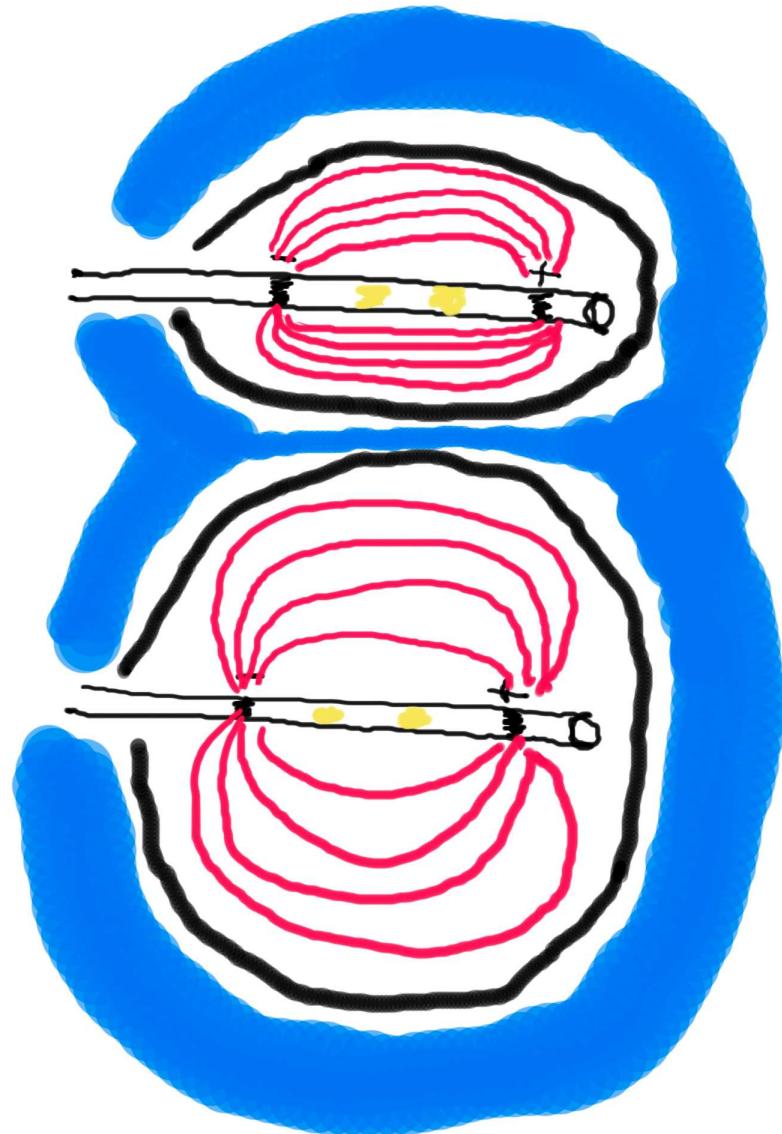
Feedback Control



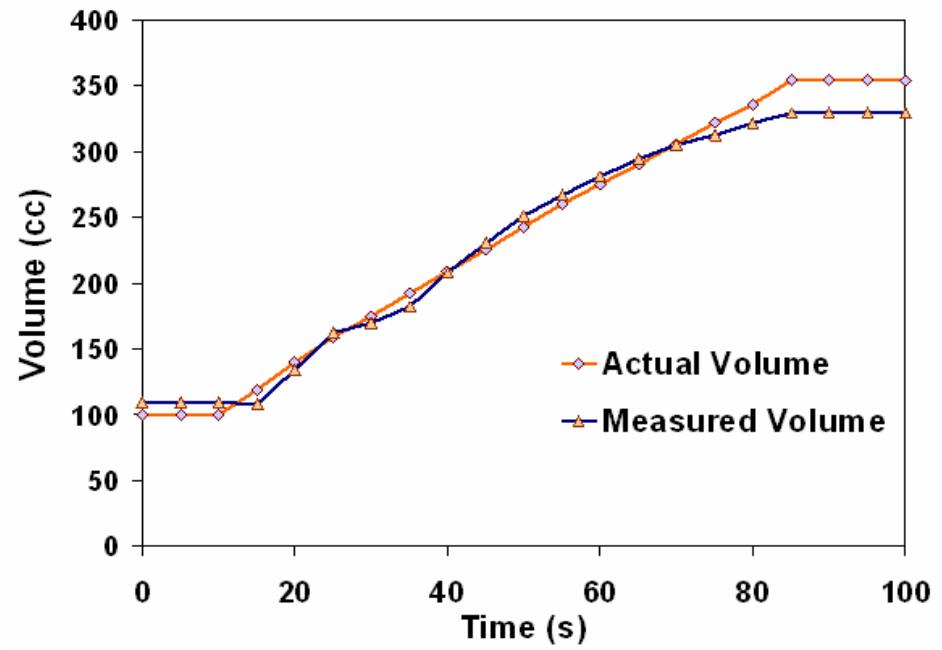
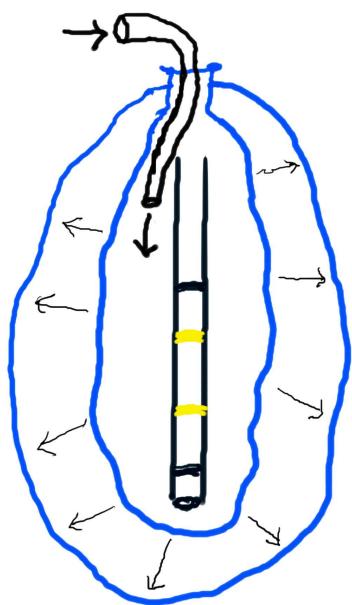
CONCEPT



