Understanding Brain Mechanics Through Computer Simulation

WIHIR Health Informatics Research Seminar

February 8, 2006

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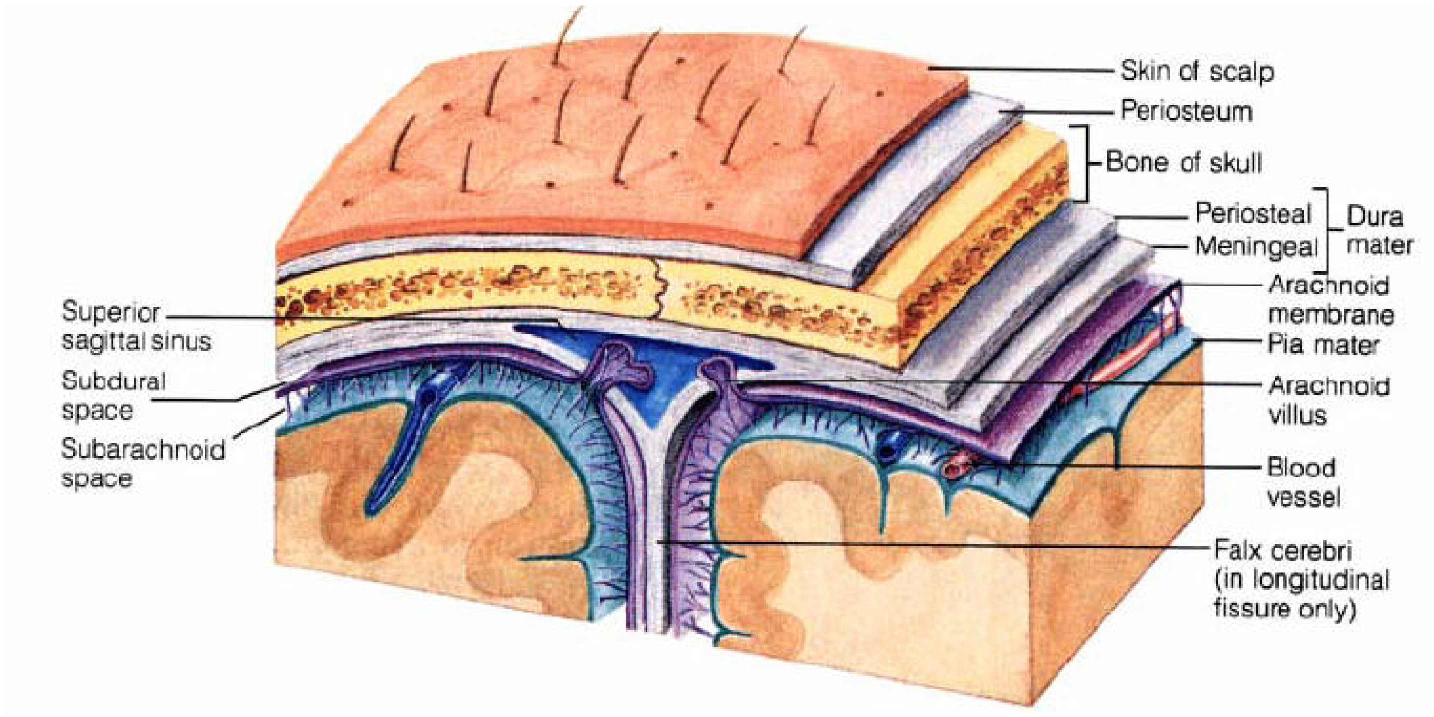
Outline

- Traumatic brain injury
- Closed head impact simulation (Halabieh)
- Hydrocephalus simulation (Lee)
- Modeling issues to be discussed:
  - Solid-fluid interface
  - Geometric modeling
  - Brain tissue modeling
  - Imaging vs biomechanical approaches

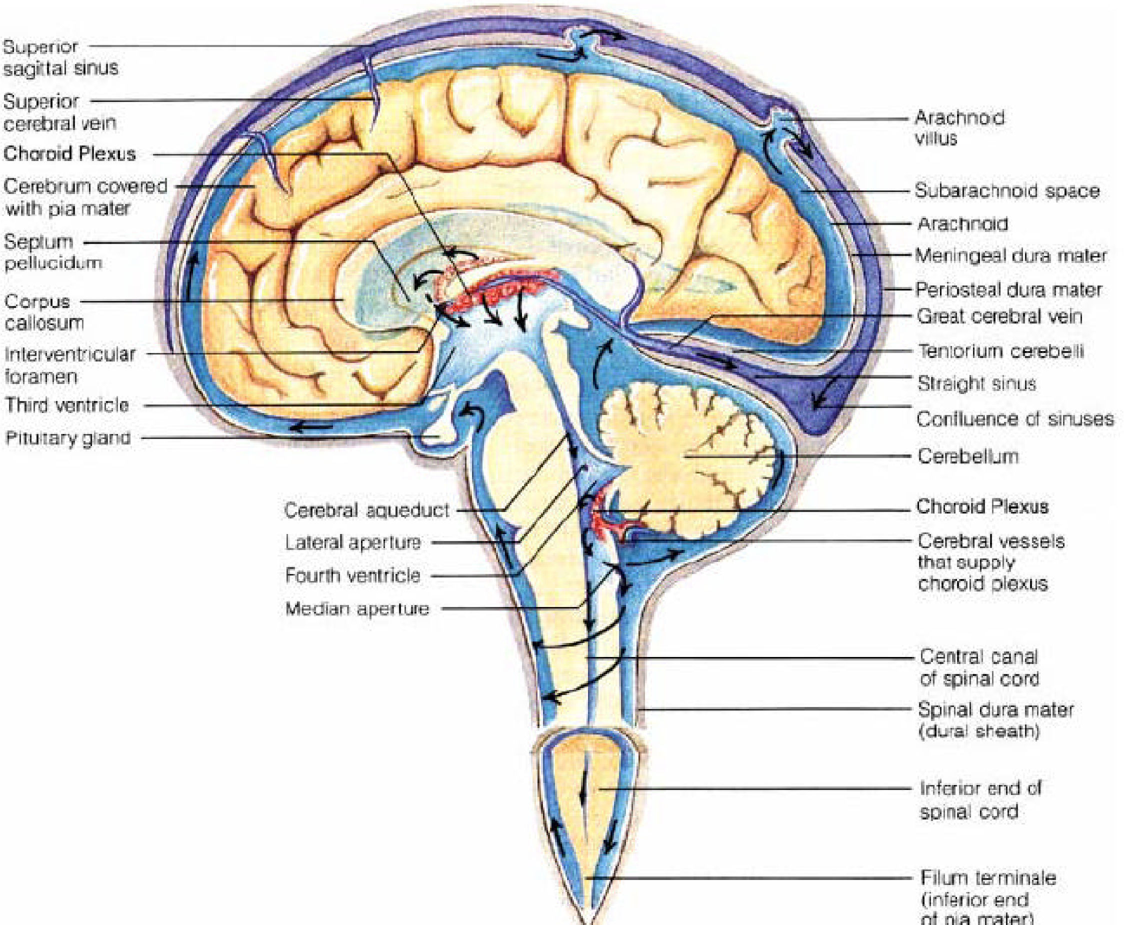
Anatomy of the Head

- Human brain is a soft structure, not as stiff as gel or as plastic as a paste.
- The soft brain tissue is covered by the dura, arachnoid, and pia membranes.

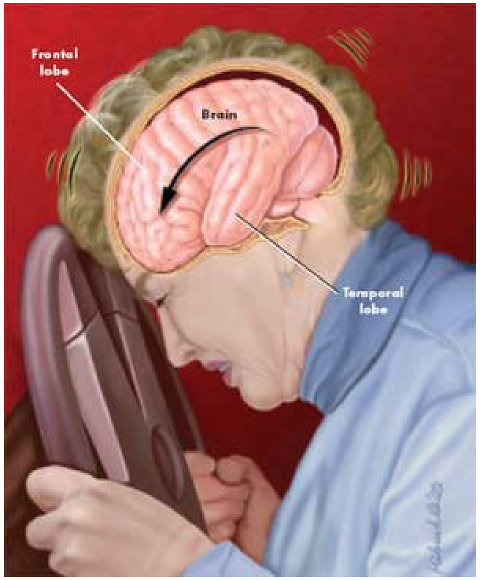


Anatomy of the Head (cont.)

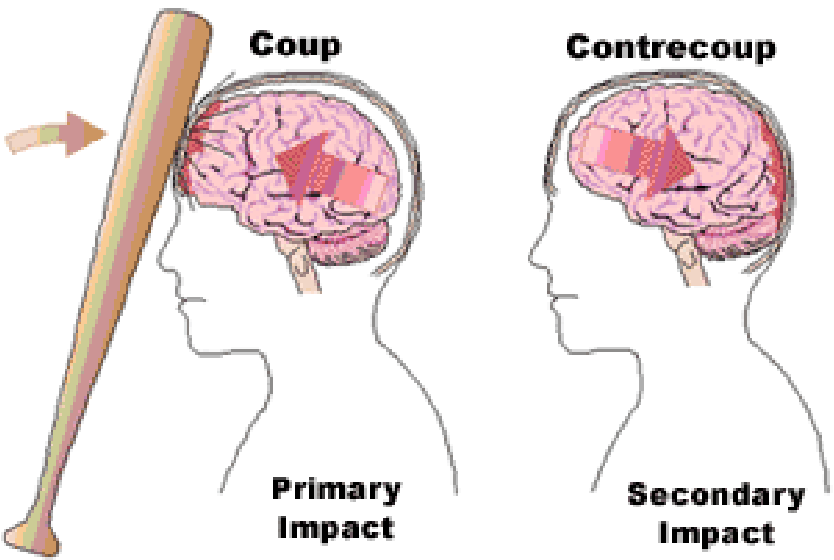
- The soft tissue consists of gray matter, containing neuronal cell bodies, and white matter, containing interconnecting fibres between areas of gray matter.
- The space between the arachnoid and pia is filled with the cerebrospinal fluid.
- The subarachnoid space communicates with the four ventricles which are cavities filled with CSF.



