

Recent Results on MR Imaging of Shear Wave Propagation in the Human Brain

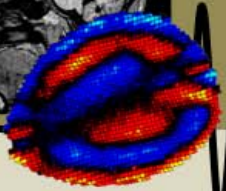
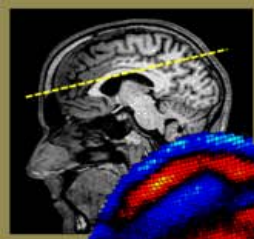
Second Traumatic Brain Injury Research Symposium
College Park, MD
19 May 2011

Erik H. Clayton^a Philip V. Bayly^{a,b}

^a Department of Mechanical Engineering and Materials Science

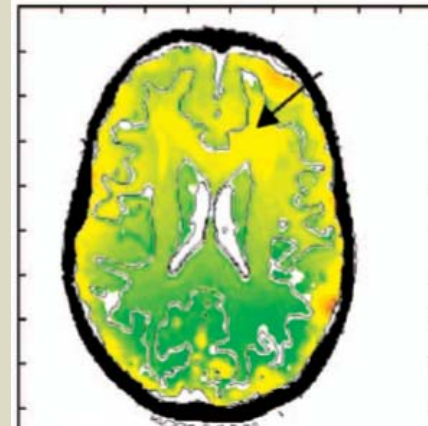
^b Department of Biomedical Engineering
Washington University in St. Louis, USA

Validation of numerical models of brain biomechanics

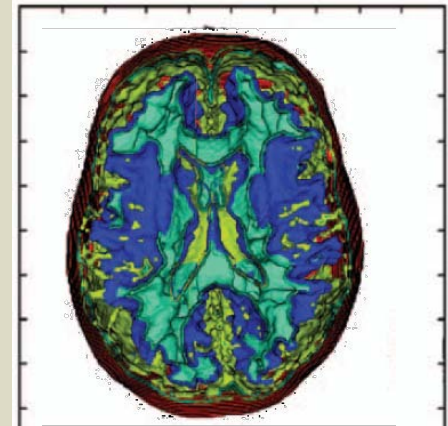


- Numerical simulations of TBI are the *wave* of the future.
 - How to evaluate accuracy of models?
- Simulations need to be experimentally **parameterized** and **validated**.
 - Magnetic Resonance Elastography

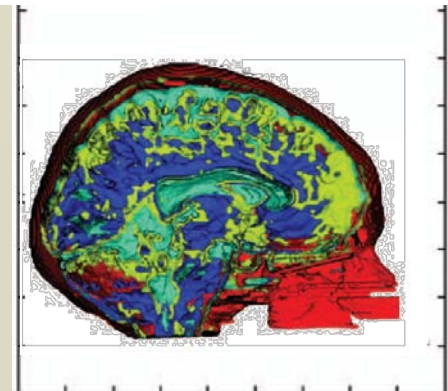
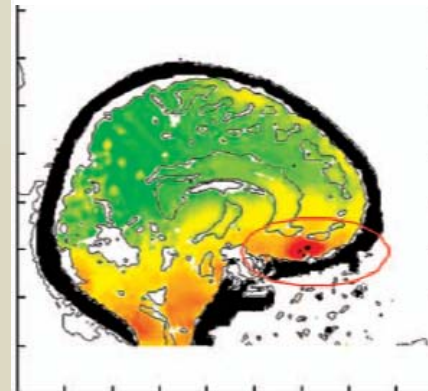
Simulated
Response to Blast

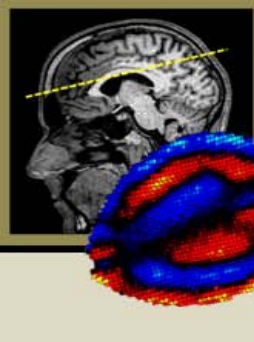


Brain FE Mesh



P. A. Taylor and C. A. Ford, "Simulation of Blast-Induced Early-Time Intracranial Wave Physics leading to Traumatic Brain Injury" *J. Biomech Eng.*, June 2009.