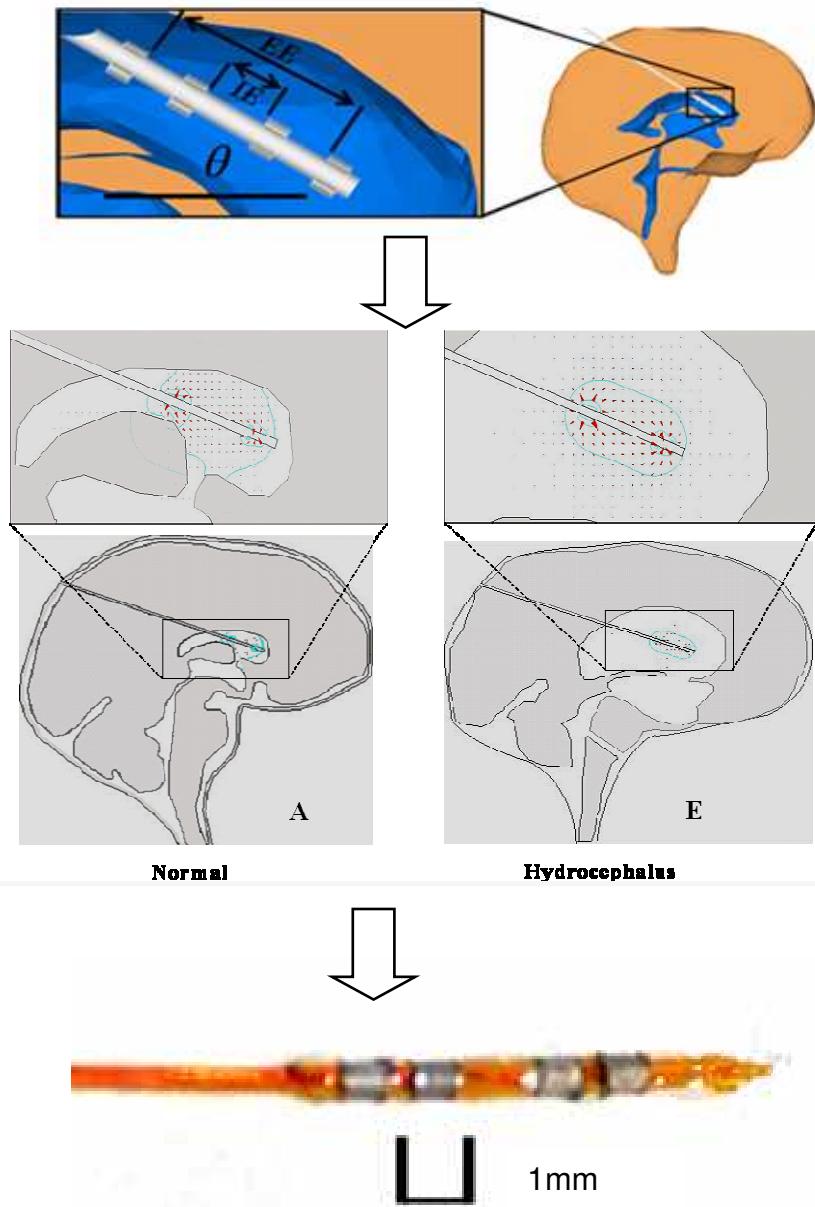
How the sensor works



Test of sensor with a balloon



Computer-aided Medical Device Design



Computer-aided device design

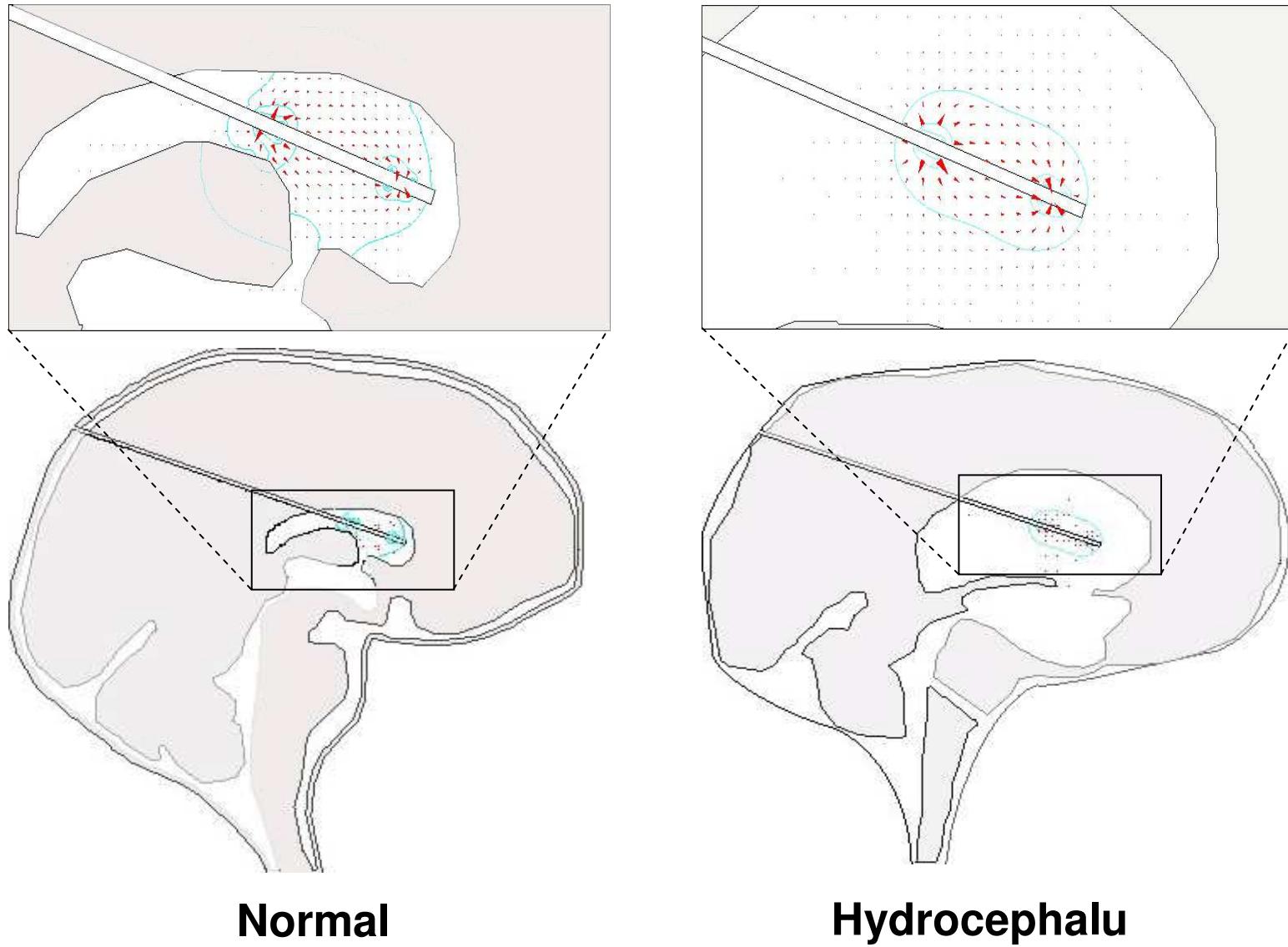
In-silico device Optimization

Sensor micro-fabrication

A. Linninger, S. Basati and R. Penn. An Impedance Sensor to Monitor and Control Cerebral Ventricular Volume. *Medical Engineering and Physics*. 31: 838-845, 2009.

More realistic models

The use of MRI scans of patients



WHAT HAS BEEN LEARNED?

The known laws of fluid dynamics explain the normal flow of CSF and the changes in hydrocephalus

The well documented increase in outflow resistance accounts for the development of hydrocephalus

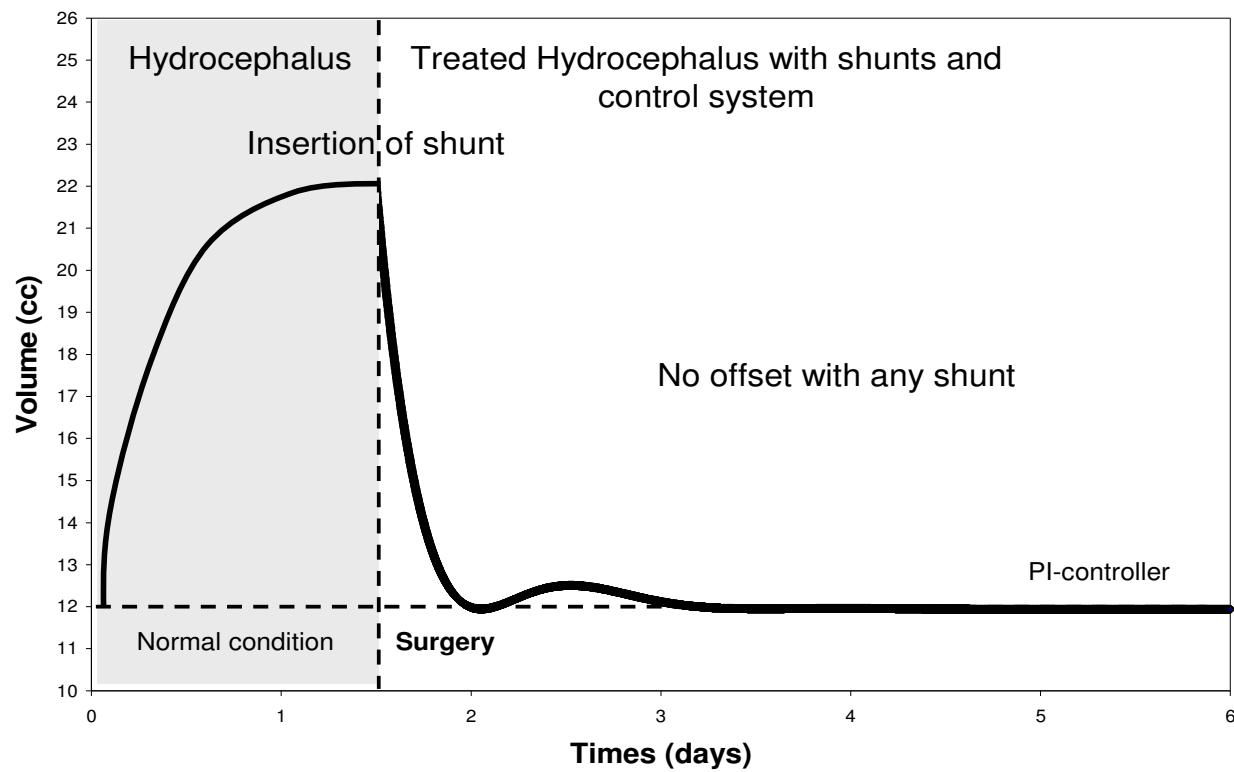
The predictions are confirmed by MRI measurements