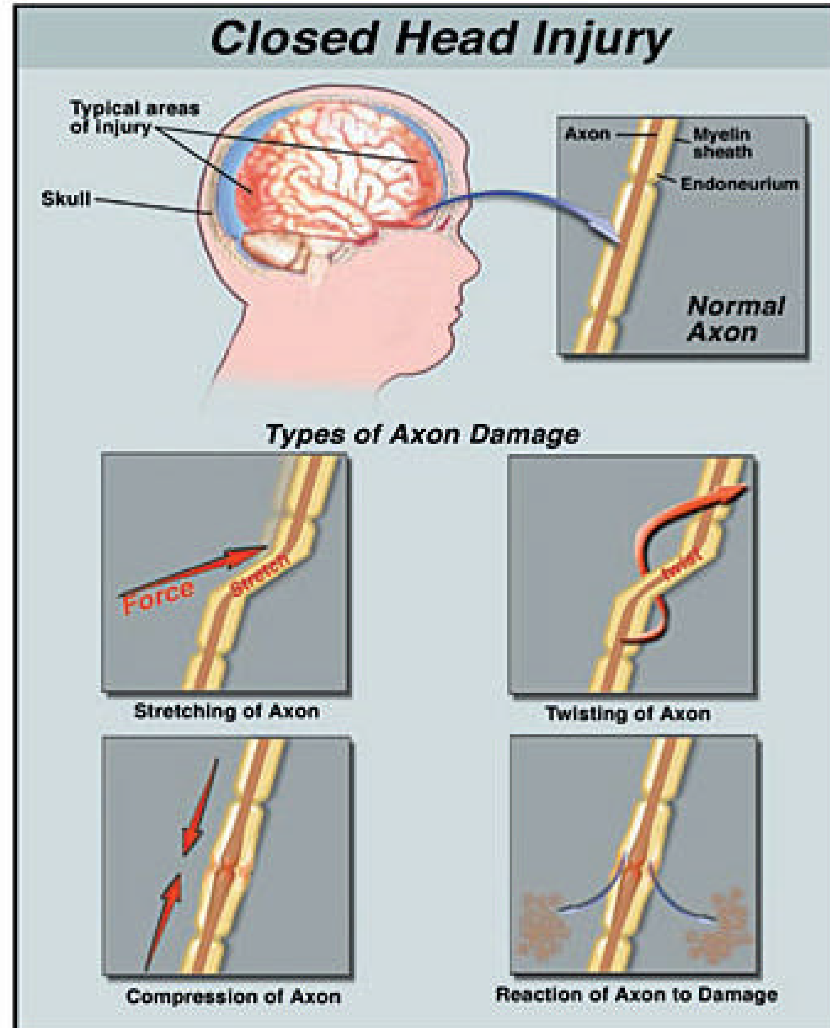
Closed Head Injury



Moving head



Stationary head

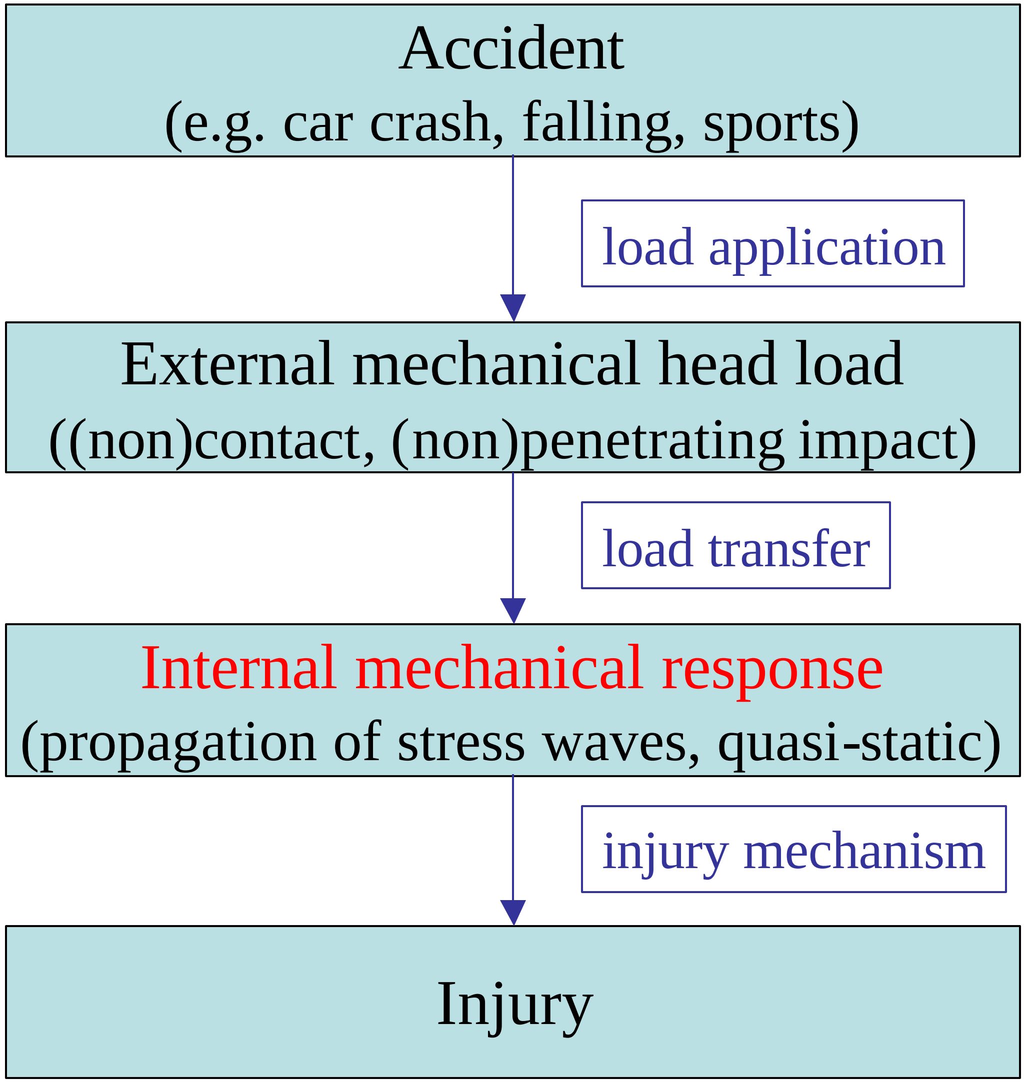


Traumatic Brain Injury (TBI)

According to The Ontario Brain Injury Association:

- TBI is the result of a blow to the head or spinning forces on the brain.
- Common causes include motor vehicle crashes, falls, assaults, and sports related injuries.
- Every year in Canada, over 11,000 people die as a result of a TBI. Over 4,000 will die in Ontario alone.
- TBI is the leading cause of death and disability among children.
- It is estimated that the direct and indirect costs associated with TBI are $3 billion annually in Canada ($1 billion in Ontario).
- Annually, over 6,000 Canadians become permanently disabled after a TBI.

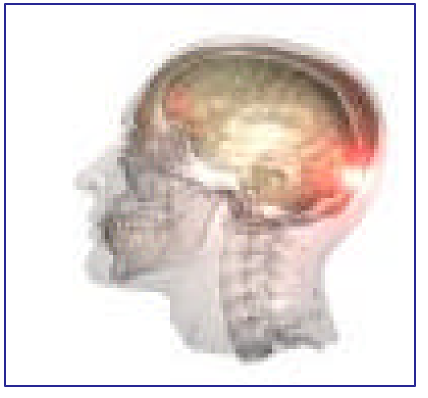
Load-Injury Scheme



Contrecoup-Coup Phenomenon

- When an individual suffers a closed head injury, forces on the brain result in injury to the brain parenchyma.
- The exact mechanisms by which these forces injure the brain are not certain.
- The coup injury: contusion to the brain that occurs at the area of brain adjacent to the location of impact.
- The contrecoup injury: contusion to the brain that occurs at the area of brain opposite the area of impact.

coup



contrecoup

Contrecoup-Coup (cont.)

- Competing theories for the mechanism of coup and contrecoup injuries.
- Until recently, it was believed that the coup injury (primary) occurs before the contrecoup injury (secondary).
- Observation: the injury to the brain opposite the location at which the skull strikes an external object is frequently more severe than the injury to the brain that occurs adjacent to the area of skull contact.
- Several theories have been developed for this counterintuitive observation: positive pressure, negative pressure, rotational shear stress and angular acceleration theories.

Positive Pressure Theory

- (e.g. Lindenberg and others)
- When the head accelerates forward prior to impact, the brain lags behind the brain.
- During impact, the brain is compressed against the lagging surface of the skull, thus leading to coutrecoup injury.
- As the brain lags behind, the CSF is displaced forward which acts a protective layer during impact.
- Cons: since the brain is attached to the dura within the skull, the lagging of the brain must be a result of a large acceleration.
- However, there is a belief that CSF is denser than the brain. Thus, CSF has a bigger inertia than the brain.
- In a sudden acceleration, the CSF, rather than the brain should be at the lagging position.

Negative Pressure Theory

- Also known as cavitation theory (Russel)
- When the head is suddenly stopped during an impact, the brain continues to move forward and produces a tensile stress at the coutrecoup position.
- This negative pressure (tension) pulls the contrecoup area of the brain apart which causes injury.
- Cons: if CSF is denser than the brain, then it should be the CSF, not the brain, to move forward due to larger inertia.

CSF Theory

- It assumes CSF is denser than the brain (by about 4%).
- When the head starts to move forward, the CSF and the brain will move in the same direction as well.
- When the head is suddenly stopped during an impact, which will continue to move forward and which will be displaced?
- Due to conservation of momentum, the denser material (CSF) will tend to continue its previous motion while the less dense material (the brain) will be displaced.

An Experiment

- Drew-Drew 2004
- Head: modelled by a plastic jar
- Brain: modelled by a balloon filled with water (density = 1.0)
- CSF: modelled by salt water with density 1.04
- The Head-CSF-Brain model was moved horizontally with a speed of 1m/s.
- The resulting motion of the “brain” was recorded by a camera.
- Other density combinations have also been tested.

Experimental Result

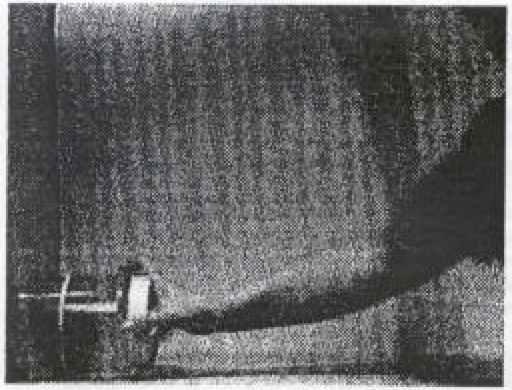


Fig. 1. Instant of impact.

(Drew-Drew 2004)

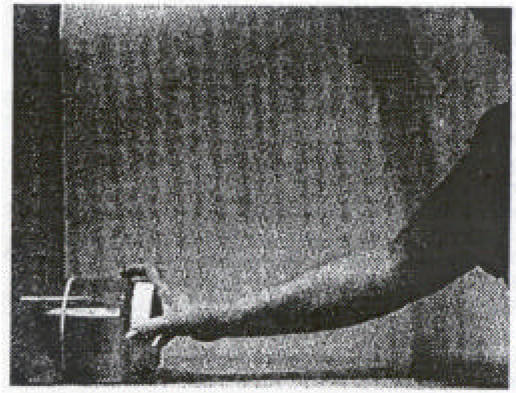


Fig. 2. Half second after impact.

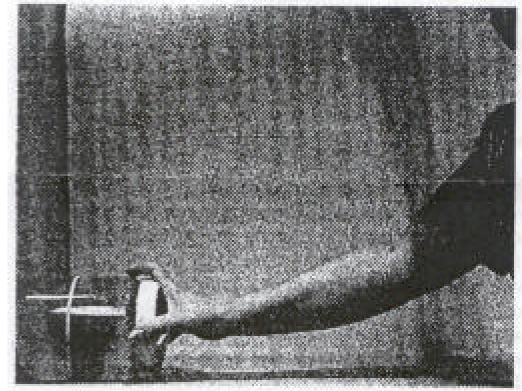
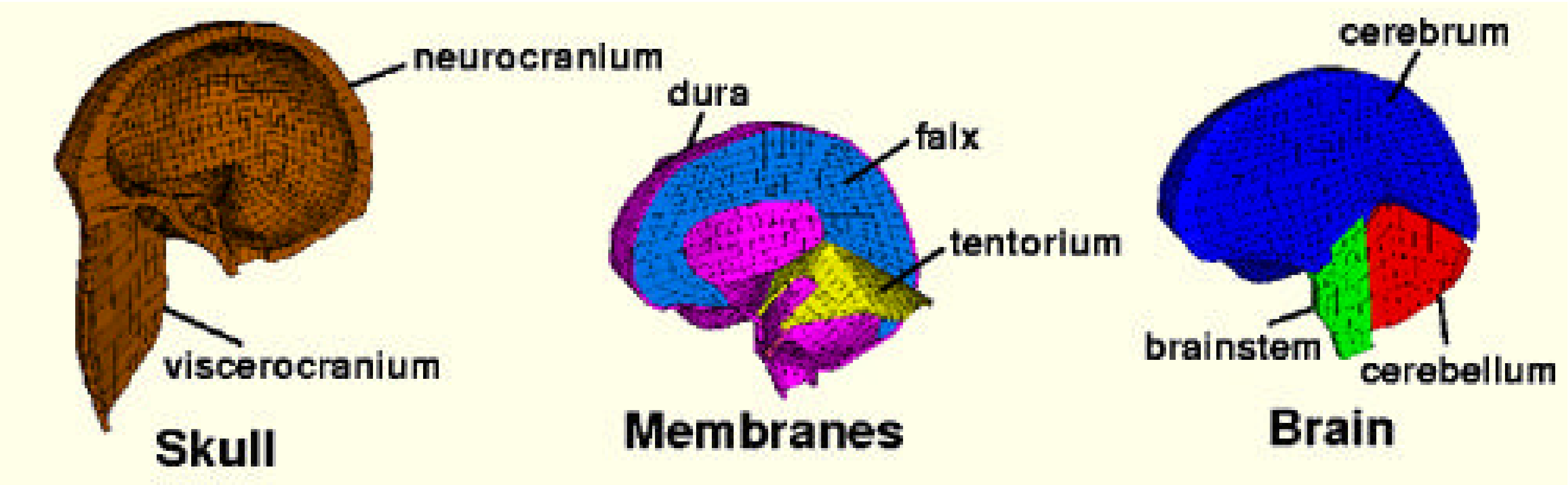


Fig. 3. One second after impact.

- 0.5 sec after impact: slight movement of the balloon away from the location of impact.
- 1 sec after impact: the balloon is displaced farther from the site of impact in the coutrecoup direction.
- 2 sec after impact: some secondary movement back toward the site of impact in the coup direction.