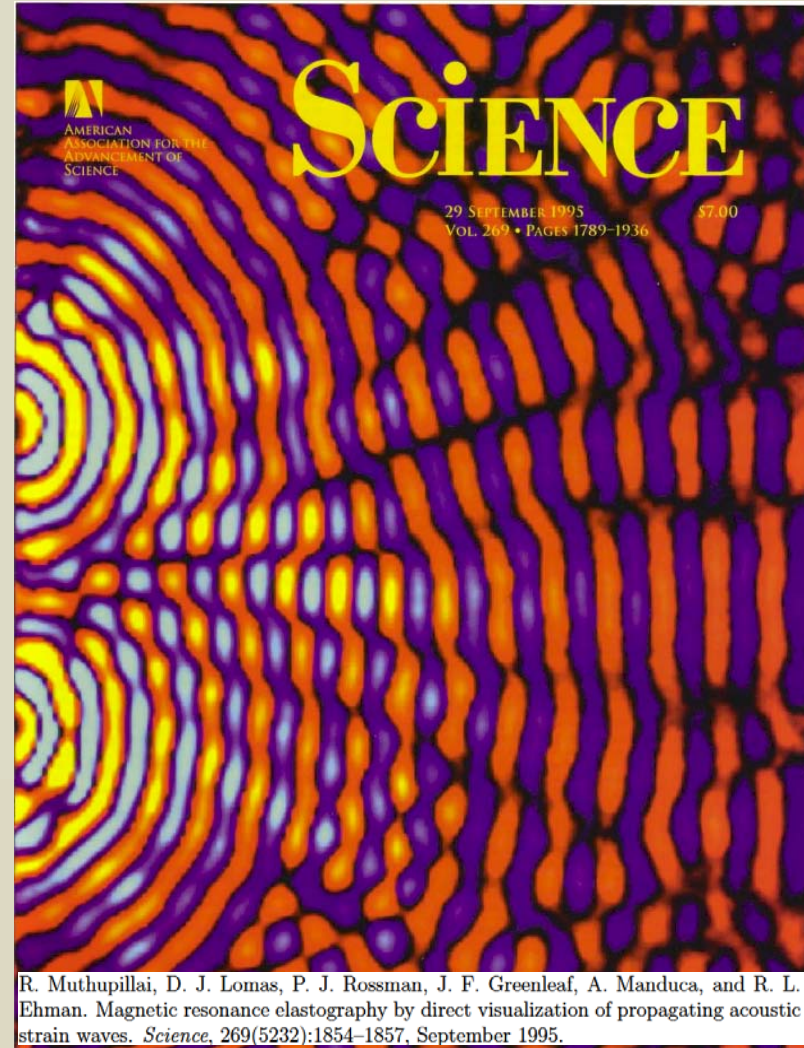




What is Magnetic Resonance Elastography?

“A nuclear magnetic resonance imaging (MRI) method...for quantitatively mapping the physical response of a material to harmonic mechanical excitation...allow[ing] calculation of regional mechanical properties...from spatial temporal [displacement fields]...”

