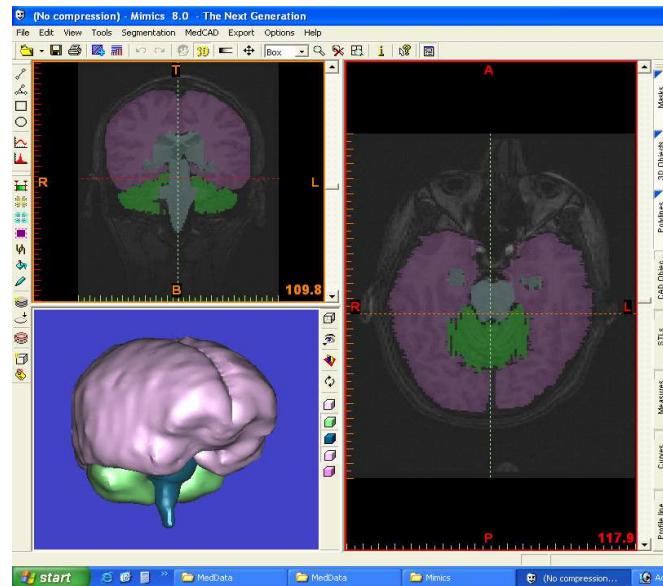


# The Physics of Hydrocephalus



Andreas Linninger, Ph.D, UIC  
Richard Penn M.D. U of C



# William of Occum



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

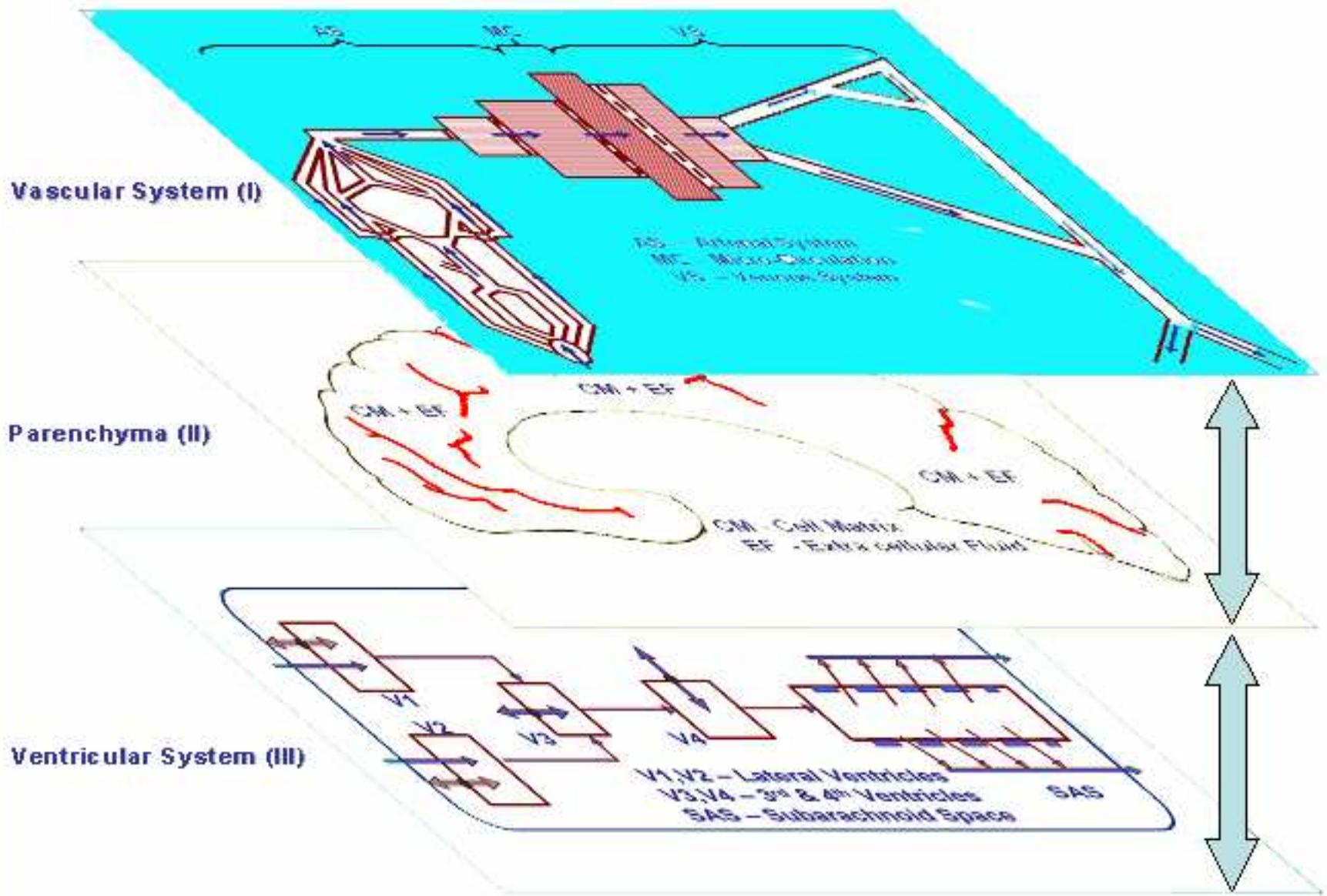
How much of hydrocephalus can be explained by applying the well known physical laws

# Methods

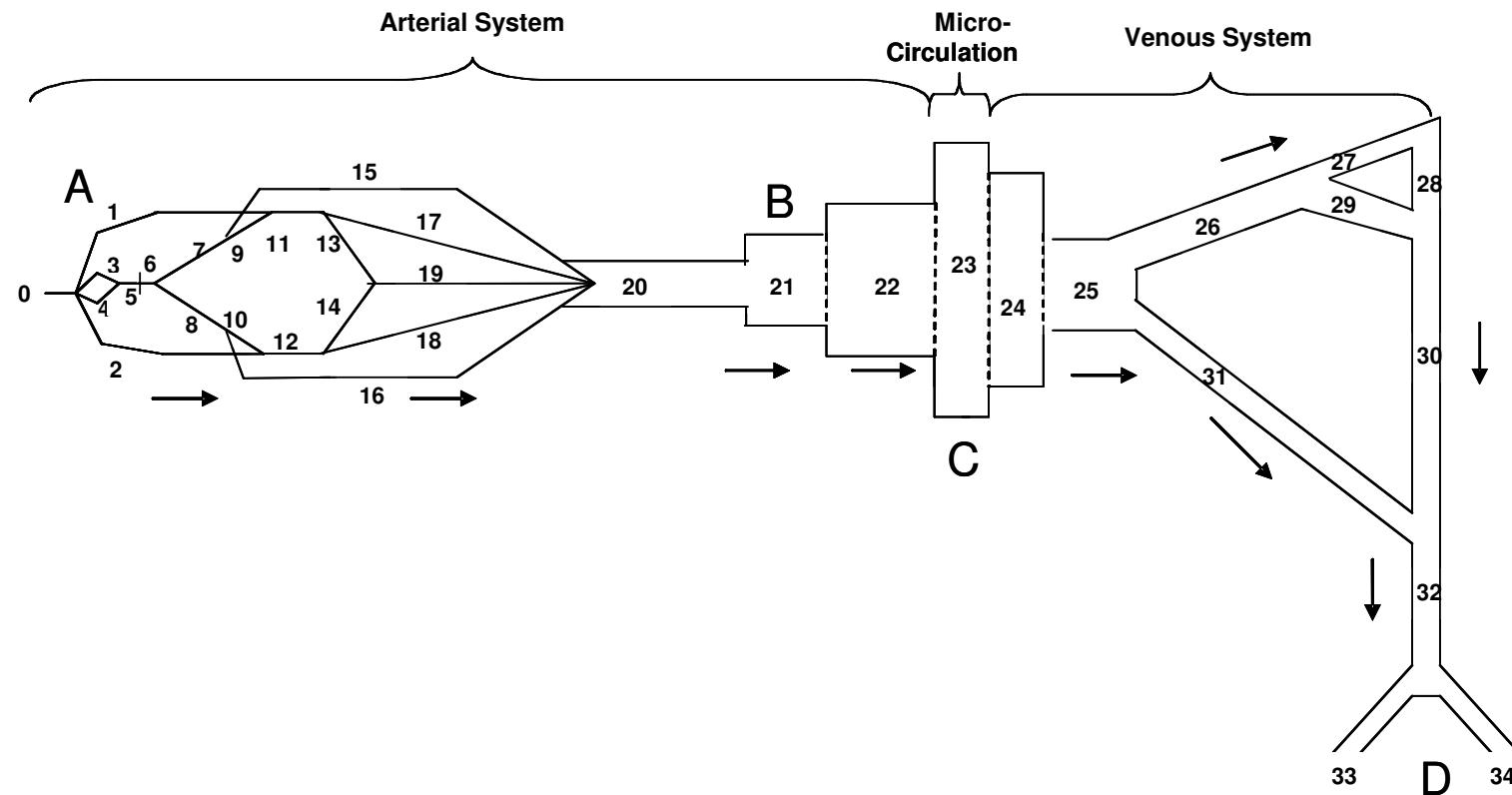
- Use MRI measurements to find important parameters e.g. brain and ventricular size, CSF flow patterns, brain water, and brain movements
- Use computer simulations of the physical laws in one to three dimensional models
- Check the results by seeing if predicted values match real patient values

# Three Interacting Compartments

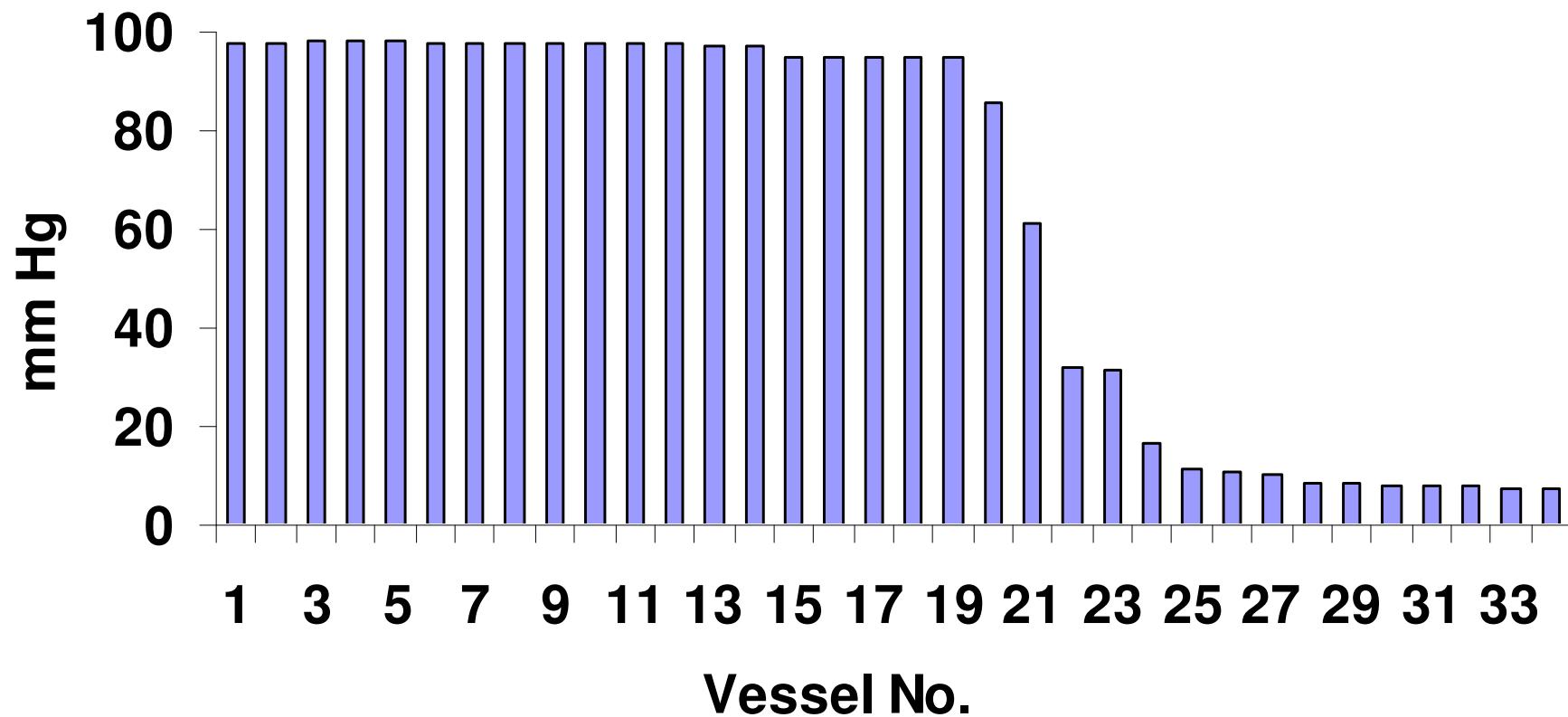
- CSF-filled ventricular and subarachnoid system
- Brain parenchyma
- Cerebral blood vessels

