Biomechanics of Brain Trauma

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joint work with:
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+
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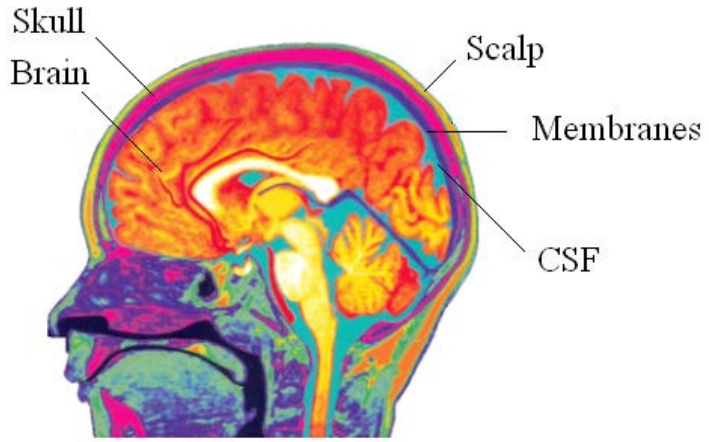
[Mary Jane Neer Fund for Research in Disability]

Blunt head trauma

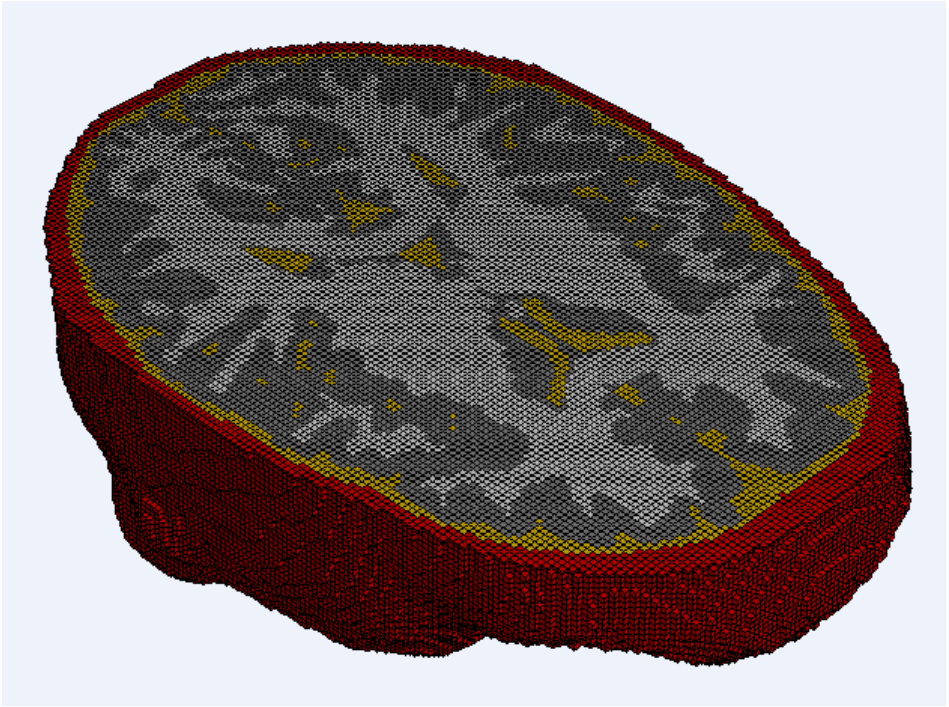
- Causes: transportation accidents, falls, sports injury, blast exposure…
- ~1.4 million people each year, > $56 billion a year, > 5 million disabled
- Injury mechanisms remain unclear
- Dynamics and … fractal brain structure

Biomechanics of head injury



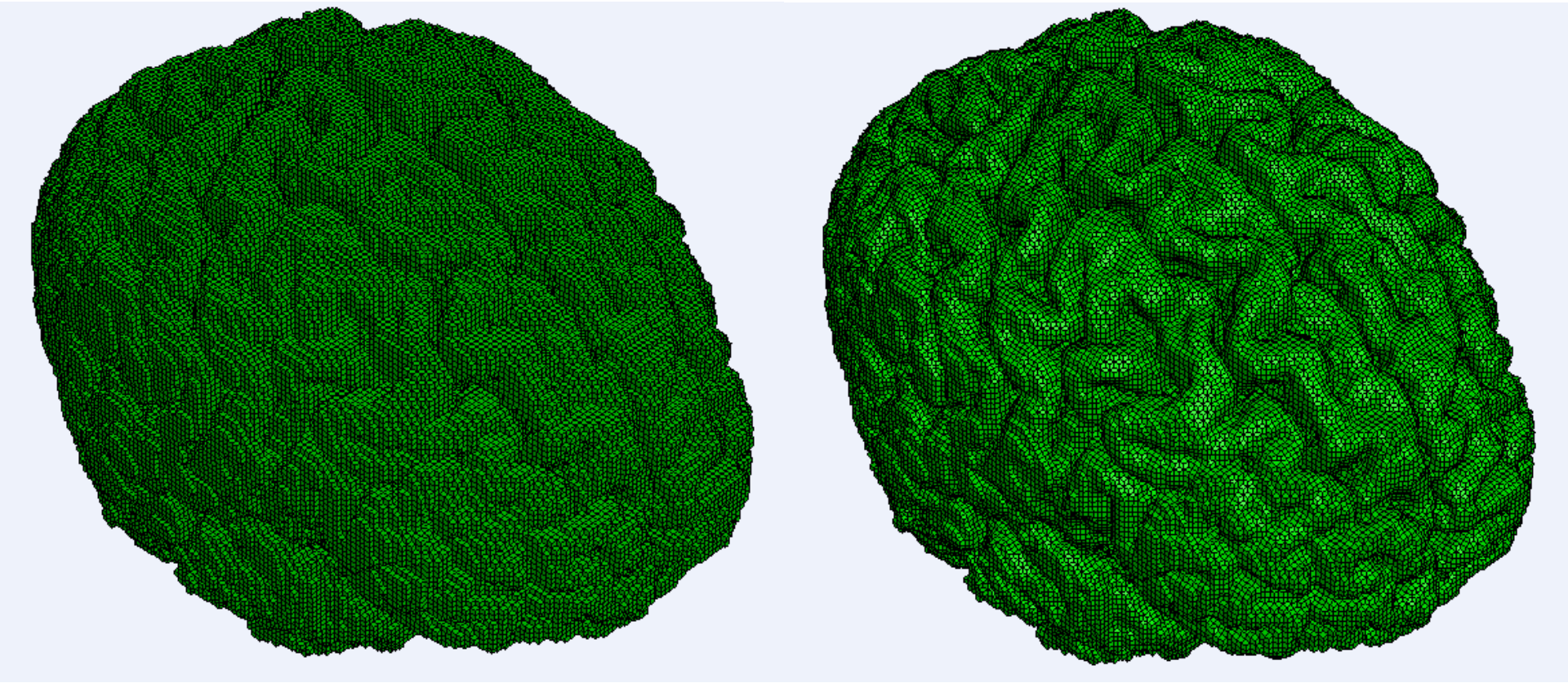
- What is the physical process producing head injury?
- What are stress wave patterns following the impact?
- Can set up a 3d finite element head model based MRI?
- How does an impact cause brain damage?
- Why does side impact cause more damage than frontal impact?
- Why does damage occur in other regions of the brain instead of right under the impact site?

MRI voxel-based finite element (FE) mesh



Axial view of the FE mesh
(skull, cerebro-spinal fluid (CSF), grey matter, white matter)

Mesh smoothing (implemented through a custom C++ code)

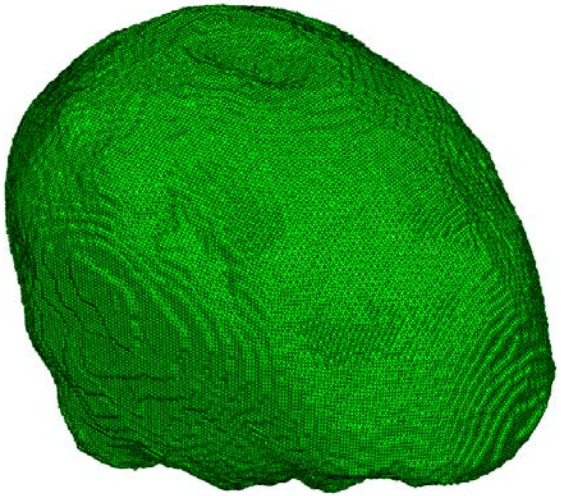


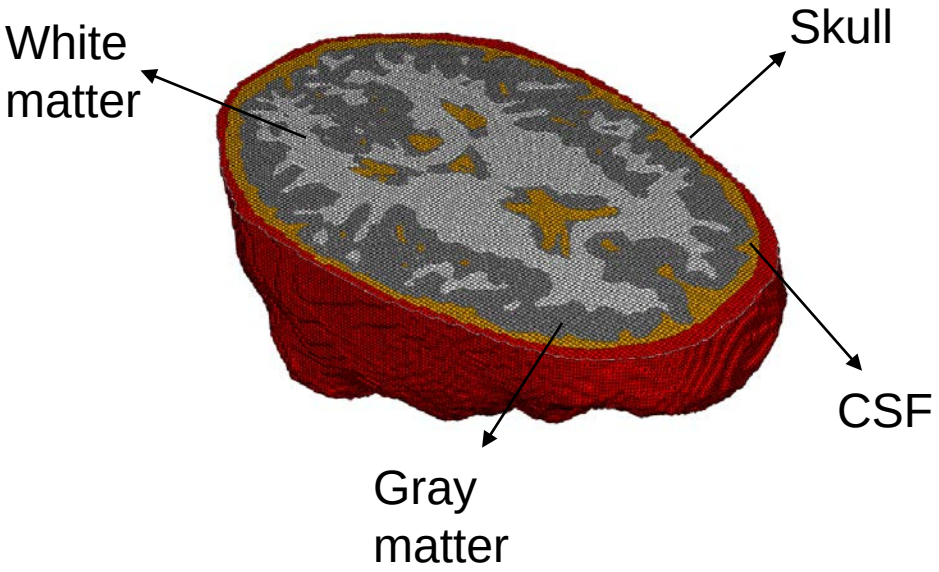
Original brain mesh

Brain mesh after smoothing

MRI voxel-based finite element (FE) mesh

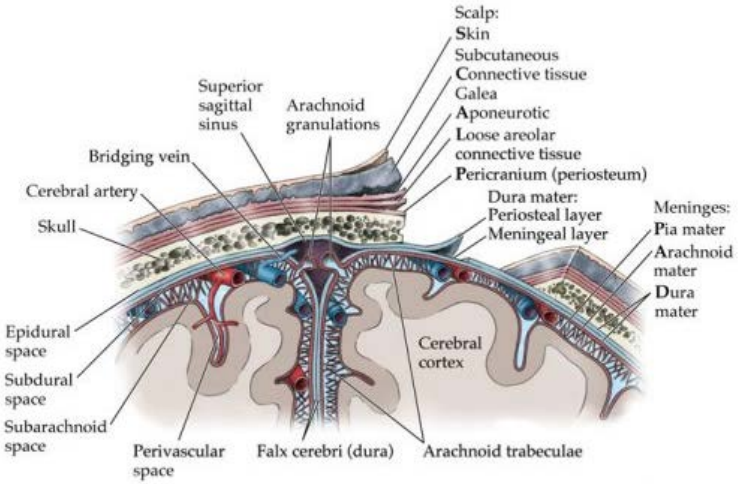
- Image voxels → 8-node brick FE (1.33 x 1.33 x 1.30 mm^3)
- Image segmentation … element tissue types





- Fine mesh able to capture stress wave propagation
- Patient-specific

Material properties

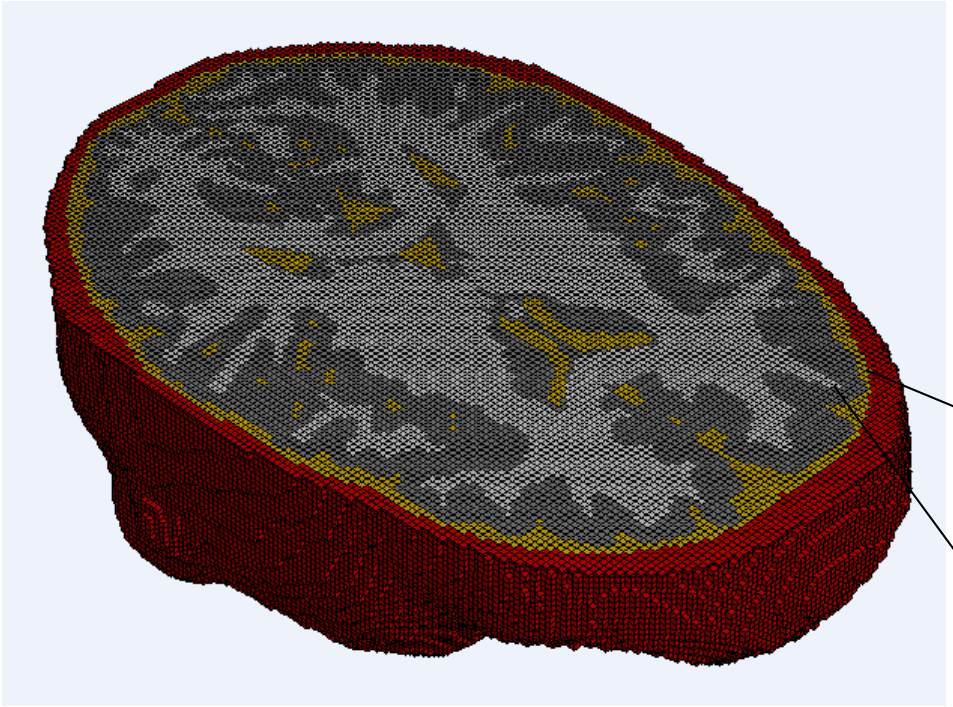


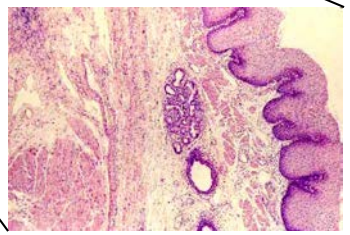
- homogeneous and isotropic
- skull and CSF: linear elastic
- brain: elastic in bulk behavior, linear viscoelastic in shear