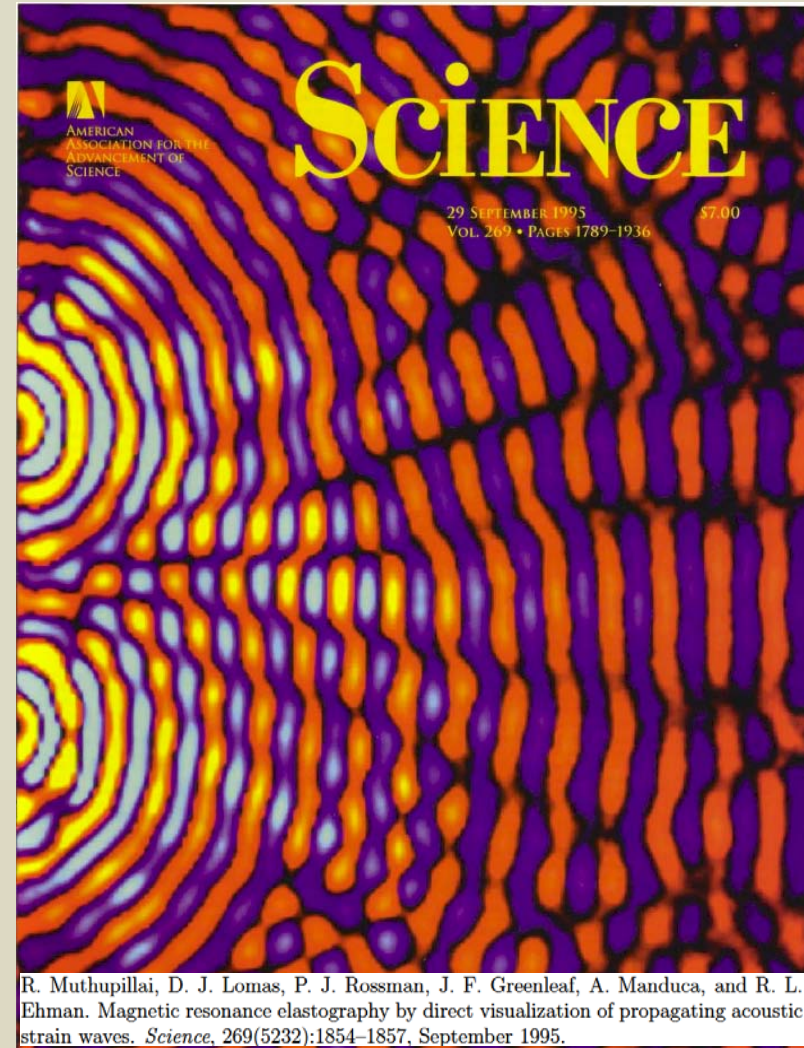
- Muthupillai et al., *Science*, 1995



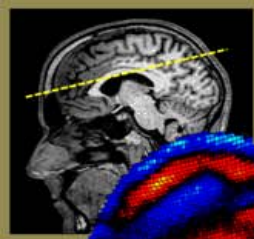
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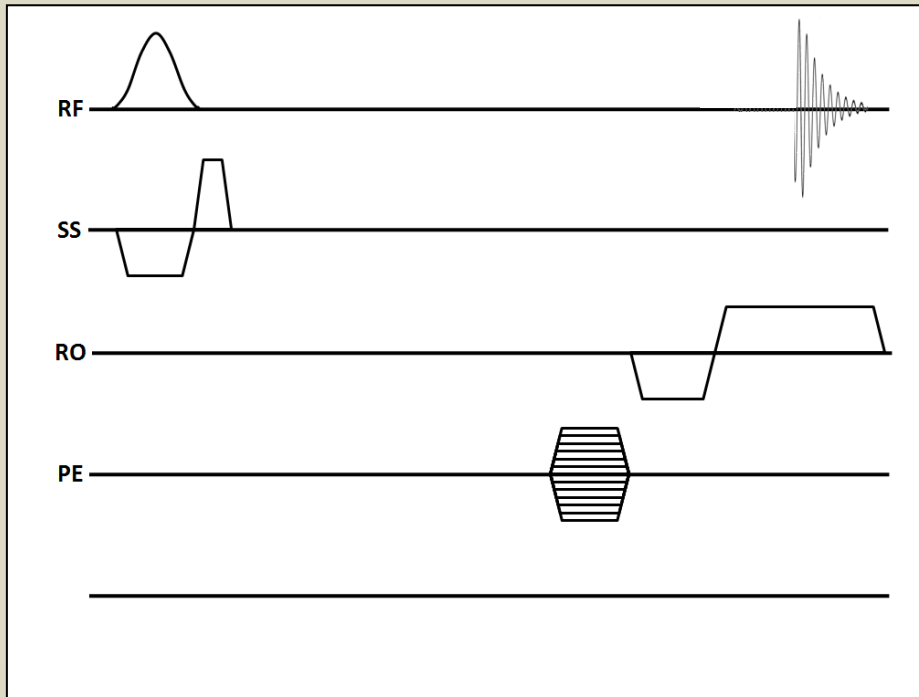
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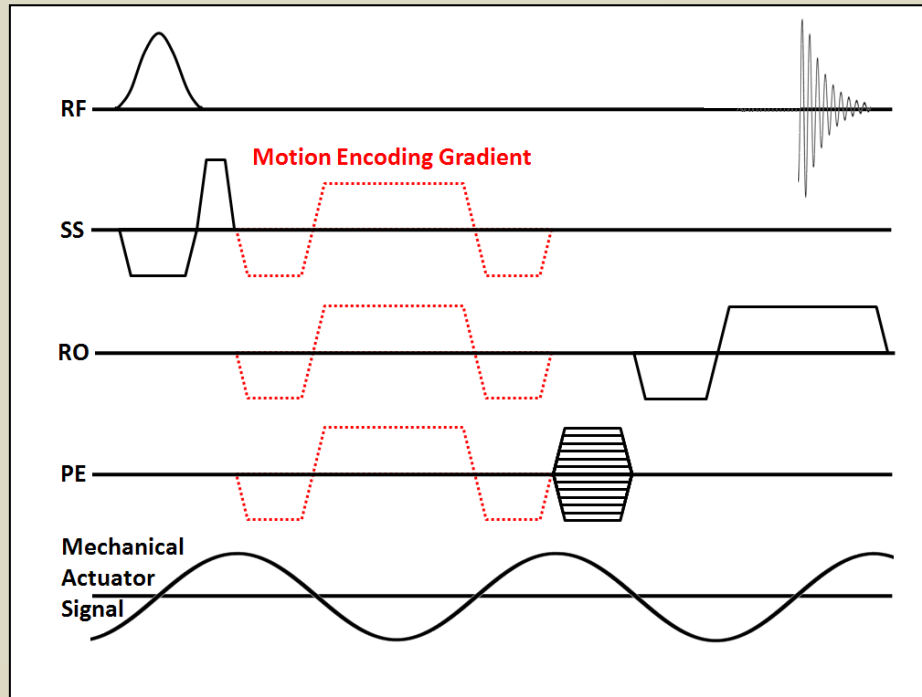
Encoding wave motion: *phase shift* in NMR signal



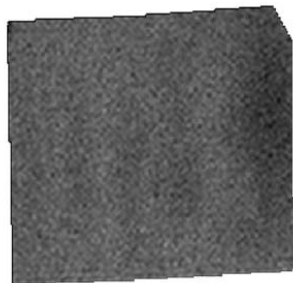
Traditional Gradient-recalled Echo



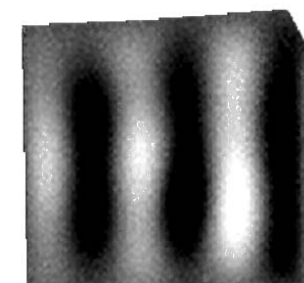
MRE Gradient-recalled Echo



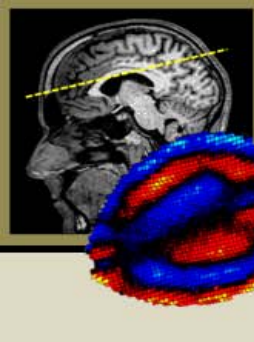
Example:
Cube of biomaterial



Intensity
Image

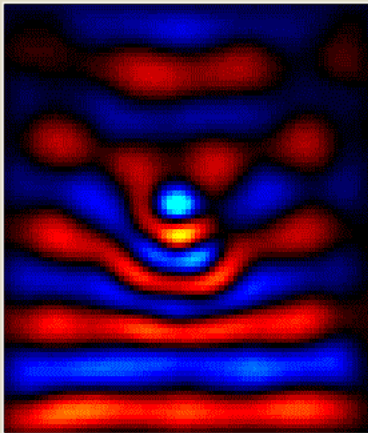


Wave
Image



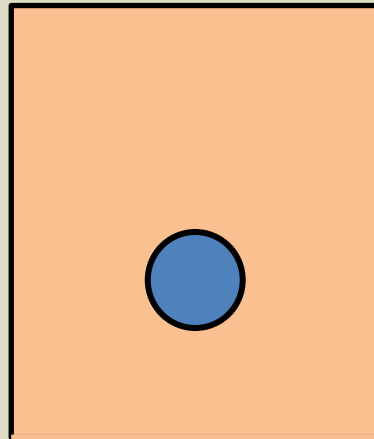
Spatiotemporal wave motion is imaged *in vivo*

y
x



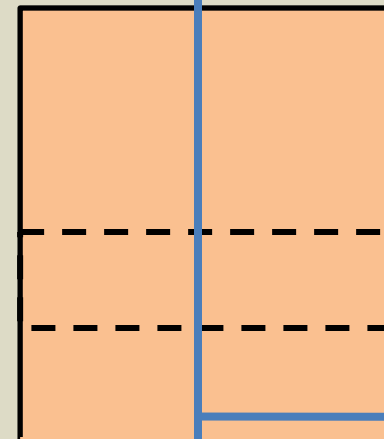
Spatiotemporal Images of Shear Wave Propagation

y
x



Container of Gelatin w/ Soft Inclusion

y
z

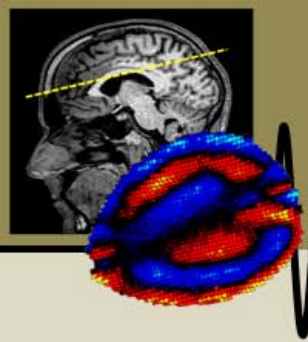


Harmonic actuator (~20 μm peak-to-peak)