Finite Element Modeling of Head Impact

- Modeling of brain tissue
  - Stress-strain relation
  - Constitutive equations: set of partial differential equations
- Geometric modeling of the head
  - Grouped in 3 components: cranium, meningeal layers, and the brain
  - All substructures are assumed to be connected to each other



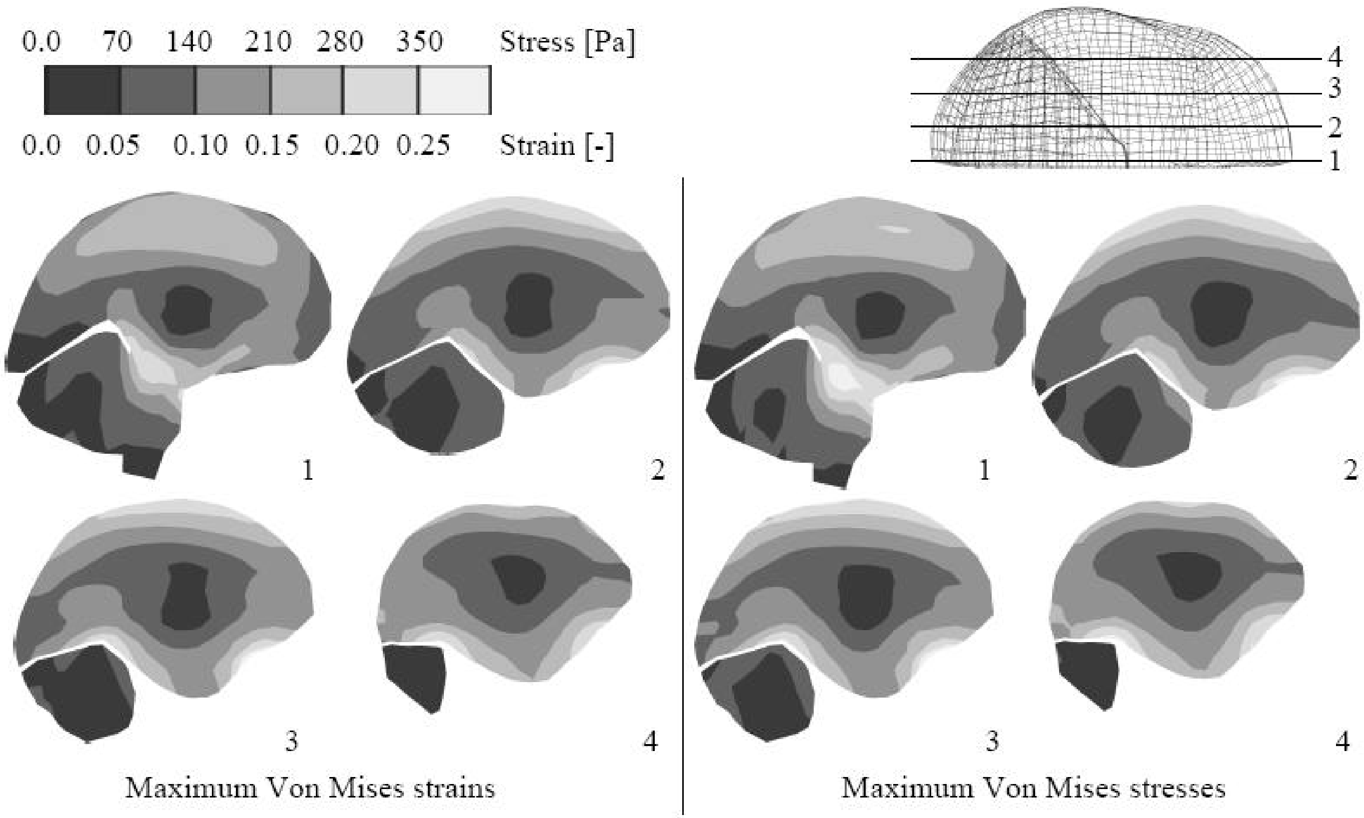
FE Modeling (cont.)

- Different layers with different physical parameters (PhD thesis, Brands, 2004).

Anatomical structure	No. of elements	Constitutive model
Cranium (skull)	3212	Rigid
viscerocranium (facial bones)	188	
neurocranium	3024	
Meningeal layers & CSF	3188	Linear elastic
Dura mater	2536	
- falx cerebri	448	
- falx cerebelli	18	
- tentorium cerebelli	186	
Brain tissue	7692	Viscoelastic*
cerebrum/corpus callosum	6758	
cerebellum	732	
brainstem	202	

- Usually solved by (commercial) FE software.

Strain Stress Distribution



Cons:

- CSF is not present as it is not solid.
- The brain is “attached” to the membranes.

Our Simulation Study: Preliminary Results

- Modeling of CSF: incompressible Navier-Stokes equations

$$u_t + (u \cdot \nabla)u = -\frac{1}{r}\nabla p + \frac{1}{r}\nabla \cdot (2mD) + F$$

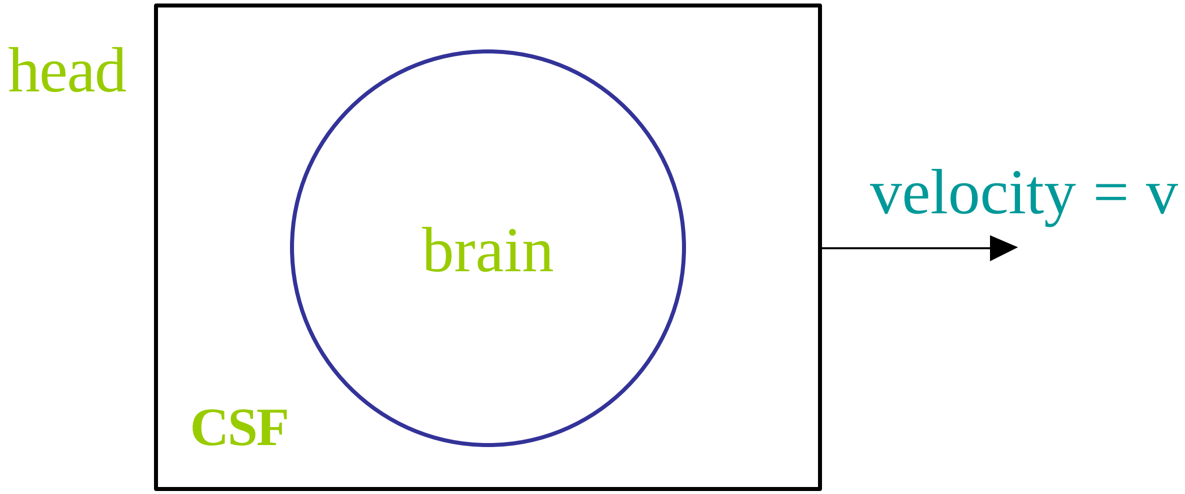
$$\nabla \cdot u = 0$$

  - u = fluid velocity, r = density, p = pressure
  - m = viscosity, D = viscous stress

- Modeling of the brain
  - Viscoelastic solid (currently, it is treated as a rigid body)

- Geometric modeling
  - Head: square box
  - Brain: spherical shape

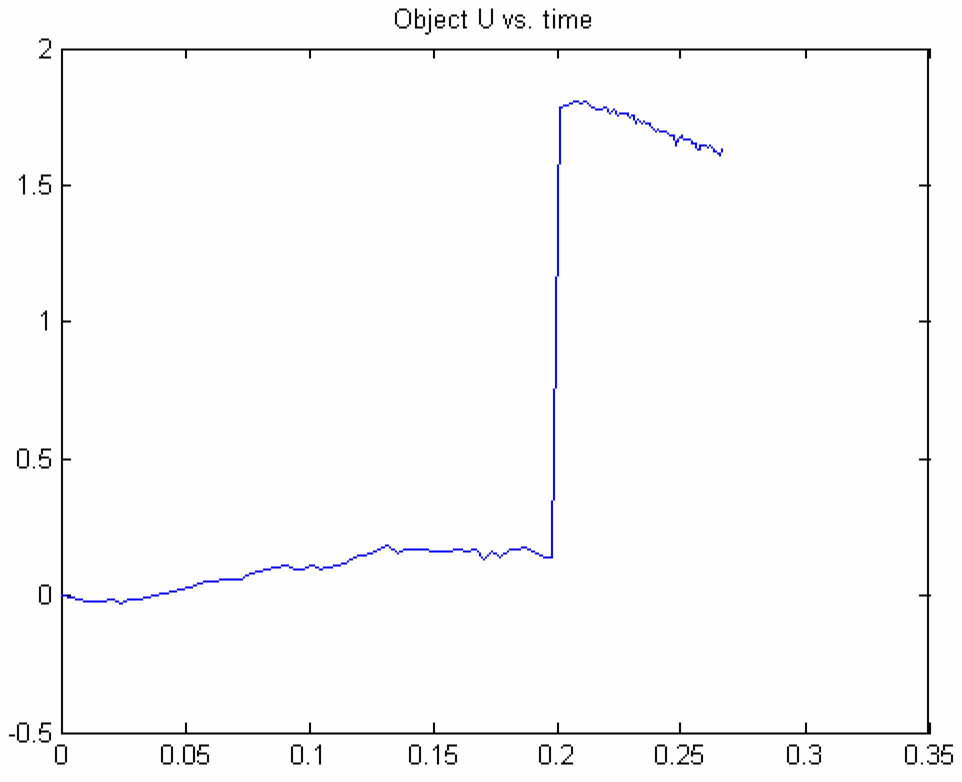
Simulation Conditions

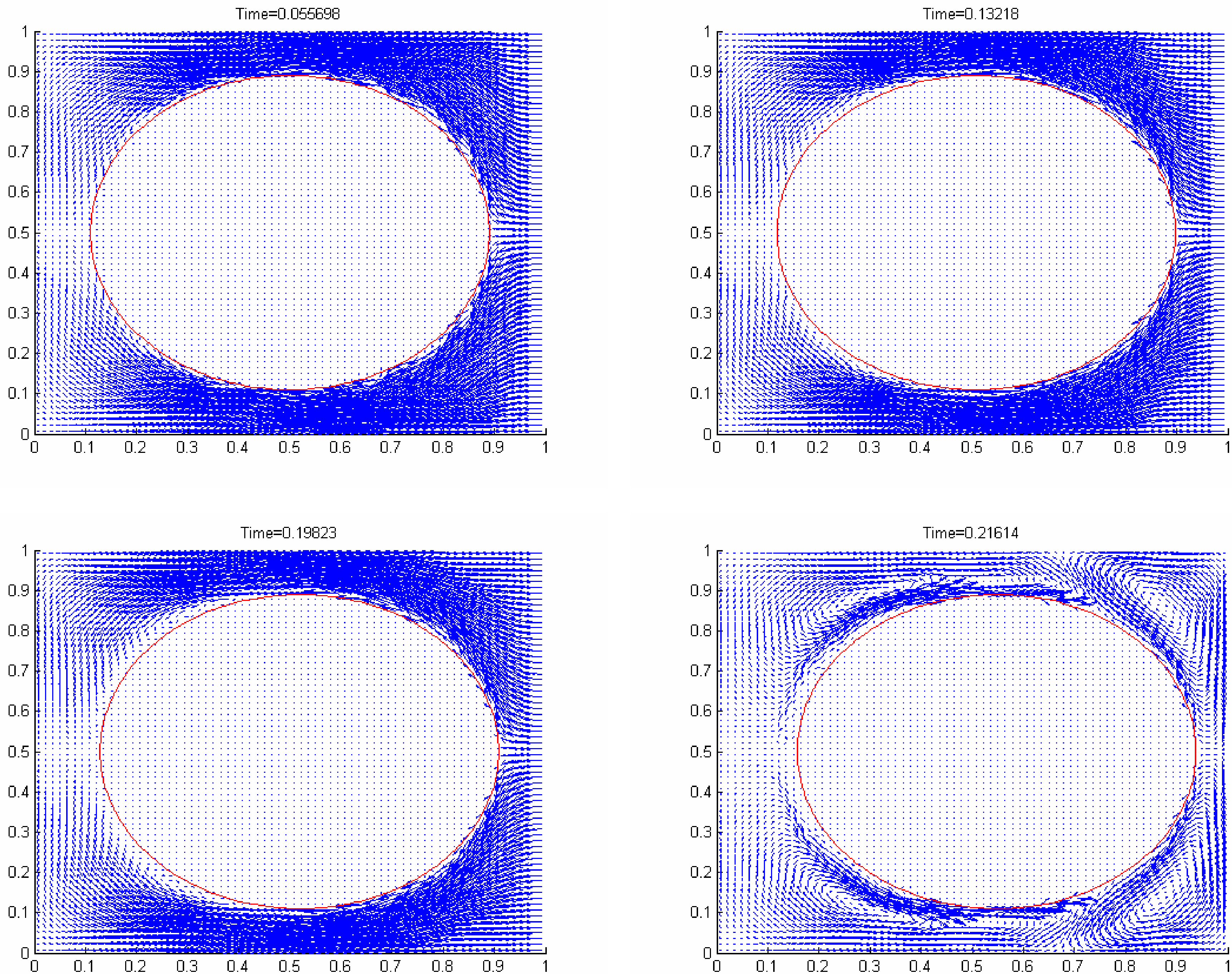


- Appropriate boundary conditions to simulate the impact situation.
- Calculation is relative to the boundary
  - Thus zero boundary conditions
  - Initial velocity of CSF = -v
  - Initial velocity of brain = 0

Numerical Result I

- Object (brain) density: 1000kg/m^3
- Fluid (CSF) density: 994 kg/m^3
- The box (head) is moved for 0.2 sec with a speed of 1m/s.