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t}$$

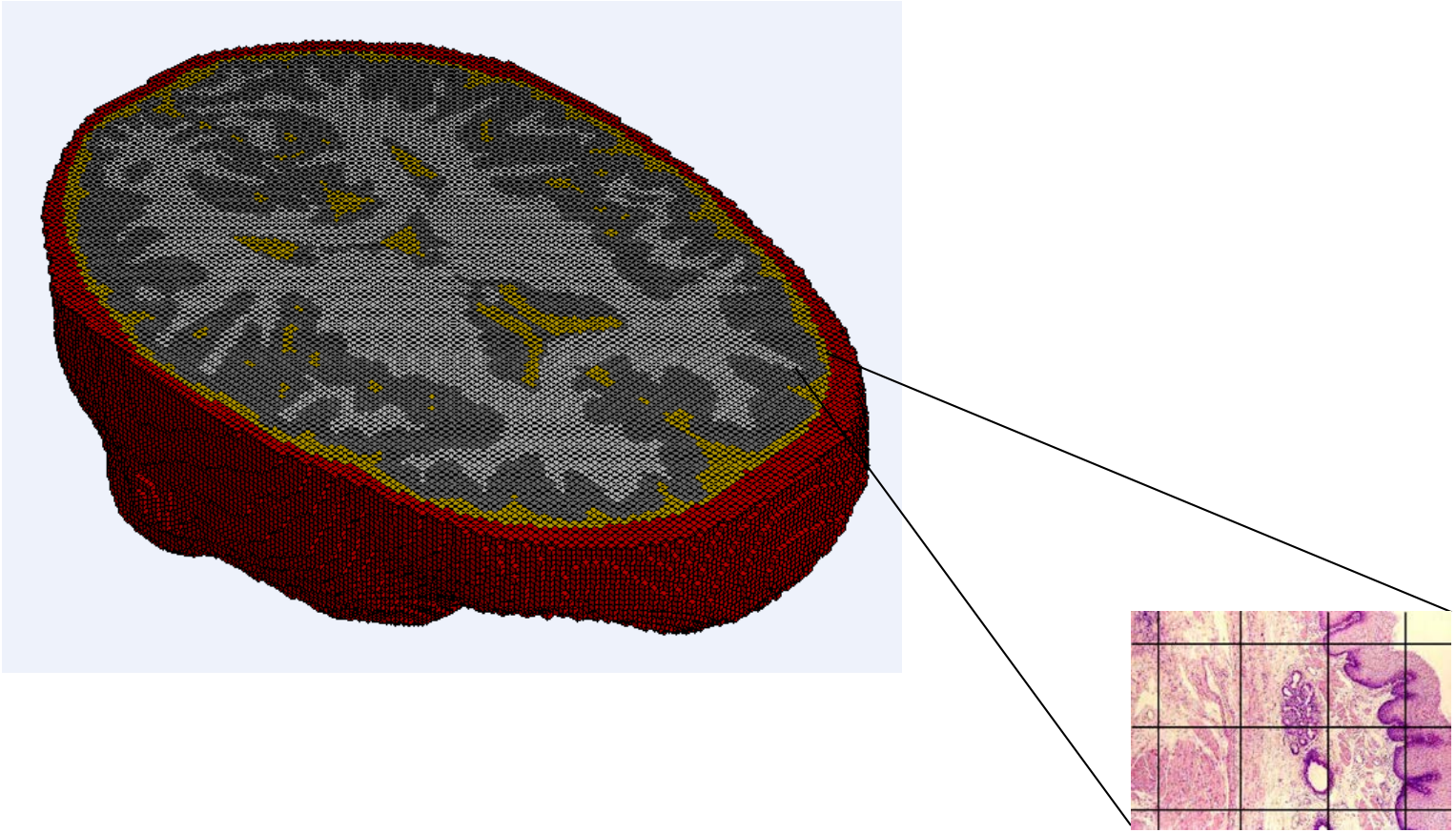
Tissue	Density (kg/m^3)	Bulk modulus K (Pa)	Short term Shear modulus G_0 (Pa)	Long term shear modulus G_∞ (Pa)	Decay Constant (sec^{-1})
Skull	2070	3.61E+9	2.7E+9		N/A
CSF	1004	2.19E+7	5.0E+4		N/A
Grey matter	1040	2.19E+9	3.4E+4	6.4E+3	400
White matter	1040	2.19E+9	4.1E+4	7.8E+3	400

MRI voxel-based FE mesh



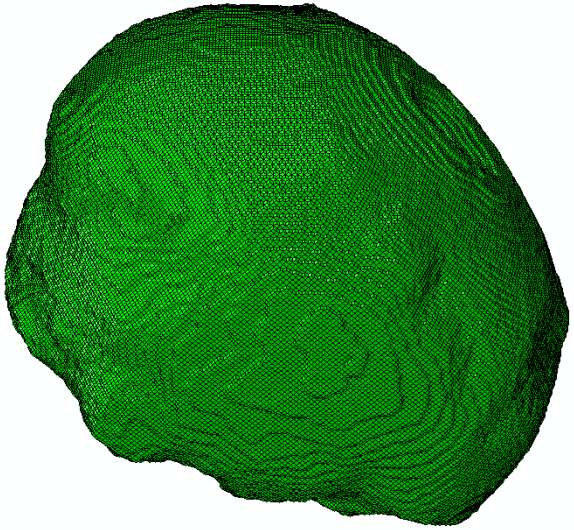


MRI voxel-based FE mesh

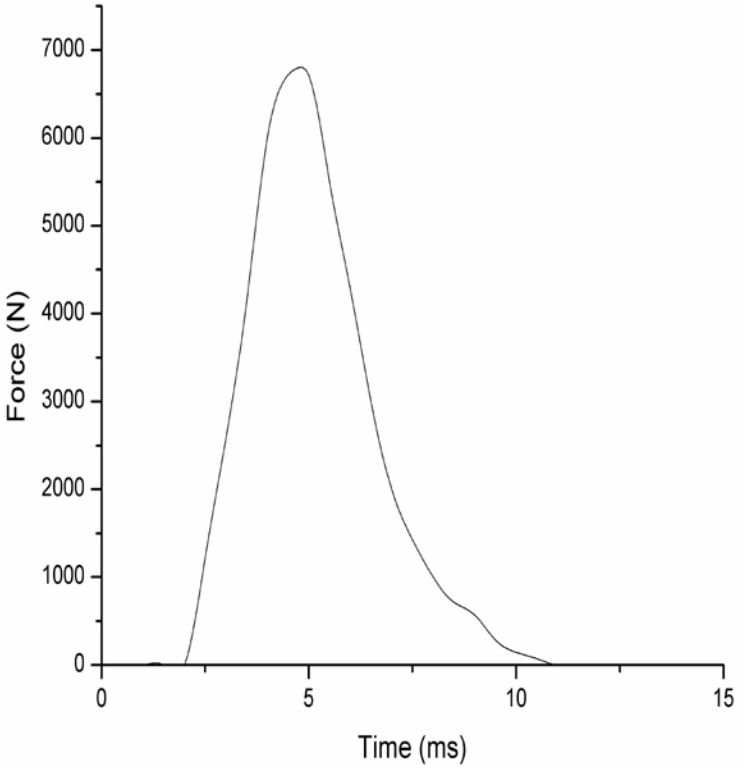


Model validation: frontal impact

…based on experiments with 9 *ms* impact pulse with peak pressure of 4.37 *MPa* to frontal region



Impact force

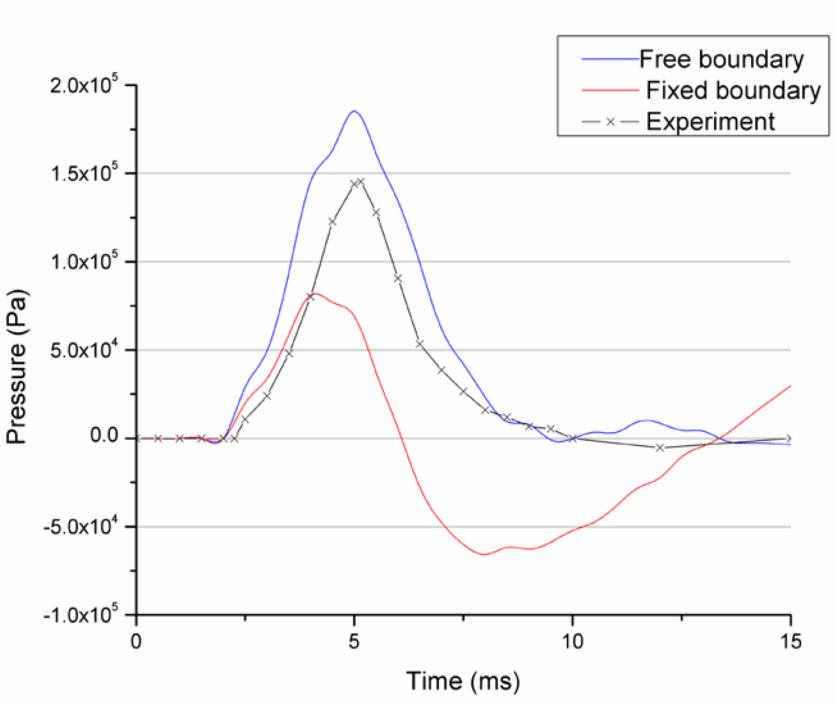


Impact force time history

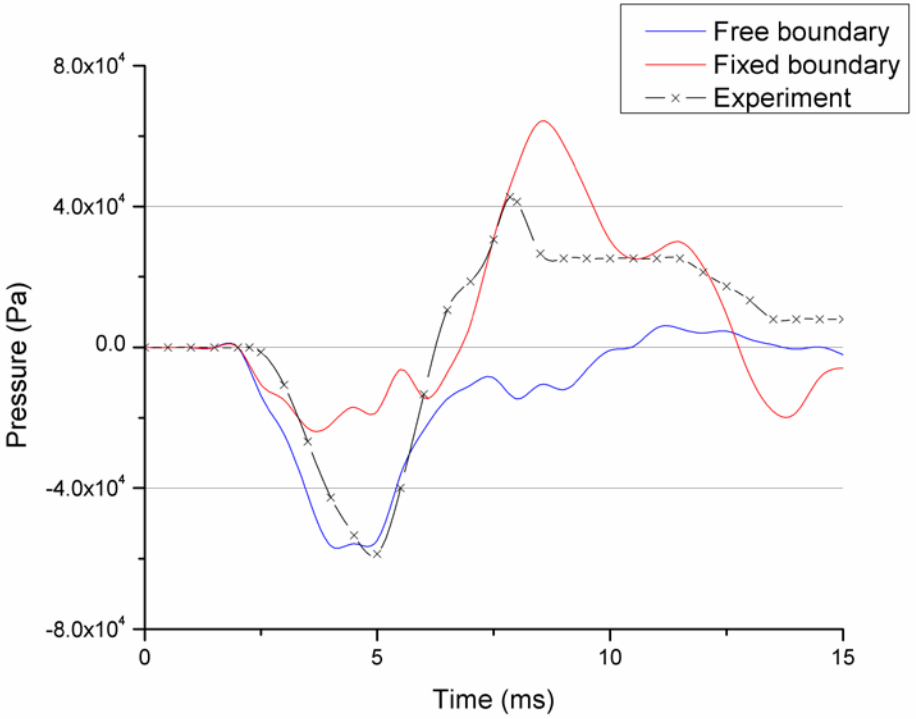
boundary condition at head-neck junction: either free or fixed

[Nahum, A., Smith, R., Ward, C. “Intracranial pressure dynamics during head impact,” 1977]