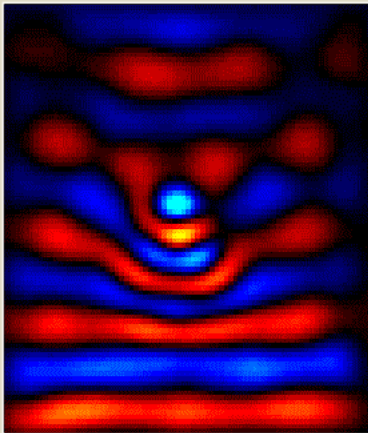
Shear wave displacement axis



Material properties can be determined from wave motion: *Stiffness*

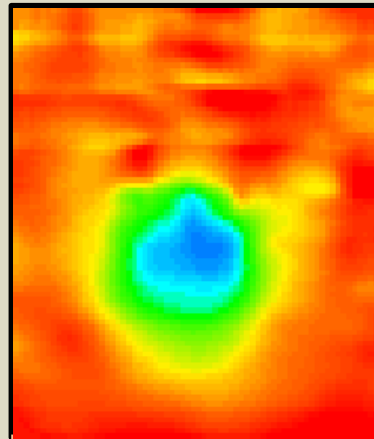


y
x



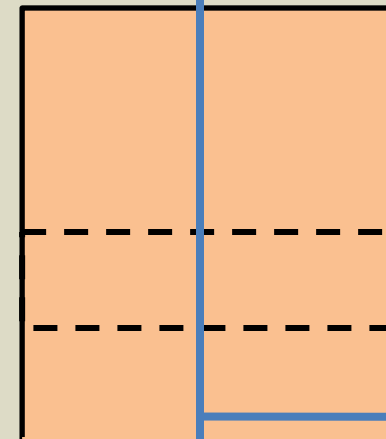
Spatiotemporal
Images of Shear
Wave Propagation

y
x



Shear Modulus
Map

y
z



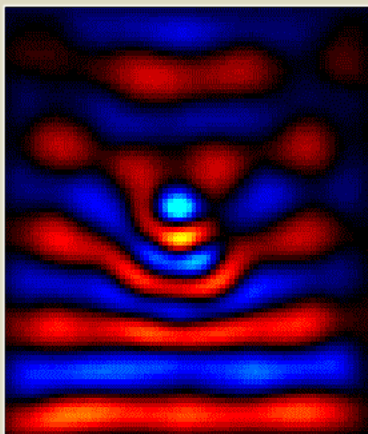
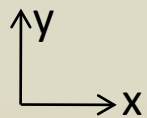
Harmonic actuator
(~20 μm peak-to-peak)

Shear wave
displacement axis

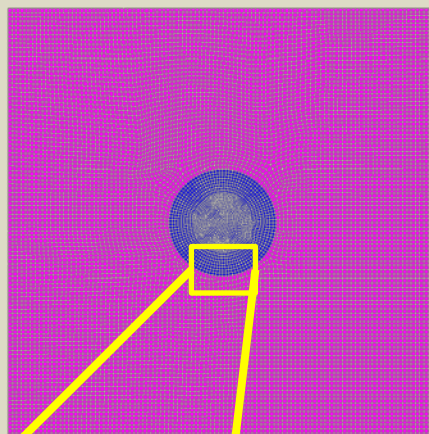
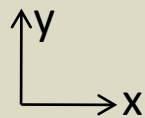


Raw MRE displacement data can be used to validate numerical models

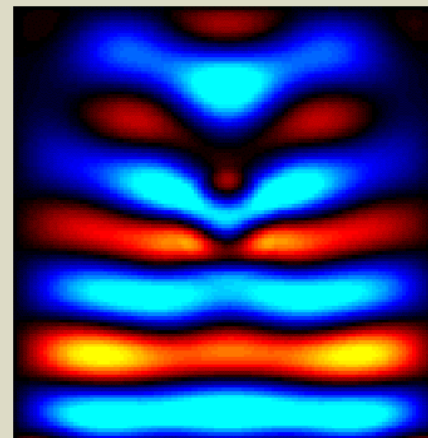
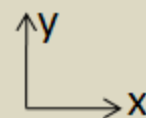
Consider the wave field itself...