The new understanding could lead to better treatment

William is beginning to smile



Extra slides



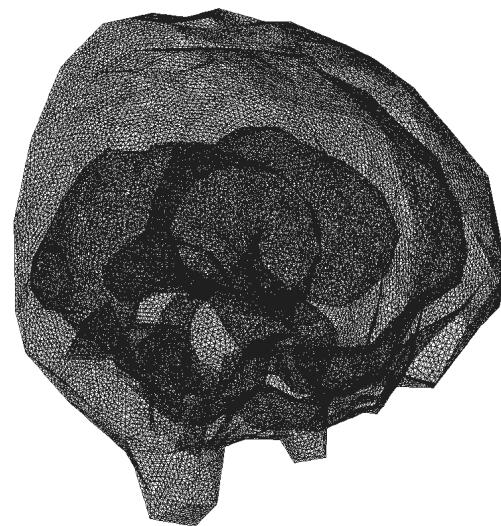
3D Normal Subject
Computational Grid



y
x—z

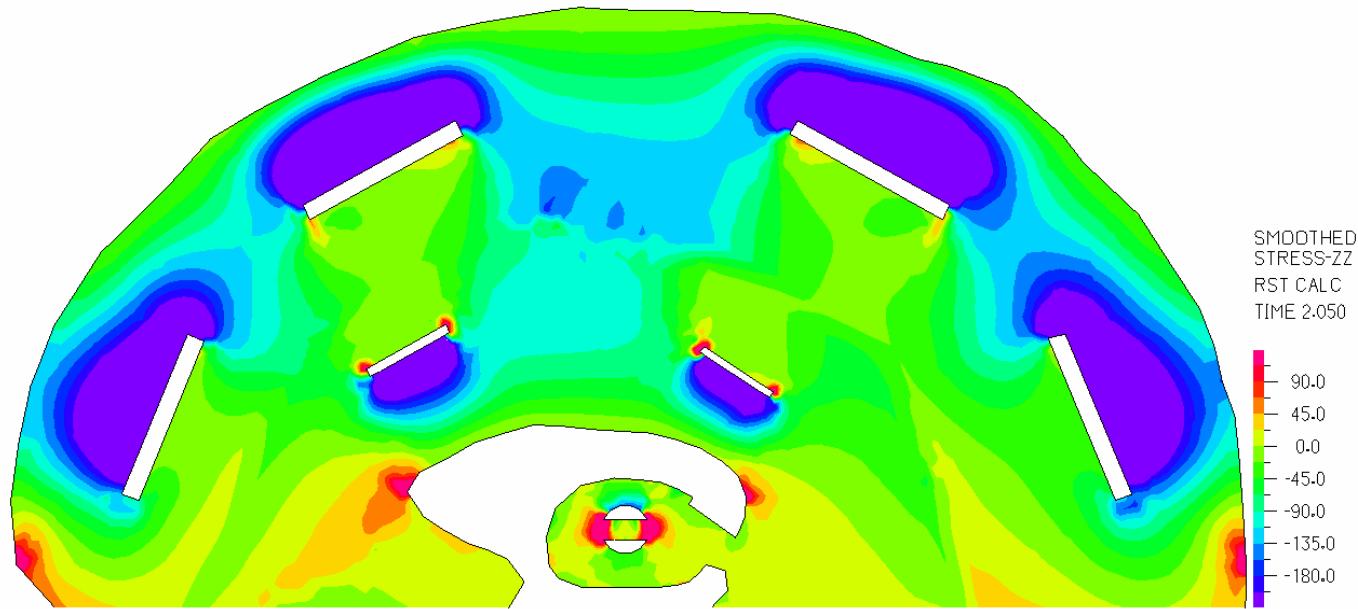
417,803 tetrahedral cells

3D Communicating HC
Computational Grid

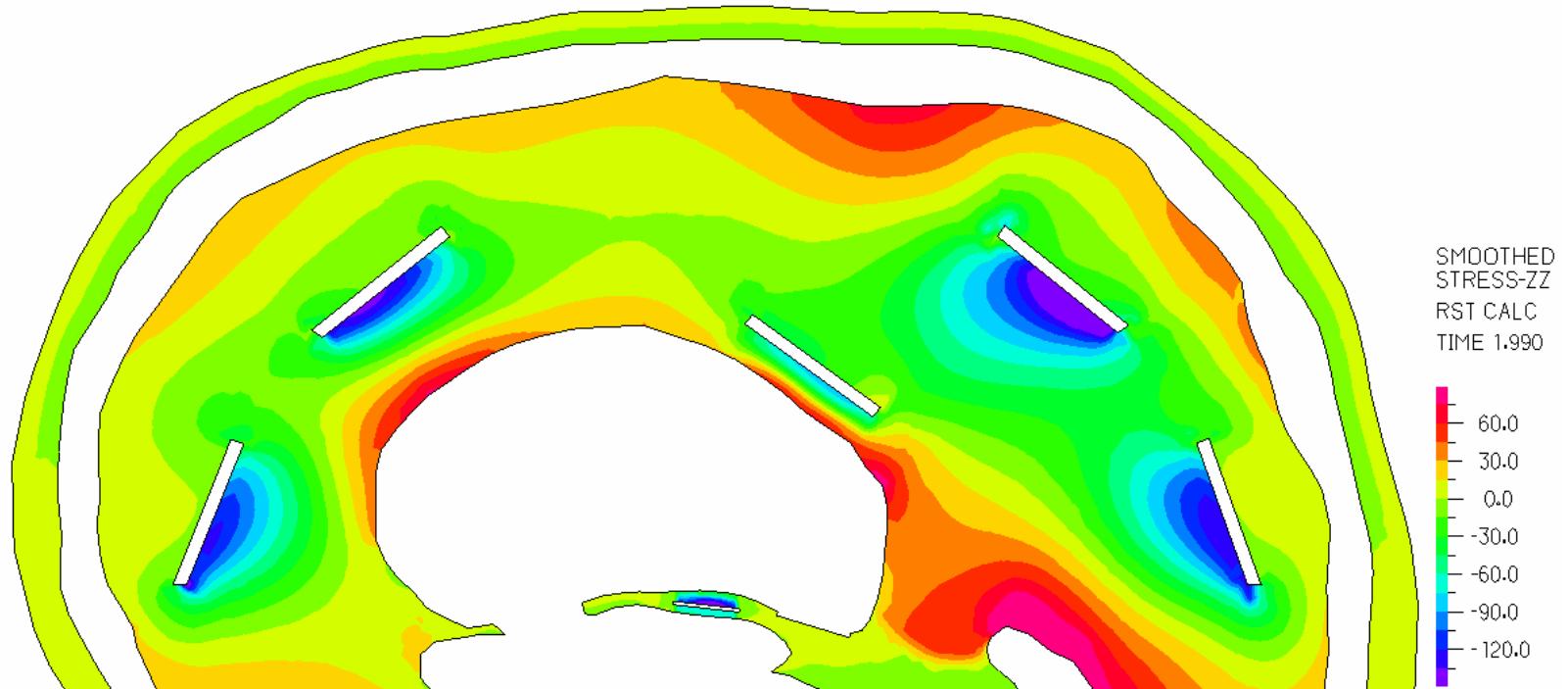


z
y—x

748,571 tetrahedral cells

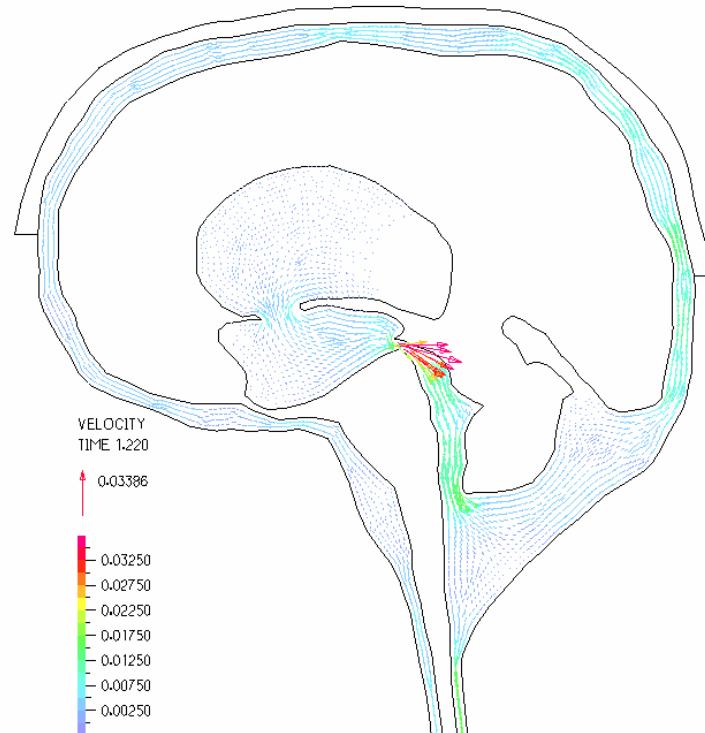
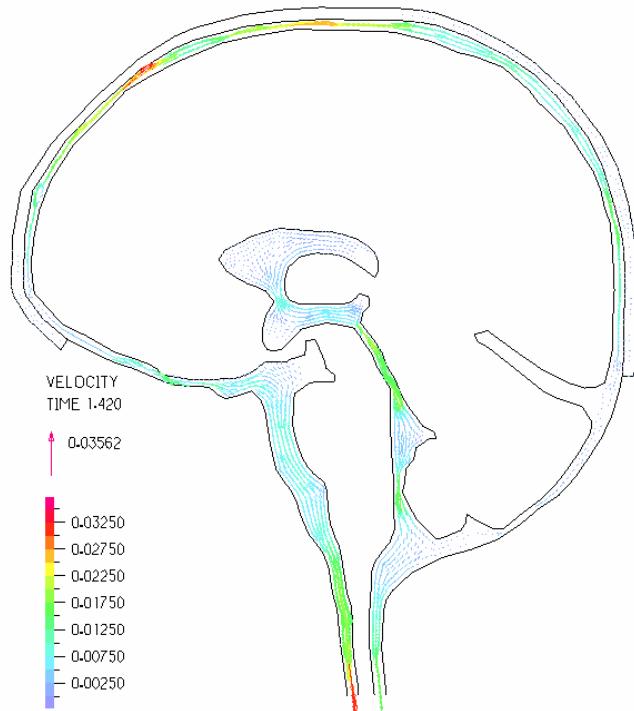


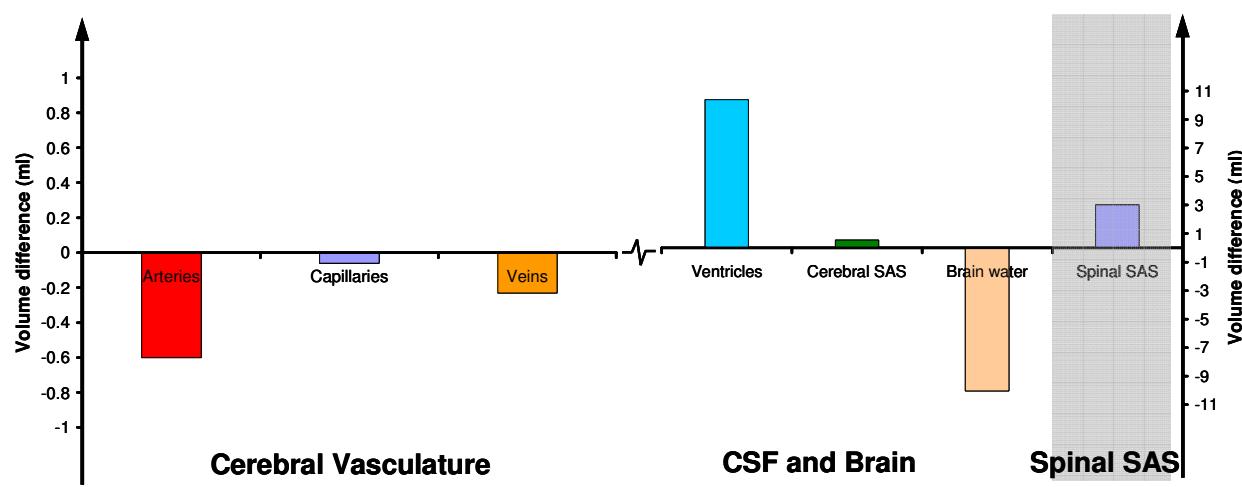