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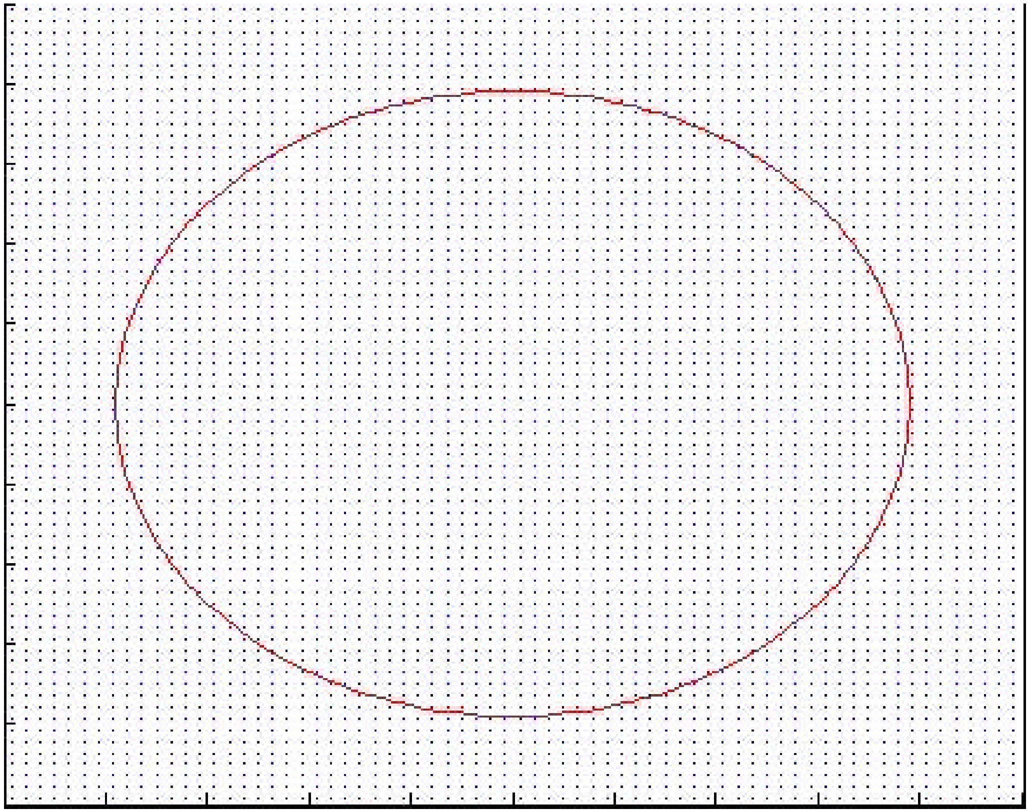
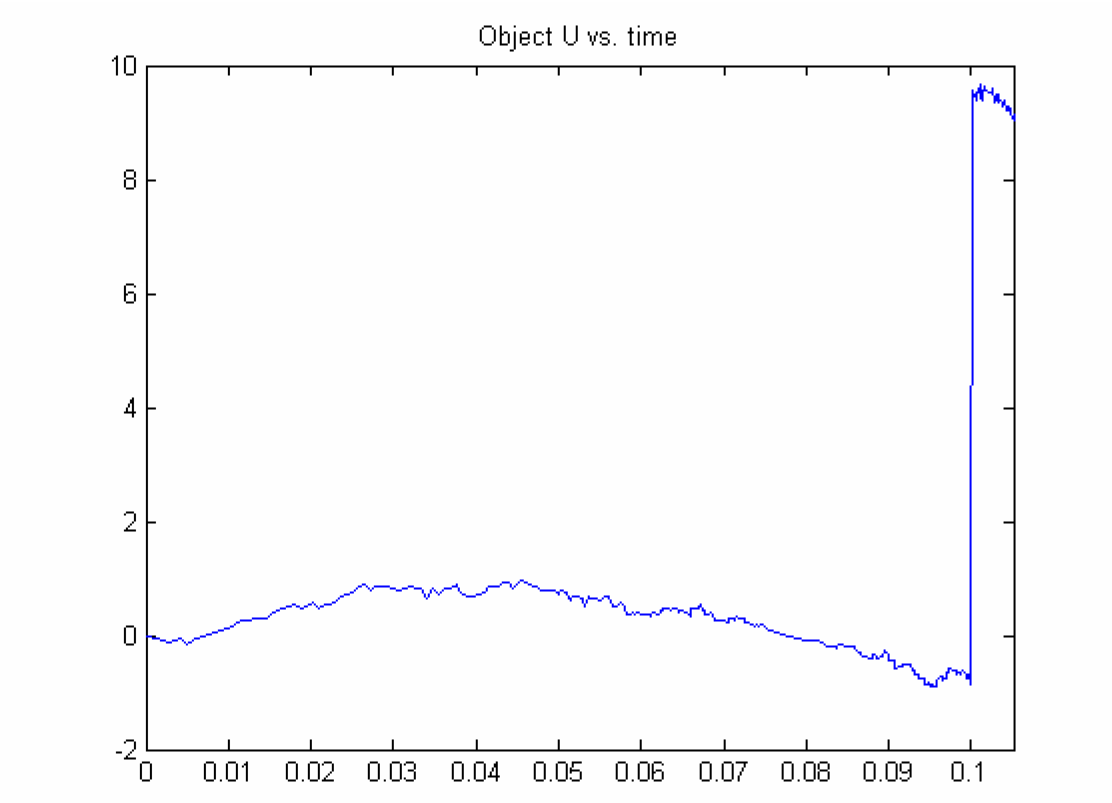
1

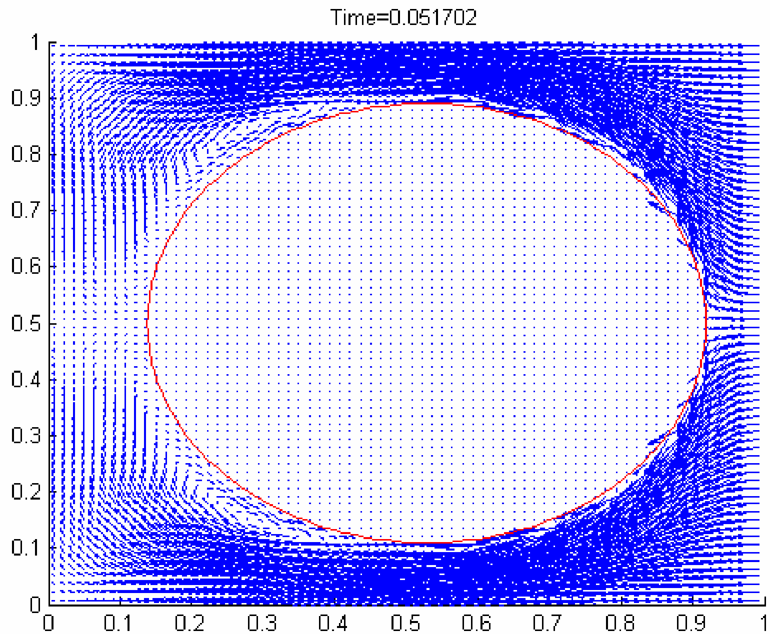
Simulation Result I



Numerical Result II

- Object (brain) density: 1000kg/m^3
- Fluid (CSF) density: 994 kg/m^3
- The box (head) is moved for 0.1 sec with a speed of 5m/s.

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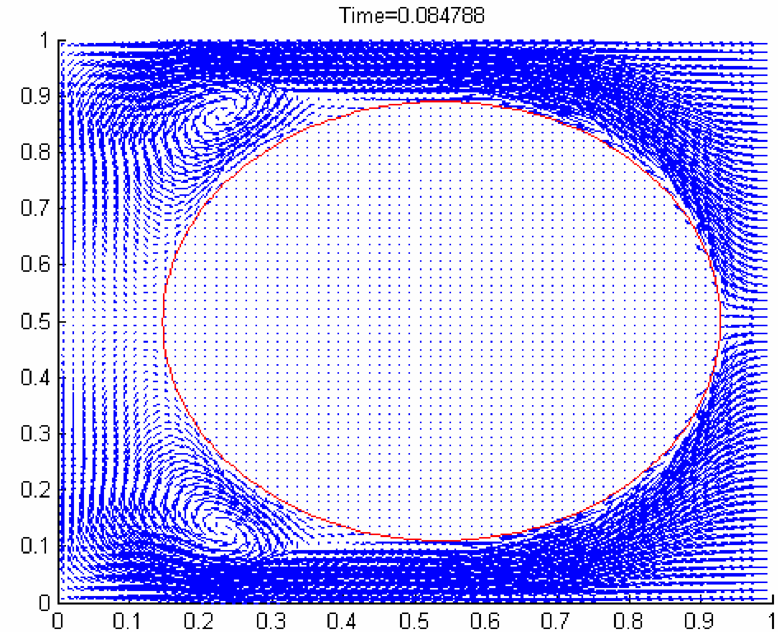
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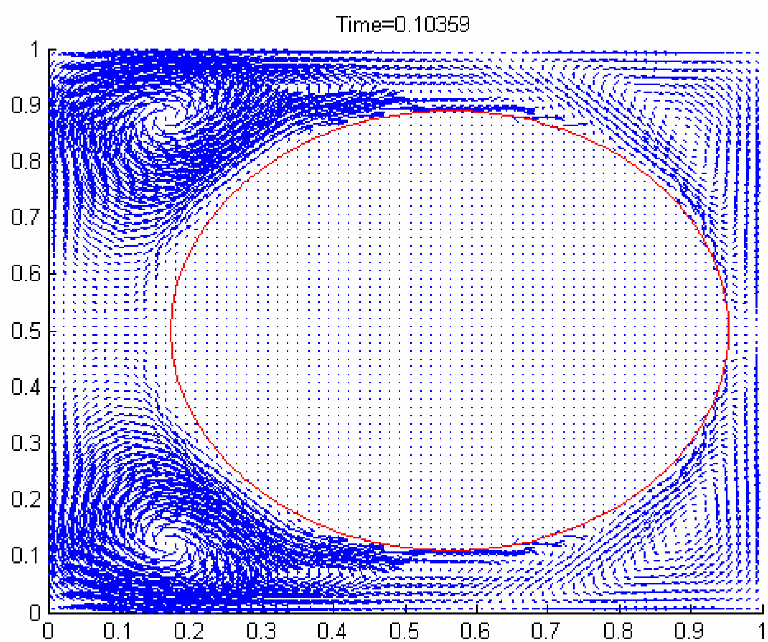
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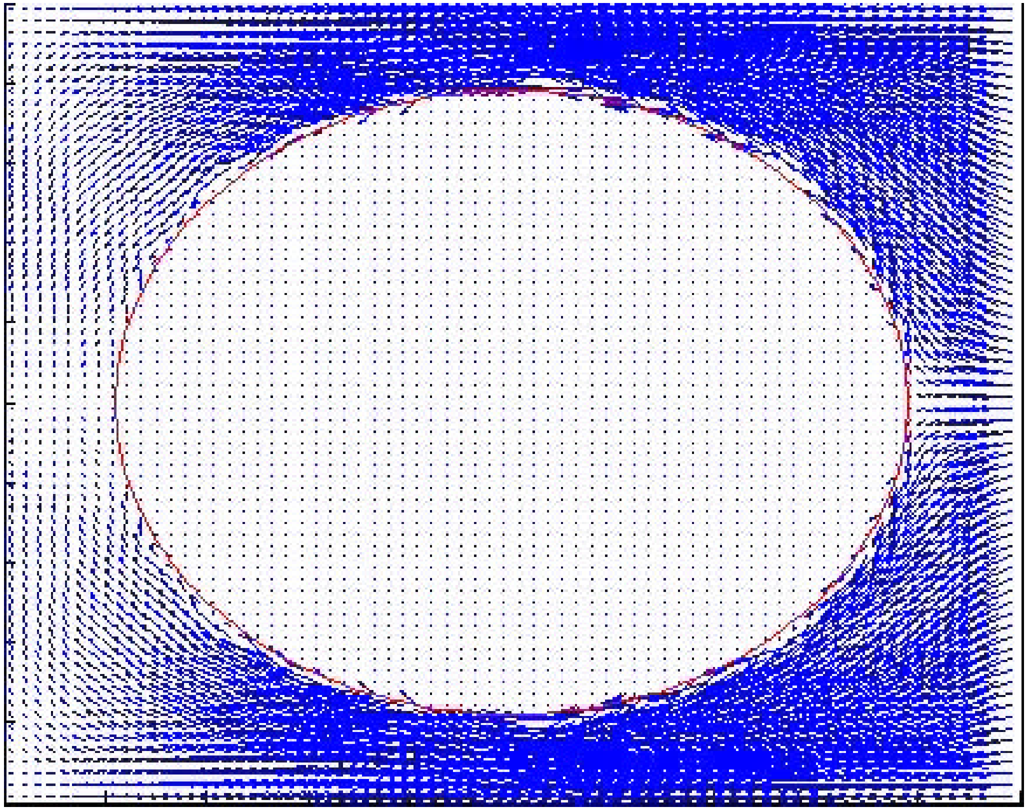
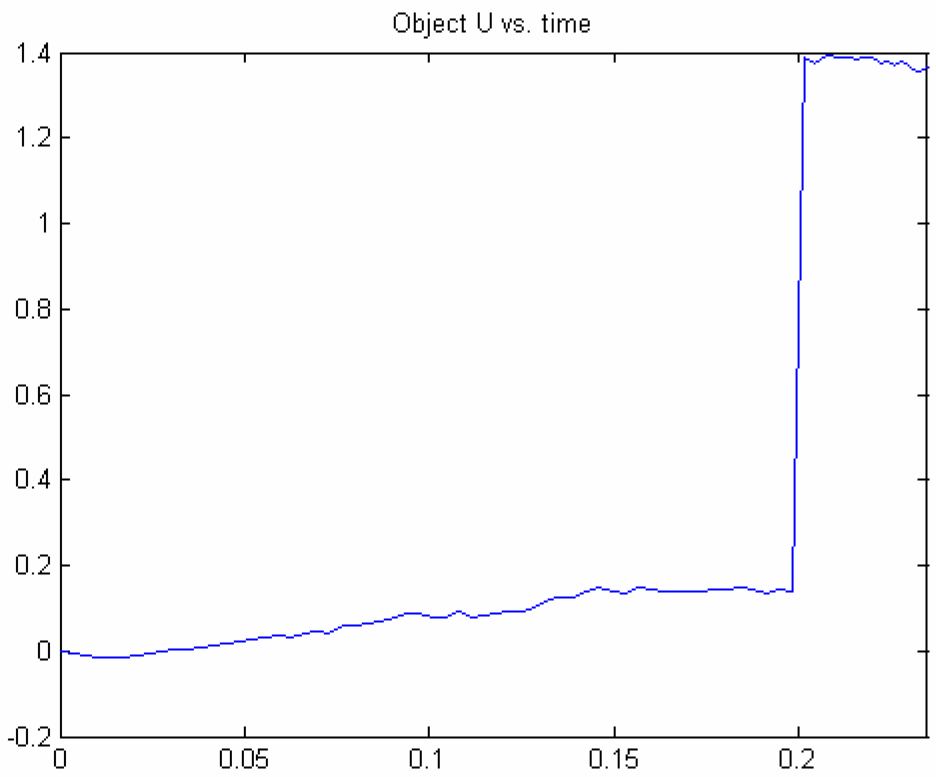
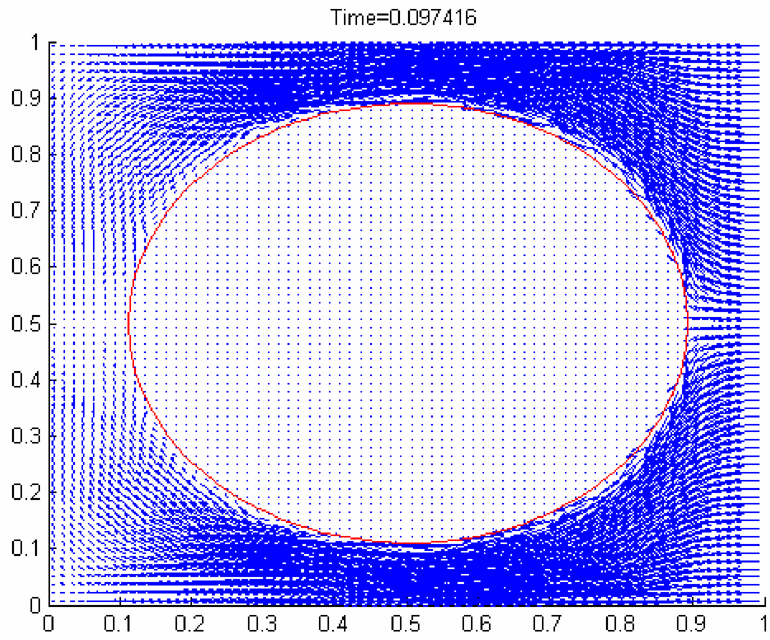
Simulation Result II