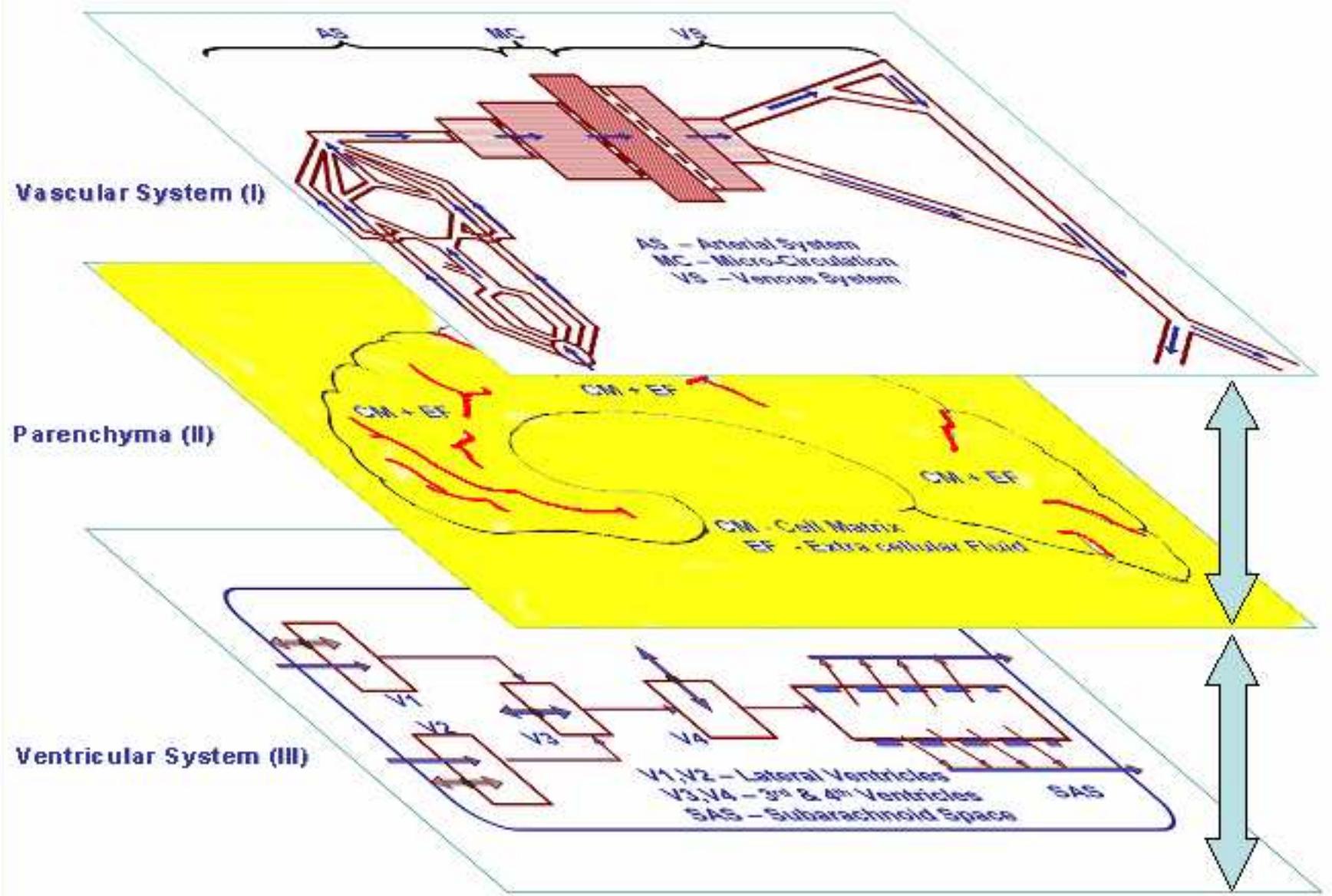


# NETWORK FOR CALCULATING FLOW AND PRESSURE DYNAMICS OF THE BRAIN VASCULATURE



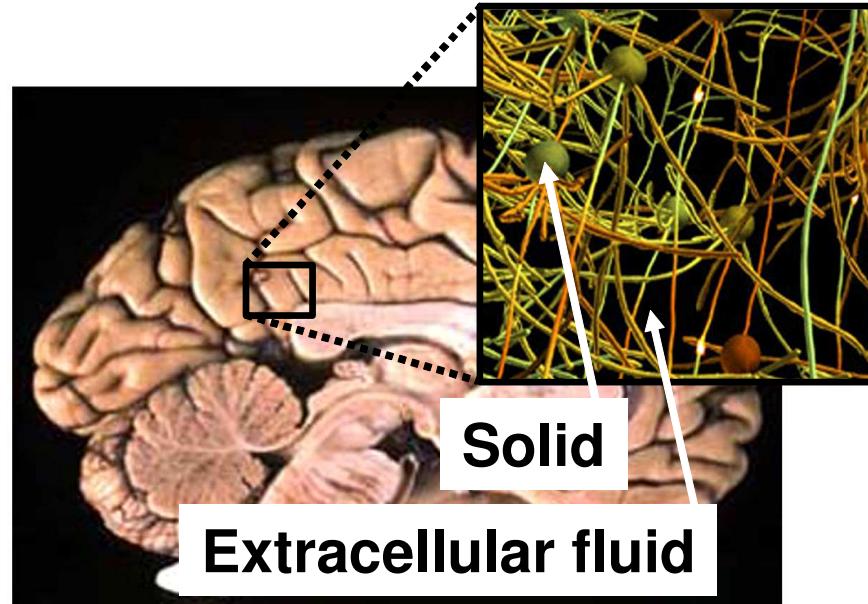
PREDICTED PRESSURE DIFFERENCES ARE WITHIN  
THE EXPECTED RANGE

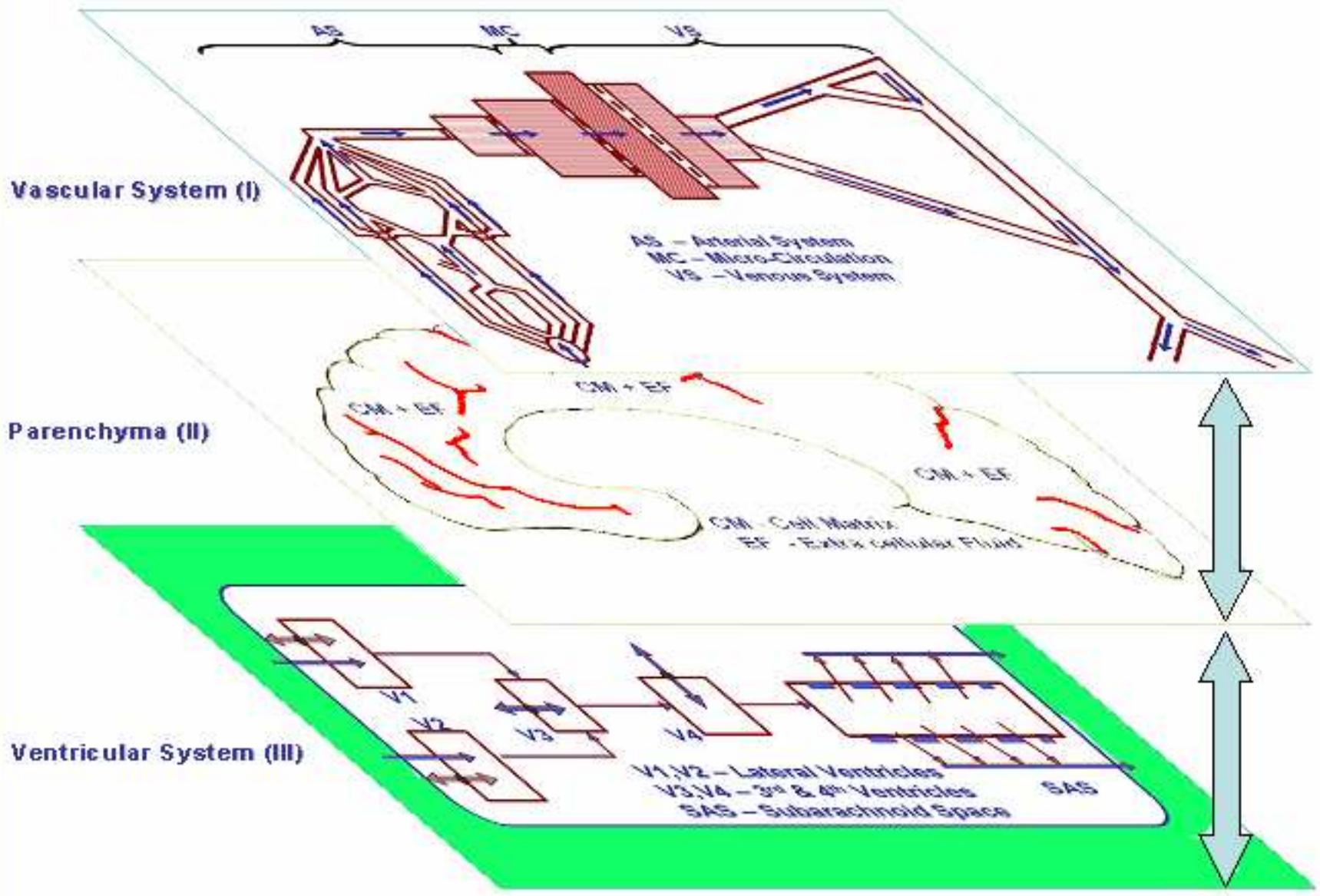




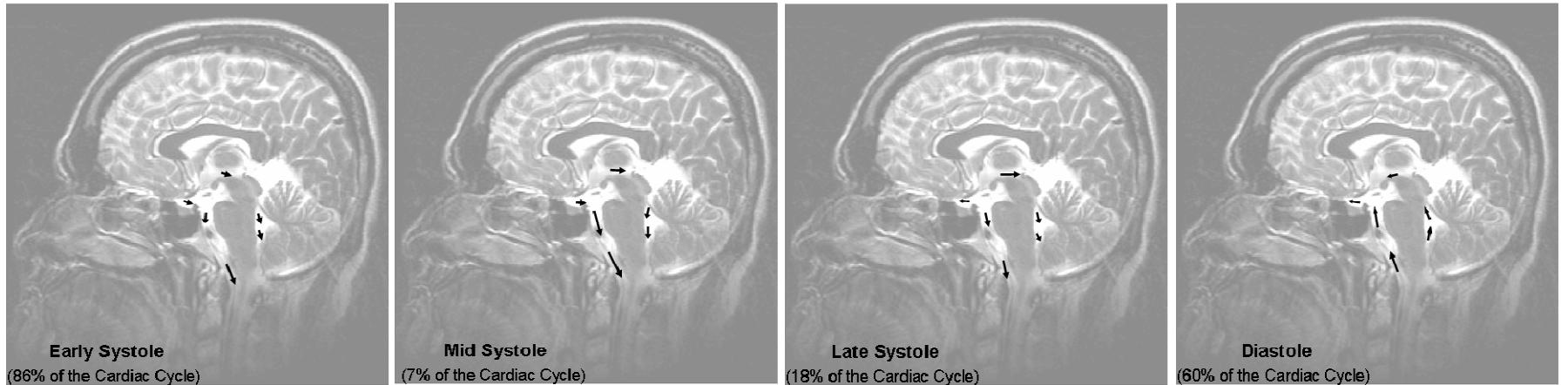
# Poro-elasticity of the Brain

- 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

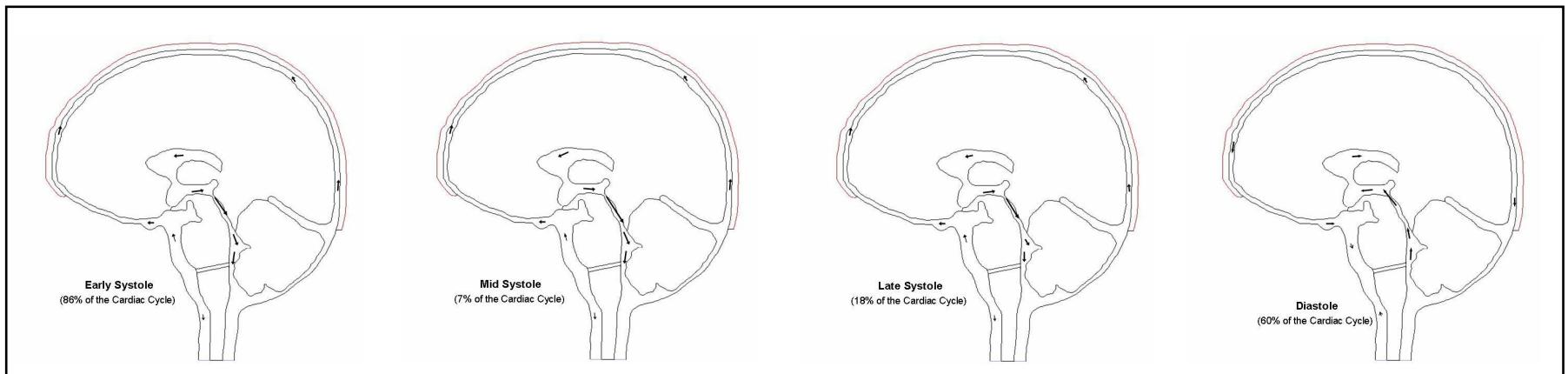




## Normal brain Comparison: Cine MRI – FSI-CFD

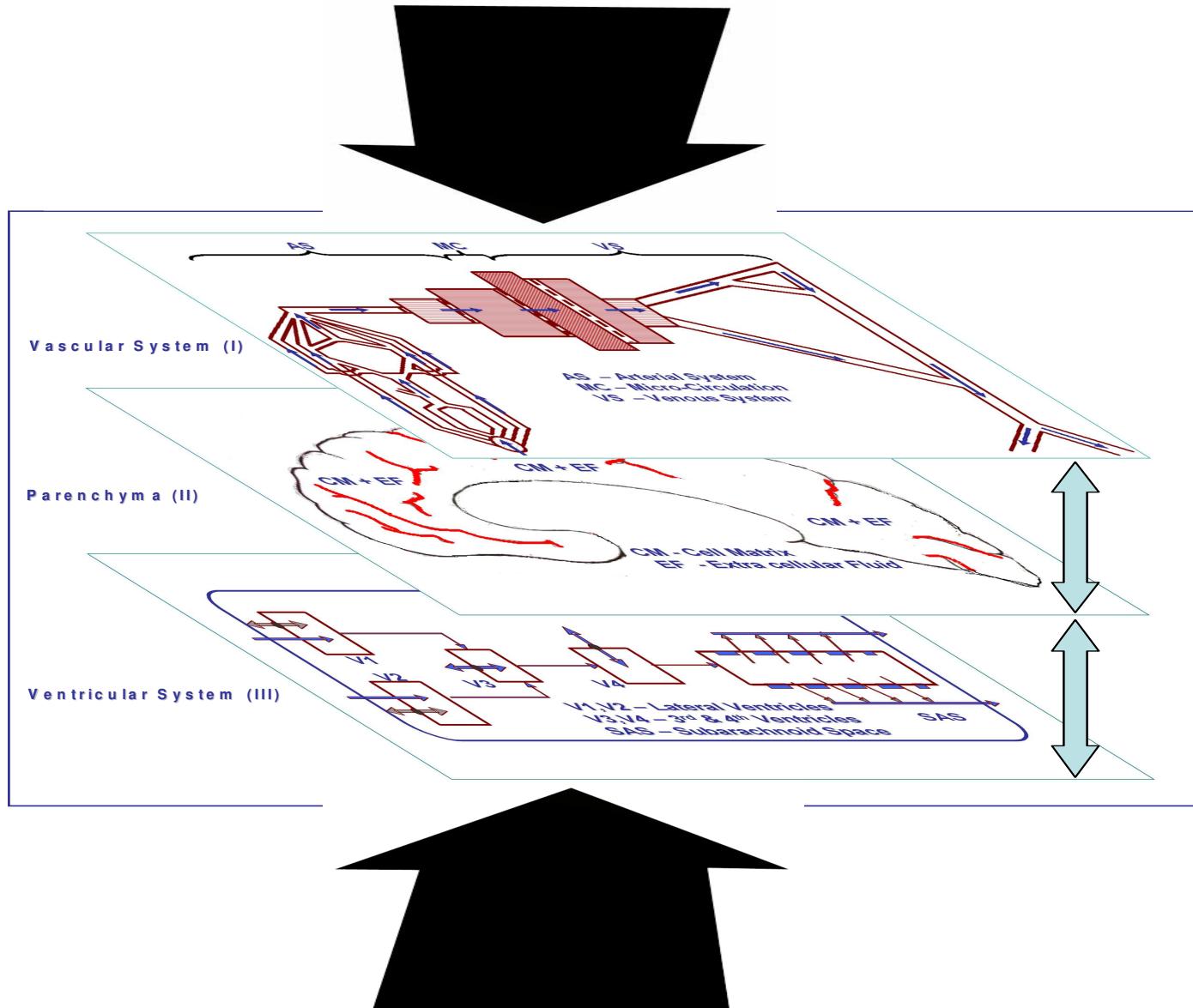