Results: intracranial pressure

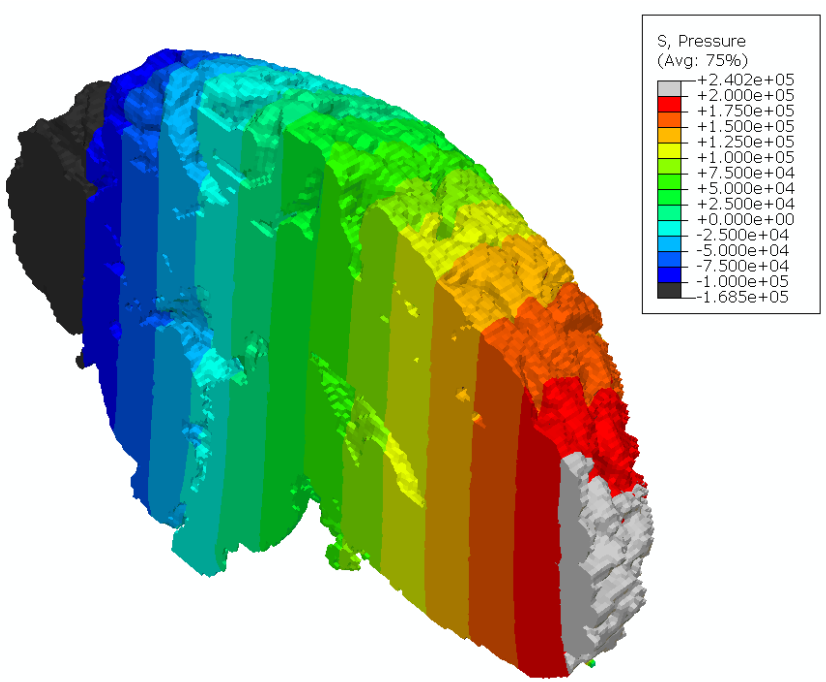


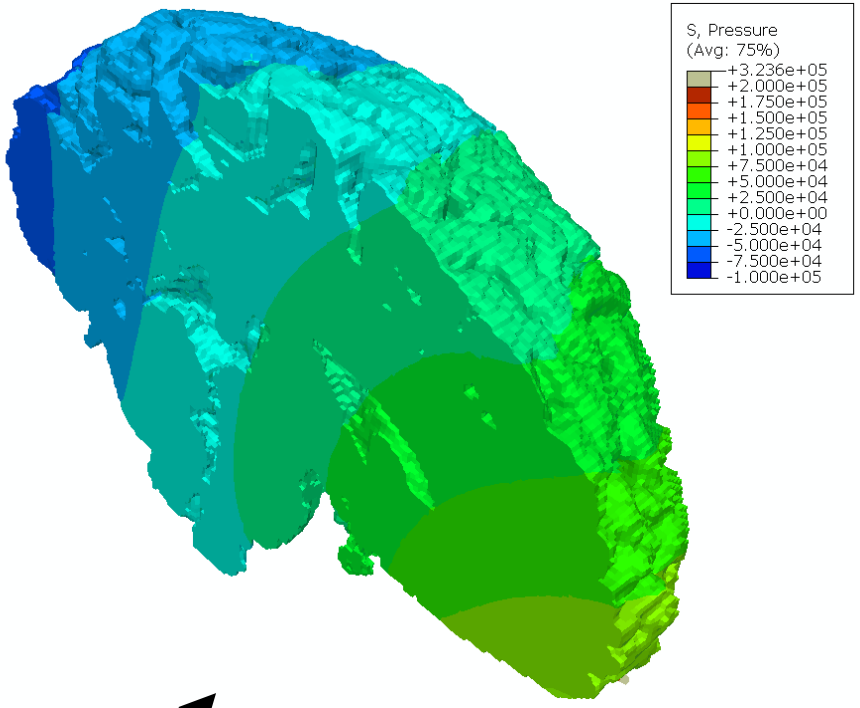
Coup pressure time history



Contrecoup pressure time history

Pressure distribution on sagittal plane

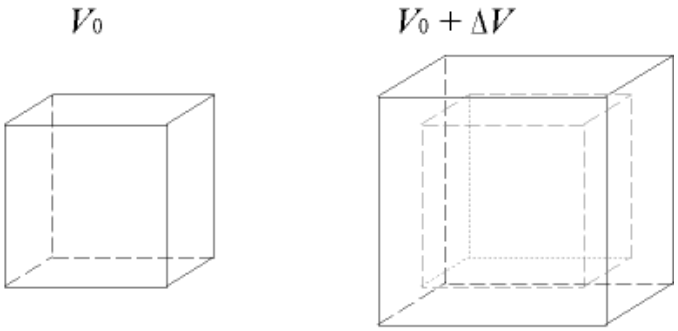




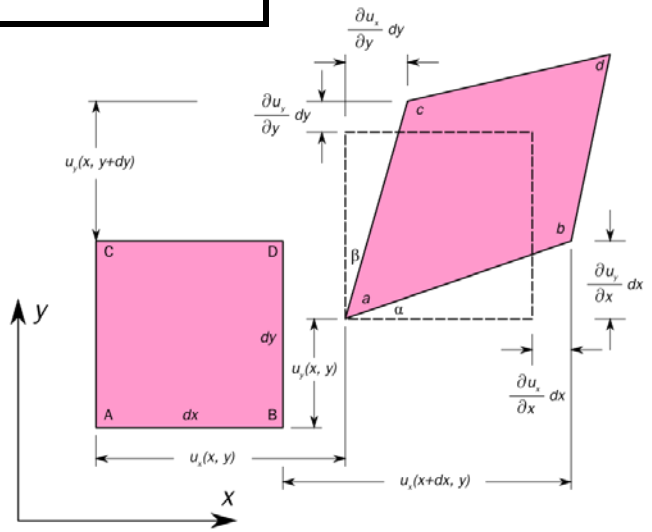
… at 5*ms* (mid-sagittal view) for free and fixed boundary condition at neck.

Pressure and shear waves in the brain

	wave speed	magnitude
pressure	~1,500 *m/s*	100 *KPa*
shear	~6 *m/s*	10 *KPa*



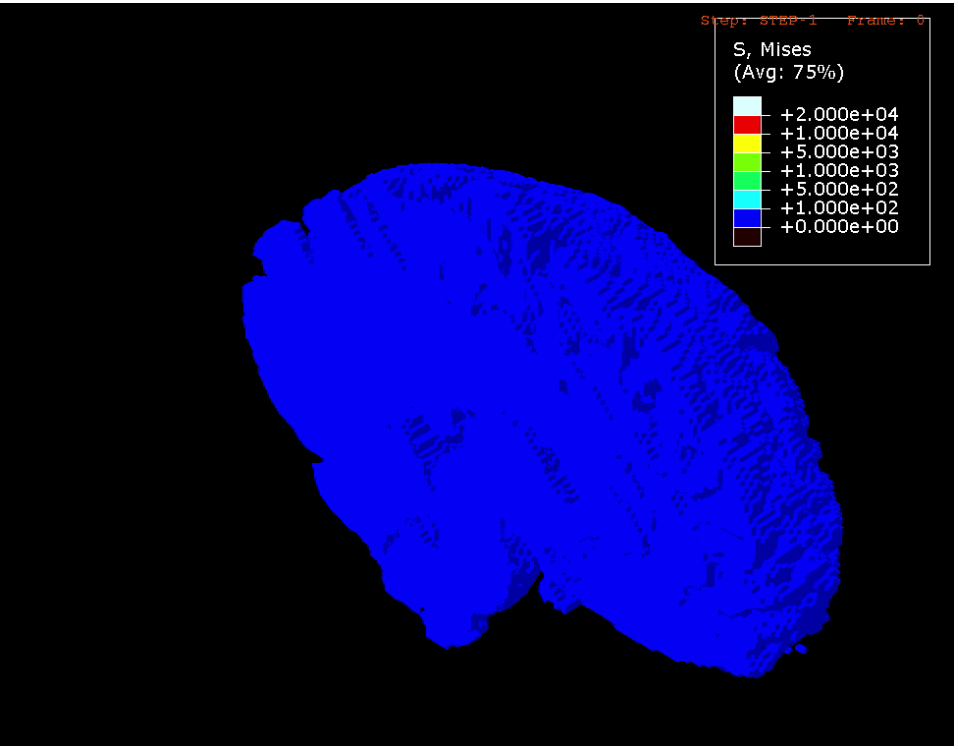
dilatation



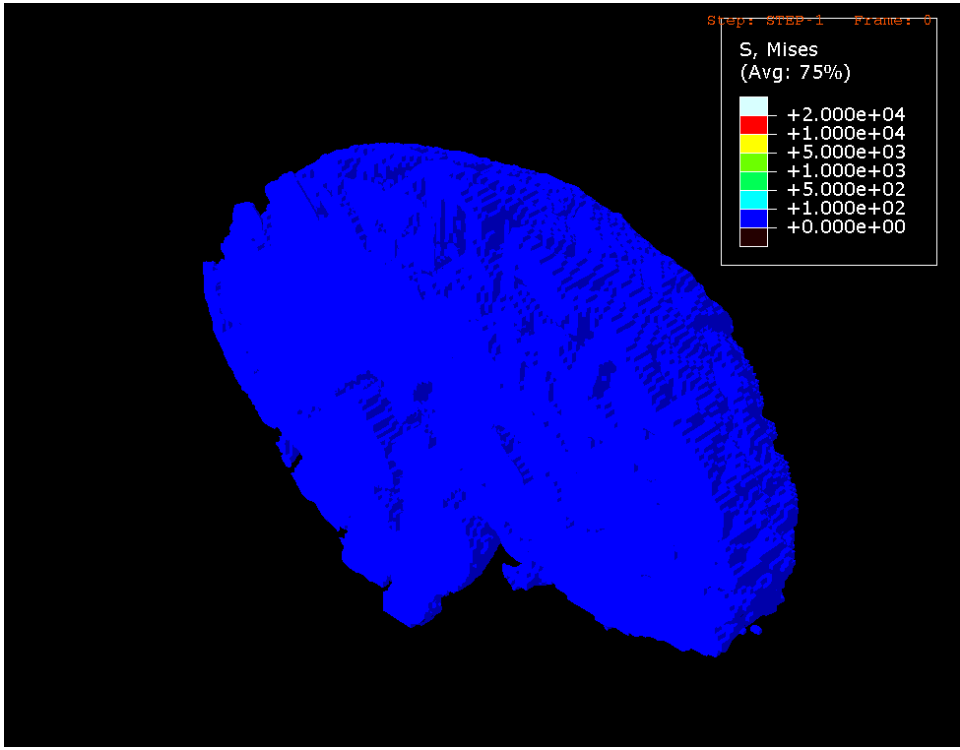
shear strain

- fast pressure waves
- slow and spherically convergent shear waves which are potentially more damaging

Spherically convergent shear wave of shear stress

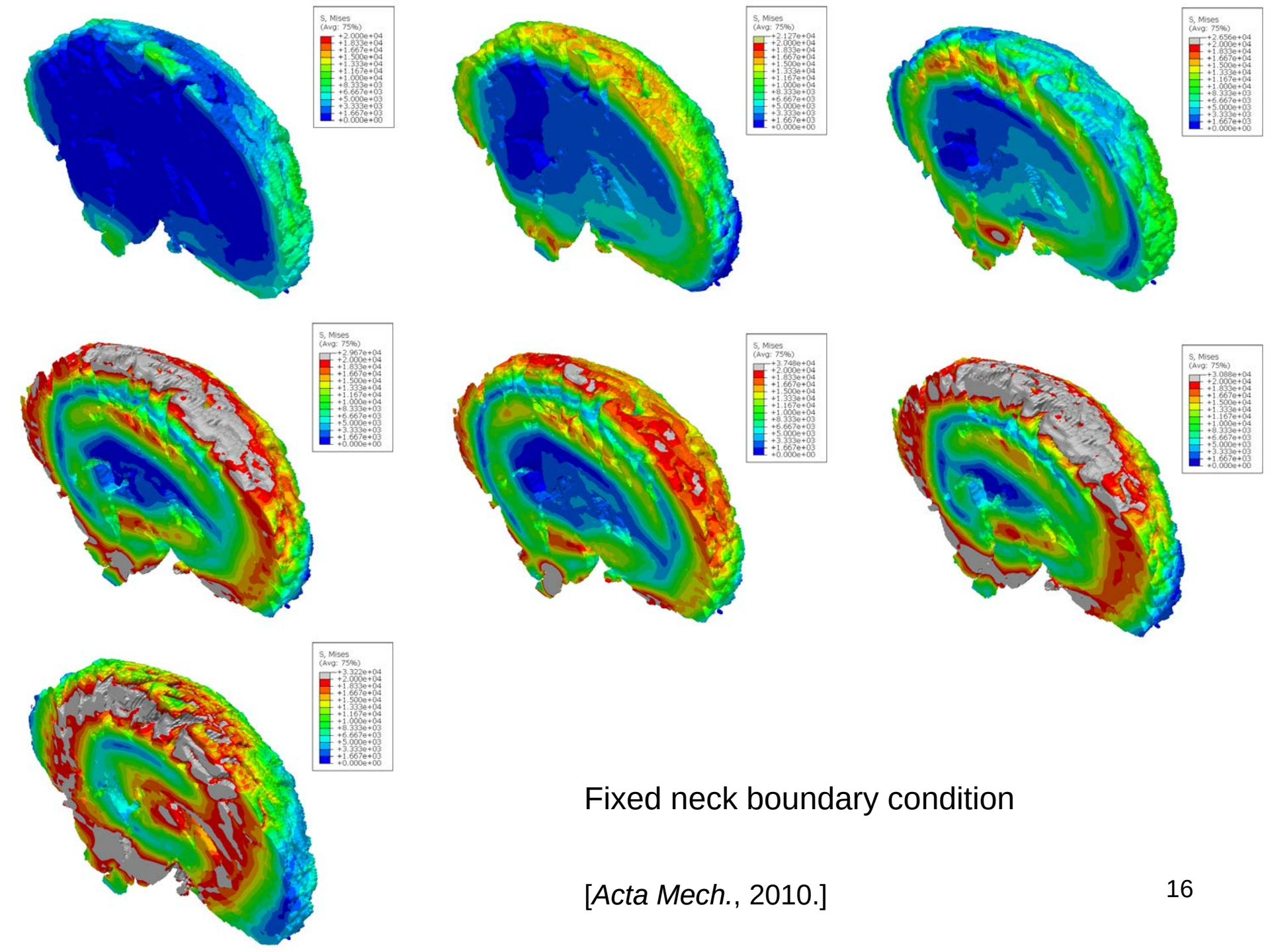


Free neck boundary condition



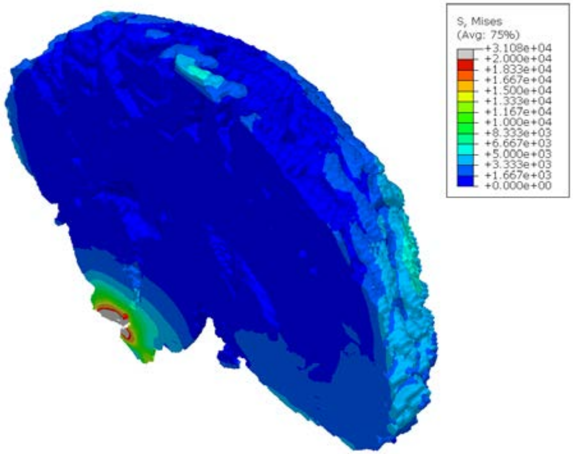
Fixed neck boundary condition

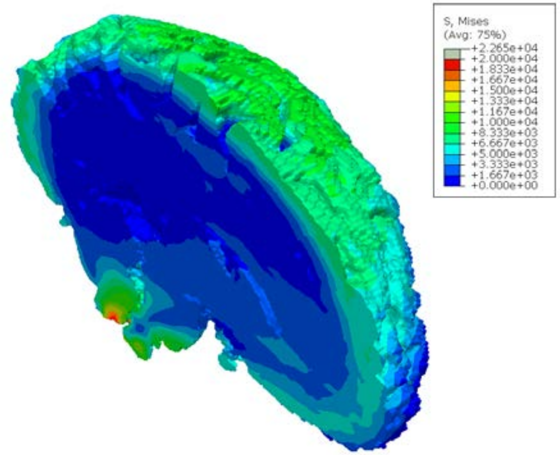
[*Acta Mech.*, 2010]