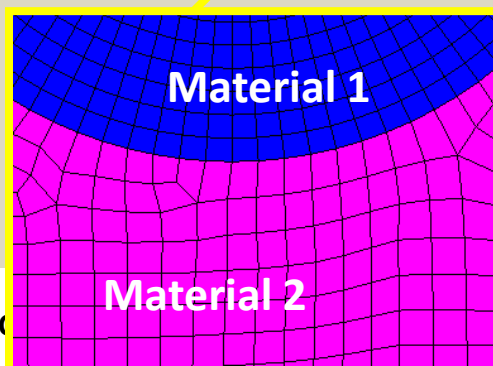
Experimental Data



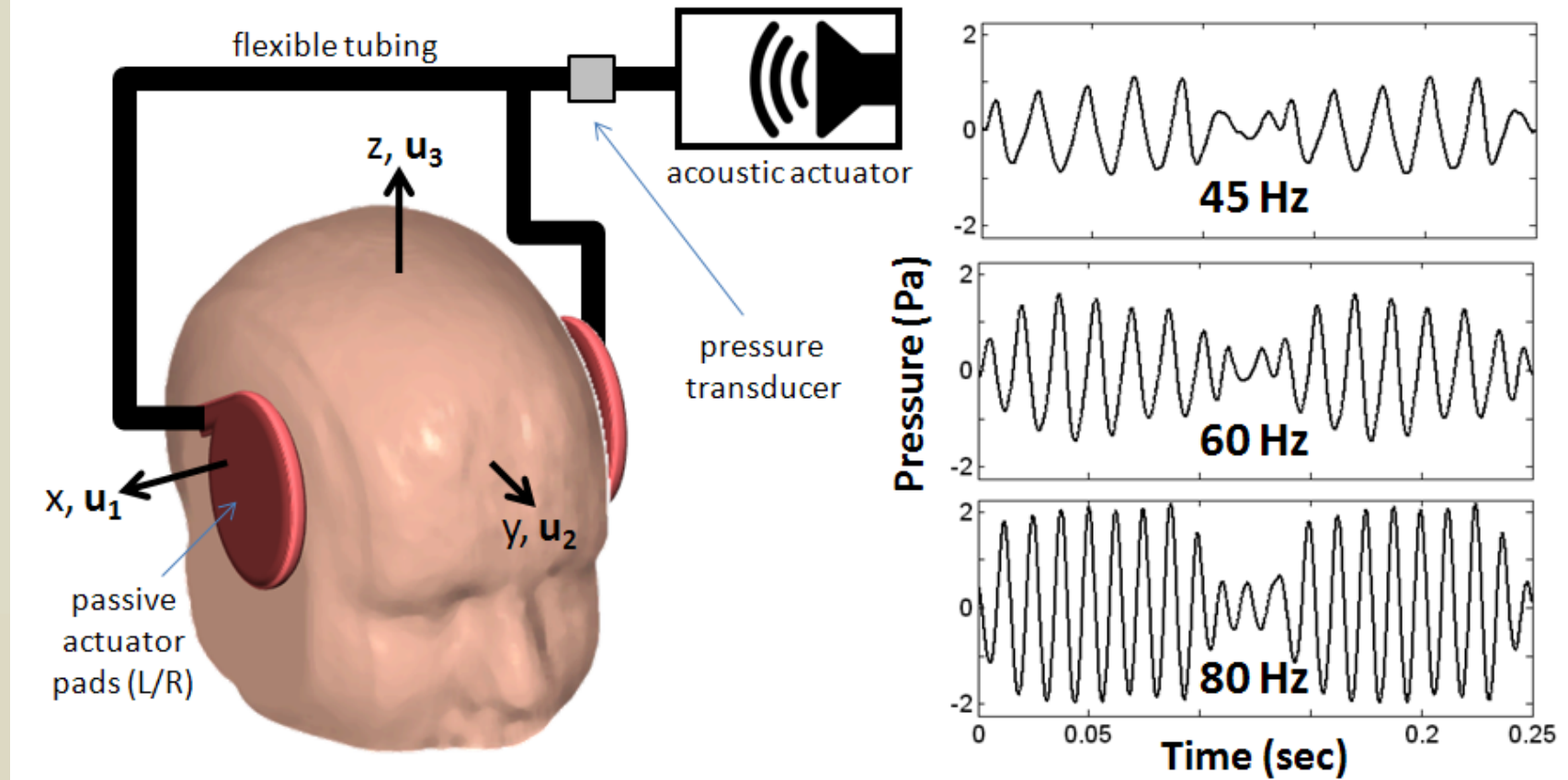
Finite Element Mesh



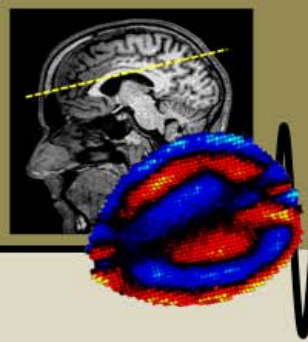
Simulated Results



Experiment setup



Human experiments at 1.5 T

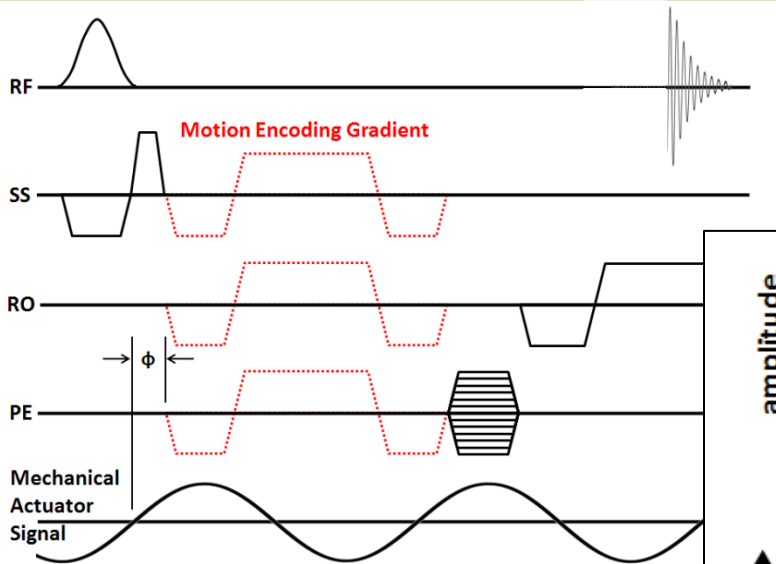


PS: GRE-MRE (Bolster/Priatna, Siemens)