Band plot of normal stress during diastole. Red indicates tensile stresses; green to blue indicates compressive stress. Dark blue are areas of large compressive stress (where displacements were applied within the parenchyma).



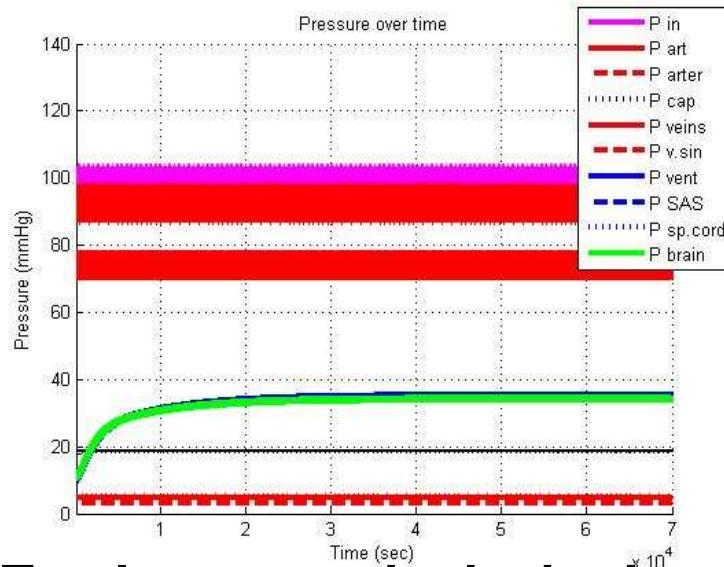
Band plot of normal stress during diastole. Red indicates tensile stresses; green to blue indicates compressive stress. Dark blue are areas of large compressive stress (where displacements were applied within the parenchyma).