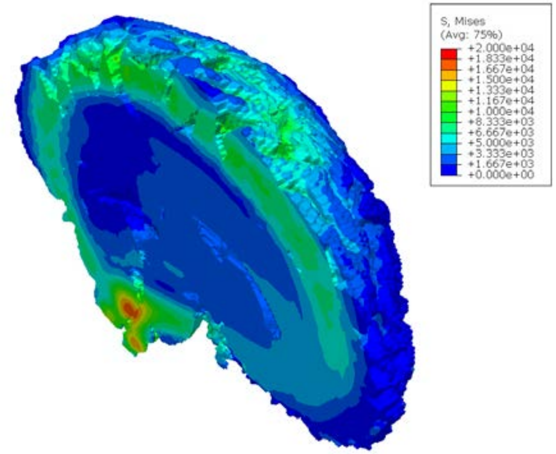


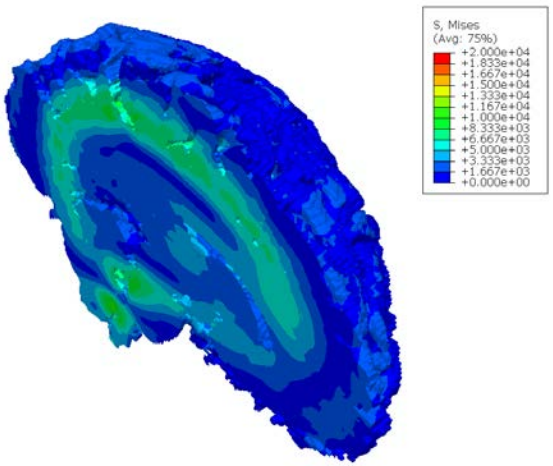
Fixed neck boundary condition

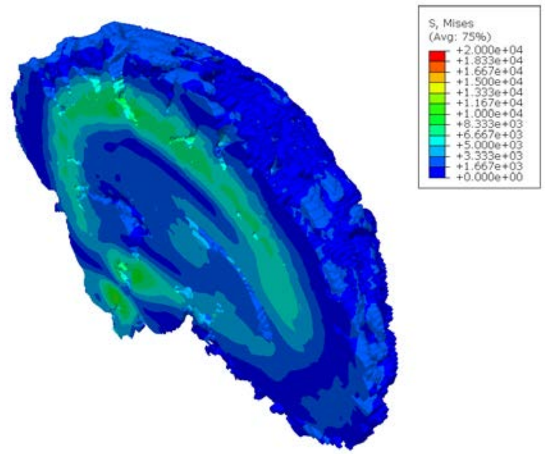
[*Acta Mech.*, 2010.]