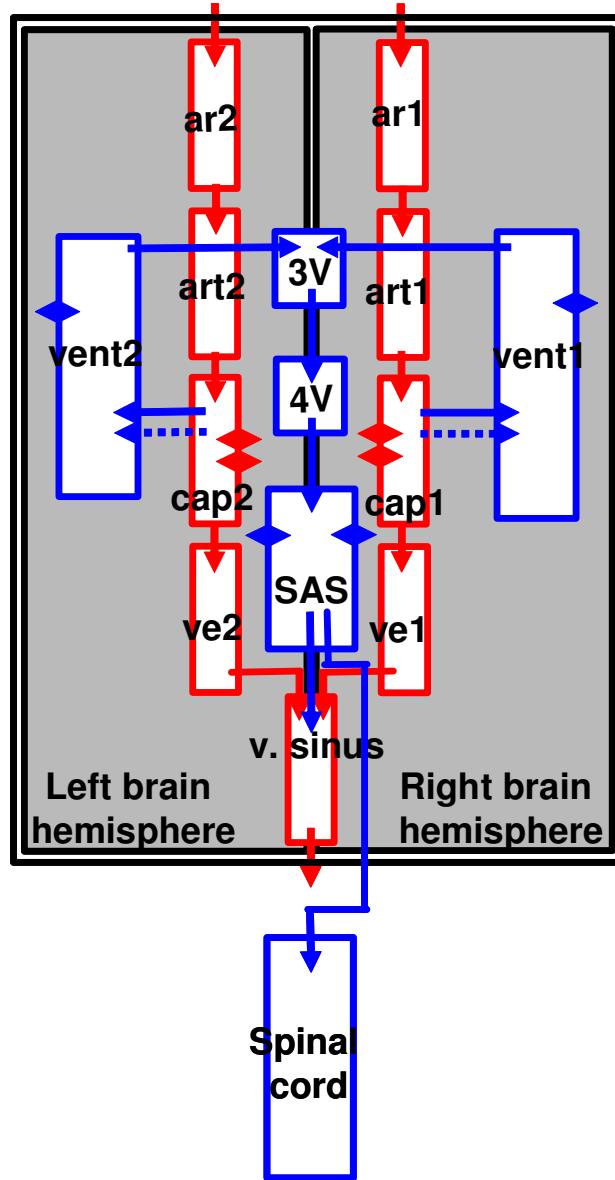
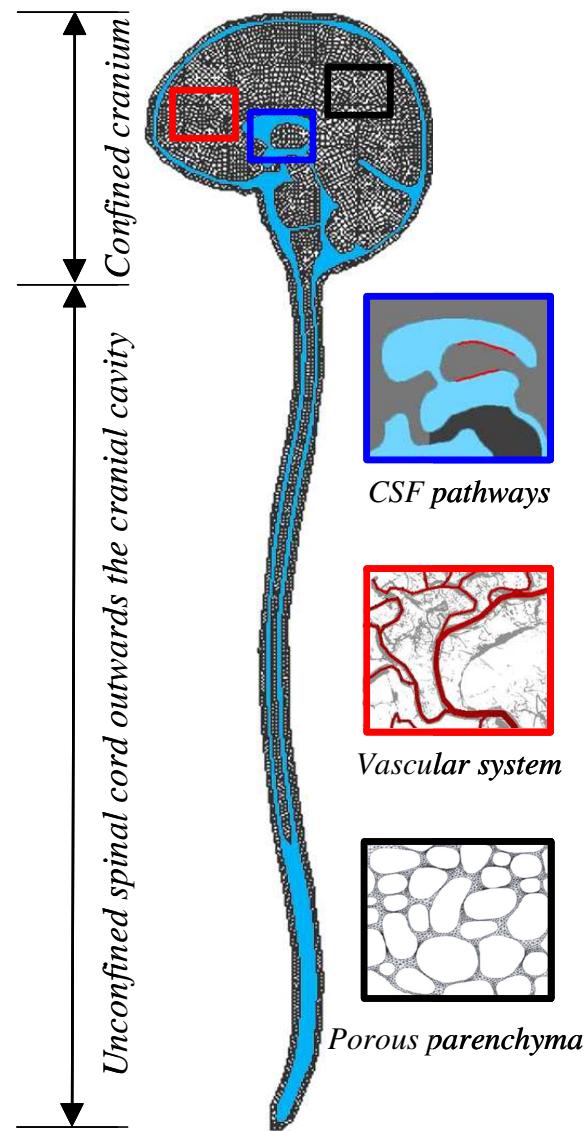
**CSF velocity vectors from MRI**



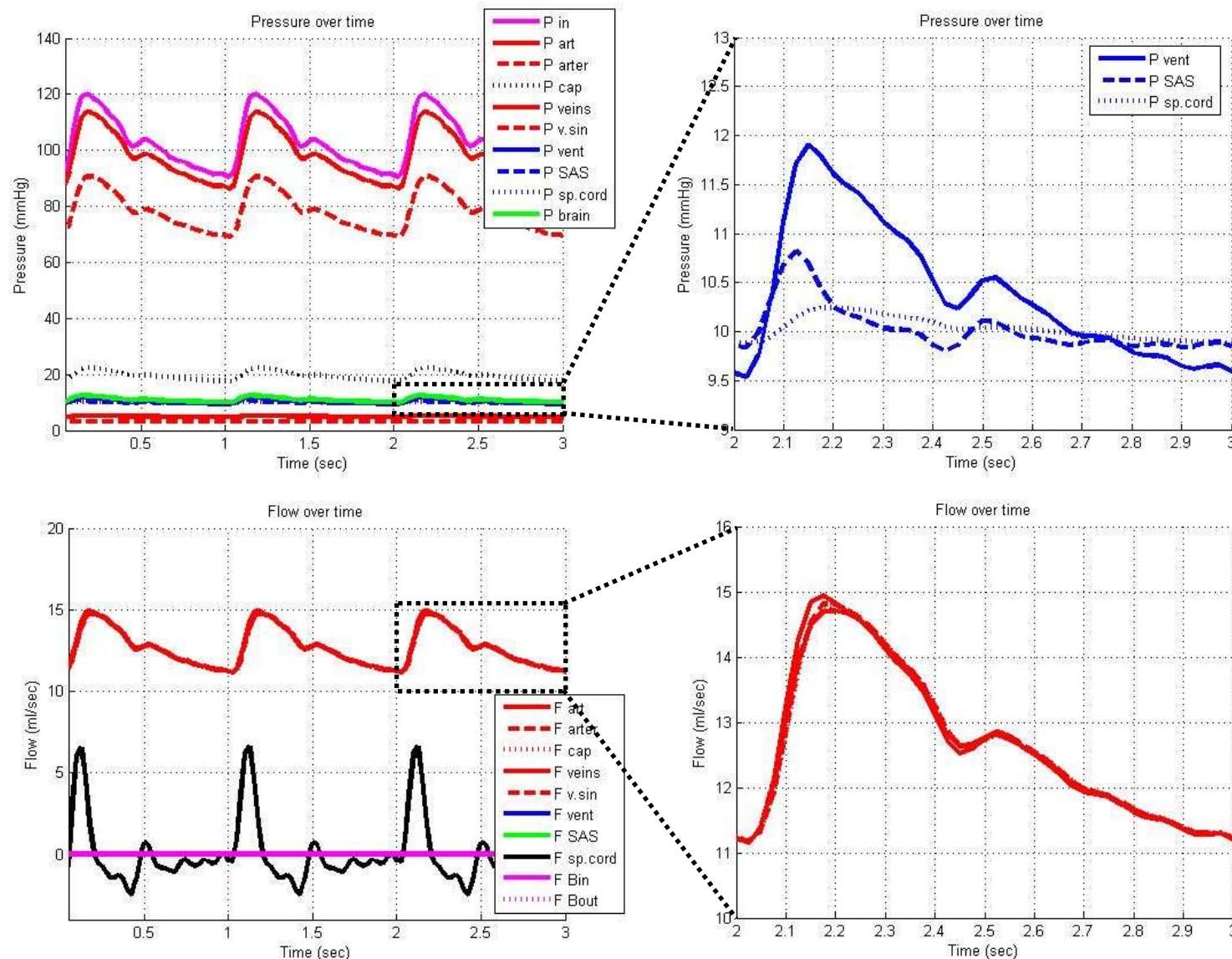
**CSF velocity vectors from FSI-CFD simulation**

Linninger, A.A., Xenos M., Zhu D.C., Somayaji MB.R., Kondapelli S., and Penn R.,  
"Cerebrospinal Fluid Flow in the Normal and Hydrocephalic Human Brain",  
IEEE Transaction on Biomedical Engineering (2007).

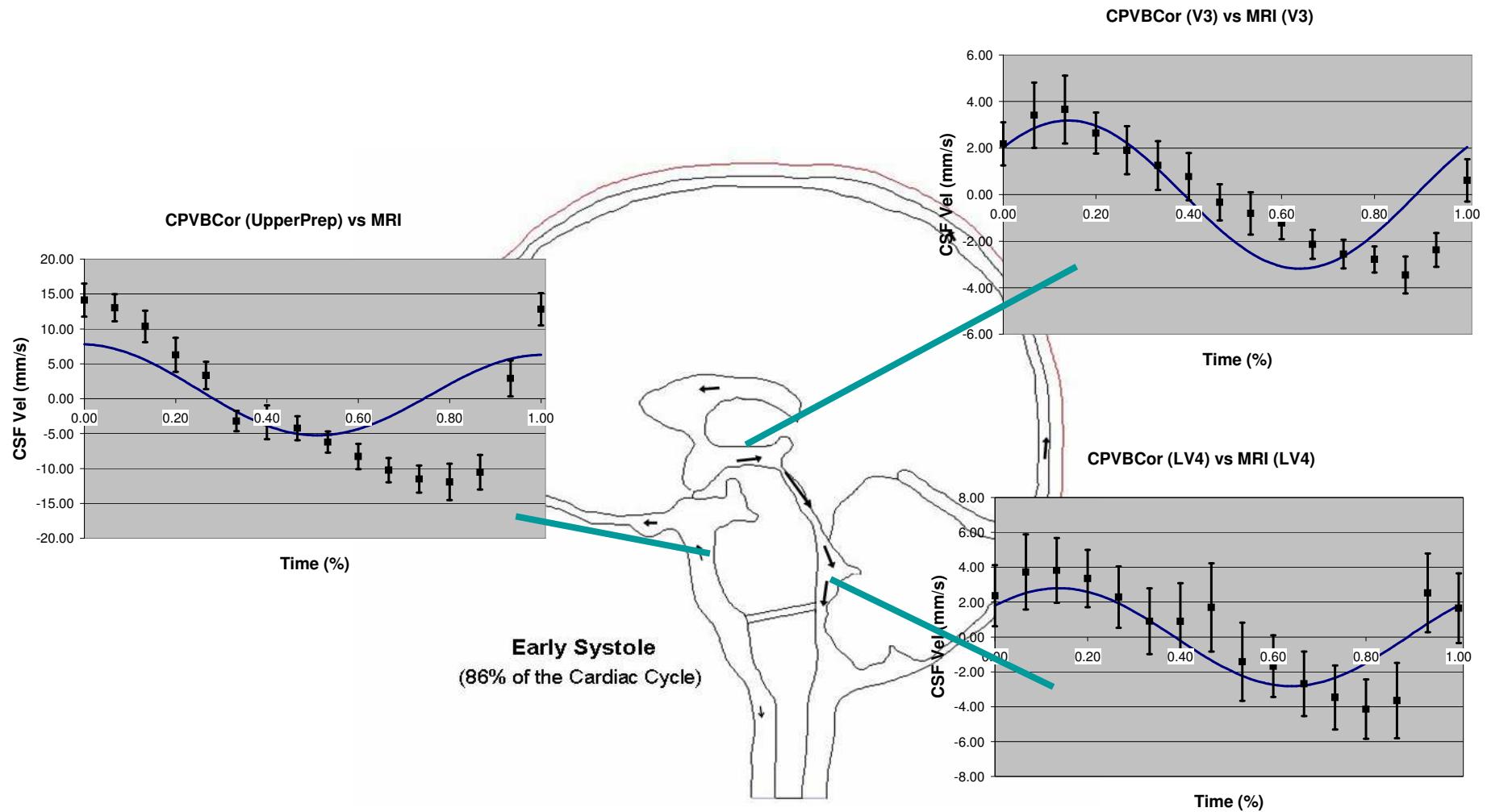




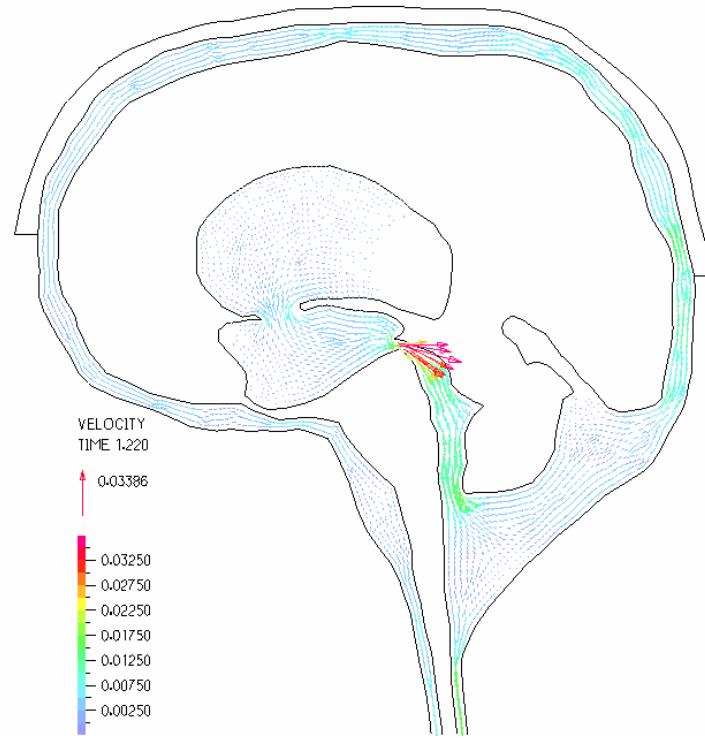
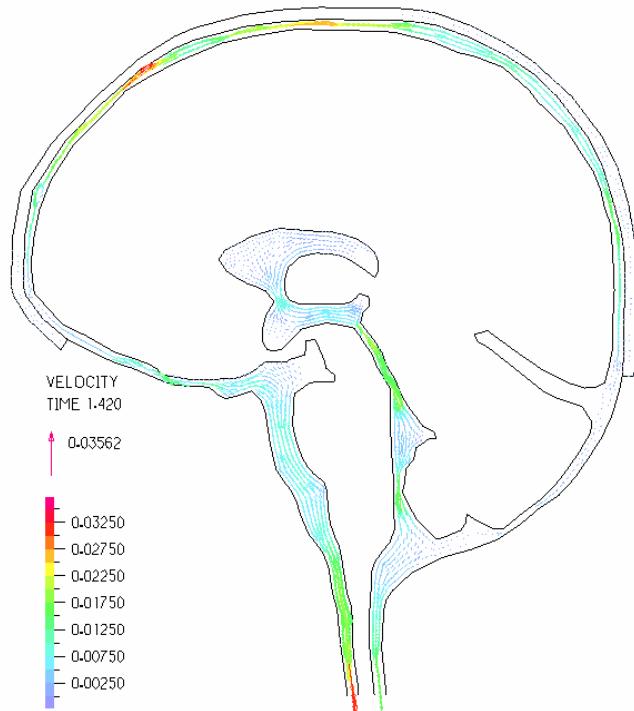
# Normal Intracranial Dynamics