TR/TE: 133.3/27.5, FA: 25°, nt: 1

DM: 128 x 128 x 1 x 4

t_{acq}: 12 minutes/frequency/direction

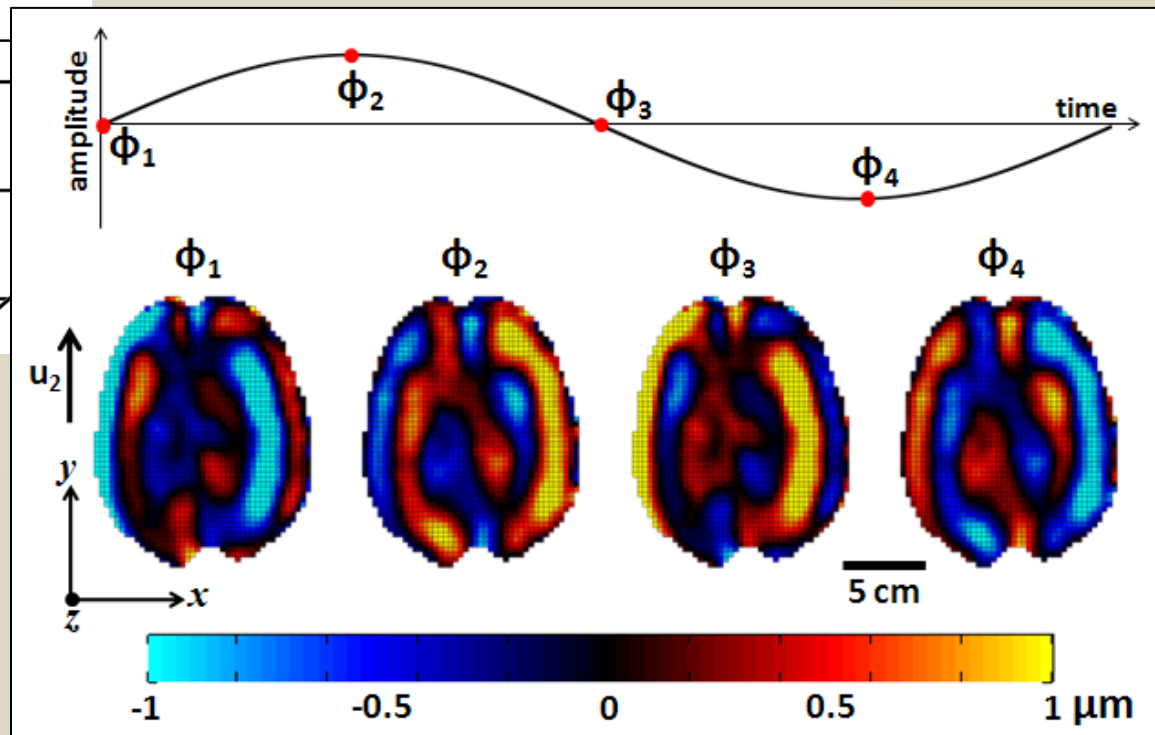


Motion components : u , v , & w

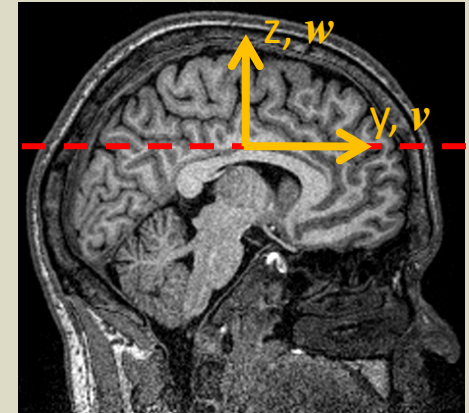
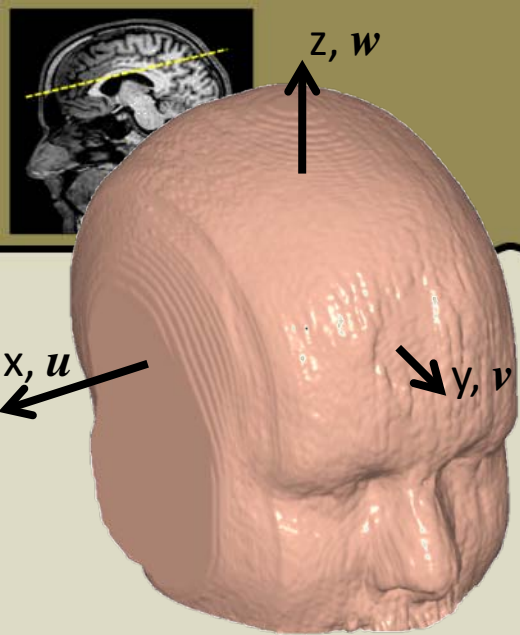
No. Image Slices : 1

Temporal Resolution : 4 point

Voxel : 3.0 x 3.0 x 3.0 mm³



All displacement components acquired



μm



u -component

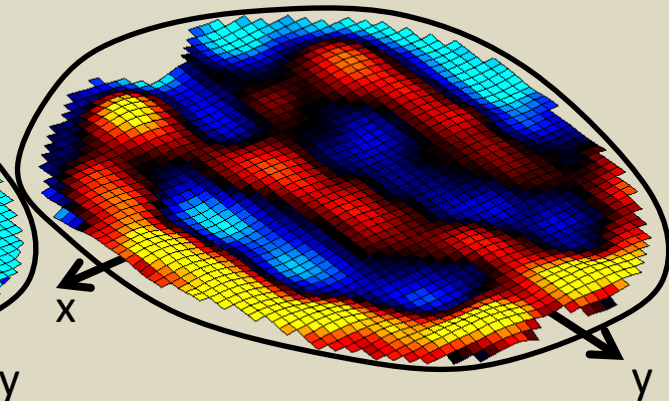
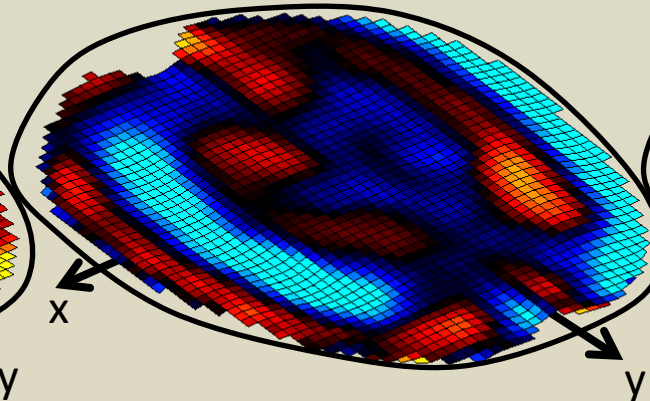
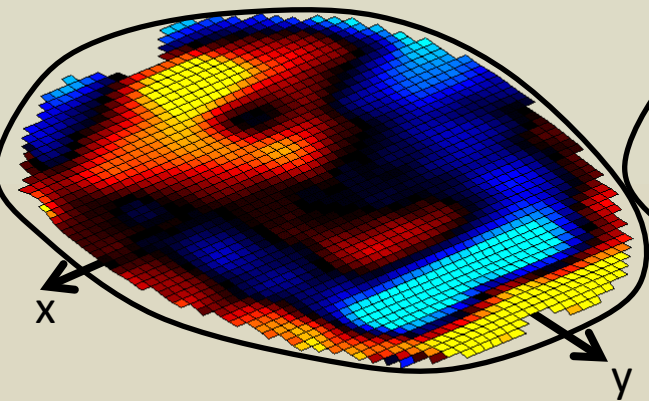
Displacements
Scaled x2000