Numerical Result III

- Object (brain) density: 1400kg/m^3
- Fluid (CSF) density: 994 kg/m^3
- The box (head) is moved for 0.2 sec with a speed of 1m/s.

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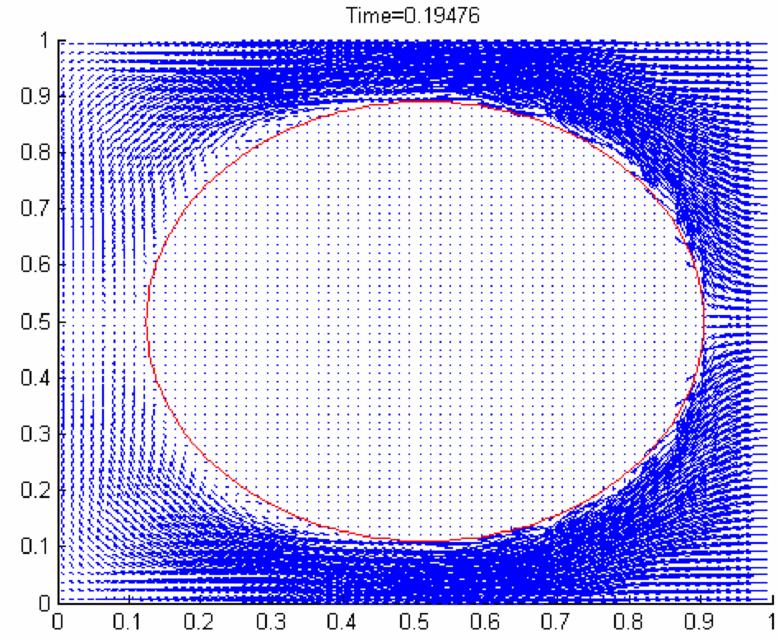
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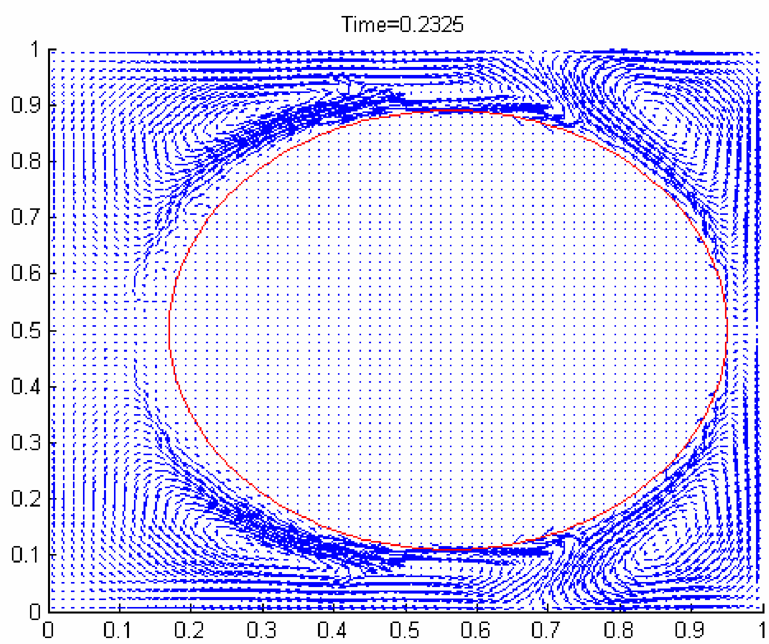
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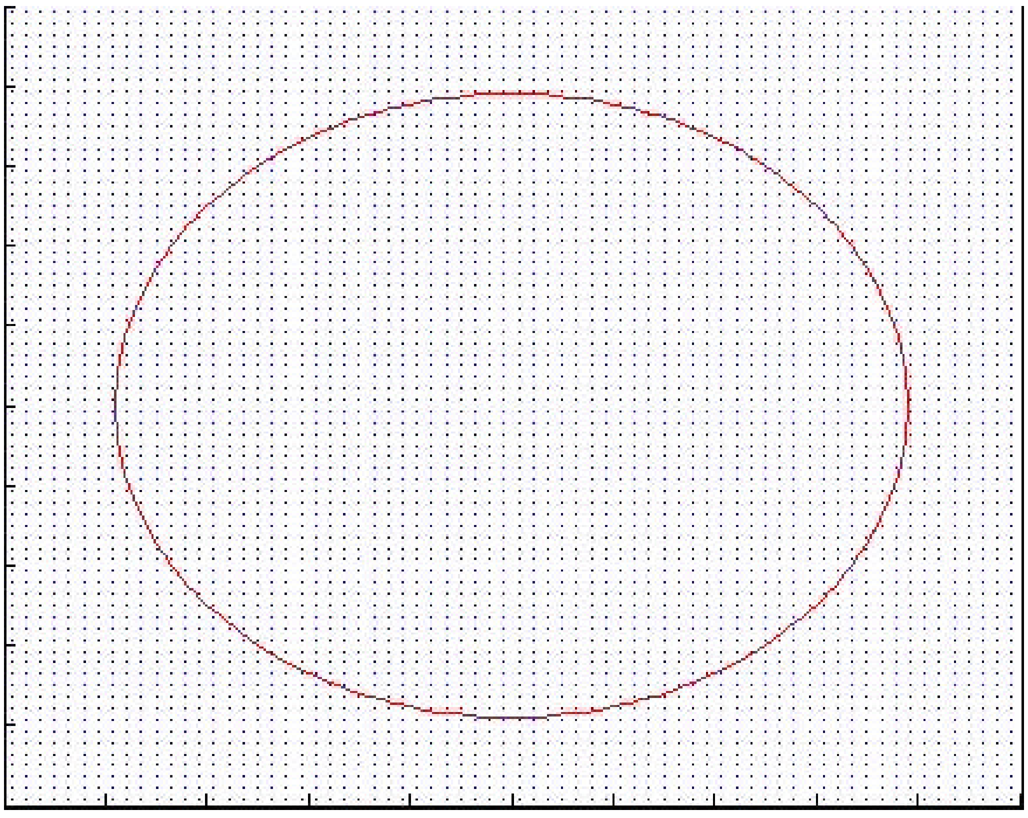
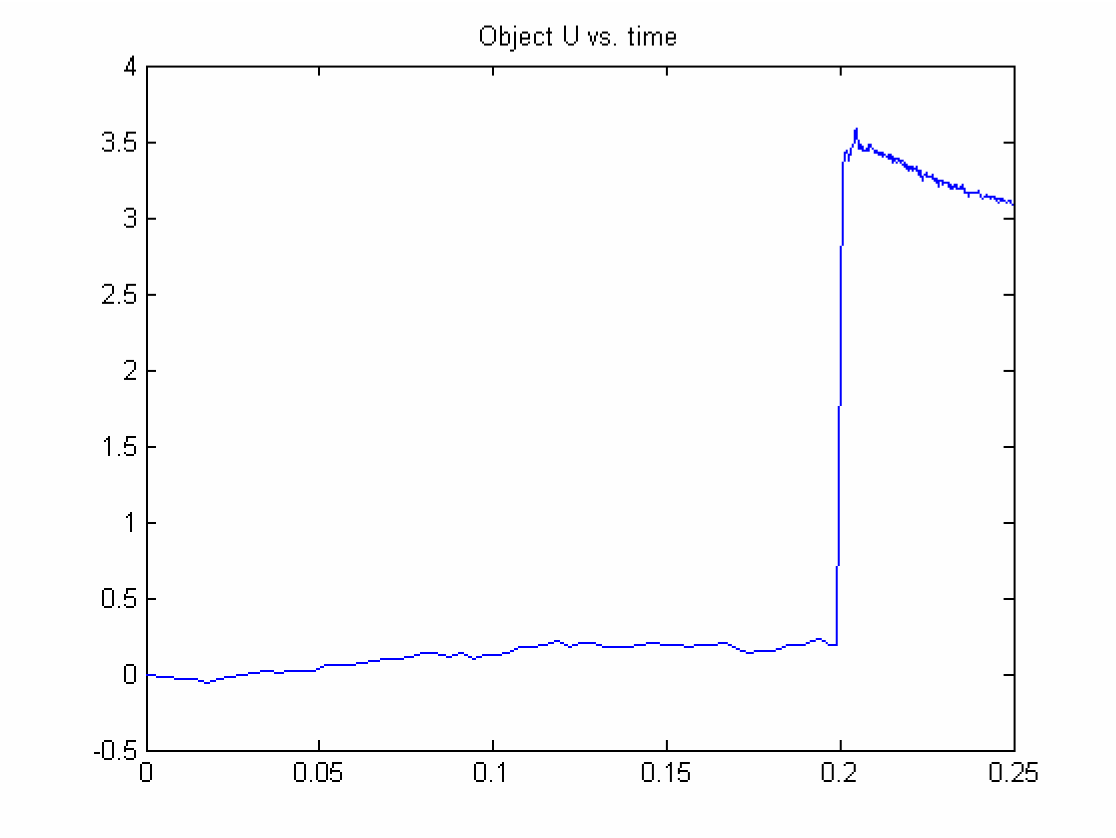
Simulation Result III



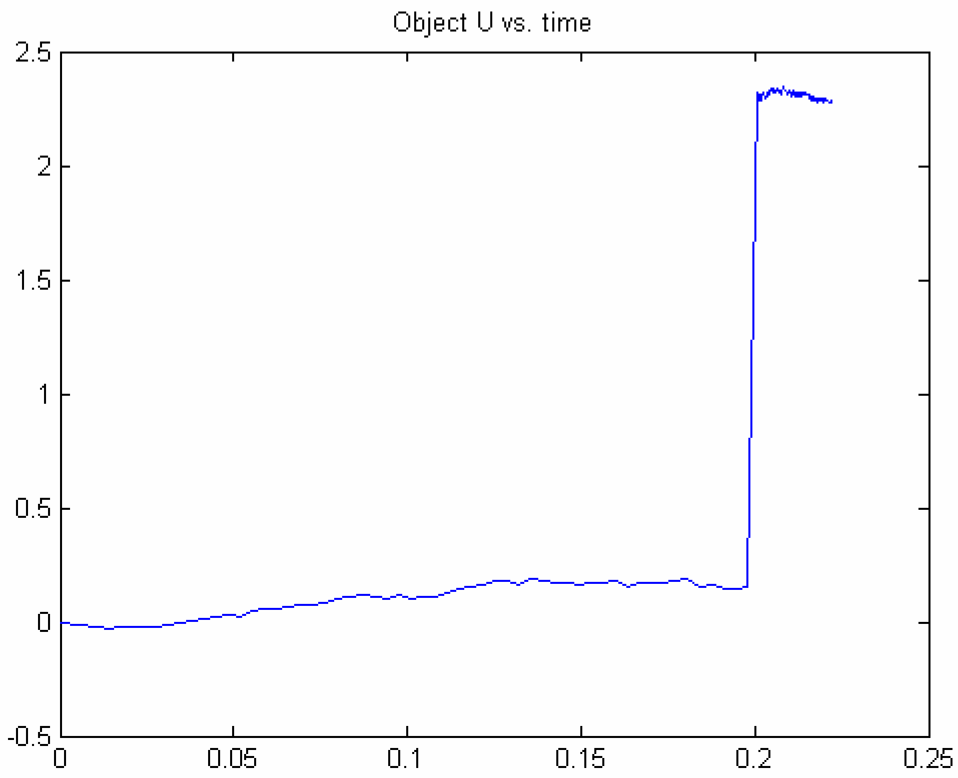
Numerical Result IV

- Object (brain) density: 700kg/m^3
- Fluid (CSF) density: 994 kg/m^3
- The box (head) is moved for 0.2 sec with a speed of 1m/s.