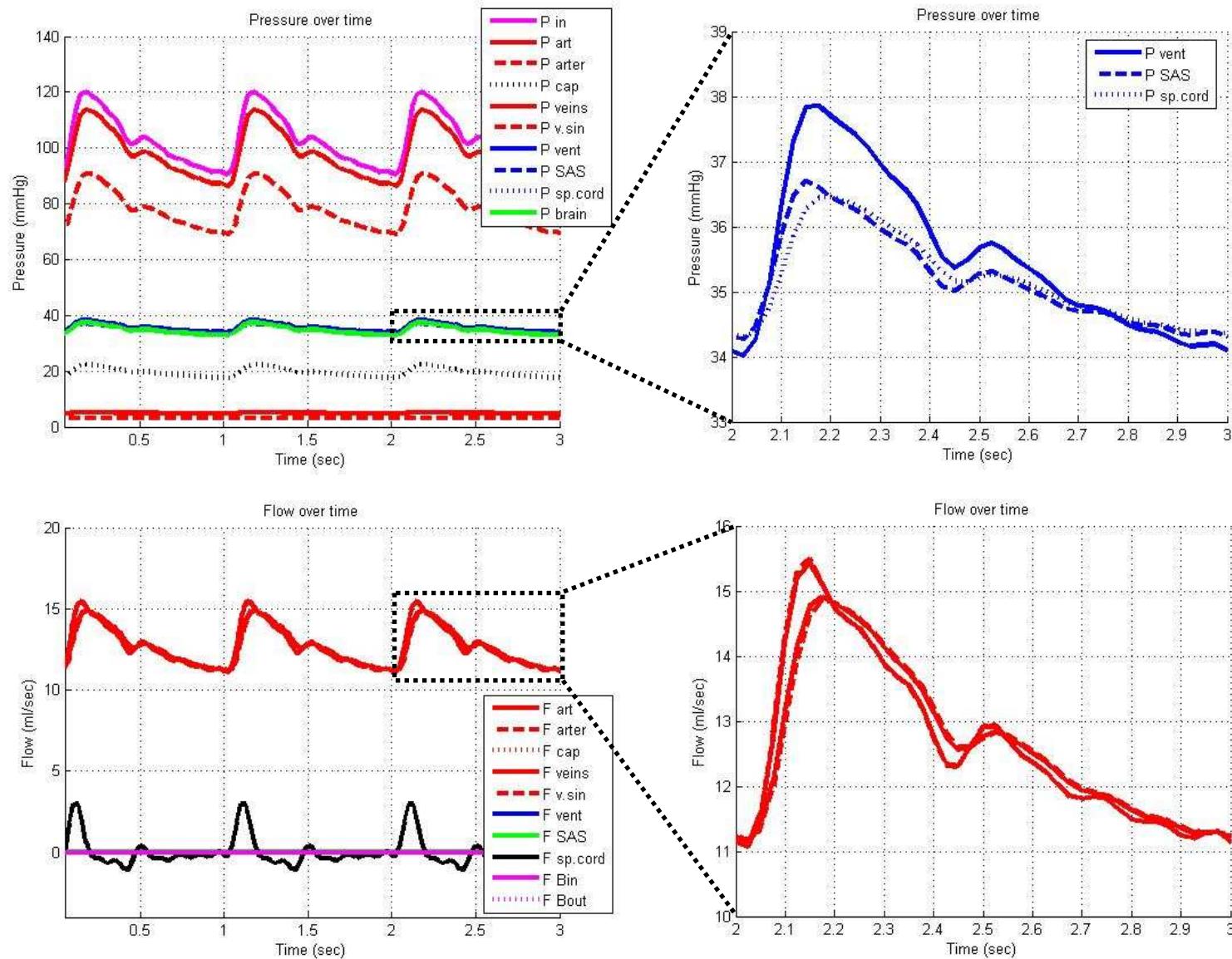
# Validation of the simulations with CINE-phase-MRI



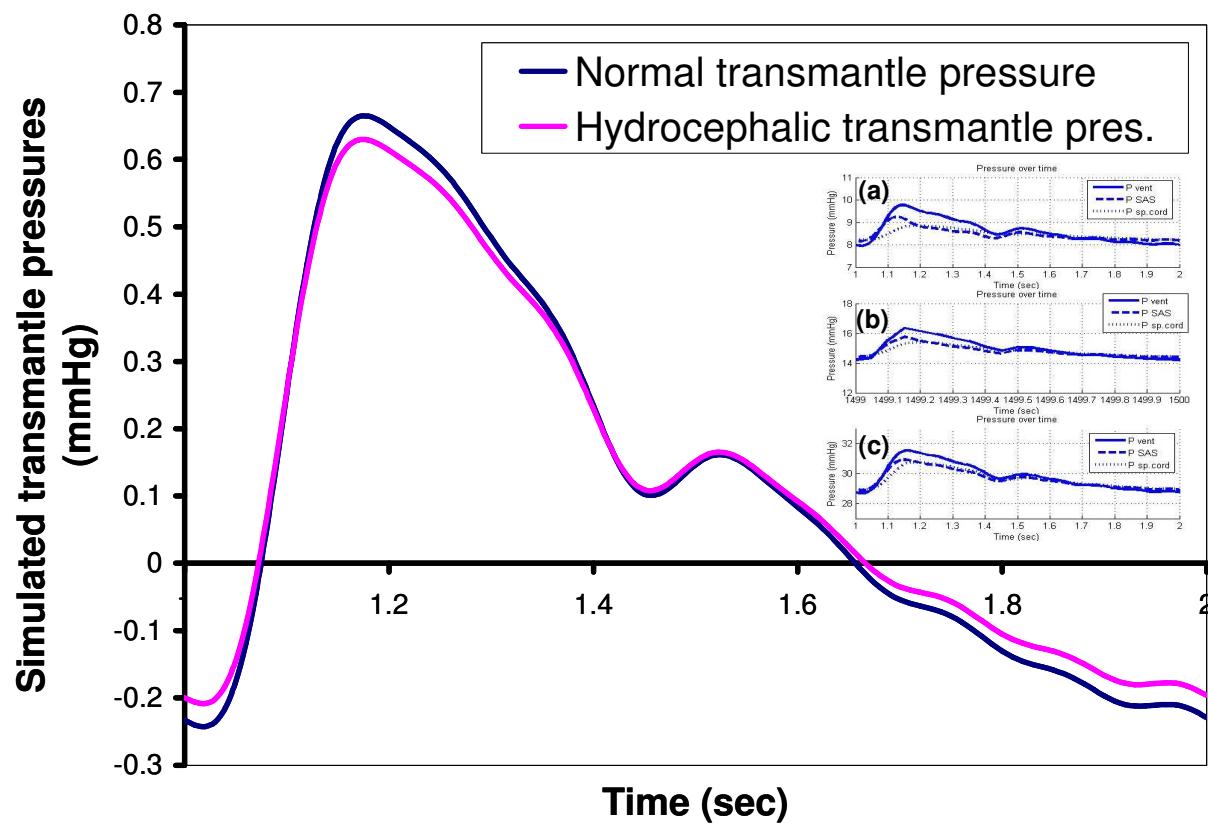
# Normal and Hydrocephalic



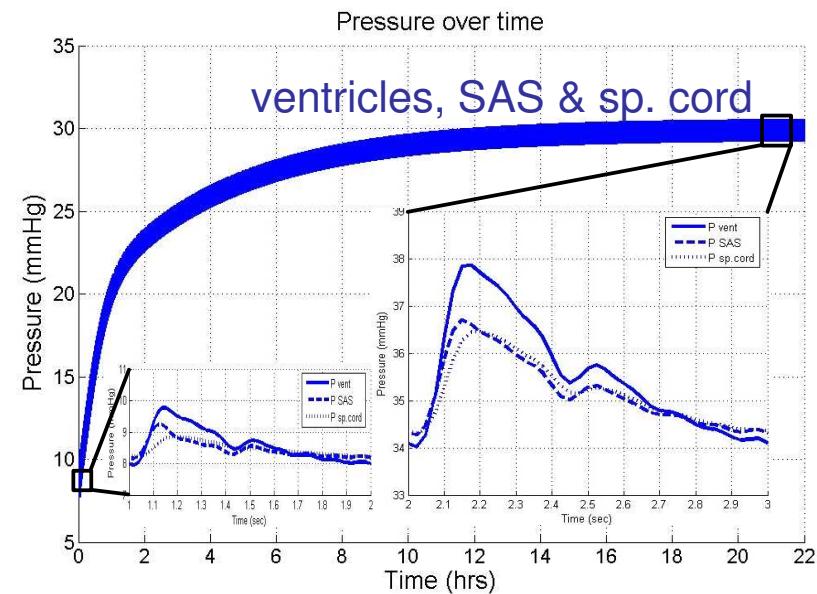
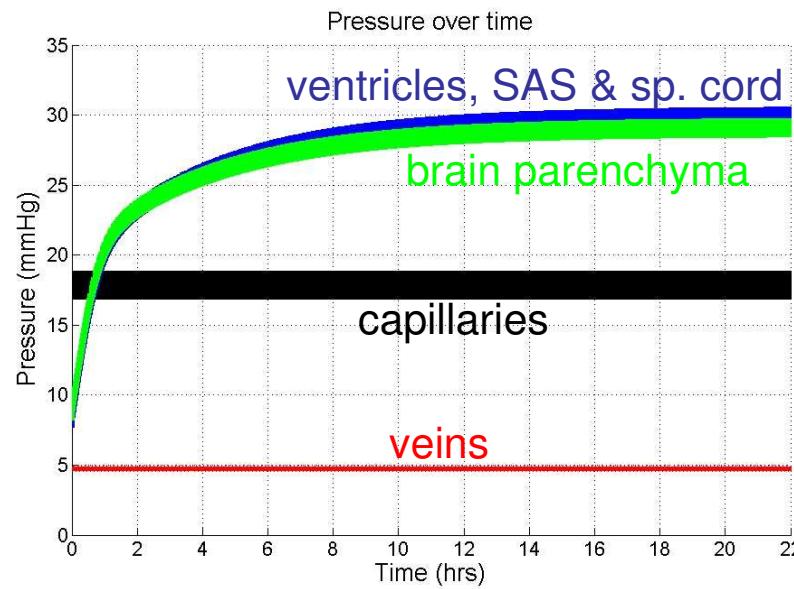
# Hydrocephalic intracranial dynamics