Normal and Hydrocephalic

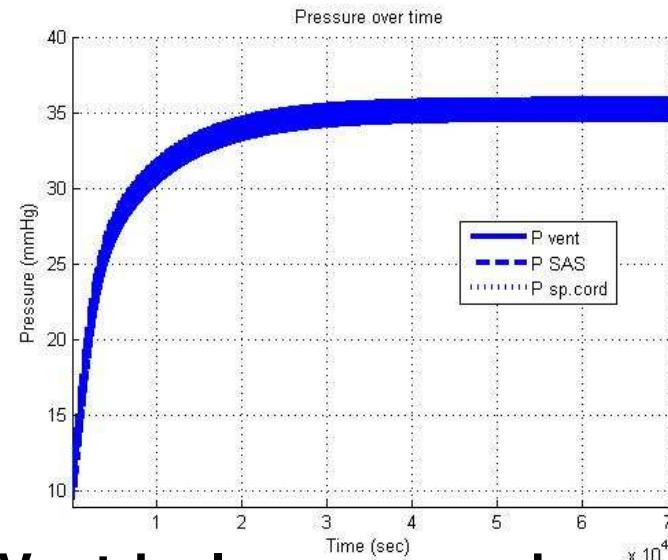




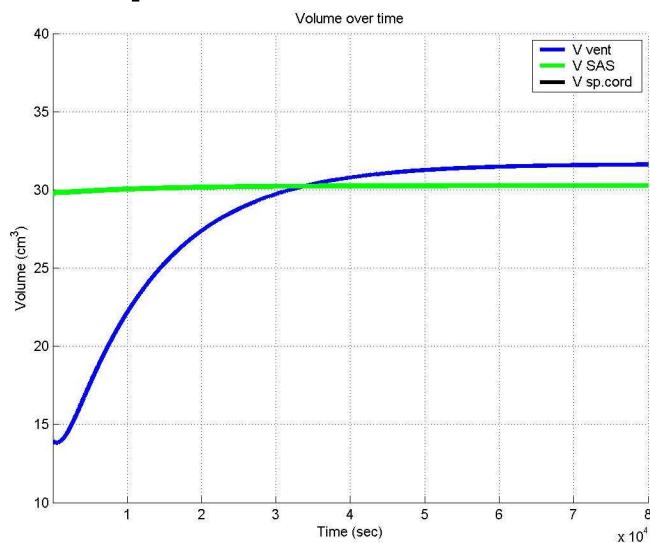
Communicating hydrocephalus



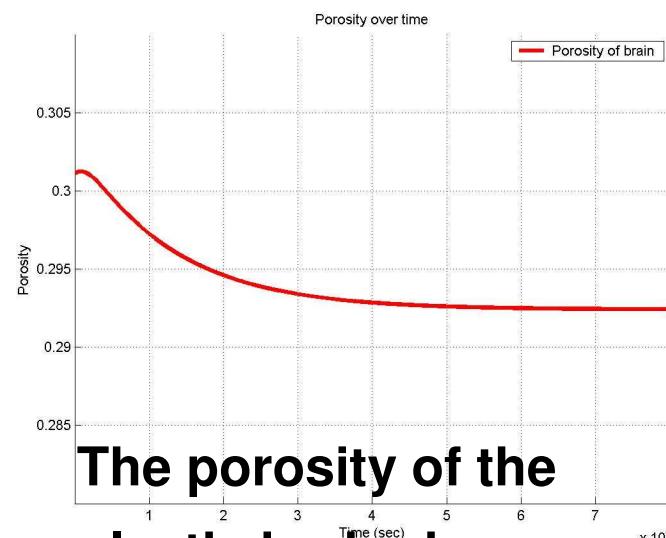
Total pressure in the brain



Ventricular pressure increase

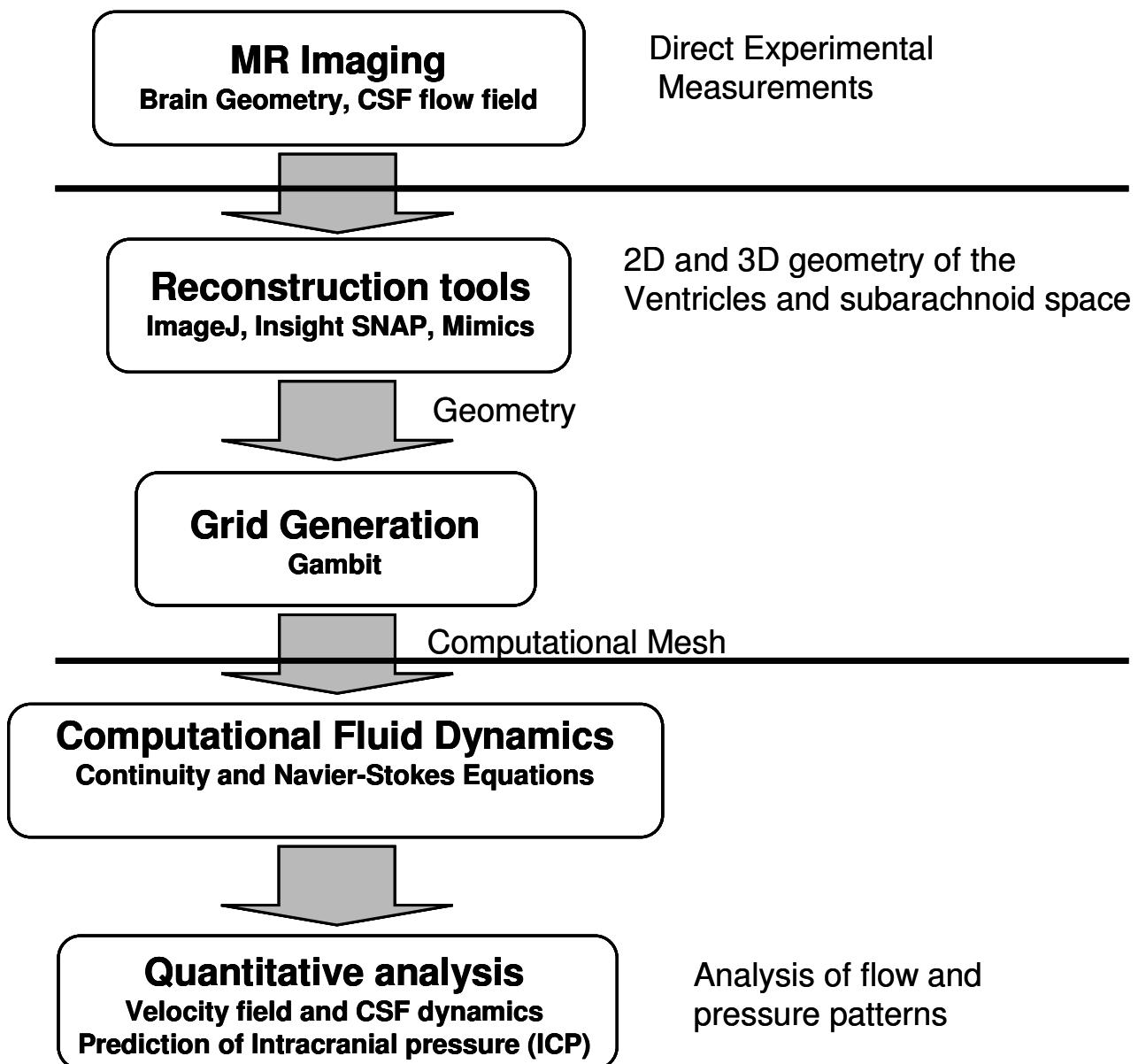