Numerical Result V

- Object (brain) density: 900kg/m^3
- Fluid (CSF) density: 994 kg/m^3
- The box (head) is moved for 0.2 sec with a speed of 1m/s.

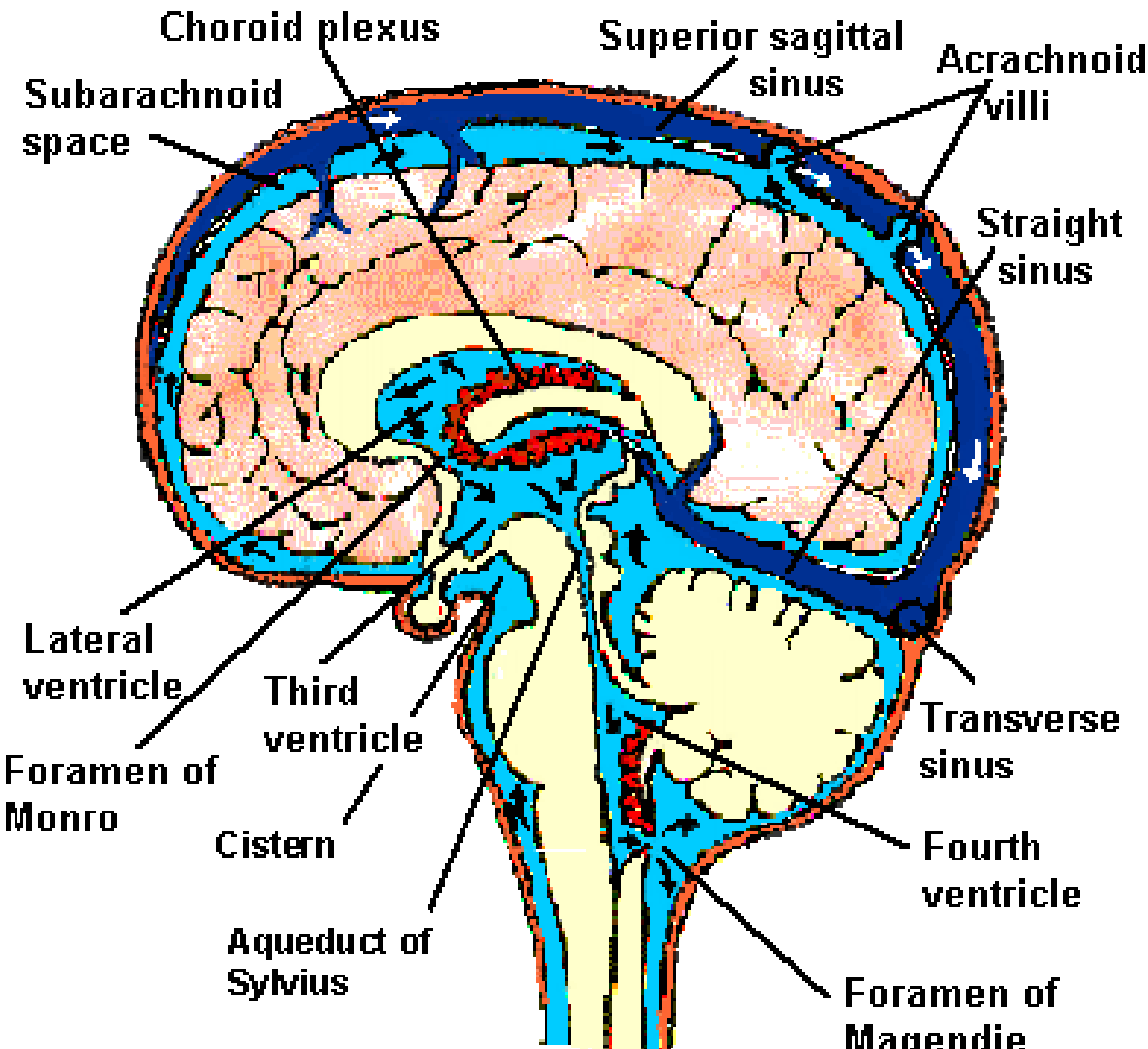


Comparison with Theories

- Initially, the brain lags behind for a short period of time (positive pressure theory).
- It then moves back to the original position and stays there (CSF density theory).
- On impact, the brain continues to move forward (negative pressure theory).
- However, the relative density of the brain does not seem to make any difference.

Cerebrospinal Fluid (CSF)

- CSF is a watery liquid produced in the parenchyma, 60% from the choroid plexus.
- Normal production 20 ml/hr (varies between 14-36 ml/hr).
- The CSF flows from the lateral ventricles into the third ventricle, down the audacity towards the sagittal sinus and the spinal sac.
- It is assumed that this is principally reabsorbed in the top of the cranial vault (other pathways may exist).
- Usually about 150ml of CSF in the intracranial space: 25 ml in the ventricles, 30 ml in the spinal subarachnoid space, 75 ml in the cerebral subarachnoid space.



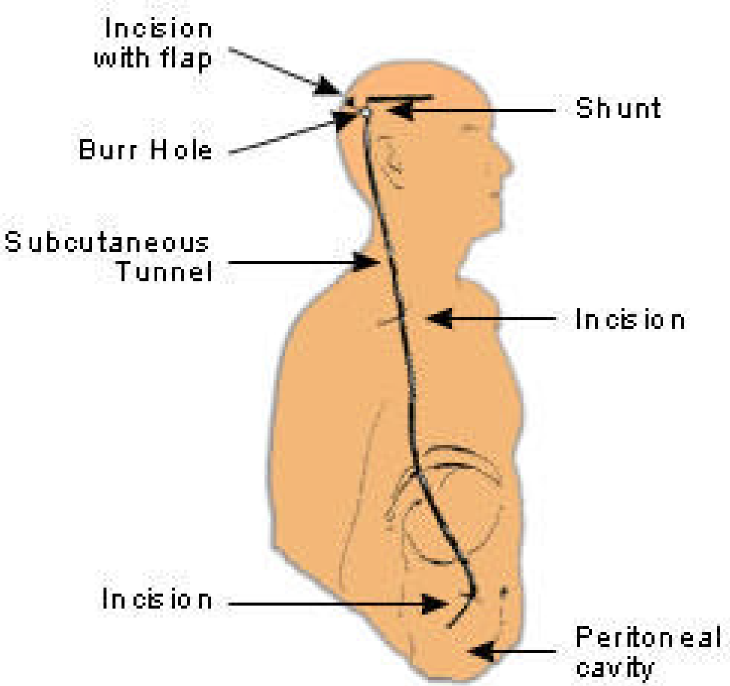
Choroid plexus
Superior sagittal sinus
Acrachnoid villi
Subarachnoid space
Straight sinus
Lateral ventricle
Third ventricle
Foramen of Monro
Cistern
Transverse sinus
Fourth ventricle
Aqueduct of Sylvius
Foramen of Magendie

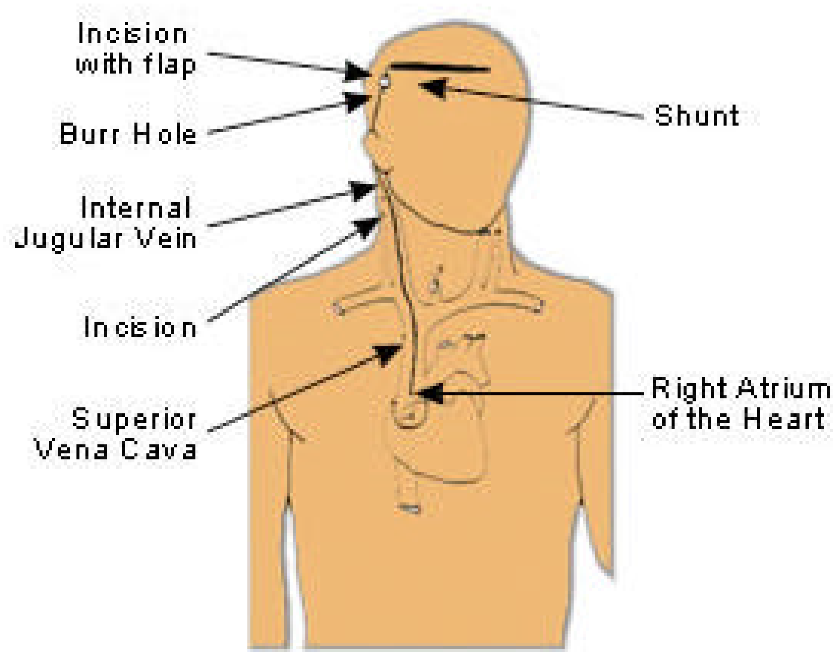
Hydrocephalus

- A medical condition resulting from an excess of CSF in the ventricles.
- Can be built up either over a long time or relatively quickly.
- Usually a result of insufficient absorption of CSF. Other causes include the blockage of drainage pathways.
- This leads to expansion of the ventricles, causing compression of the brain against the skull.
- For babies, an increase in intracranial pressure will result in expansion of the skull, which relieves some of the compression, but is still very damaging and painful.
- Congenital: present at birth (or detected soon after), or acquired: result of infection, head trauma, brain tumour.

Hydrocephalus Shunts

- Lifelong condition; patient is treated rather than "cured".
- Hydrocephalus is primarily treated by draining excess CSF from the ventricles through a shunt.
- A catheter is inserted through the brain into the ventricles.
- The fluid is drained into the heart or into the abdominal cavity.





Hydrocephalus Statistics

- In the US, about 1 in 1000 births are affected by hydrocephalus.
- Hydrocephalus is one of the most common “birth defects” and afflicts in excess of 10,000 babies each year.
- Studies by WHO show that one birth in every 2000 result in hydrocephalus.
- More than 50% of hydrocephalus cases are congenital.
- As many as 75% of children with hydrocephalus will have some form of motor disability.

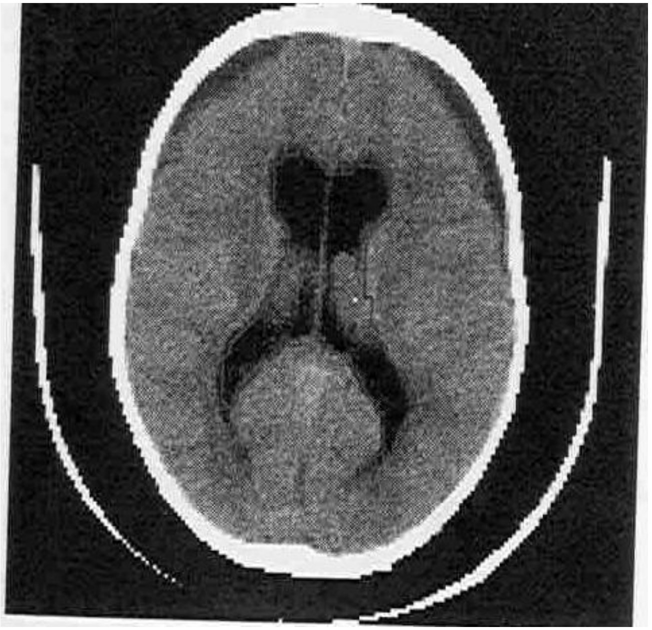
Shunts Statistics

- 25,000 shunt operations performed each year in the US. Of those 18,000 are initial shunt placements.
- Some 85% of people with shunts have had at least two shunt operations.
- Studies show that the risk of shunt failure in an infant's first year is 30%.
- Shunts are revised about two times in the first 10 yrs of use per patient.
- CSF shunting procedures account for almost $100 million dollars of national health care expenditures in the US.
- Nearly half of these dollars are spent on shunt revisions.