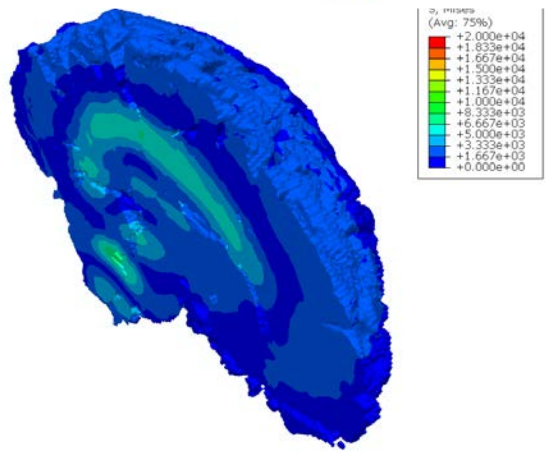


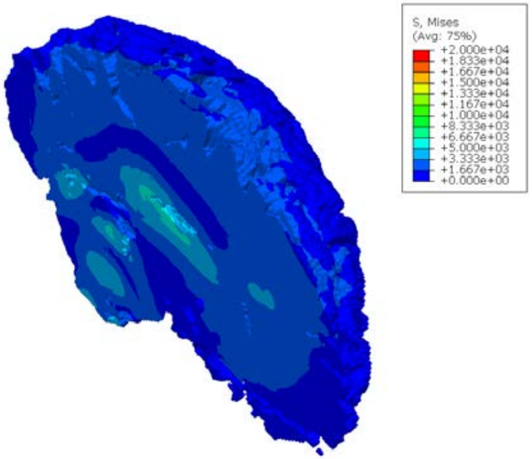






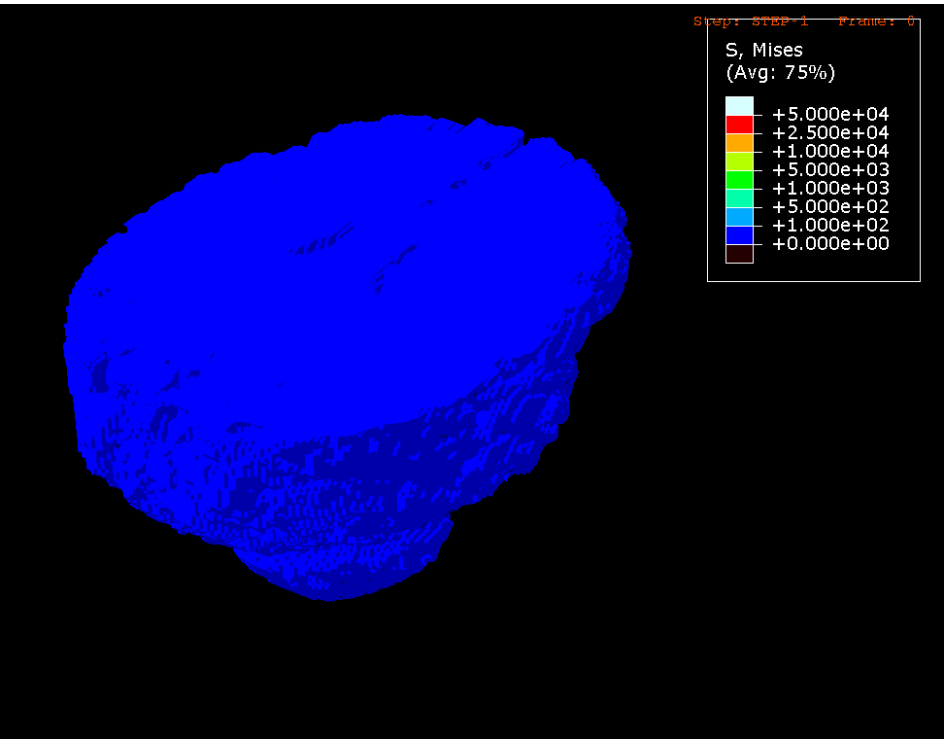




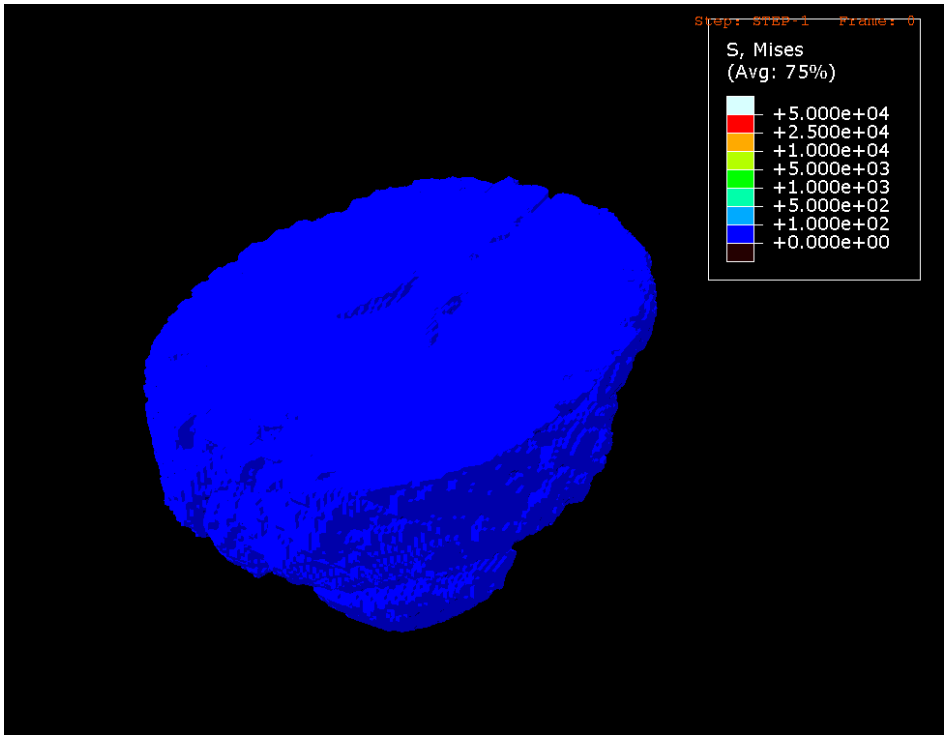


Free boundary condition at neck

side impact

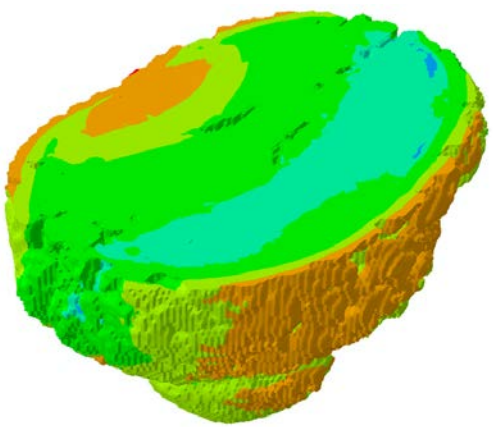


Free neck boundary condition

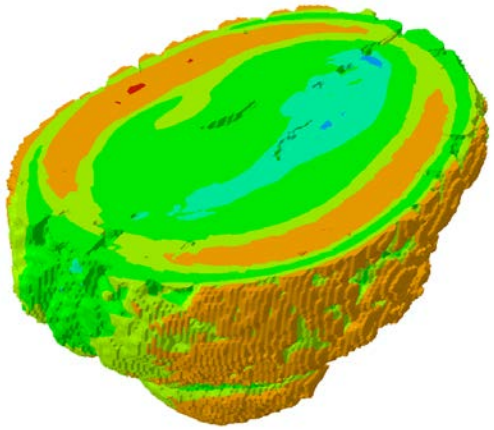


Fixed neck boundary condition

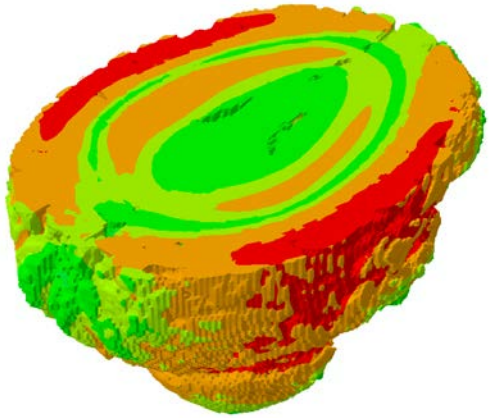
side impact



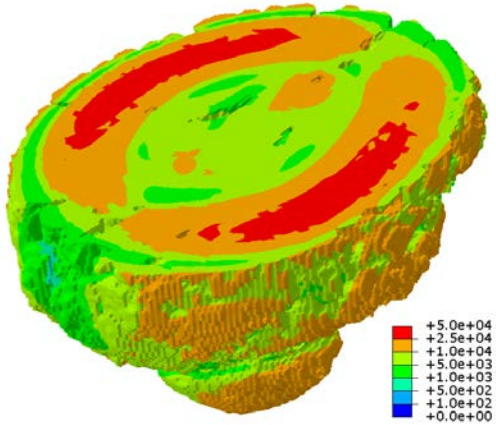
5 *ms*



8 *ms*

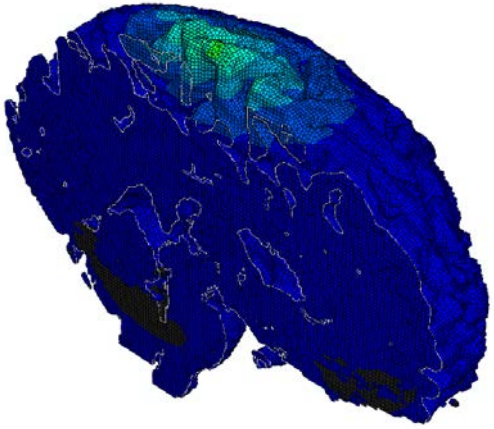


11 *ms*

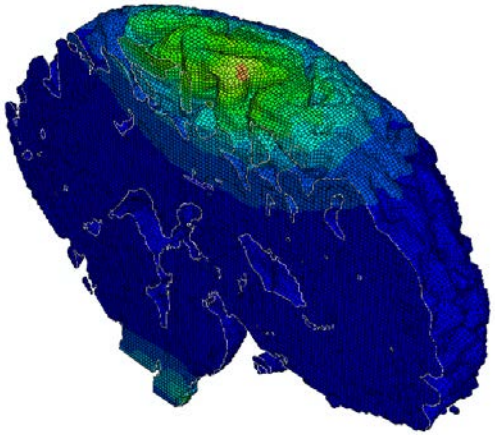


13 *ms*

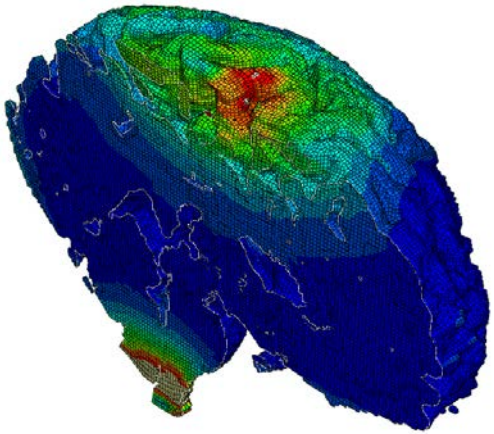
top impact



3 *ms*



4 *ms*



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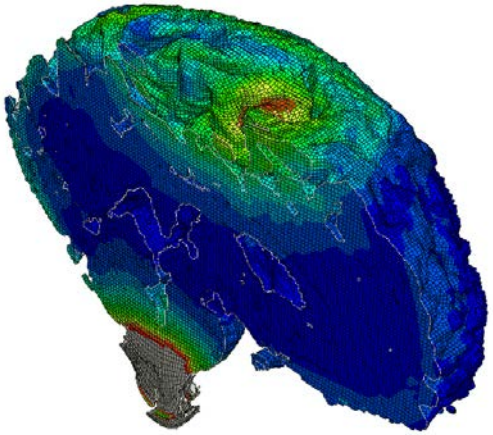
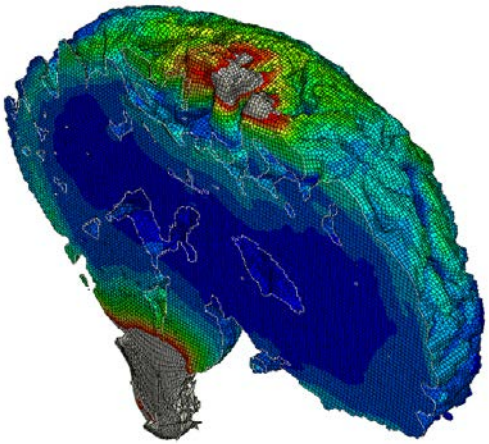
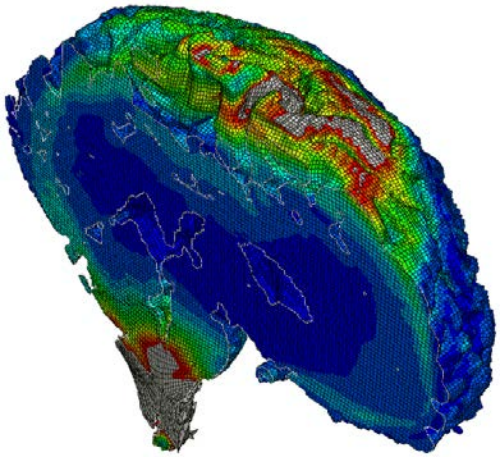


6 *ms*

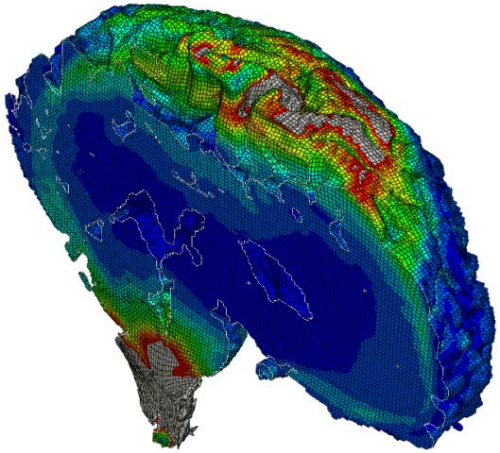


7 *ms*

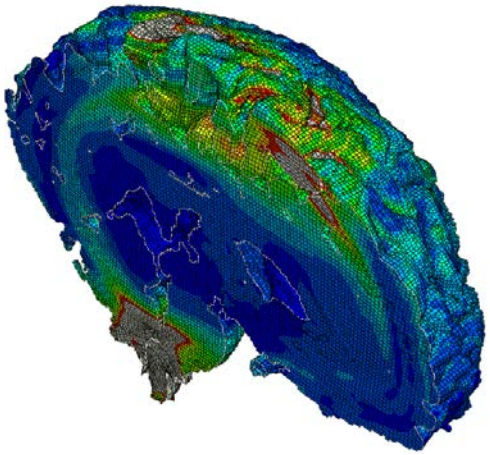


8 *ms*

top impact



9 *ms*



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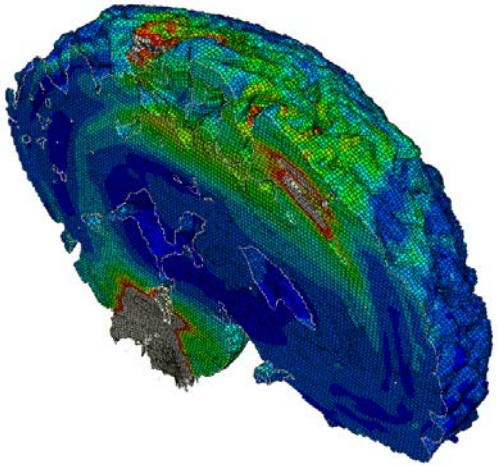

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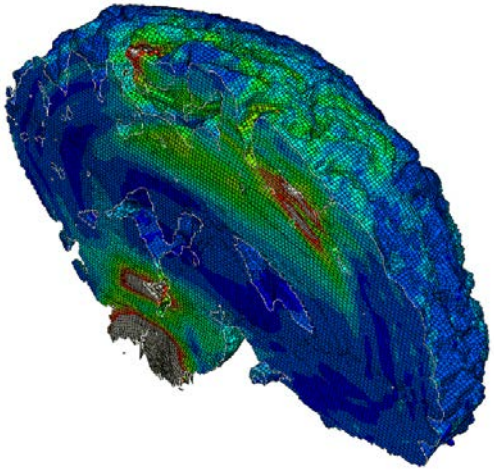
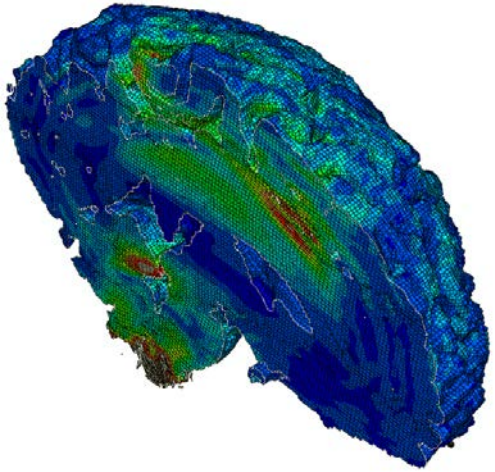


12 *ms*



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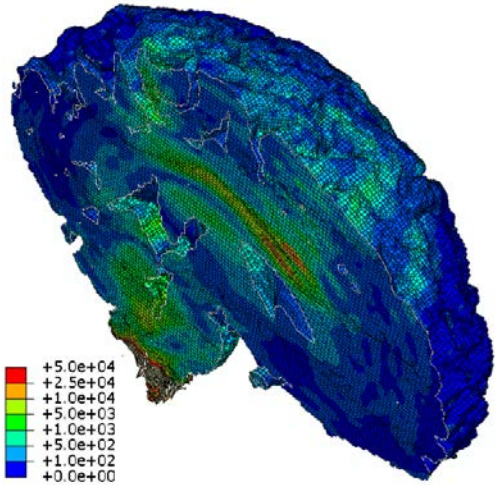
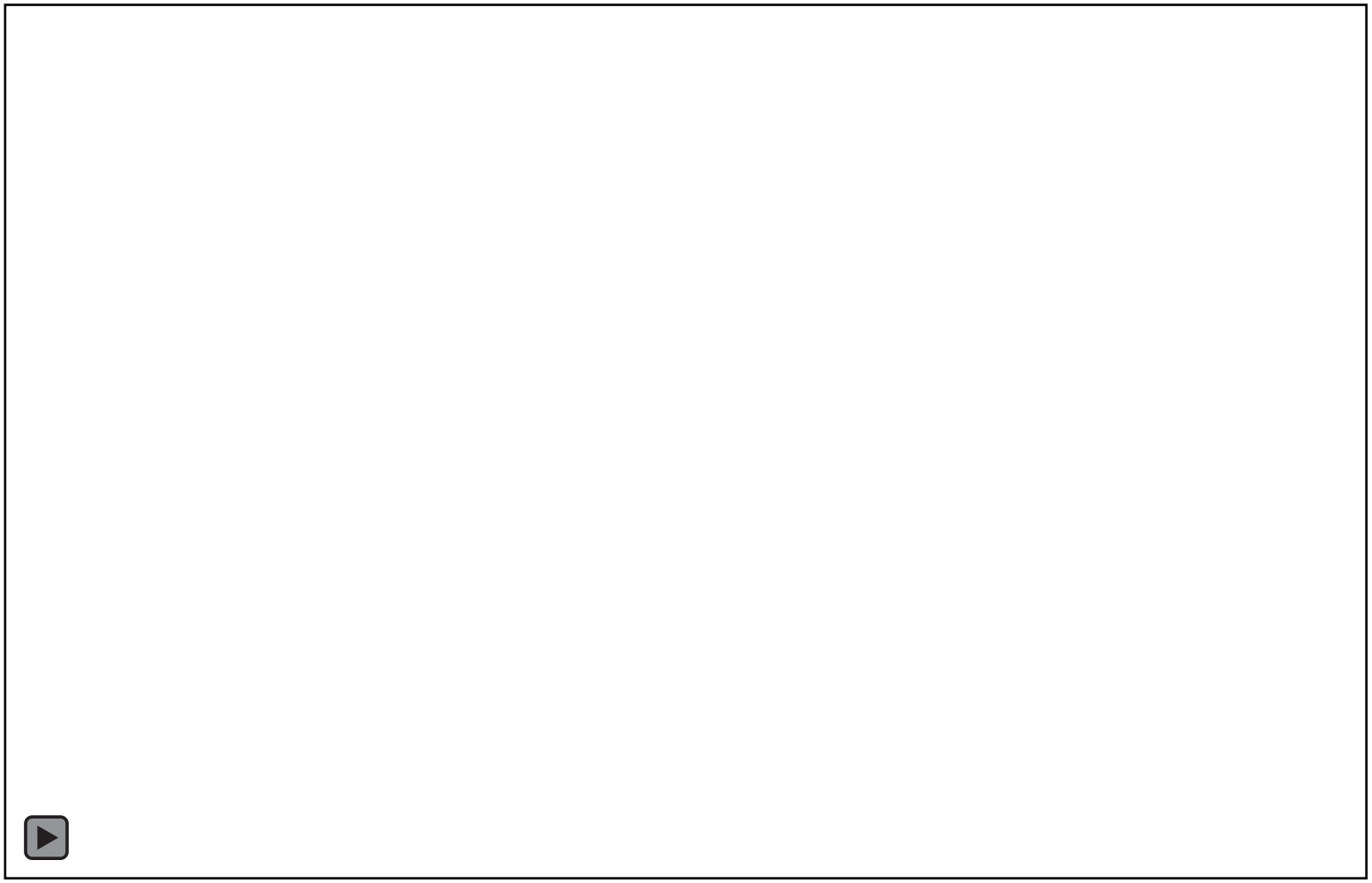