v -component

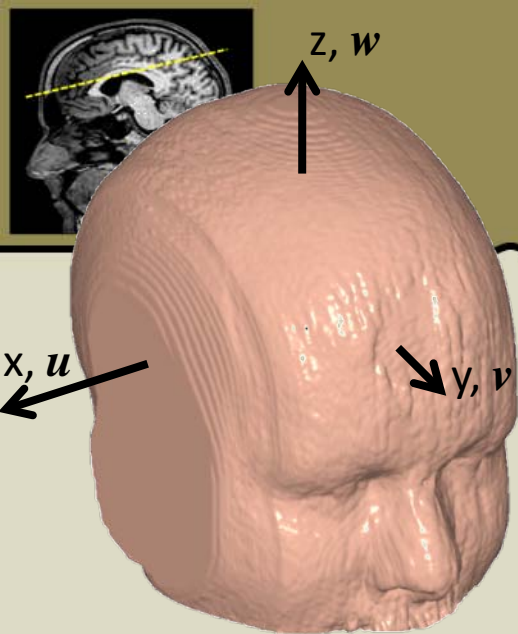
Displacements
Scaled x2000

w -component

Displacements
Scaled x2000



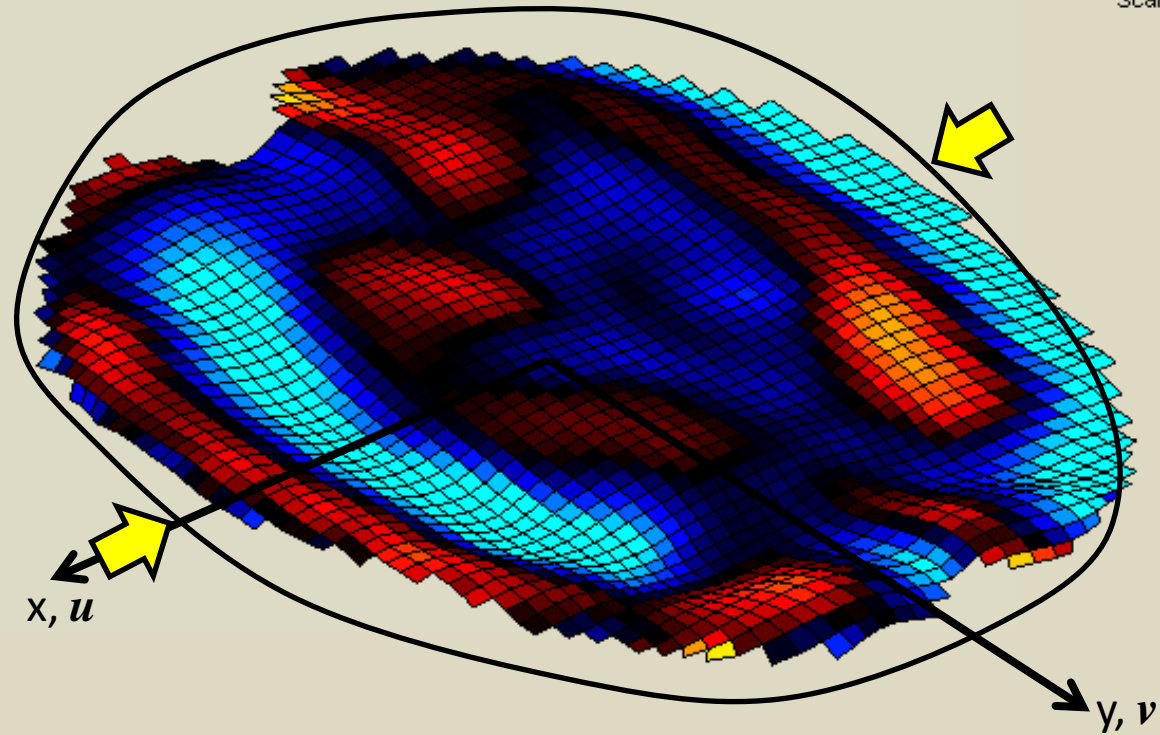
3-D displacement response to pressure load



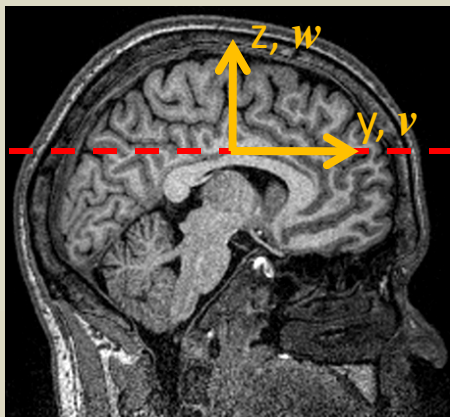
S014 MREB016

45 Hz

Displacements
Scaled x2000



Contour: v – displacement component (μm)