Pre and Post Shunt Surgery

- Shunt insertion surgery:

Pre-shunt



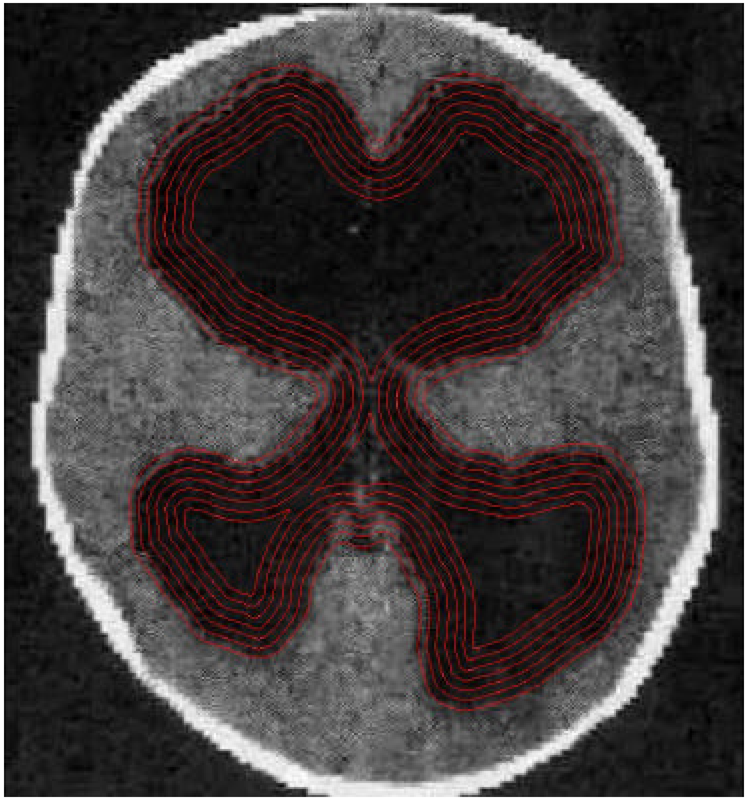
Post-shunt

  - Shunts become blocked by swelling and deflation of the brain.
  - Rate of shunt failure: 50%

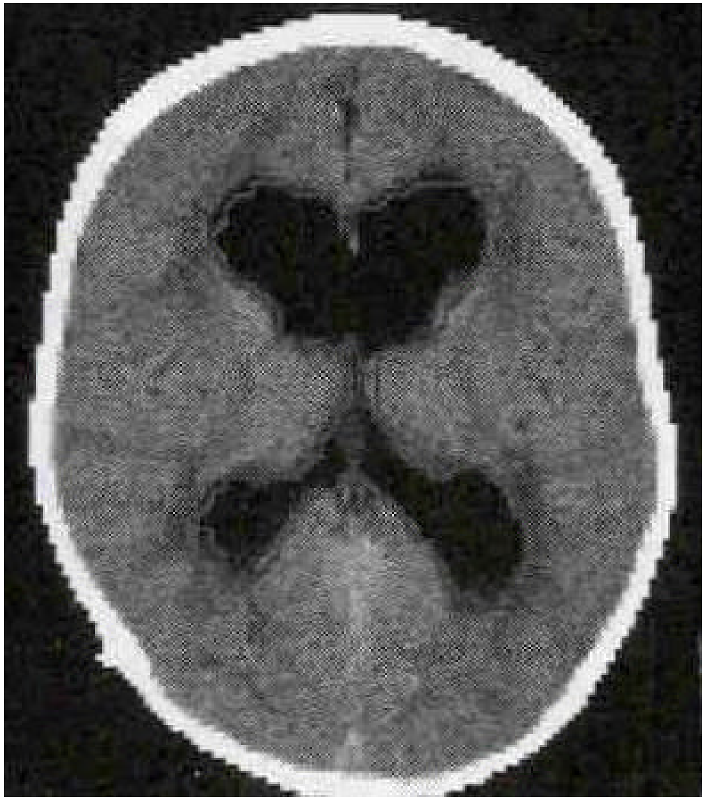
- Can one predict the outcome of shunt insertion?

Imaging Approach

- Simulating the ventricle motion using the level set method.
- Evolve curves with speed function F.
- Allow topological changes (one curve to multiple curves).



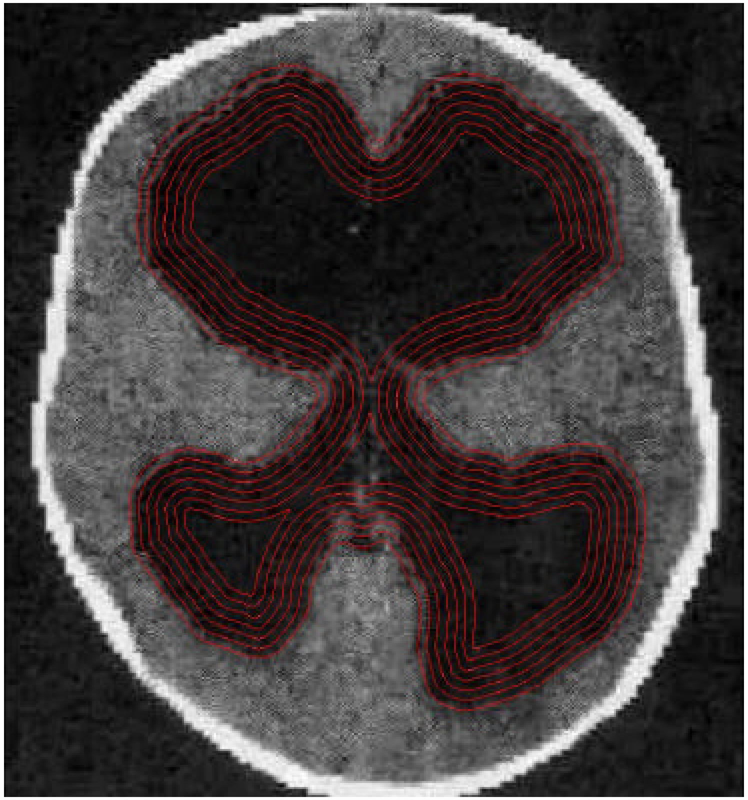
Pre-shunt



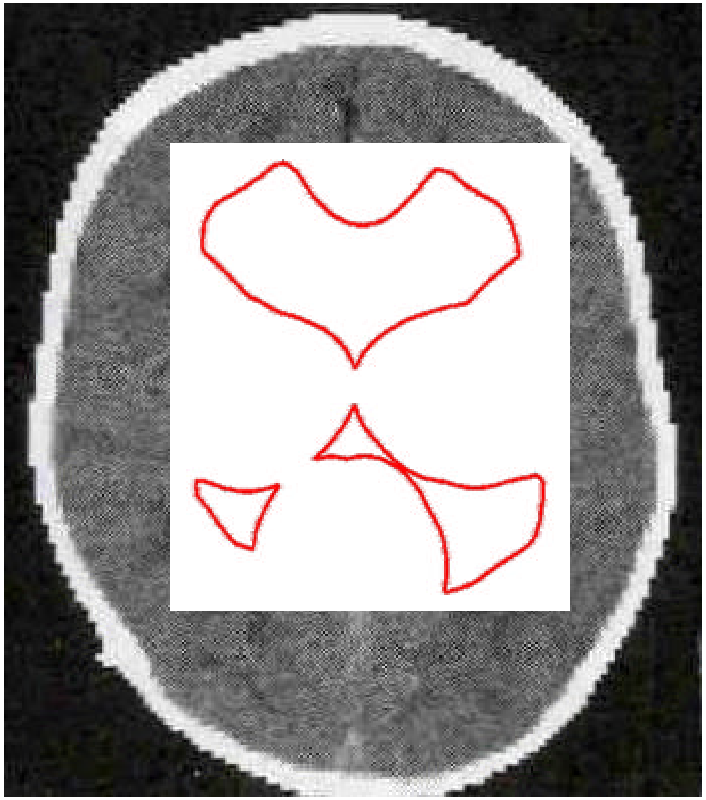
Post-shunt

Imaging Approach

- Simulating the ventricle motion using the level set method.
- Evolve curves with speed function F.
- Allow topological changes (one curve to multiple curves).



Pre-shunt



Post-shunt

Biomechanics Approach

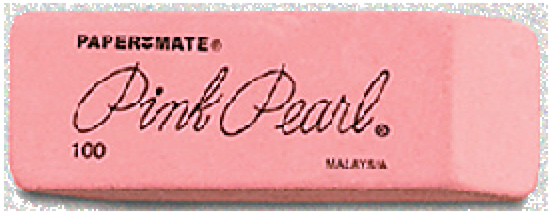
- Imaging approach does not use any of the biomechanical properties (e.g. elasticity of brain tissue, hydrostatic pressure).
- “Simulating the mechanical behaviour of the human brain will be an important milestone in neurosurgery.” Kyriacou-Miller-Neff 2002.
- Accurate simulation tool to predict the level of stress within the tissue would avoid injury to tissue from retraction strains.

Constitutive Models for Brain Tissue

- Constitutive models are used to quantify the behaviour of materials.
- The mechanical behaviour of brain tissue may be modeled differently depending on:
  - specific conditions of interest
  - magnitude of the stress and strain
  - time scale
- Quasi-static processes: neurosurgical retraction, brain shifting during surgery, hematomas, hydrocephalus, etc.
  - poroelastic, viscoelastic, linear and nonlinear elastic models
- Impact: during falls or car accidents
  - linear and nonlinear viscoelastic models

Is Our Brain a Rubber, Silly Putty, or Sponge?

- Elastic model
  - stress state depends only on strain



- Viscoelastic model
  - stress state depends both on strain and strain history

- Poroelastic model
  - two or more phases, with one phase elastic solid and the other a fluid

Other Issues

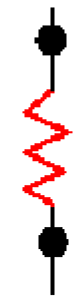
- Compressible/incompressible model. Incompressible material has Poisson ratio 0.5. Poisson ratio of the brain:
  - 0.4 (Tenti et al. 99, linear poroelastic material)
  - 0.45 (Miga et al. 98, from experiment)
  - 0.35 (Guillaume et al. 97, linear elastic material)
- Fluid/solid model
  - Brain tissue exhibits both fluid and solid behaviour.
  - Viscoelastic fluid and viscoelastic solid models are both used.
- Mesh generation of ventricles from medical images.
- Image registration problem when comparing several brain images.

Brain Modeling in Our Simulation

Viscoelastic model

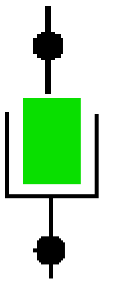
- Linear spring: obey Hooke's law

$$\text{stress} \propto \text{strain} \quad s = Ee$$



- Linear dashpot: obeys phenomenological law

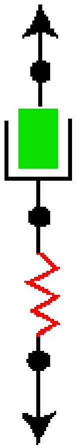
$$\text{stress} \propto \text{strain rate} \quad s = h \frac{de}{dt}$$



Viscoelastic Models

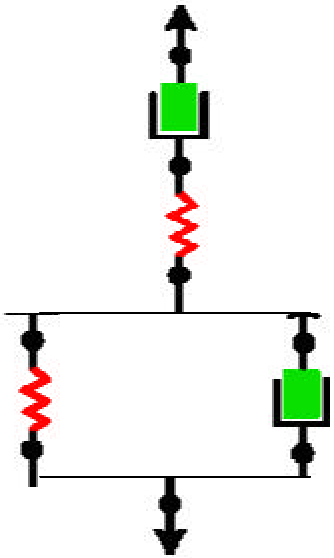
- Maxwell model:

$$\frac{de}{dt} = \frac{1}{E}\frac{ds}{dt} + \frac{s}{h}$$



- Burgers model:

$$s + \left(\frac{h_1}{E_1} + \frac{h_1}{E_2} + \frac{h_2}{E_2}\right)\frac{ds}{dt} + \frac{h_1 h_2}{E_1 E_2}\frac{d^2 s}{dt^2}$$
$$= h_1 \frac{de}{dt} + \frac{h_1 h_2}{E_2}\frac{d^2 e}{dt^2}$$



Mathematical Modeling of Hydrocephalus

- Assumptions:
  - Quasi-static approximation
  - Infinitesimal deformation
  - No external force
- Equations of motions:

$$0 = \frac{\partial s_{ij}}{\partial x_j}$$

- Kinematic equations:

$$e_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

Modeling of Hydrocephalus (cont.)