14 *ms*

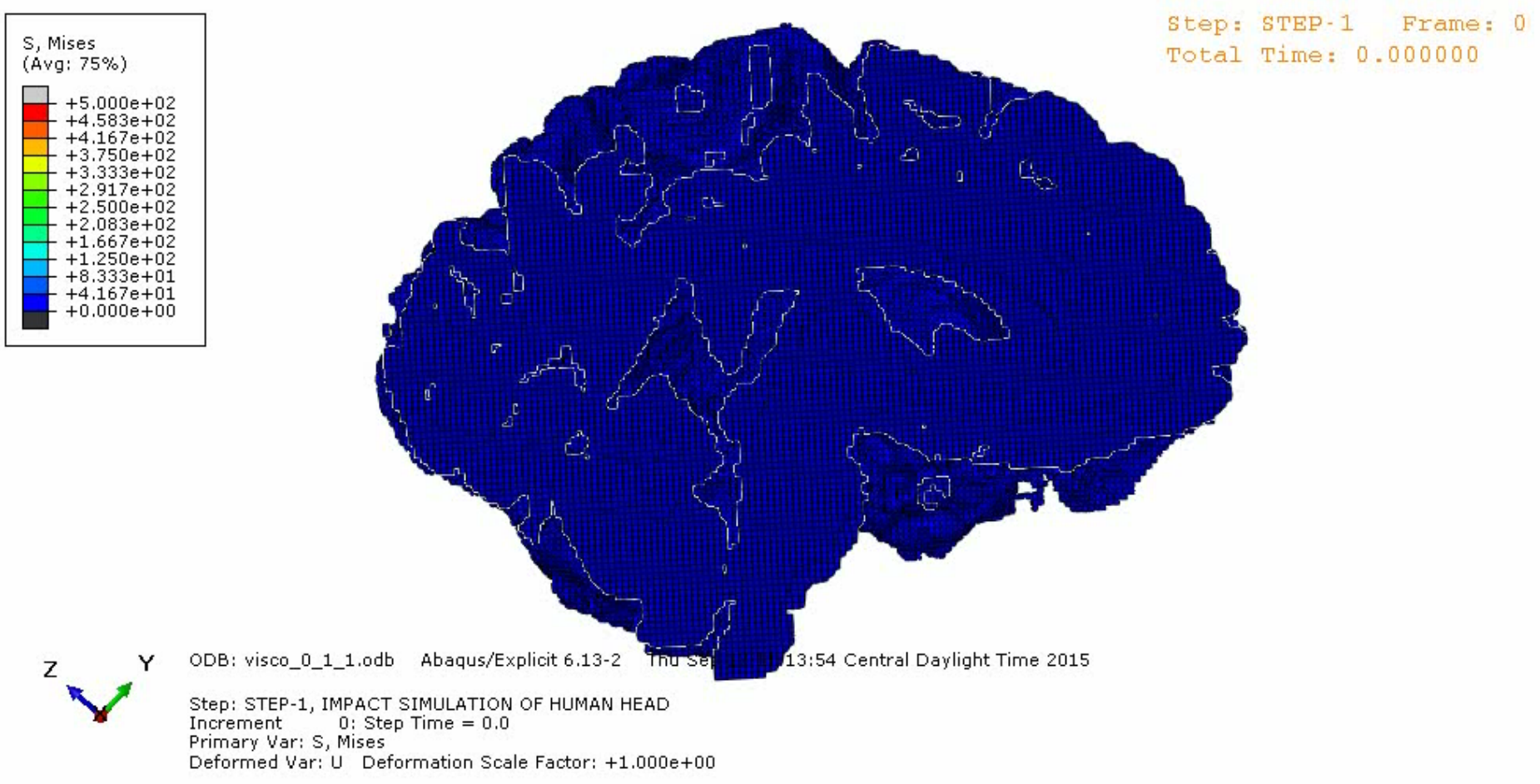
Incompressible Solid Elastic Constitutive Model of CSF



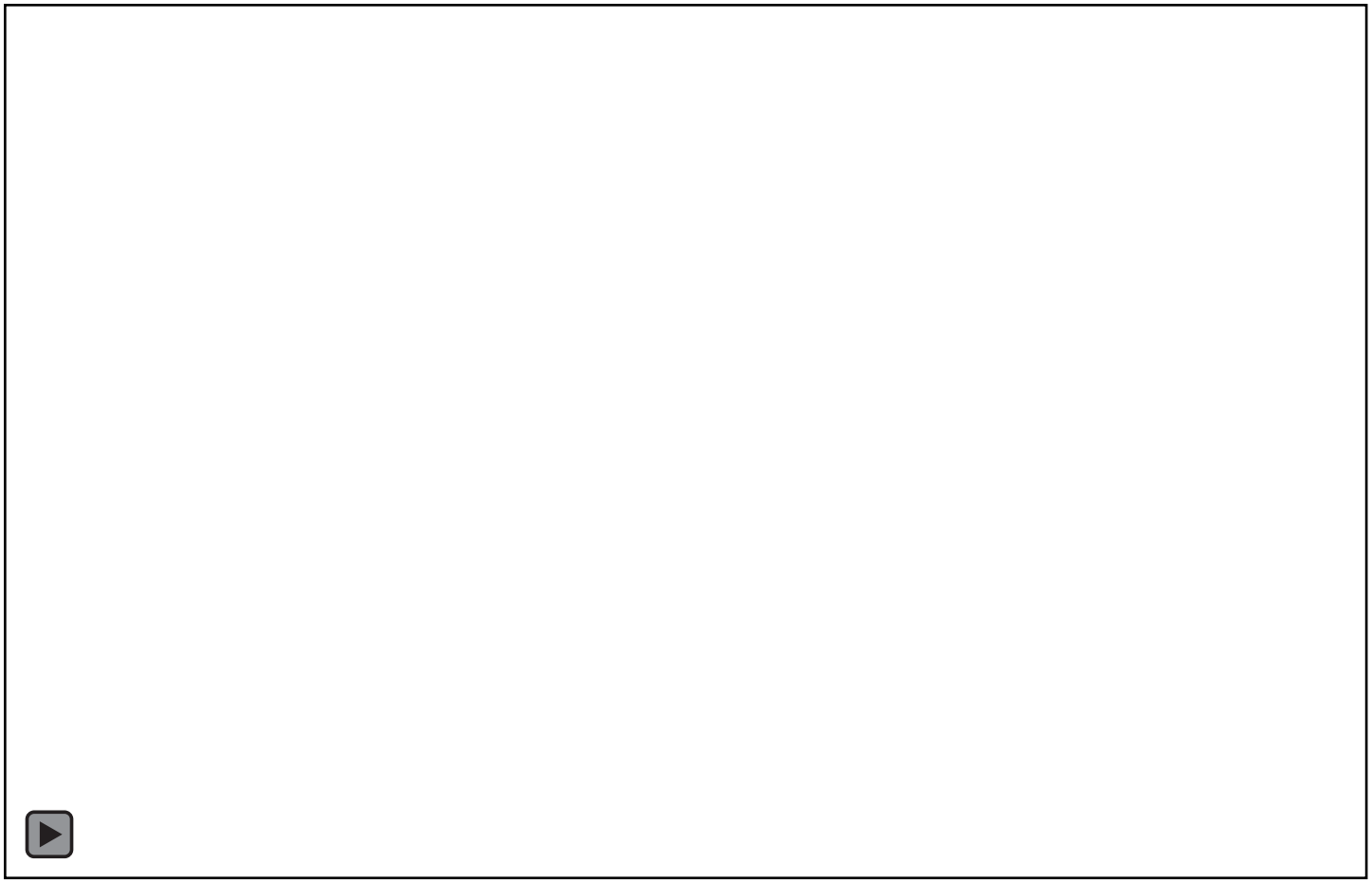
“Effect of cerebrospinal fluid modelling on spherically convergent shear waves during blunt head trauma,” *Int. J. Num. Meth. Biomed. Eng.*, on line 2017. DOI: 10.1002/cnm.2881

Viscoelastic Constitutive Model of CSF

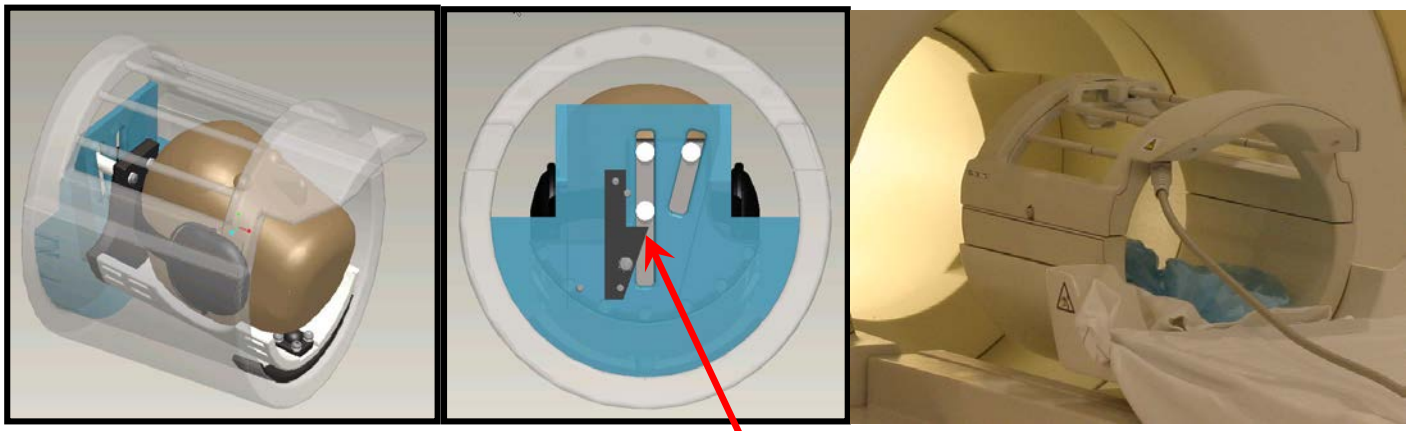
Long term shear modulus is set to zero, while short-term shear modulus is taken to be much smaller than bulk modulus



Fluid-like Elastic Constitutive Model



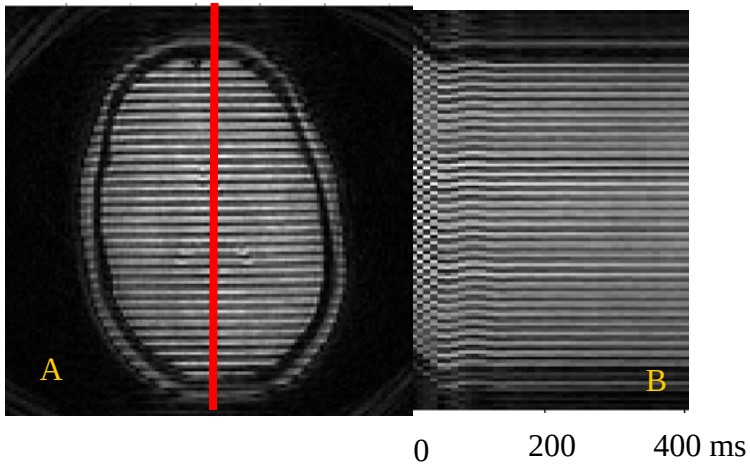
(a) (b) (c)



head drop device (HDD)

release mechanism for drop motion

HDD fits within Allegra 3 Tesla Head Coil Unit



From tagged MRI and harmonic phase (HARP) imaging analysis of an axial head drop experiment:

(A) tagged image at 100 *ms*

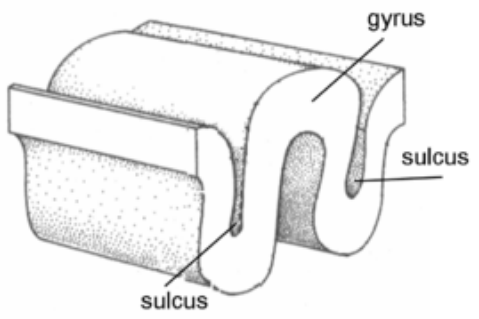
(B) time series of the central line of the image in (A)

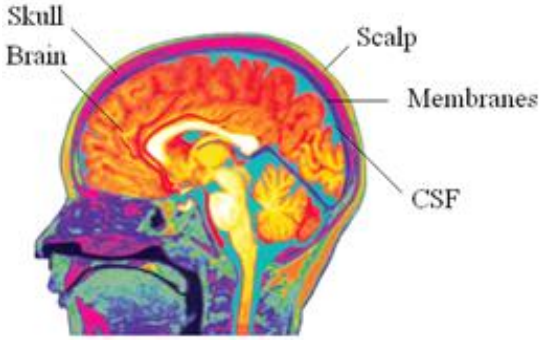
(C) time series of HARP motion estimated images.

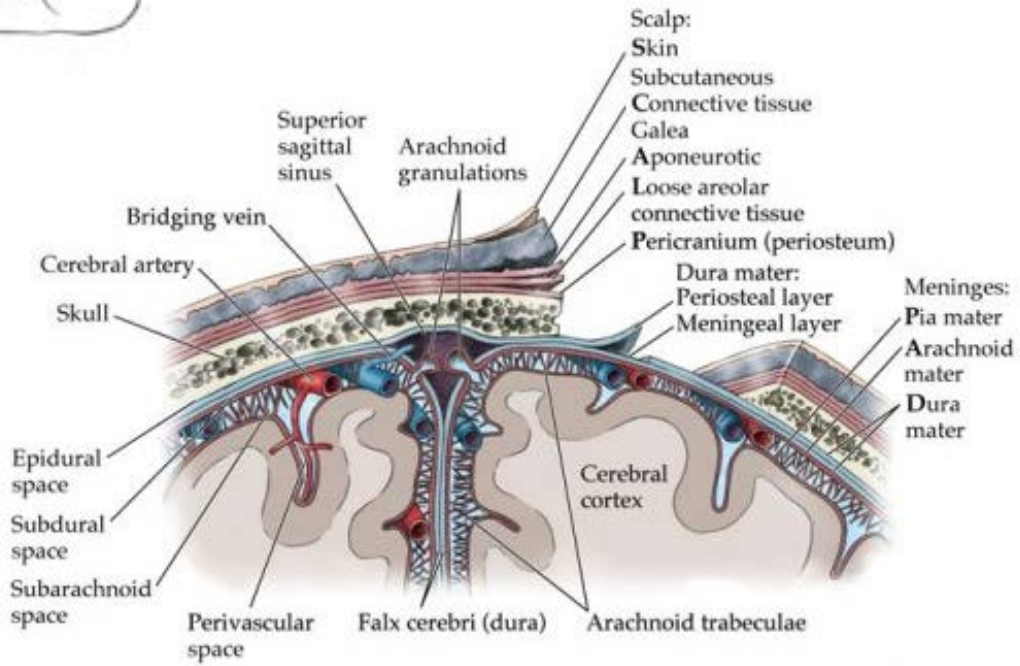
In a *2 cm* head drop tissue in the brain center displaces 2-3 *mm* relative to the skull, with maximum strains 5-10%.