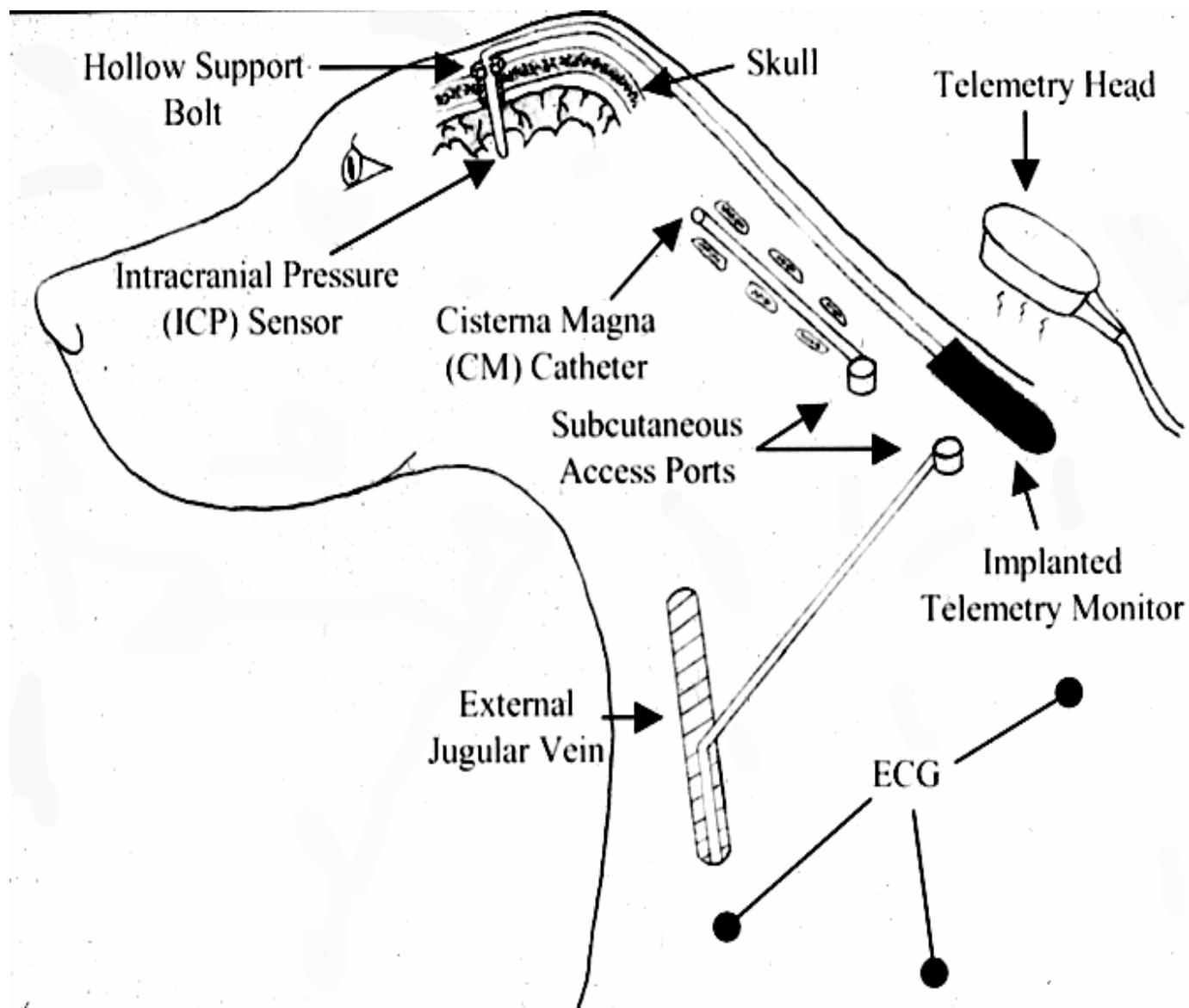


# TRANSMANTLE PRESSURE DIFFERENCES ARE SMALL IN NORMALS AND HYDROCEPHALUS

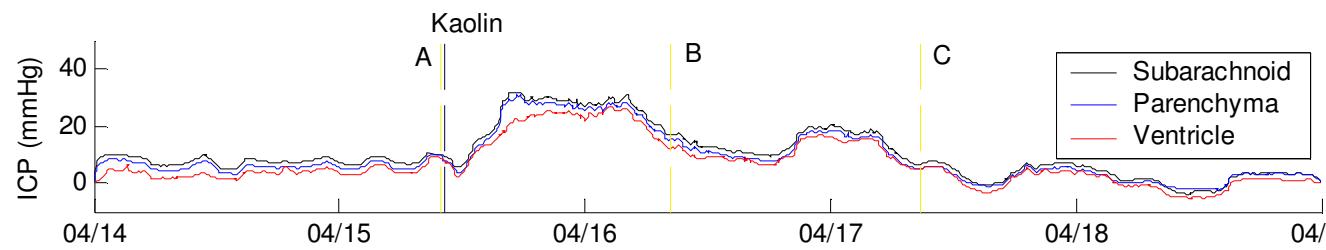


# Development of Hydrocephalus over time





# Real Time Waveforms



**A**  
Prior to kaolin

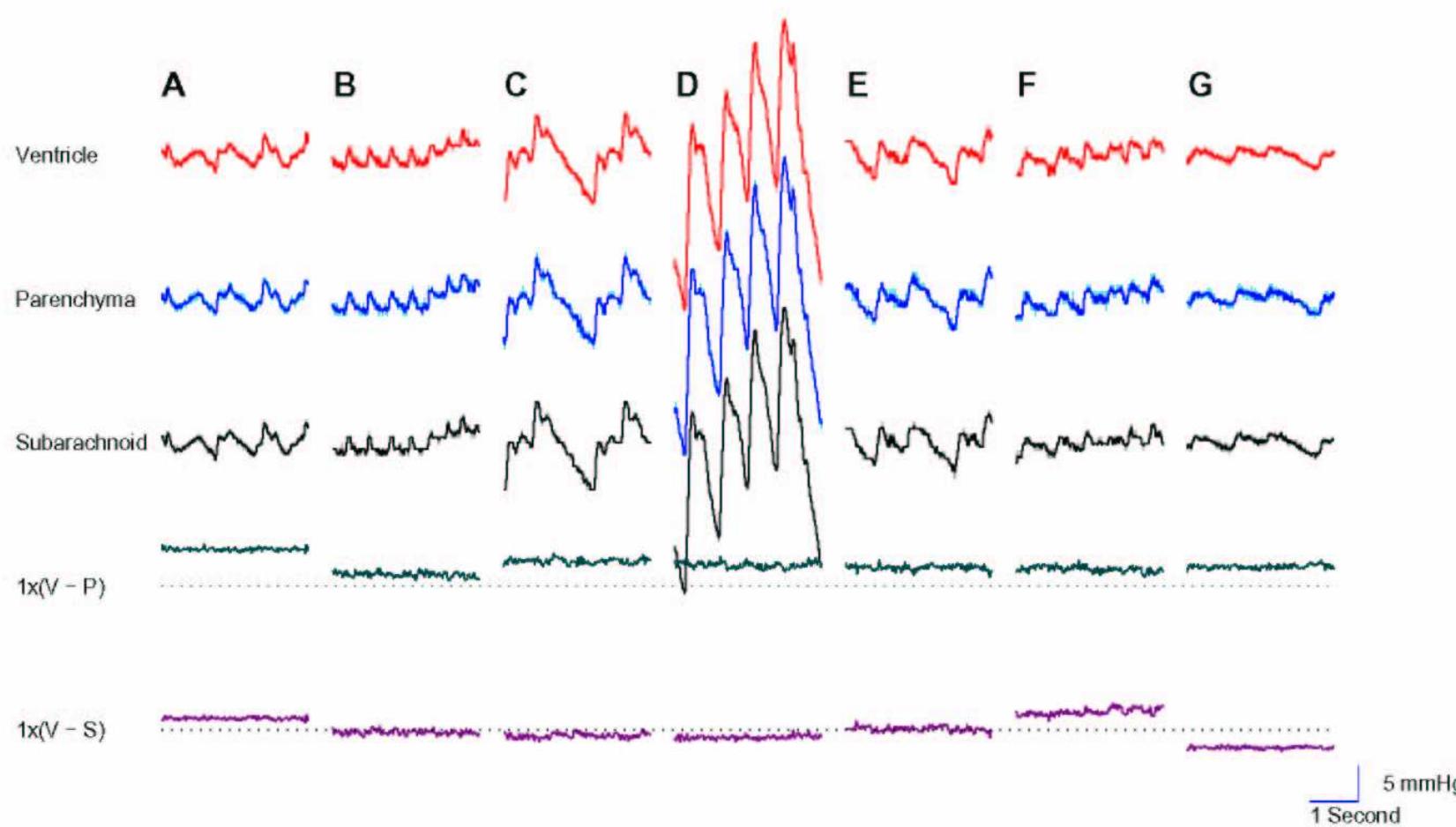
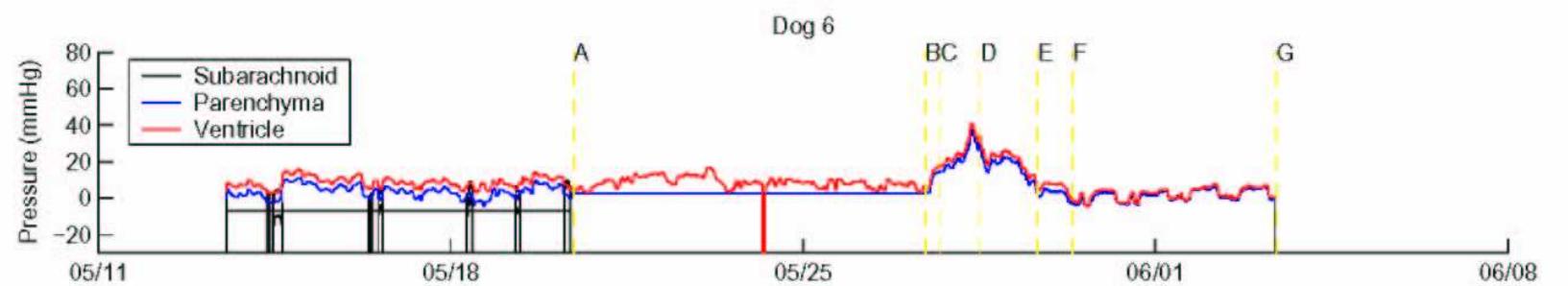
**B**  
~1 day post kaolin

**C**  
~2 days post kaolin

0 mmHg

5 mmHg

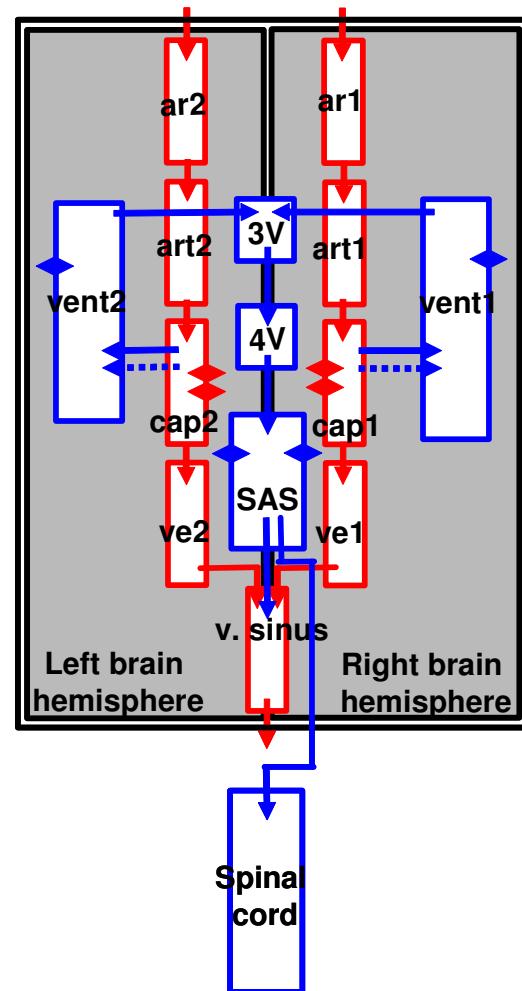
1 Second



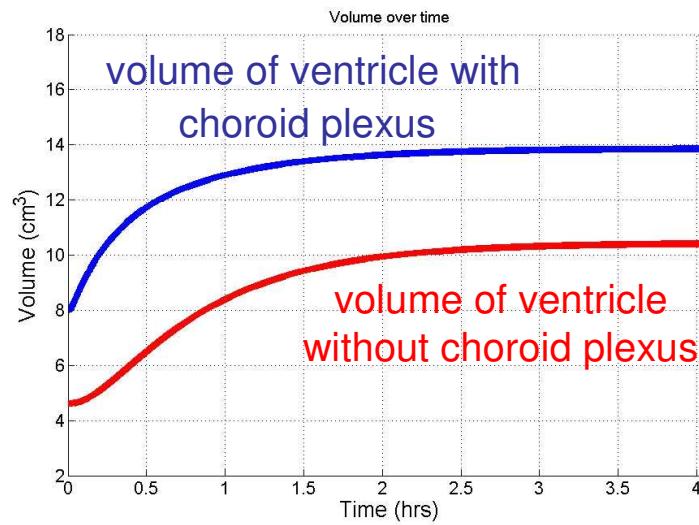
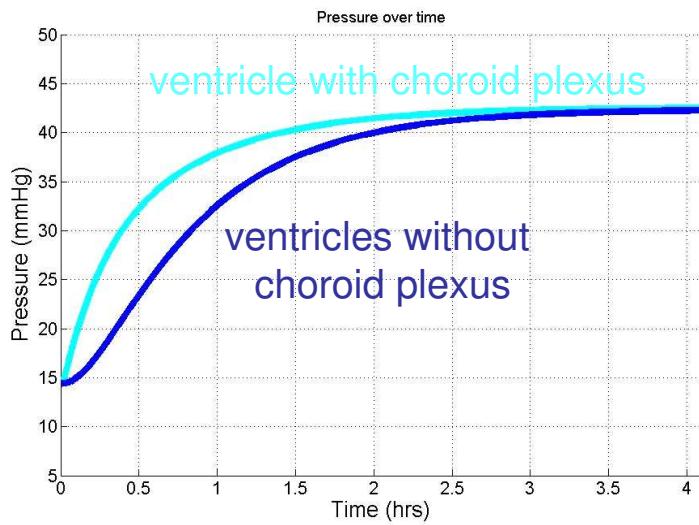
# No measurable pressure gradients (above 1 Torr)

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

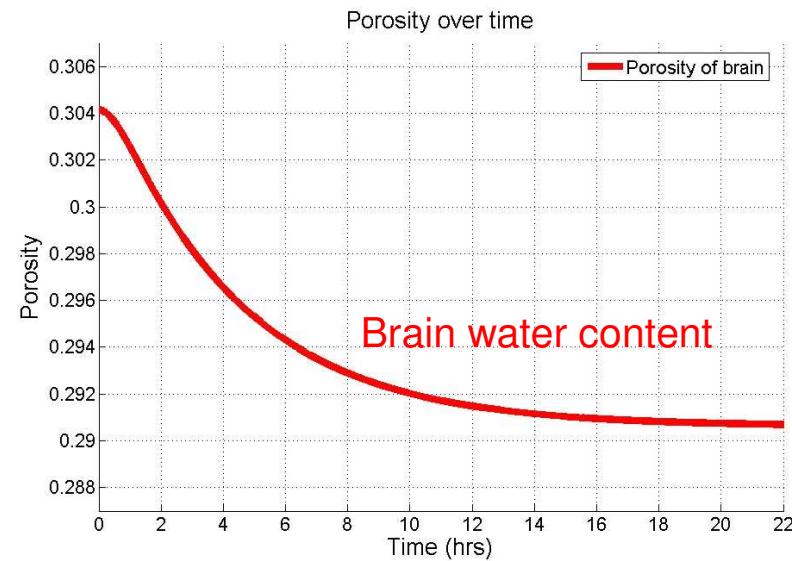
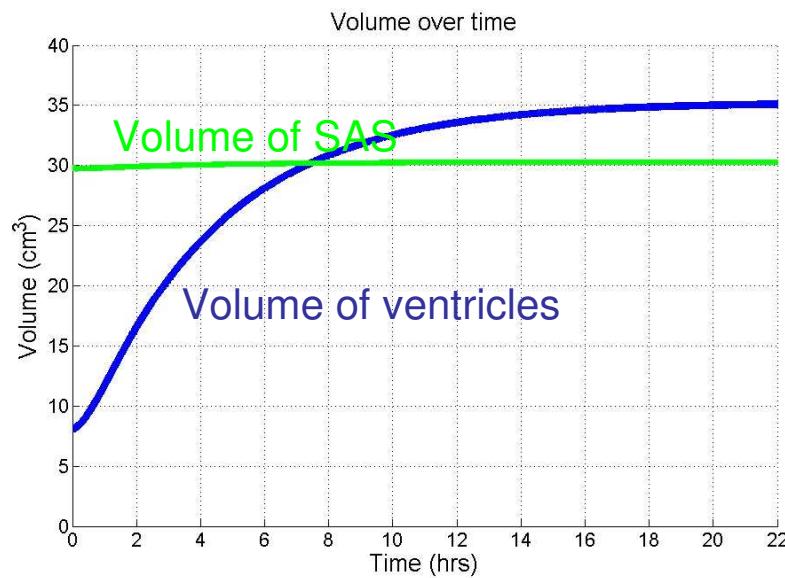
# Unilateral Hydrocephalus