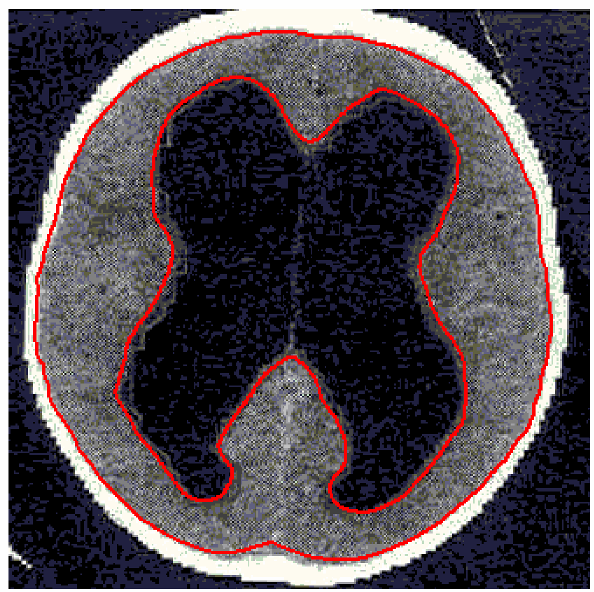
- Constitutive equations:
  - homogenous, non-ageing material
  - Burgers model
  - Relaxation function:

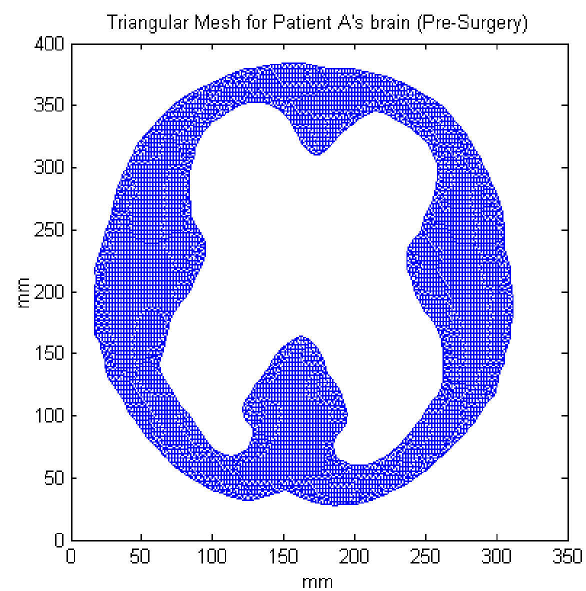
$$j(t,s) = \frac{P_2}{A}\left[(q_1 - q_2 r_1)e^{-r_1 t} - (q_1 - q_2 r_2)e^{-r_2 t}\right]$$

$$e_{ij}(x,t) = j(t,0)e_{ij}(x,0) + \int_0^t j(t-0)\frac{de_{ij}}{ds}(x,s)ds$$

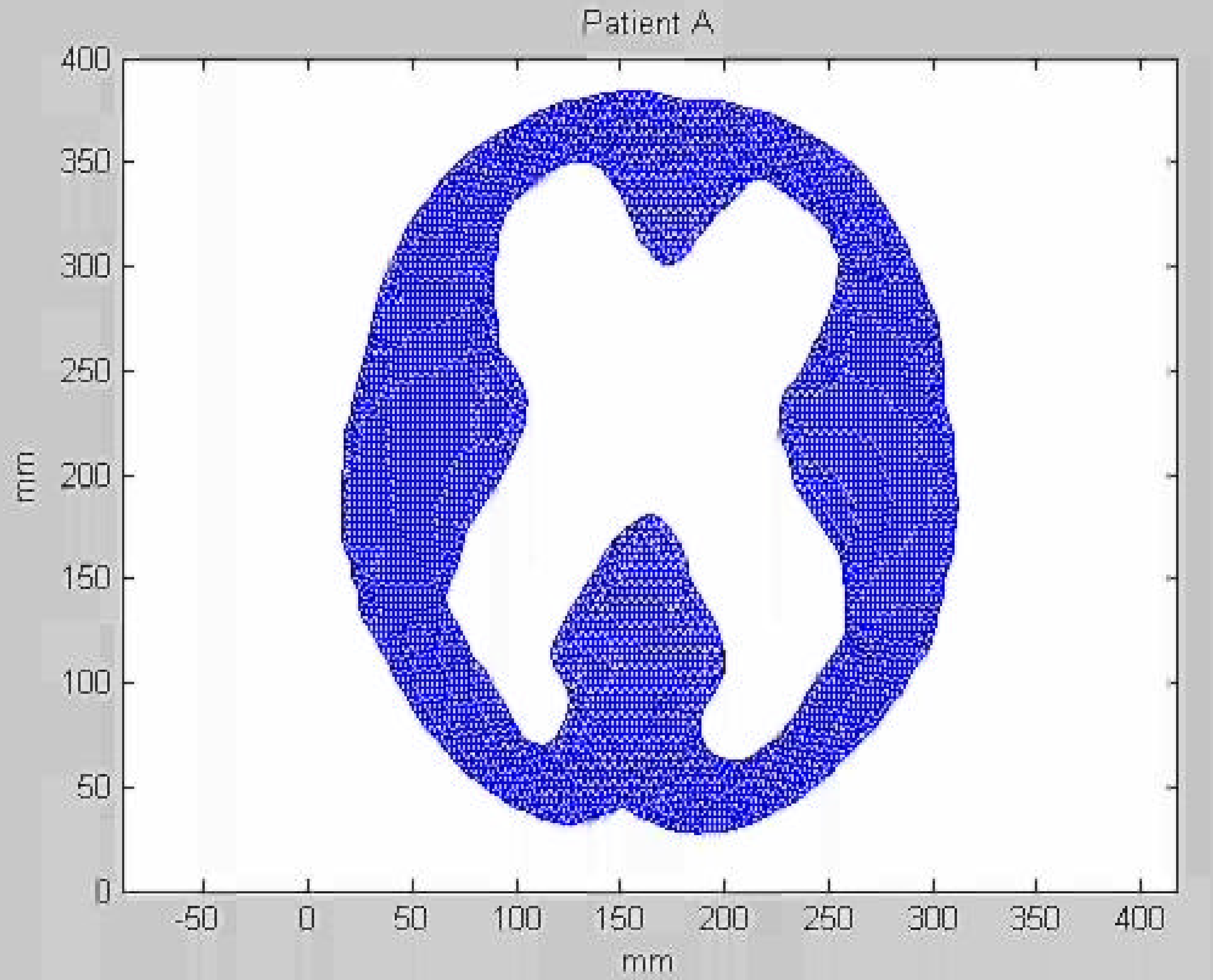
- Boundary conditions:
  - brain boundary: u = 0
  - ventricle boundary: $\sigma_{ij} n_j = -p(t)$, $\sigma_{ij} t_j = 0$

Geometric Modeling of Ventricle

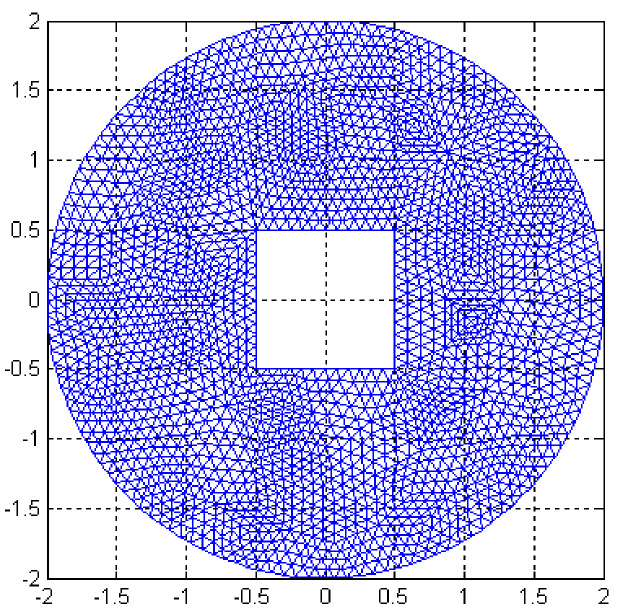




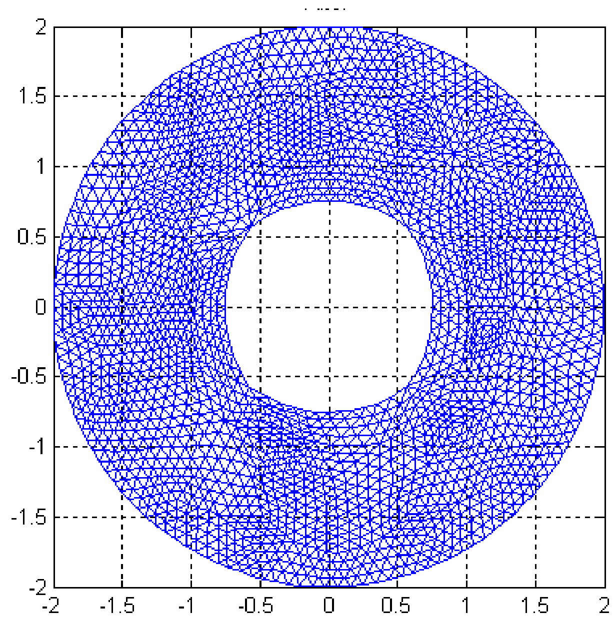
- Segmentation of boundary curves using active contour techniques.
- The curves are represented by level set functions.
- The mesh is generated using the level set functions as input.


Patient A
400
350
300
250
200
150
100
50
0
mm
-50
0
50
100
150
200
250
300
350
400
mm

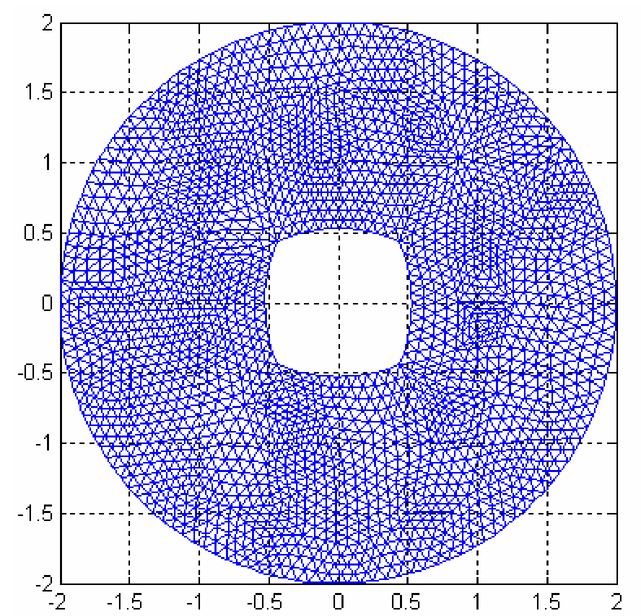
Small Deformation



original



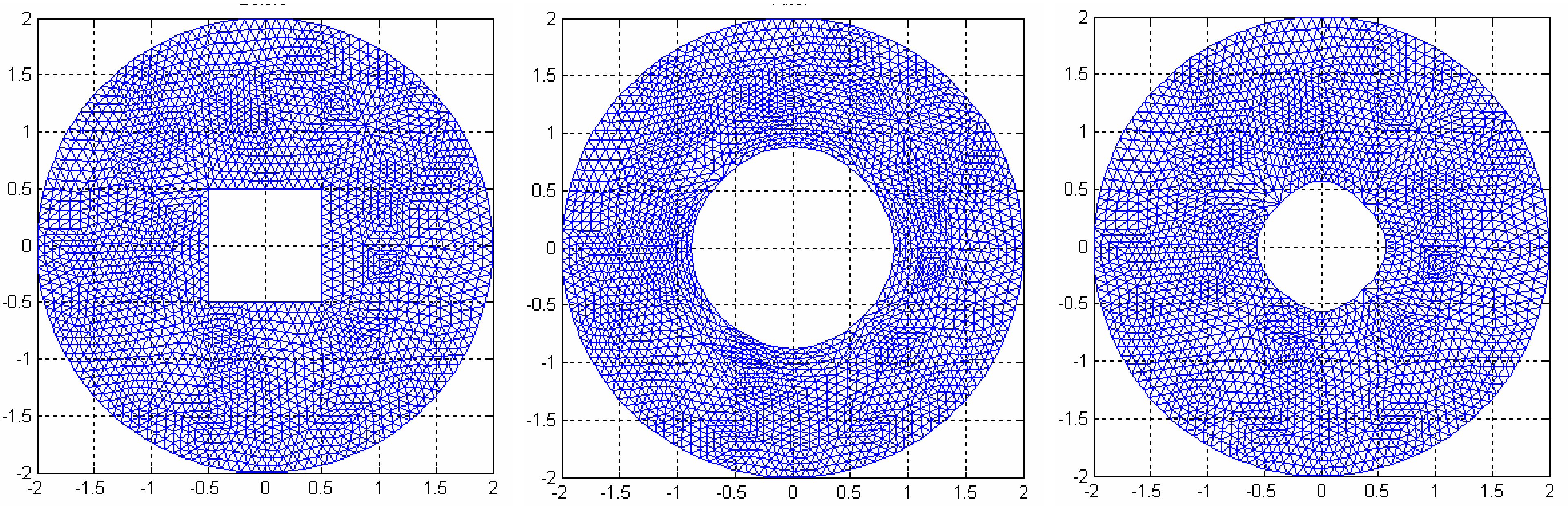
expanded



shrinked

- Linear elastic model.
- An elastic object is deformed under an external force. When the external force disappears, it should restore its original shape.

Large Deformation



original expanded shrinked

- It is necessary to know the stress and strain of the deformed object in order to restore its original shape.
- Otherwise, the shape after shrinking for an expanded circular shape will remain more or less circular.

Concluding Remarks

- Simulation provides another means to study brain mechanics.
- Compared to imaging approach, it uses mechanical properties of biological tissues.
- Compared to experimental approach, it is much easier to change boundary conditions, etc.
- Lack of data is a serious challenge
  - CSF density, brain density
  - Elasticity constants, Young’s modulus, Poisson ratio
  - Stress/strain information of hydrocephalus brain
- Difficult to verify results.
- Future work: 3D modeling and simulation