["Brain deformation under mild impact: Magnetic resonance imaging-based assessment and finite element study," special issue "Brain Neuro-Mechanics" of *Int. J. Num. Anal. Model. Ser. B* **3**(1), 20-35, 2012]

- MRI voxel-based 3D FE head model – fast, accurate, patient-specific
- Validation against cadaver frontal impact experiment – good correlations are found
- Fast pressure waves
- Slow and spherically convergent shear stress waves, …
  potentially more damaging
- Such waves do not exist in all-fluid models of brain !
- *in vivo* human brain transient kinematics found by MRI
- Displacements predicted by FE model agree reasonably well with deformation estimated from image-based analysis
- … first validation of an FE head injury model on *in vivo* brain deformation data







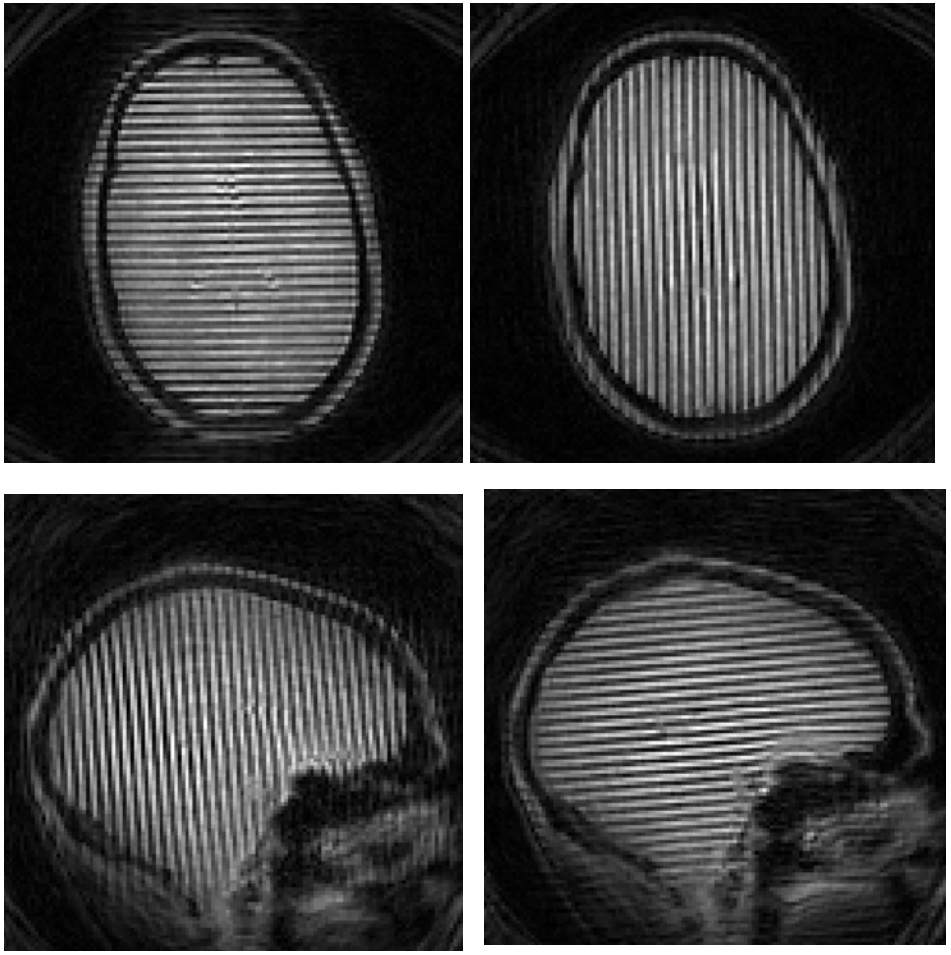
The surface of the brain, where the highest level of thinking takes place contains a hierarchical structure of folds.

A human (the most intellectually advanced “animal”) has the most folded surface of the brain: **fractal dimension *D* = 2.73 – 2.79**.

Future/Ongoing Work

- Geometry: add structures such as membranes
- Boundary/interface conditions: head/neck, brain/skull
- Multiscale material properties: brain tissues (fractal material geometry and homogenization)
- Better rheological model of CSF
- Validation: more experimental data … dynamic imaging on live subjects
- Collaboration with neurologists, clinicians

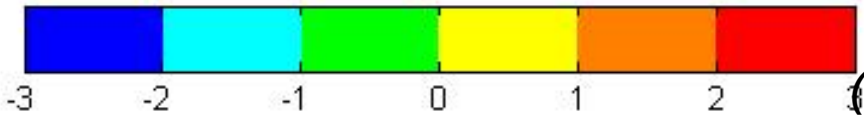
- Better continuum-type models/theories of fractal media … to tackle fluid, solid problems

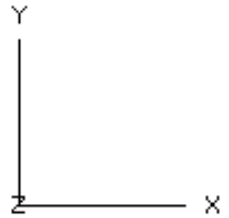


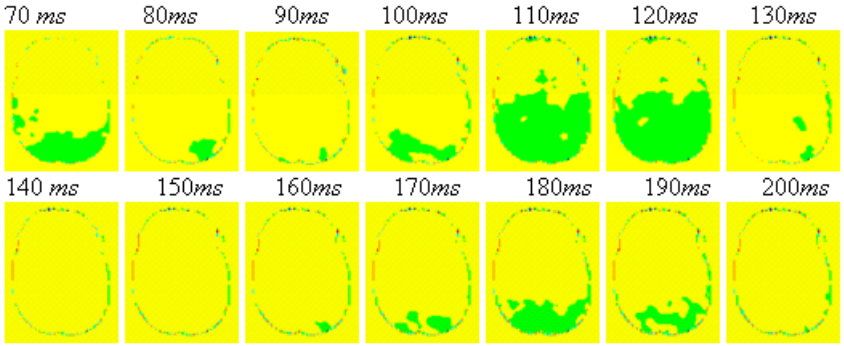
Tagging images of head drop.

Each image corresponds to the 10th time point (100 *ms*) of the drop.

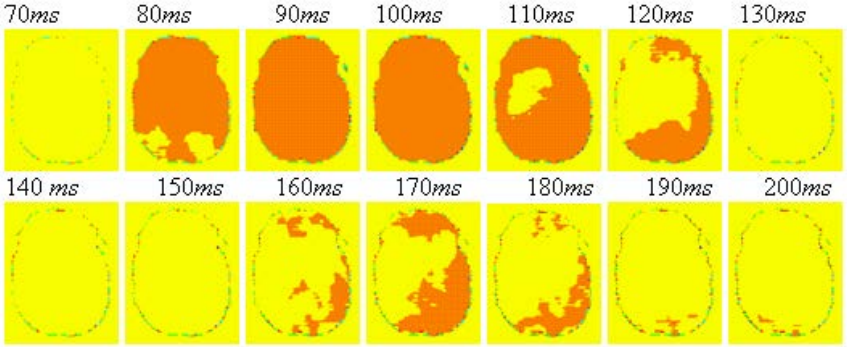
2D displacements



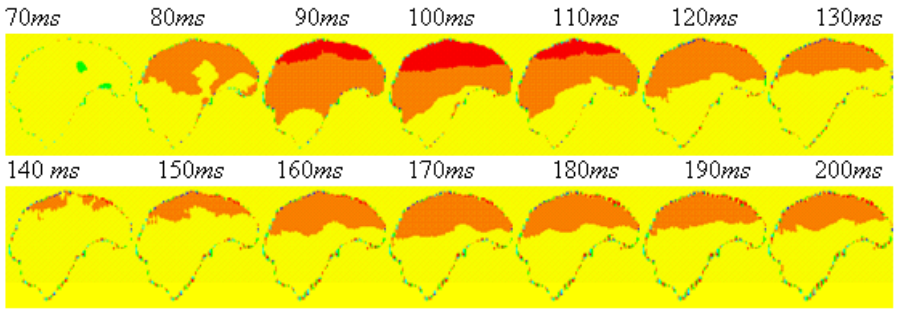




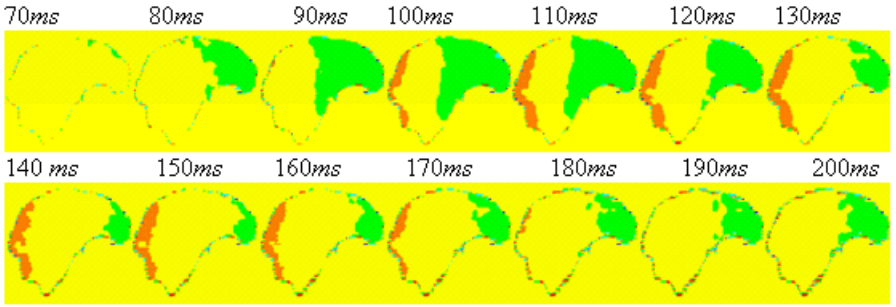
Axial u_x



Axial u_y

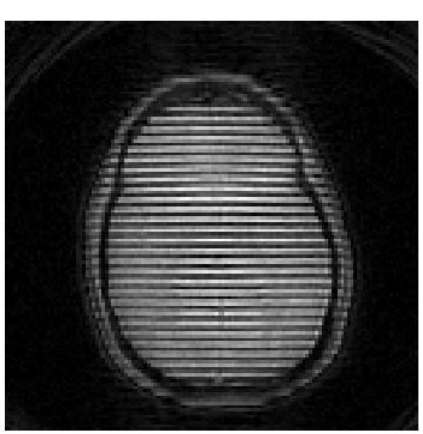


Sagittal u_y

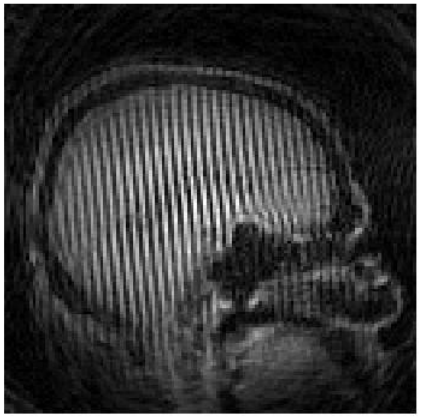


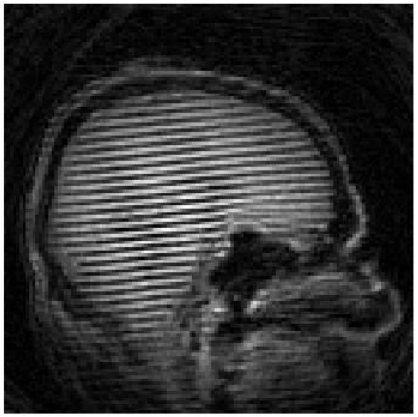
Sagittal u_z

Tagged MRI images



Axial slice

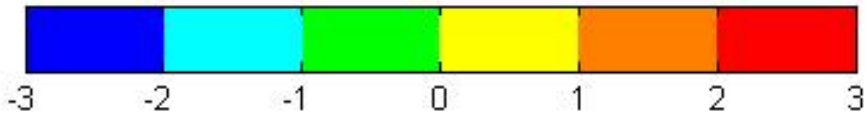




Sagittal slice

- 200 tagged images each series
- 10 *ms* temporal resolution
- Covering the first 2 seconds after the head drop
- MRI: multi-shot spiral acquisition, requiring only 12 drops

Image-based analysis vs. FE simulation – Axial Slice



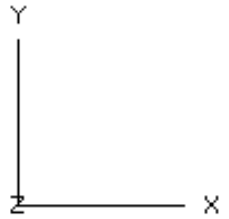
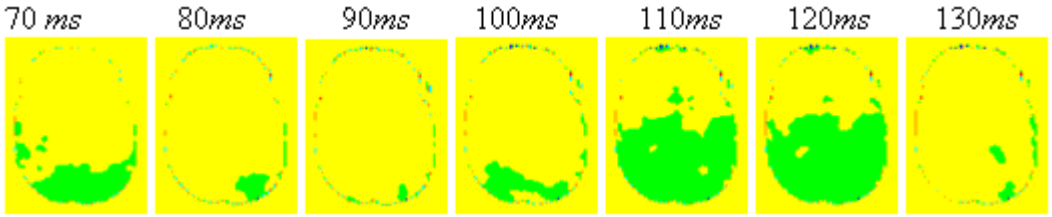