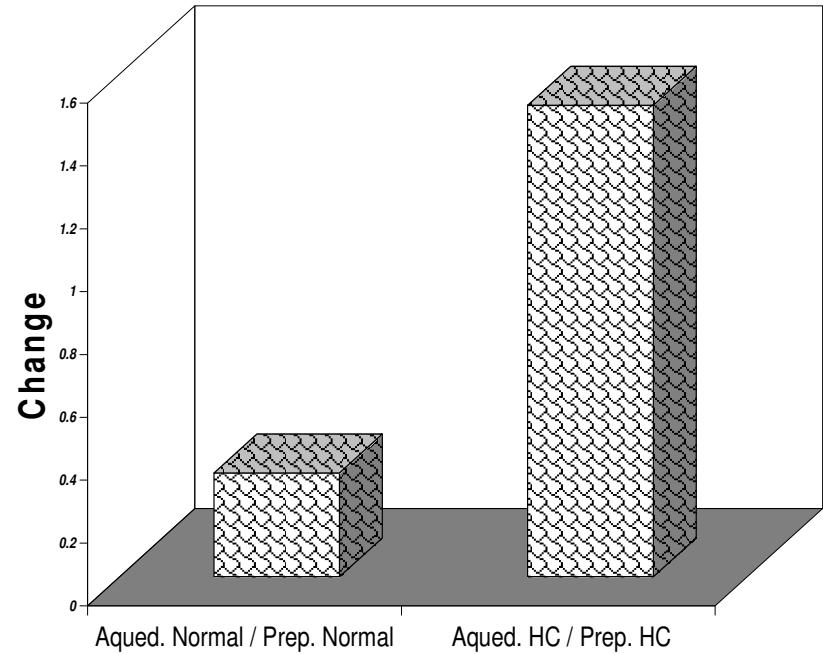
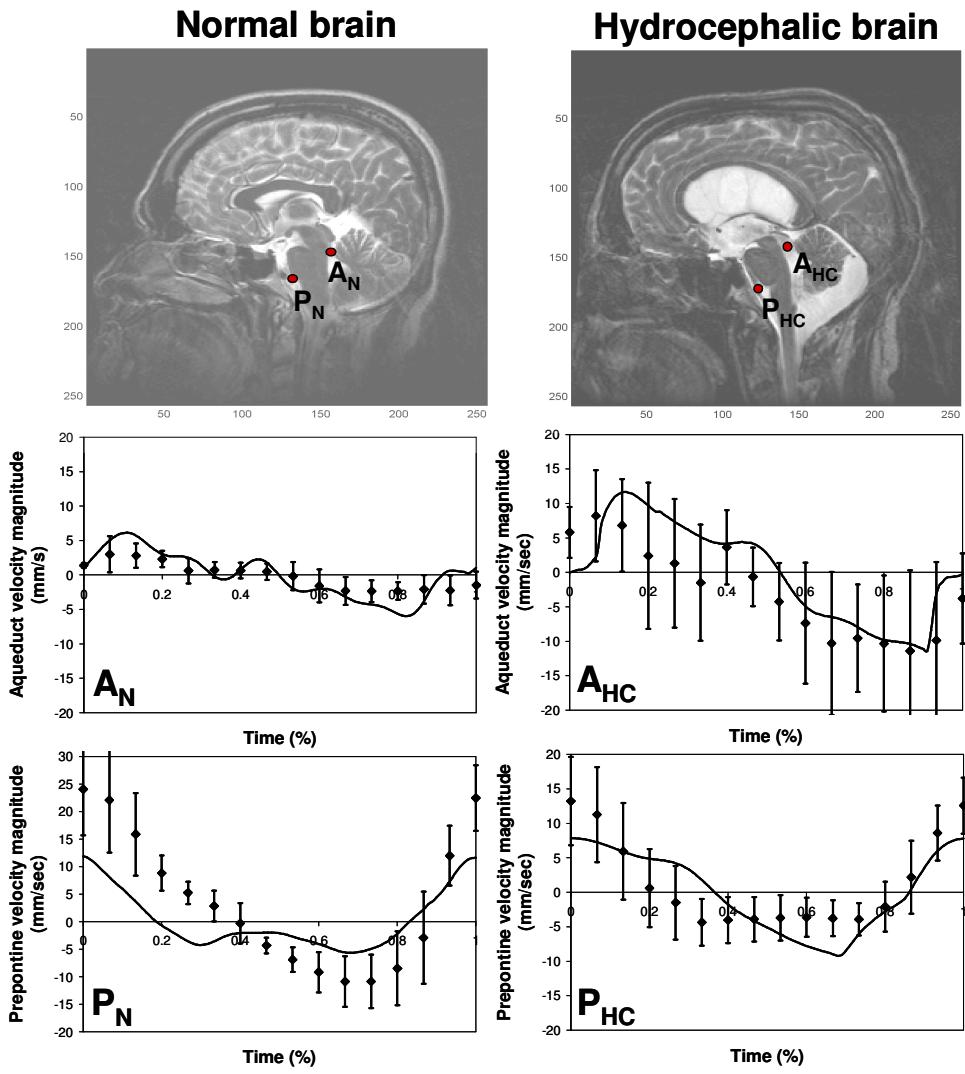
# Unilateral Hydrocephalus

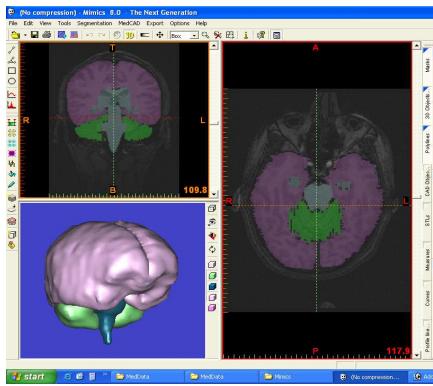


# Fluid Movement as Hydrocephalus Develops



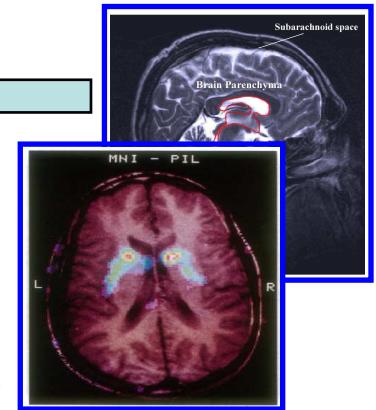
# RATIO OF A.S. FLOW TO PREPONTINE FLOW INCREASES IN HYDROCEPHALUS





## MR Imaging/Histological data Current state-of-the-art approach

Direct experimental measurements



## Reconstruction tools ImageJ, Insight SNAP, Mimics

Capturing the anatomic complexity of the brain

## Grid Generation

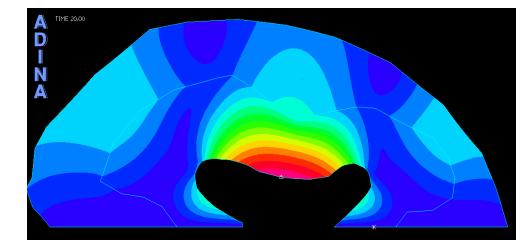


## Computational Fluid-Structure Dynamics and Deformations Commercial solvers (ADINA)

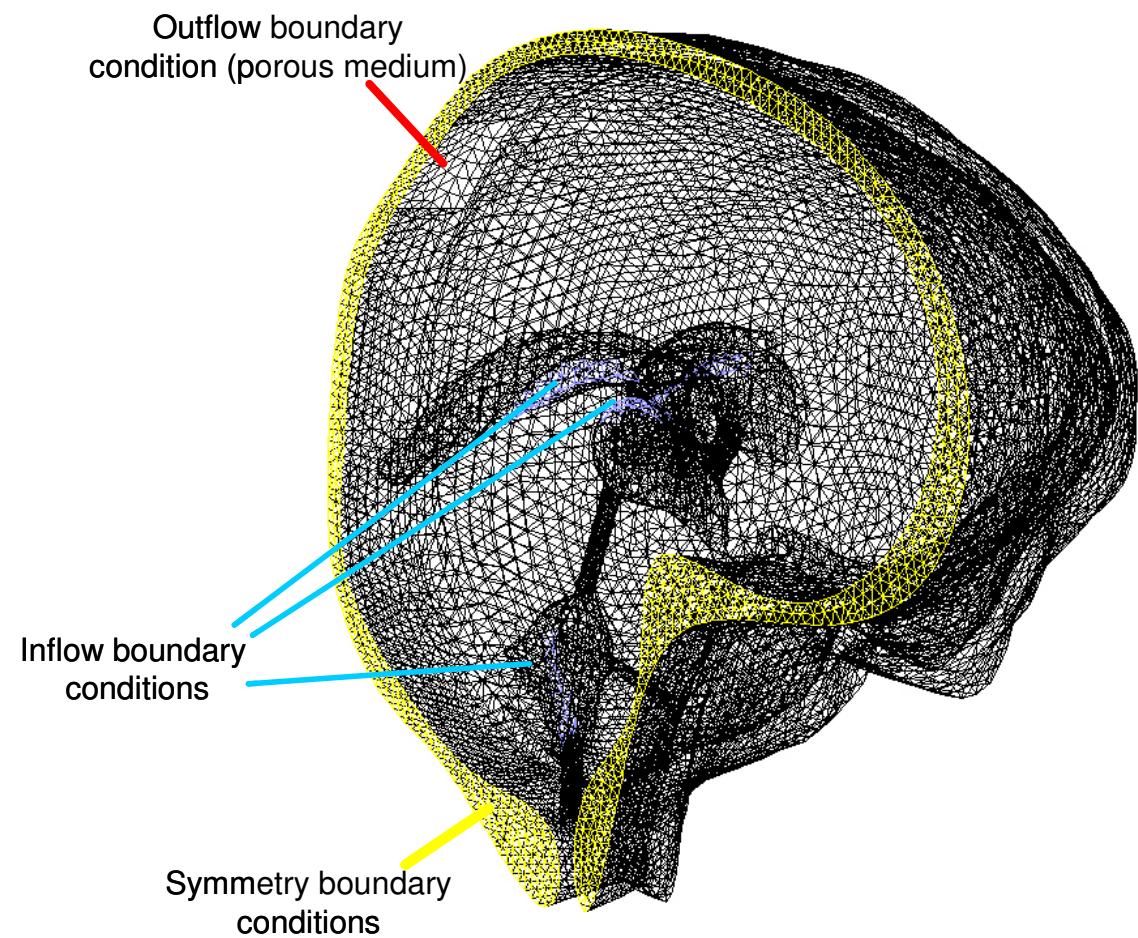
Mathematical modeling  
of normal and pathological  
intracranial conditions  
based on first principles

## Quantitative analysis of normal and pathological intracranial conditions

- Understanding of intracranial dynamics
- Predict causes of pathological conditions
- Design of therapeutic/preventative measures