Ventricular volume increase

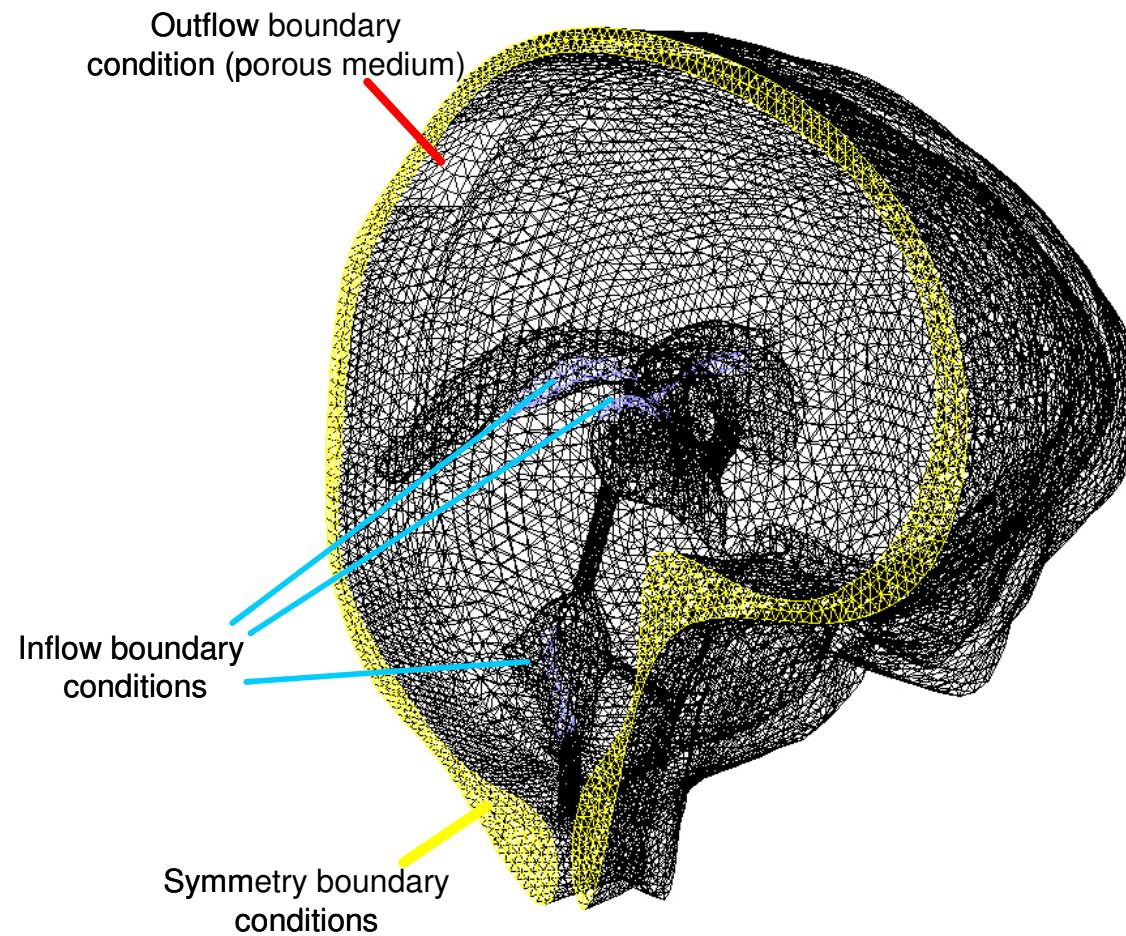


The porosity of the

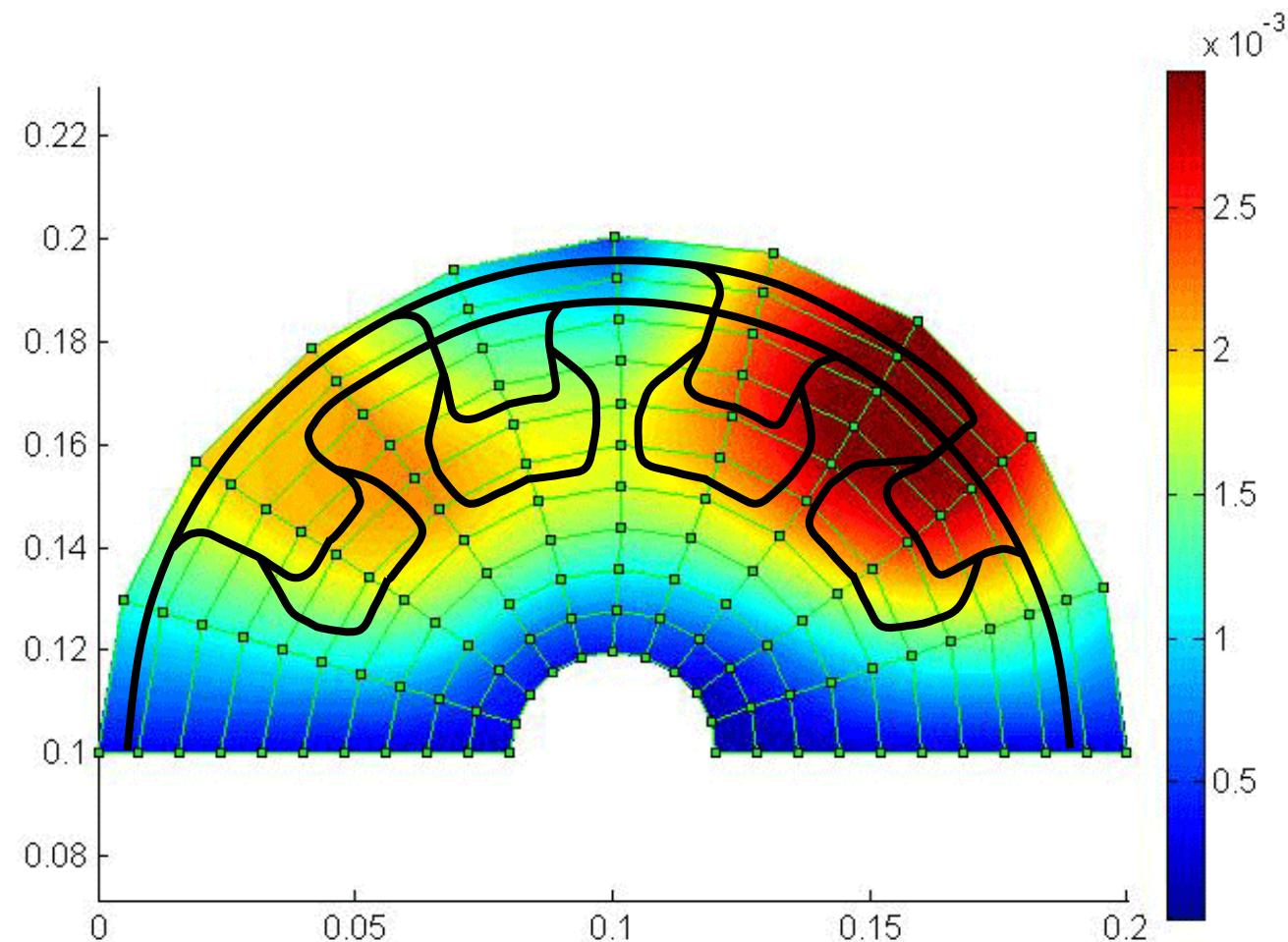
poroelastic brain decreases



Mesh Reconstruction

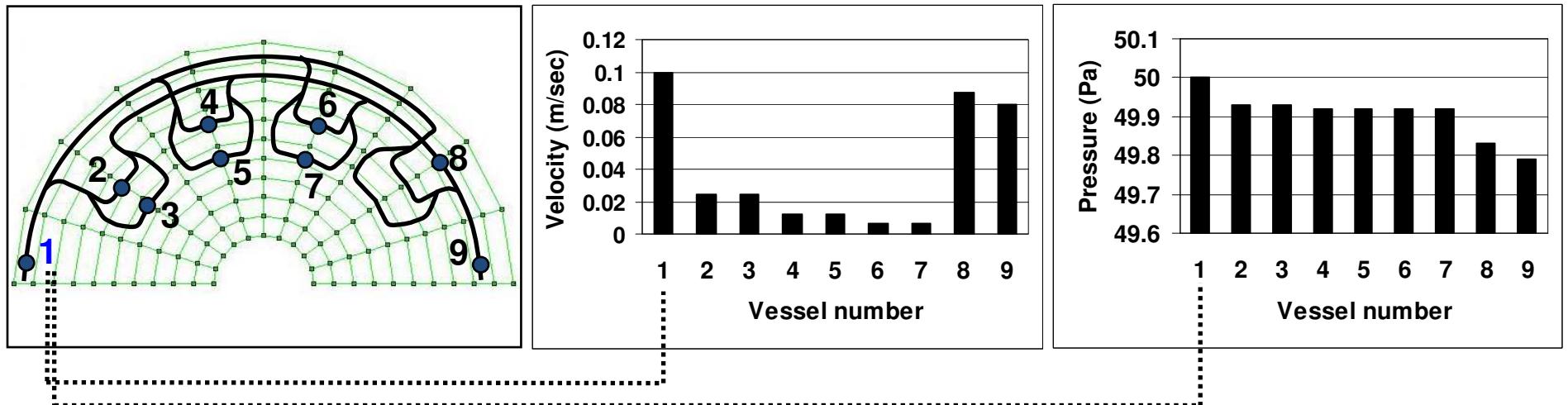
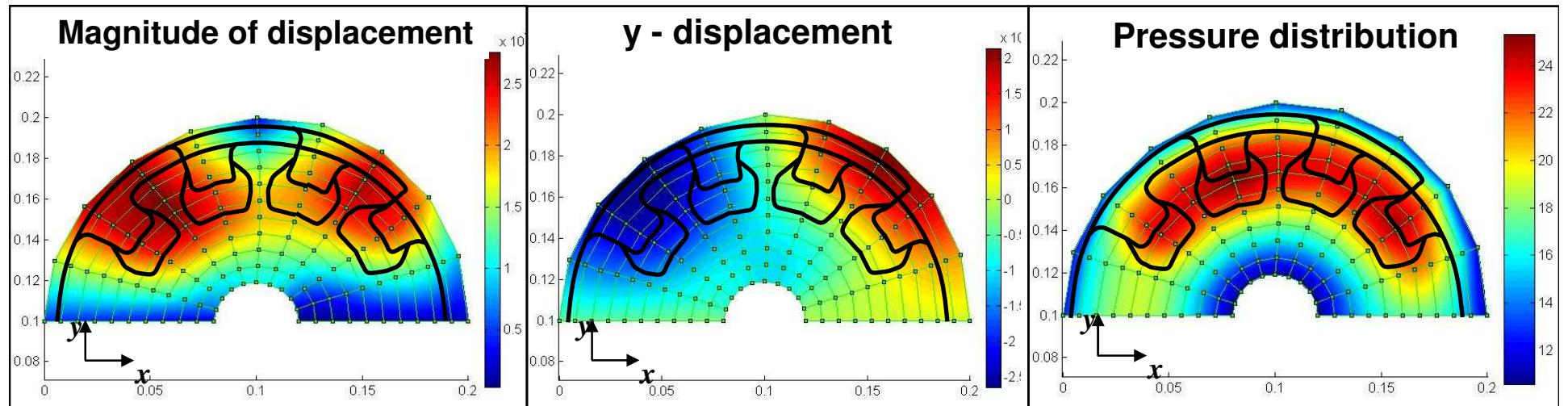