Image analysis



u_x

FE simulation

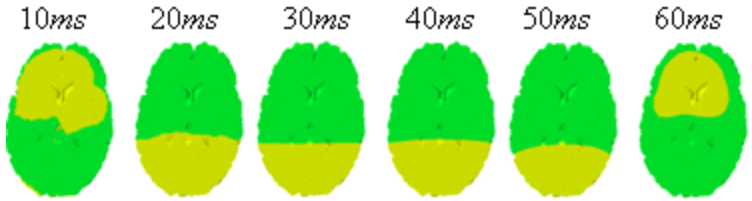
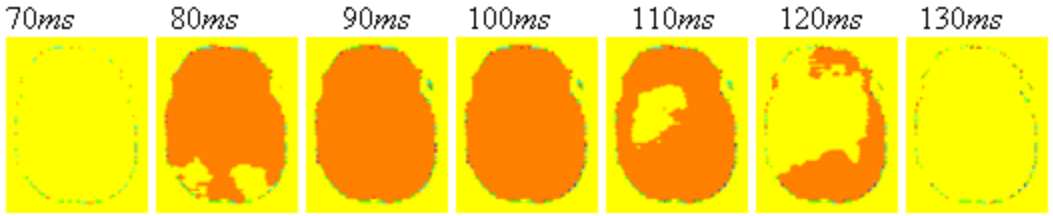


Image analysis



u_y

FE simulation

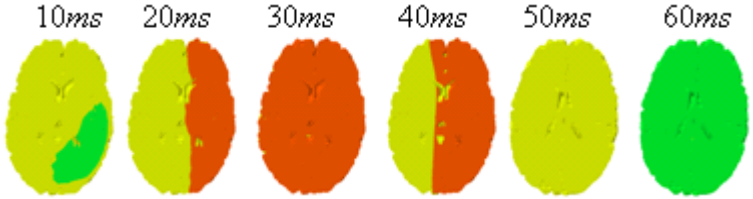
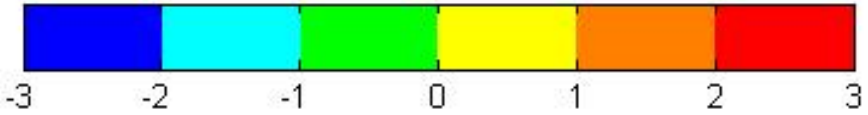


Image-based analysis vs. FE simulation – Sagittal slice



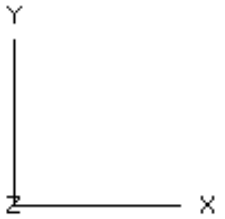
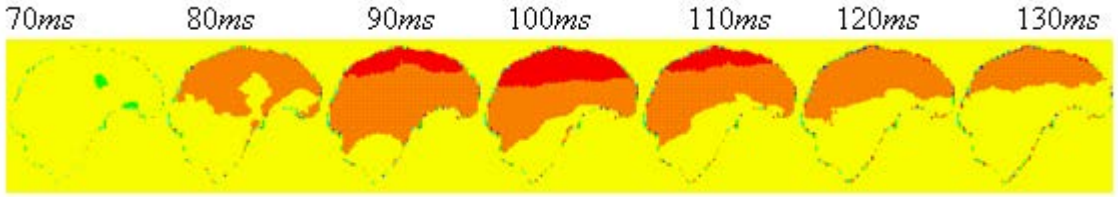


Image analysis



u_y

FE simulation

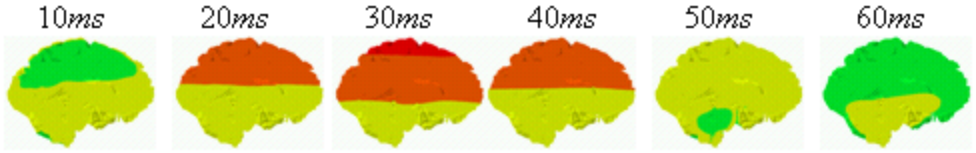
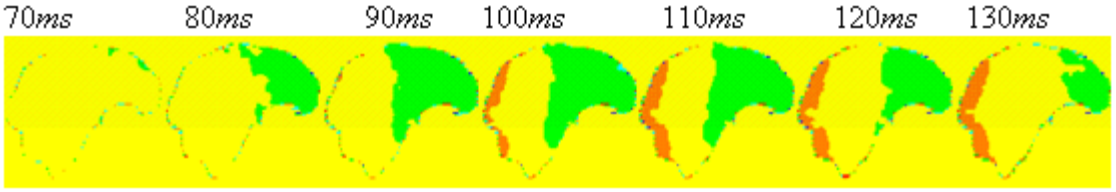
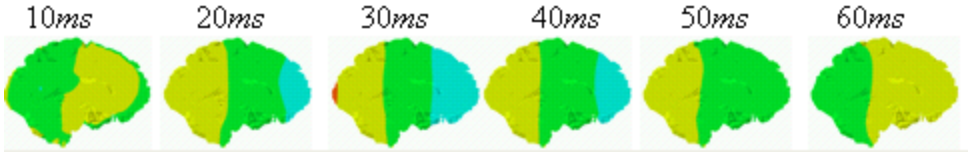


Image analysis

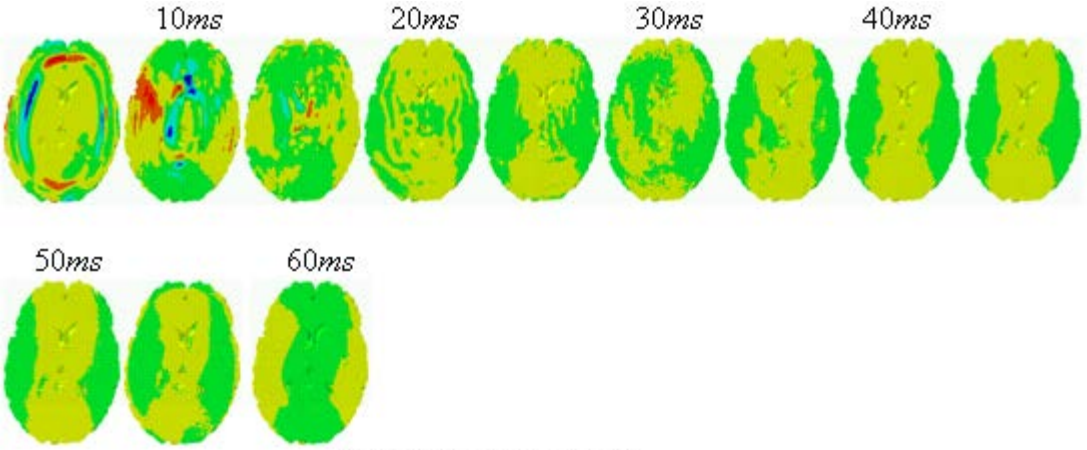


u_z

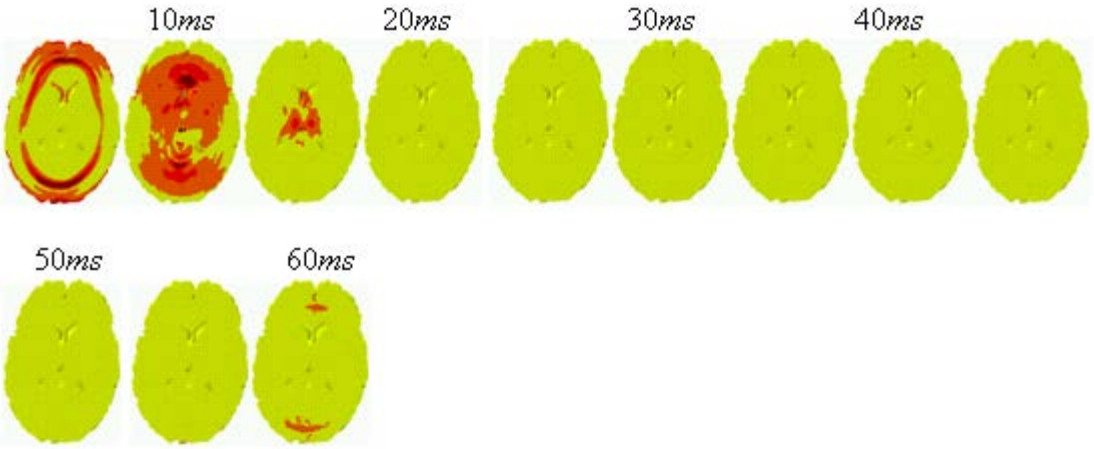
FE simulation



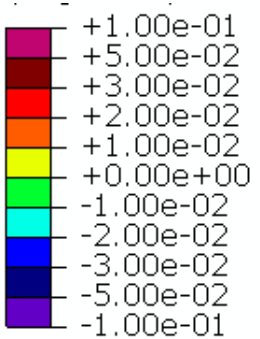
Strain – Axial slice

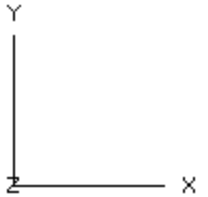


(a) In-plane shear strain



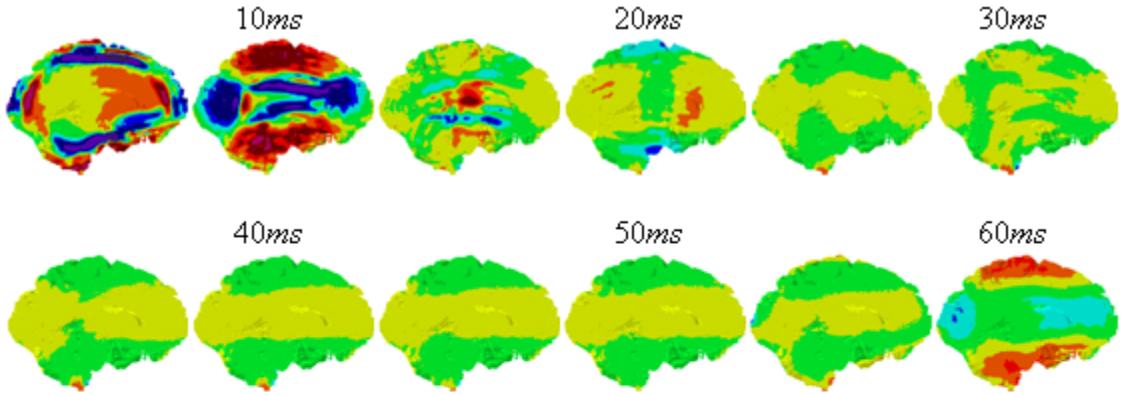
(b) Maximum principal strain



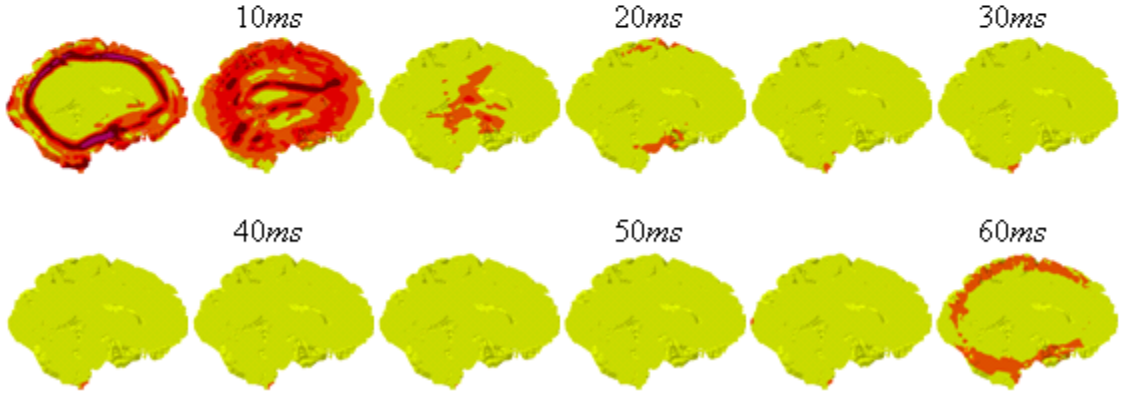


Maximum strain: < 5%

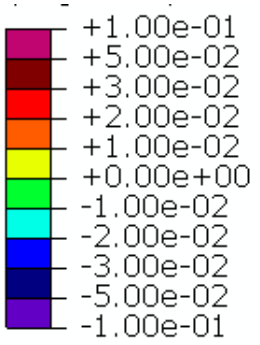
Strain – Axial slice

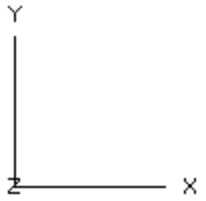


(a) In-plane shear strain



(b) Maximum principal strain





Maximum strain: < 10%

Harmonic phase image analysis

SPAMM-tagged image $I(\mathbf{y},t)$

→F.T. $F\{I(\mathbf{y},t)\}$

→Isolate one harmonic peak $F_k \cdot F\{I(\mathbf{y},t)\}$

→Inverse F.T. $I_k(\mathbf{y},t) = F^{-1}\{F_k \cdot F\{I(\mathbf{y},t)\}\}$

harmonic image

magnitude image

phase angle image

~ tissue motion

2D displacements (cont.)

- First oscillation: 70*ms*-140*ms*

  Second oscillation: 150*ms*-200*ms*
- Maximum displacement: 2-3*mm*
- Larger displacement during the first oscillation

FE simulation of mild impact

- MRI voxel-based head mesh
- same material properties, interface condition
- friction coefficient between the human head and the rigid surface: 0.3
- boundary condition: fixed at head-neck junction

- Maximum strains occur in the first few milliseconds after impact during the first oscillation of the brain
- Strain exceeds 10% under moderate and severe impact during the initial time after the impact
- A reasonably good correlation was found between the displacement fields obtained through MRI-based HARP analysis and through the FE simulation