# Mesh Reconstruction



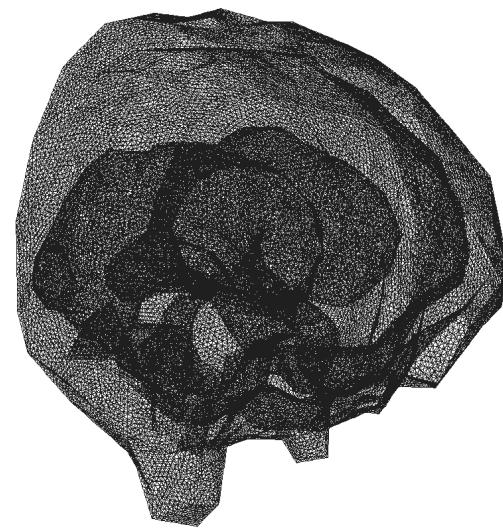
3D Normal Subject  
Computational Grid



y  
x—z

417,803 tetrahedral cells

3D Communicating HC  
Computational Grid



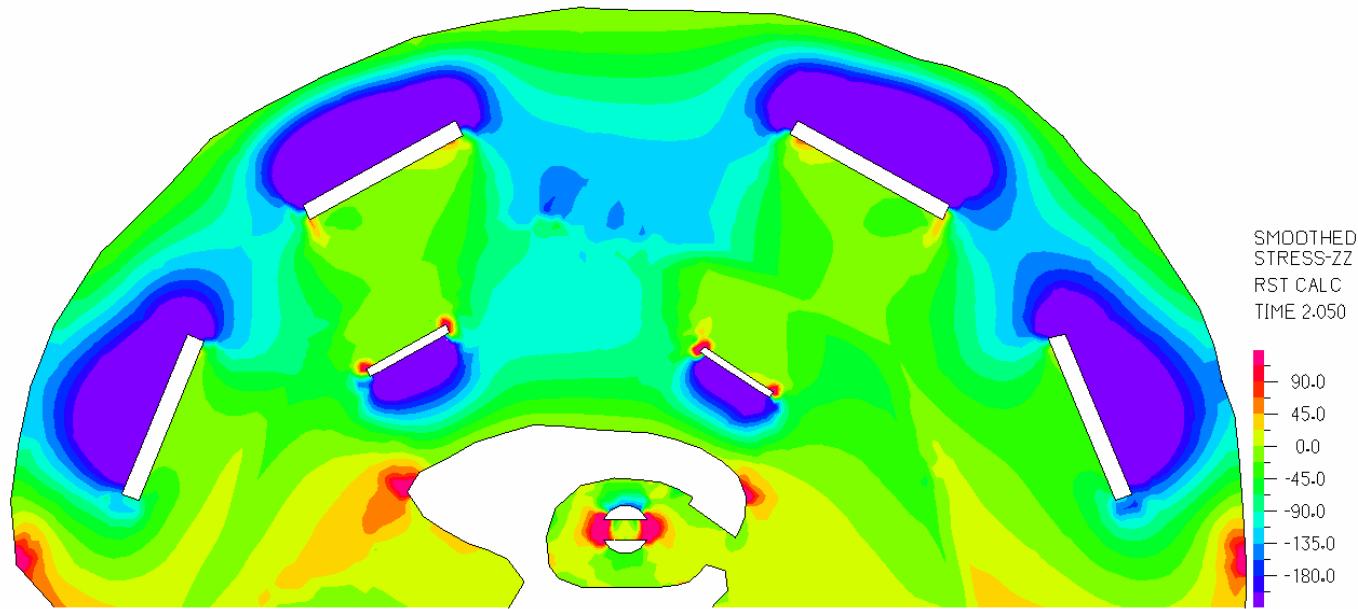
z  
y—x

748,571 tetrahedral cells

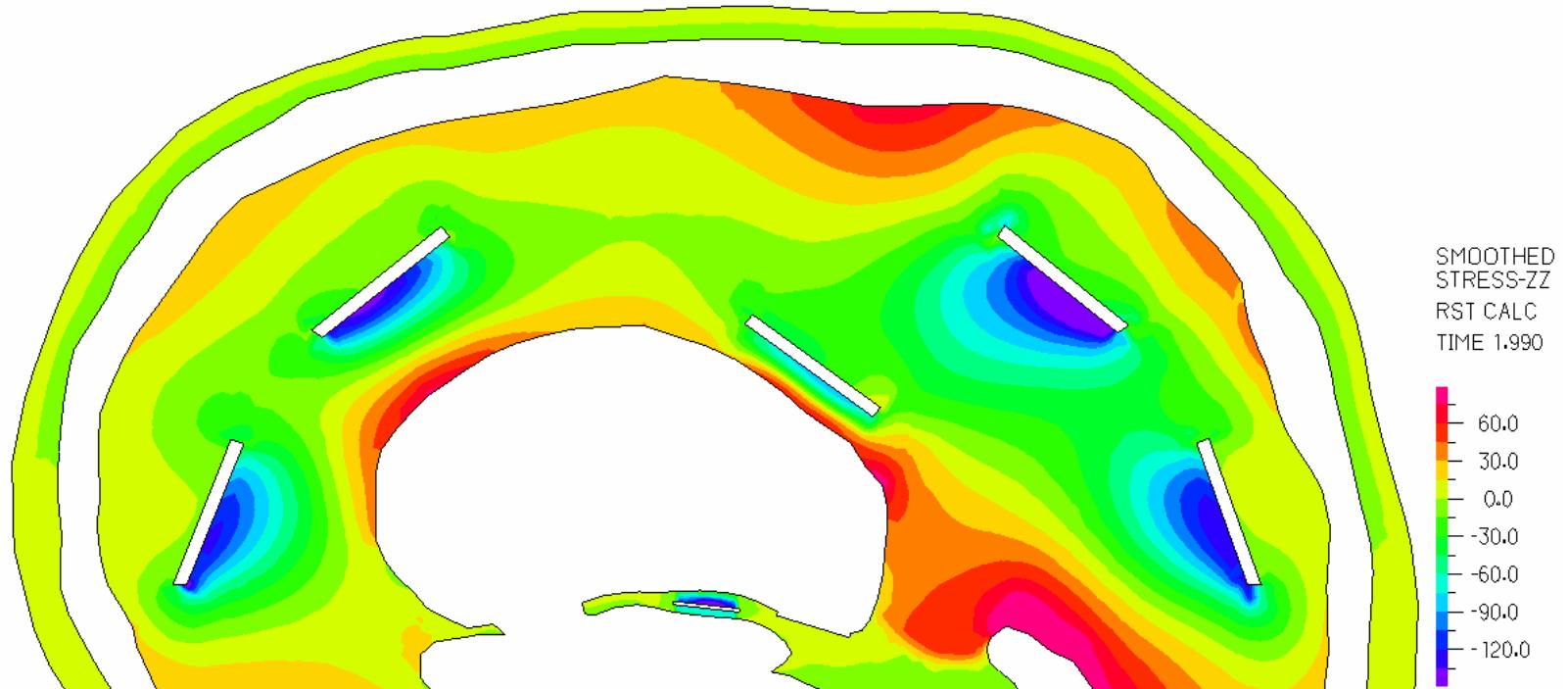
# Brain compression due to pulsating blood flow



view slide show to see animation



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).

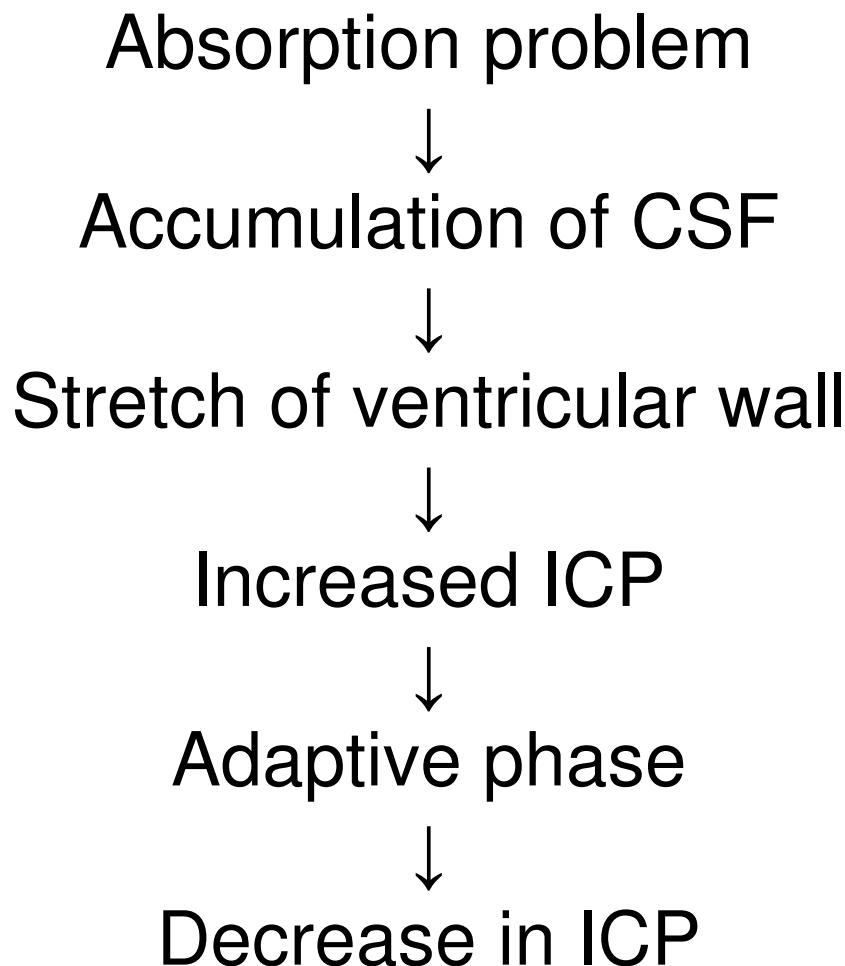


Band plot of normal stress during diastole. Red indicates tensile stresses; green to blue indicates compressive stress. Dark blue are areas of large compressive stress (where displacements were applied within the parenchyma).

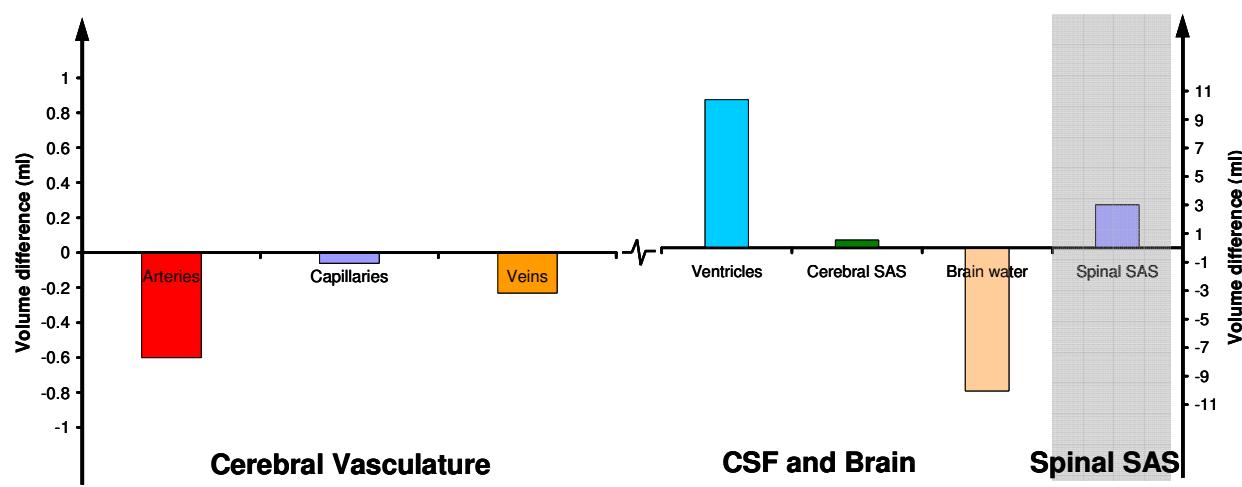
# Physical laws can explain

- CSF flow fields
- Lack of transmural pressure
- Development of hydrocephalus starting from the normal state
- Unilateral hydrocephalus
- Pressure / volume relationships