Brain compression due to pulsating blood flow



[view slide show to see animation](#)

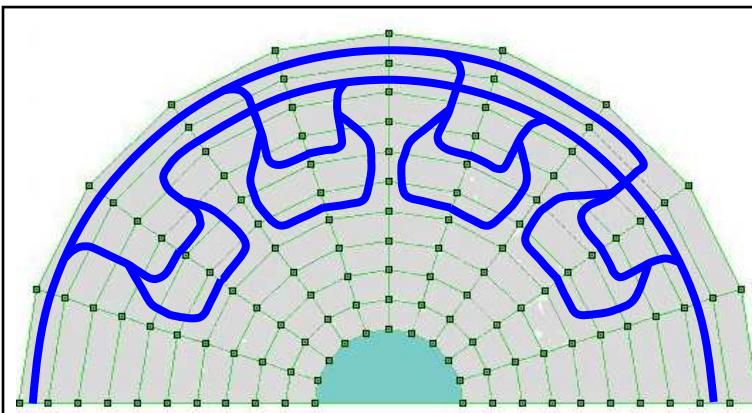
Preliminary results for vasculature



An FSI model with brain vasculature



Brain vasculature



continuity

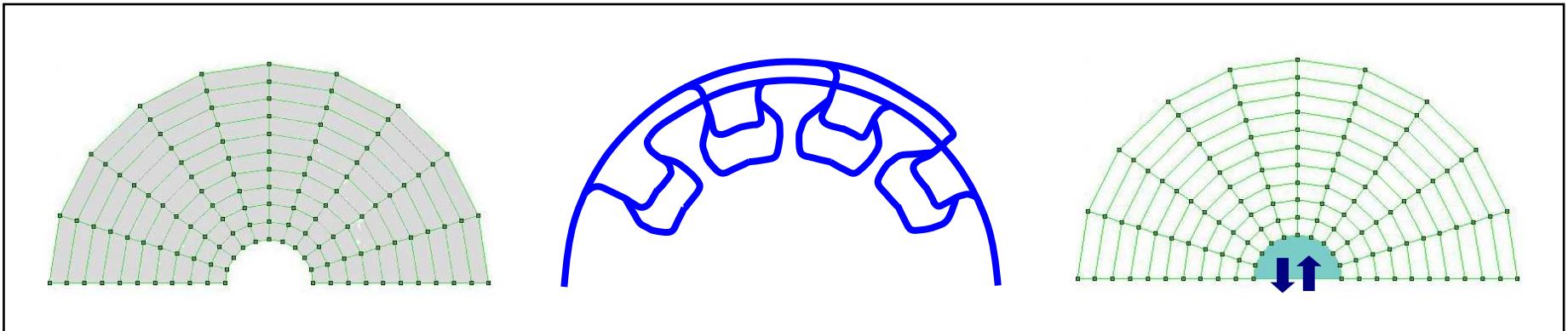
$$\frac{\partial A}{\partial t} + \frac{\partial(Au)}{\partial x} = 0$$

momentum

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial x} \left(\frac{u^2}{2} + \frac{p}{\rho} \right) = -F, \quad F = \frac{8\pi\mu}{\rho} \frac{u}{A}$$

tube law

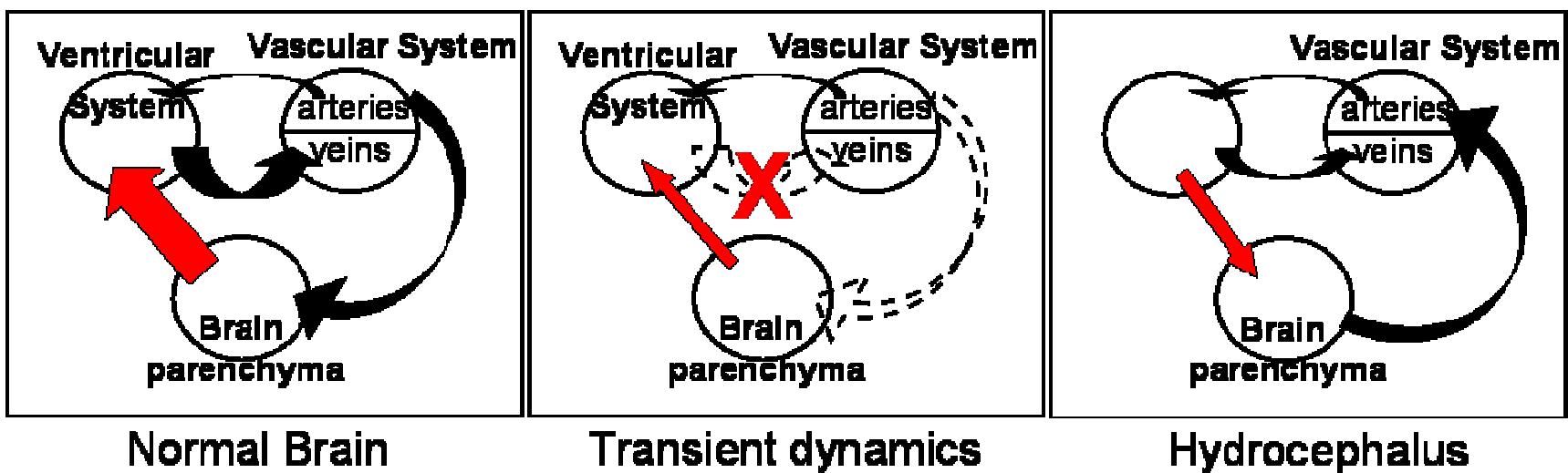
$$p - p_{out} = E_A \left(\frac{A}{A_0} - 1 \right)$$



Brain modeled as a linear elastic body using Navier eq.

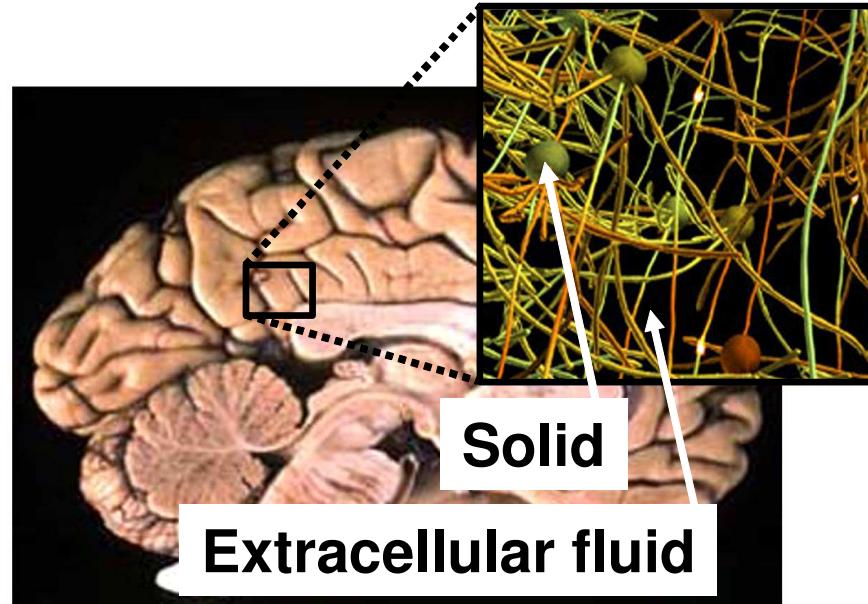
Brain vasculature composed of elastic tubes

Pulsatile motion of CSF modeled using Navier-Stokes eq.

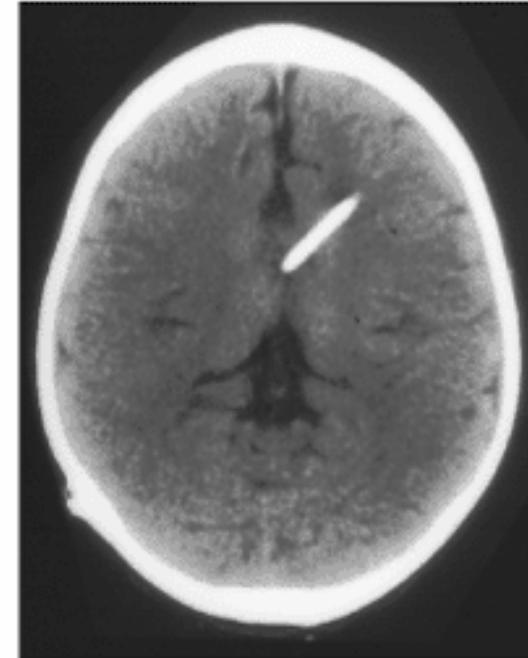
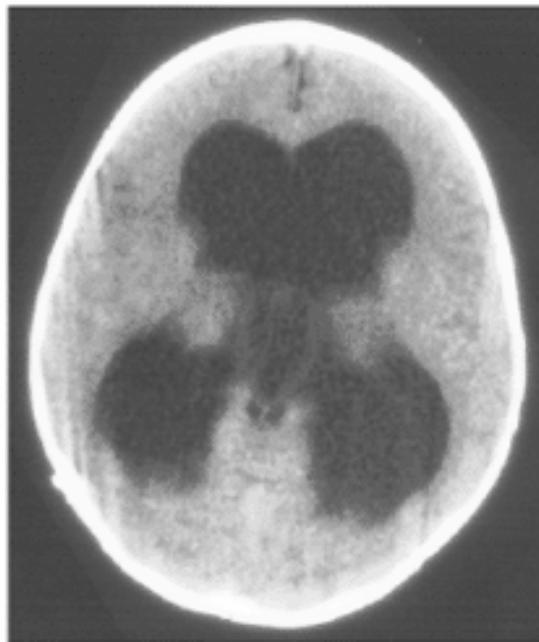


Poro-elasticity of the Brain

- Brain is a porous, elastic, deformable medium through which fluid flows
- Parenchyma is neither solid nor fluid
 - Solid brain matter
 - CSF filled pores
 - Deformation is a function of flow and pore pressure

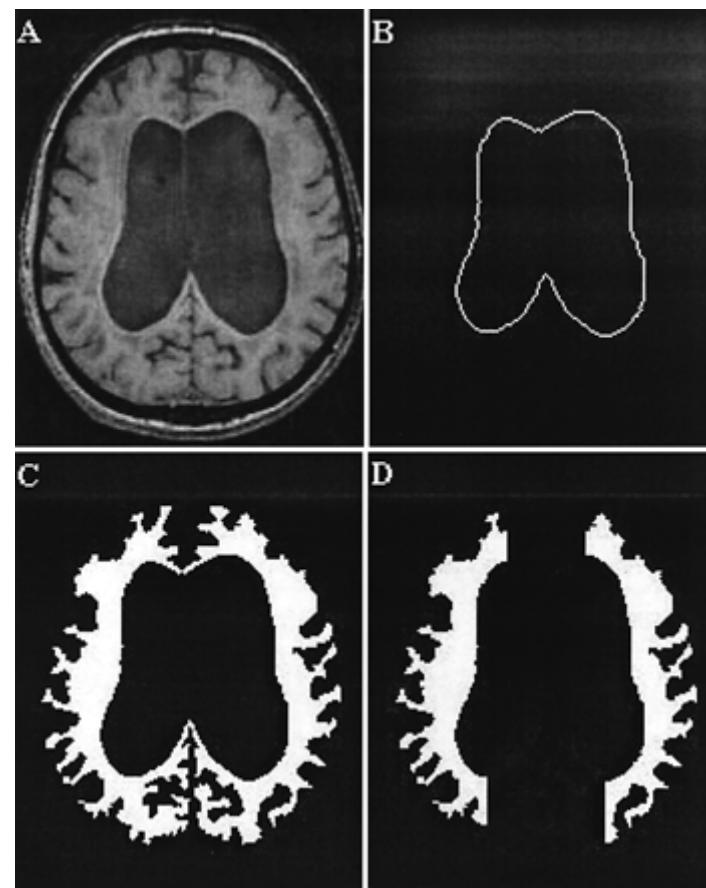


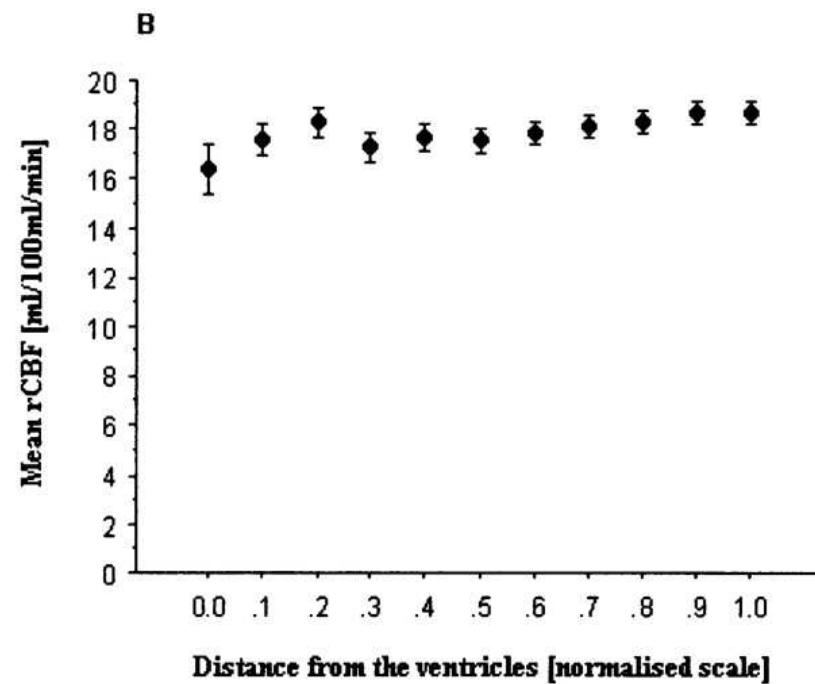
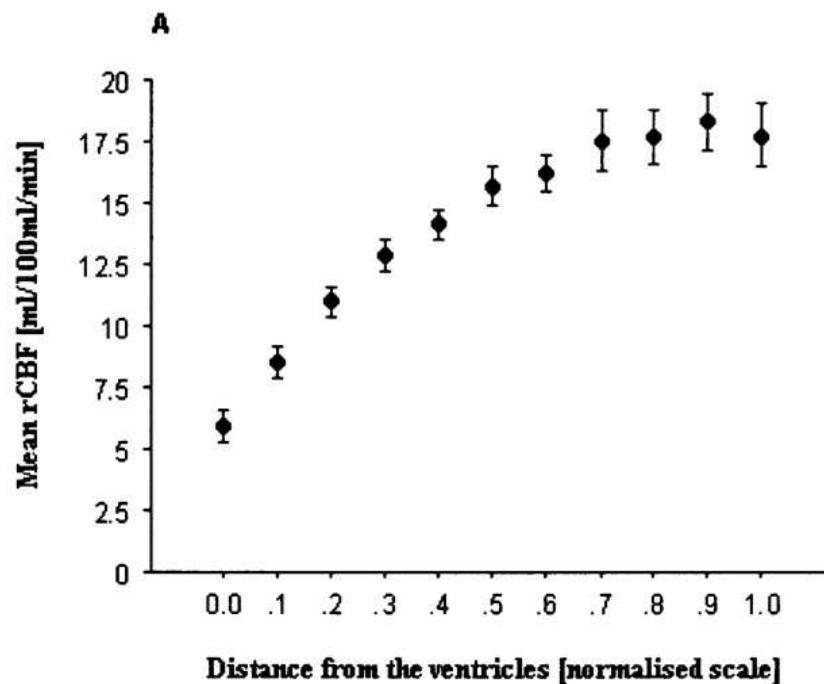
Acute Hydrocephalus Pre and Post Shunting



Cerebral Blood Flow

Cambridge Group





Decrease in Regional rCBF with increase of ICP