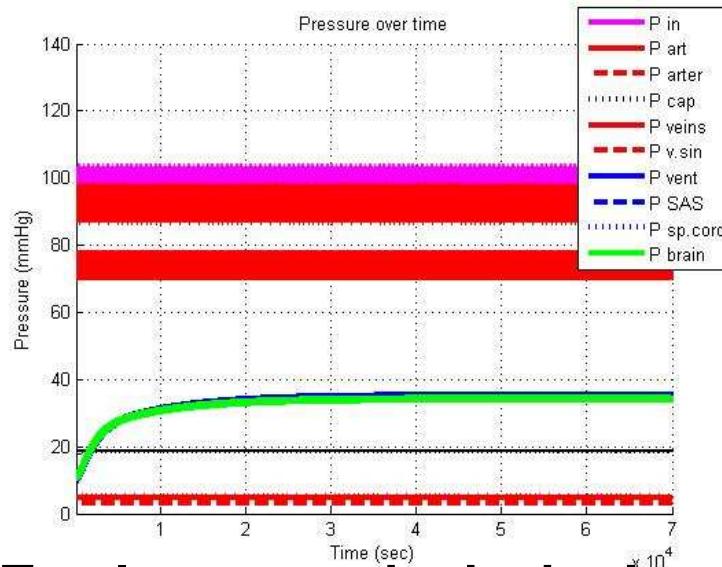
# Steps in Hydrocephalus



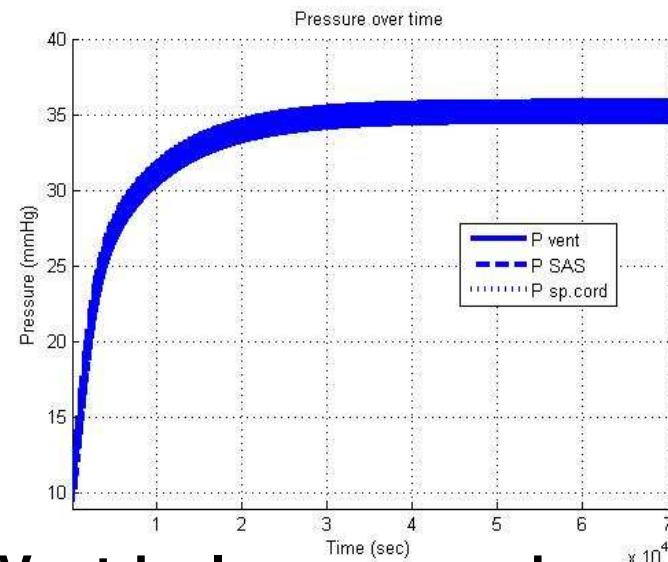
# Extra slides



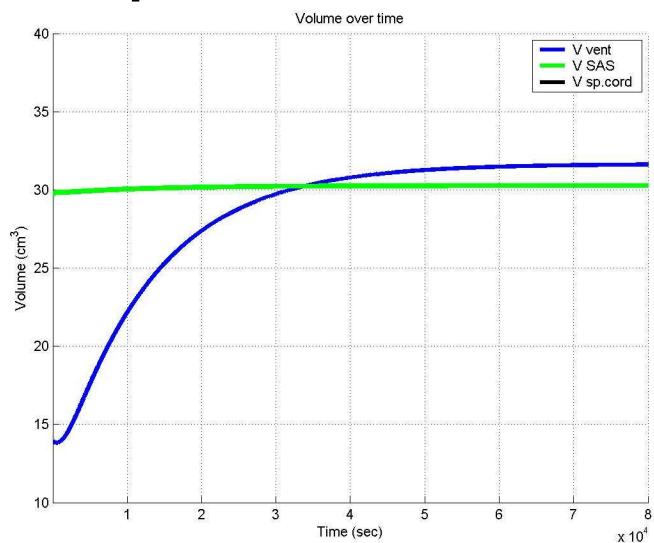
# Communicating hydrocephalus



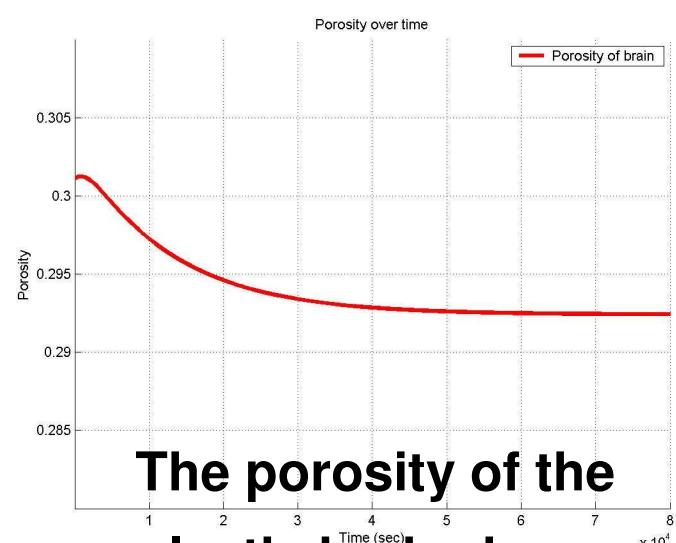
Total pressure in the brain



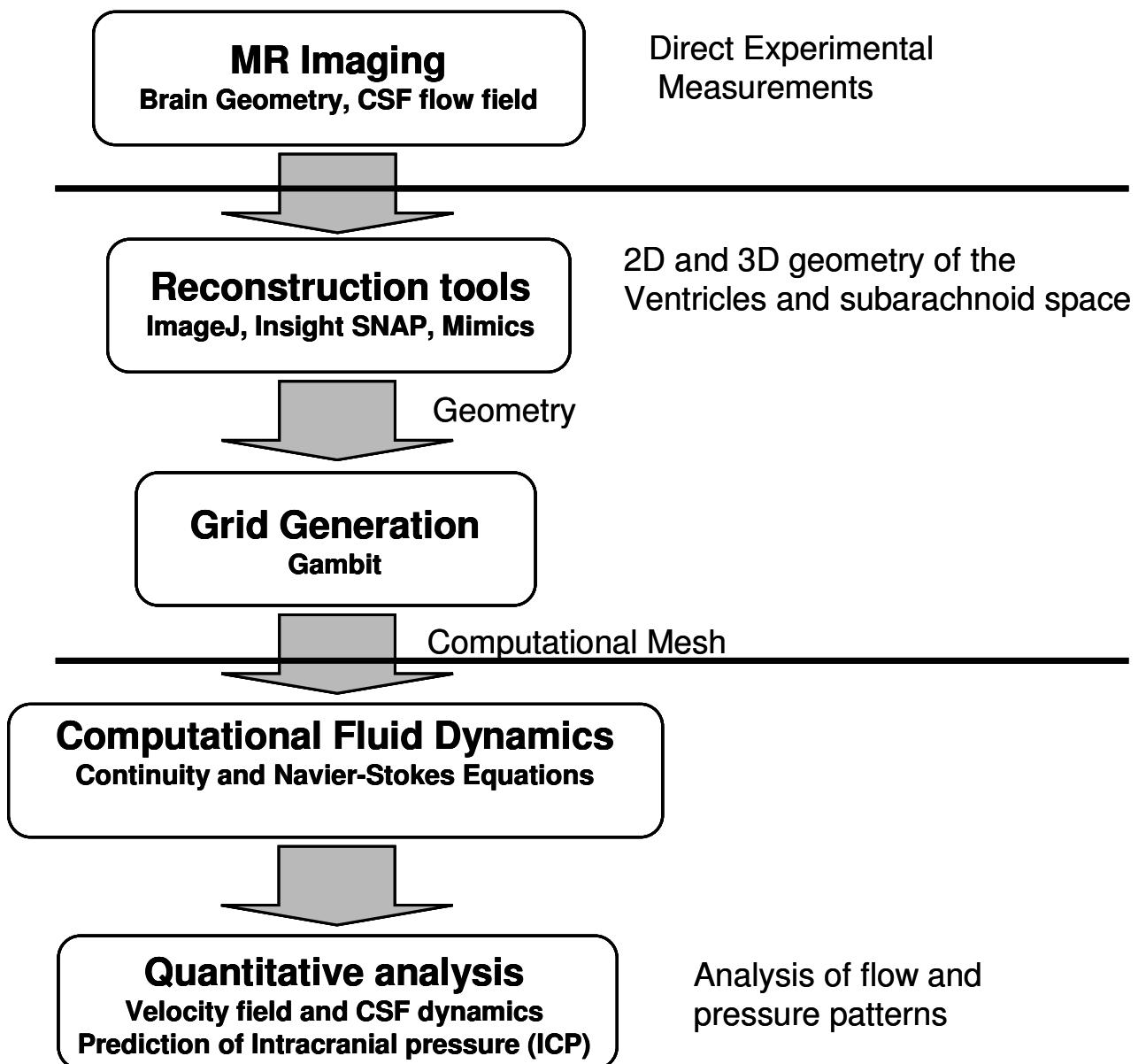
Ventricular pressure increase



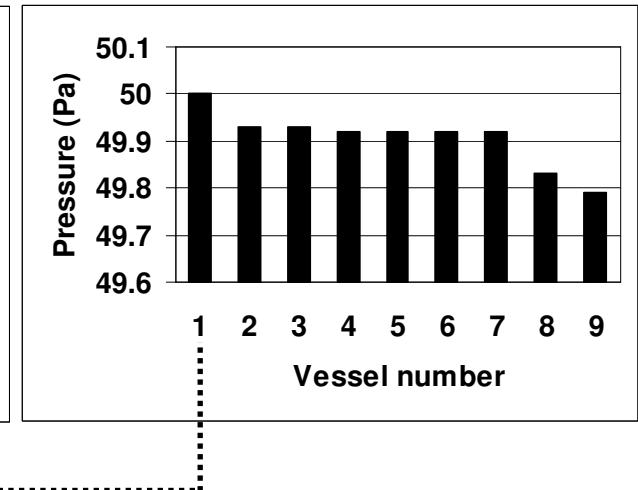
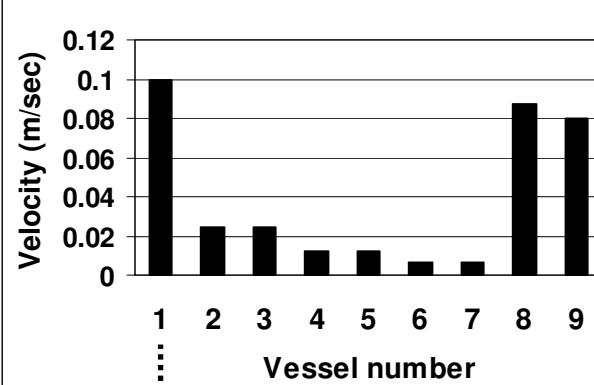
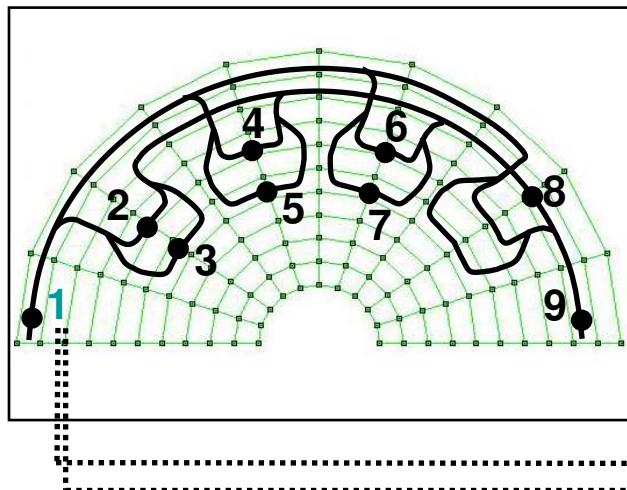
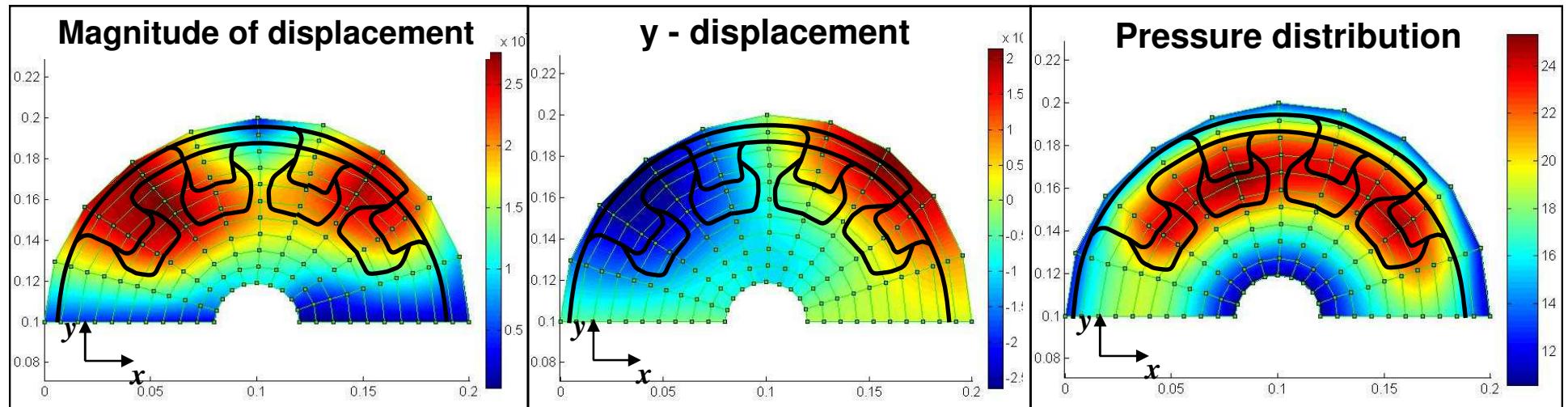
Ventricular volume increase



The porosity of the  
poroelastic brain decreases



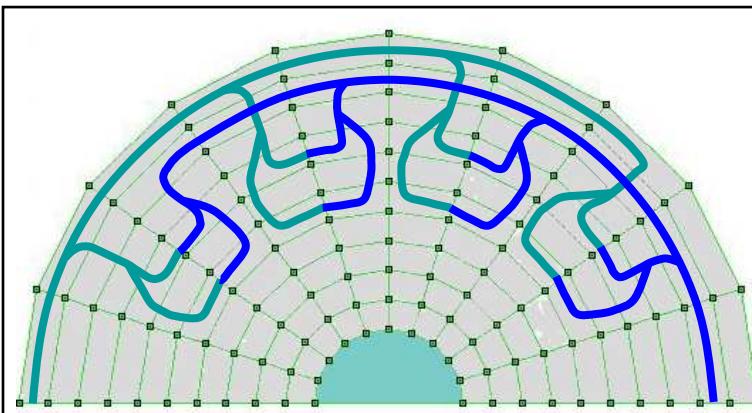
# Preliminary results for vasculature



# An FSI model with brain vasculature



**Brain vasculature**



**continuity**

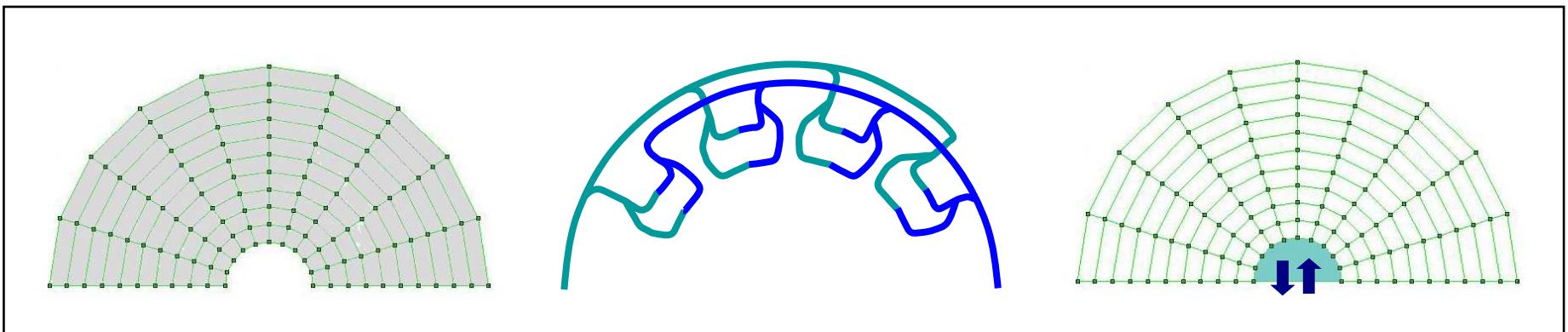
$$\frac{\partial A}{\partial t} + \frac{\partial(Au)}{\partial x} = 0$$

**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**

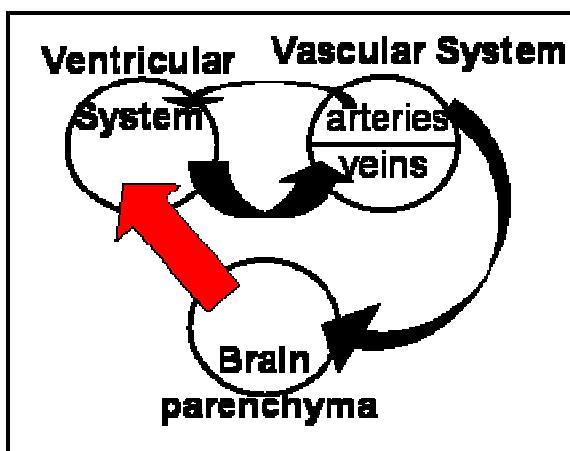
$$p - p_{out} = E_A \left( \frac{A}{A_0} - 1 \right)$$



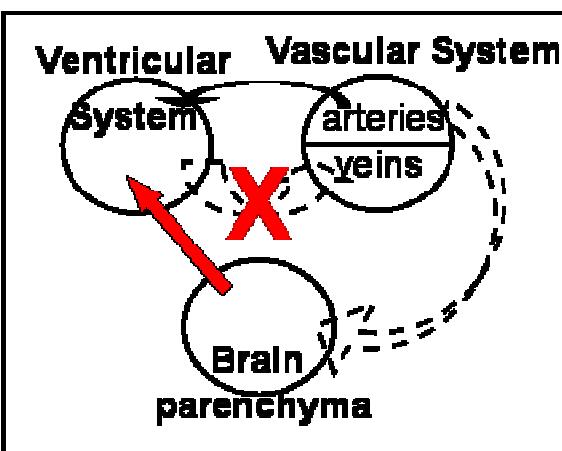
Brain modeled as a linear  
elastic body using Navier eq.

Brain vasculature composed of elastic tubes

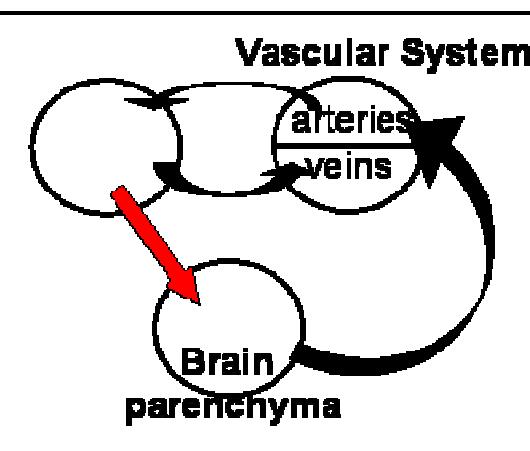
Pulsatile motion of CSF modeled  
using Navier-Stokes eq.



Normal Brain



Transient dynamics



Hydrocephalus