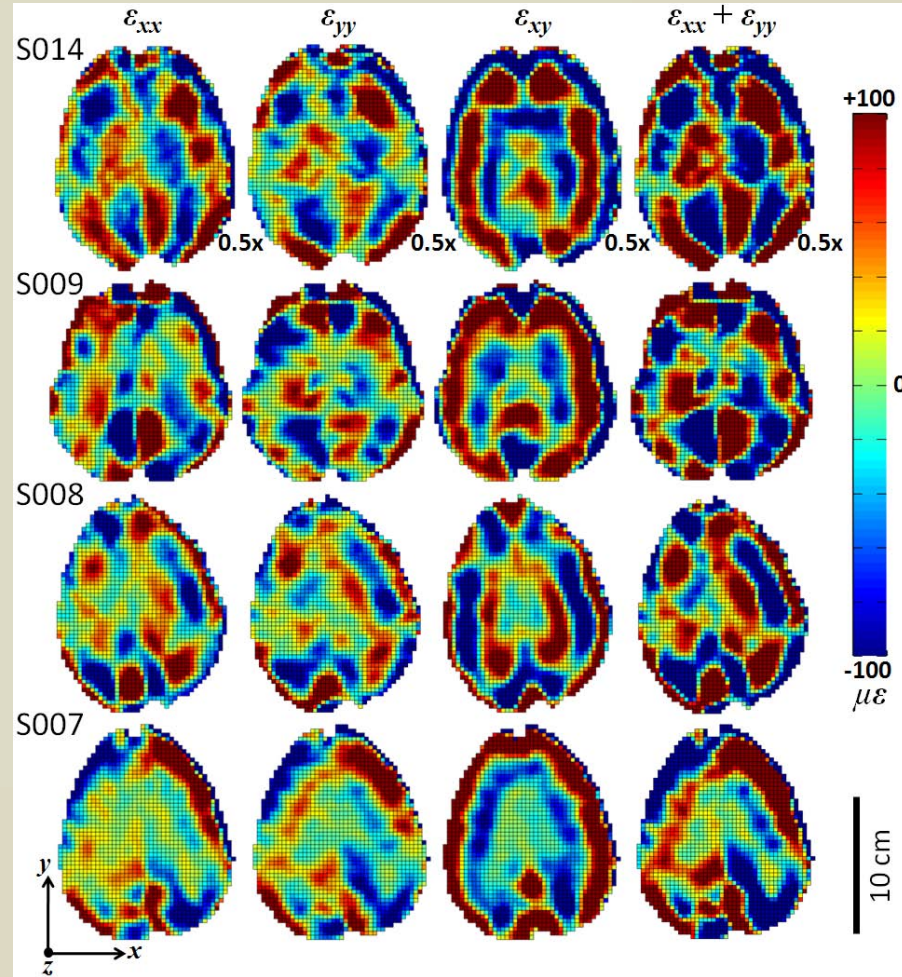
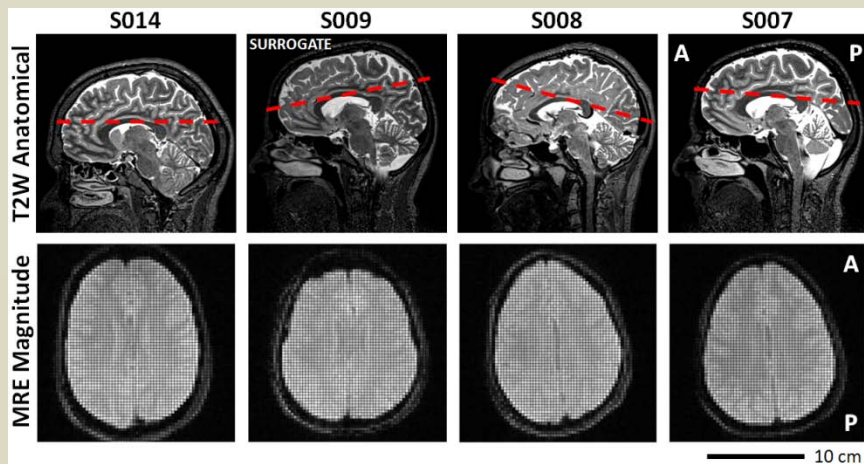
Brain Motion Captured via MR Elastography

Quantifying relative tissue deformation: *Strain*

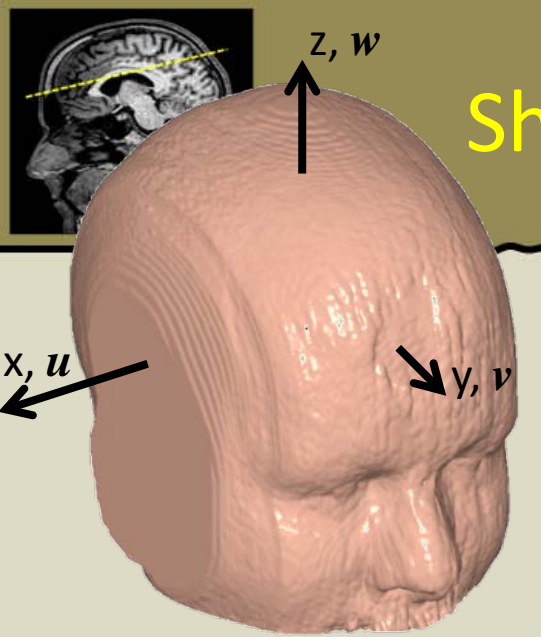
Def. Strain: $\epsilon_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i})$

displacement
gradients

45 Hz, single slice data



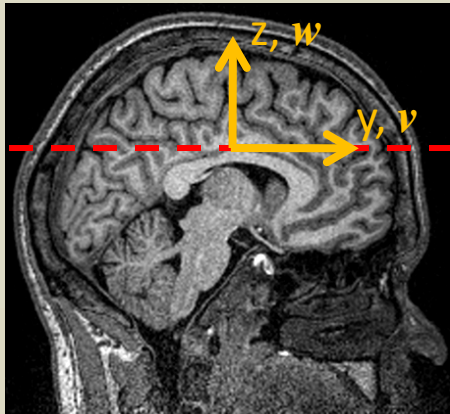
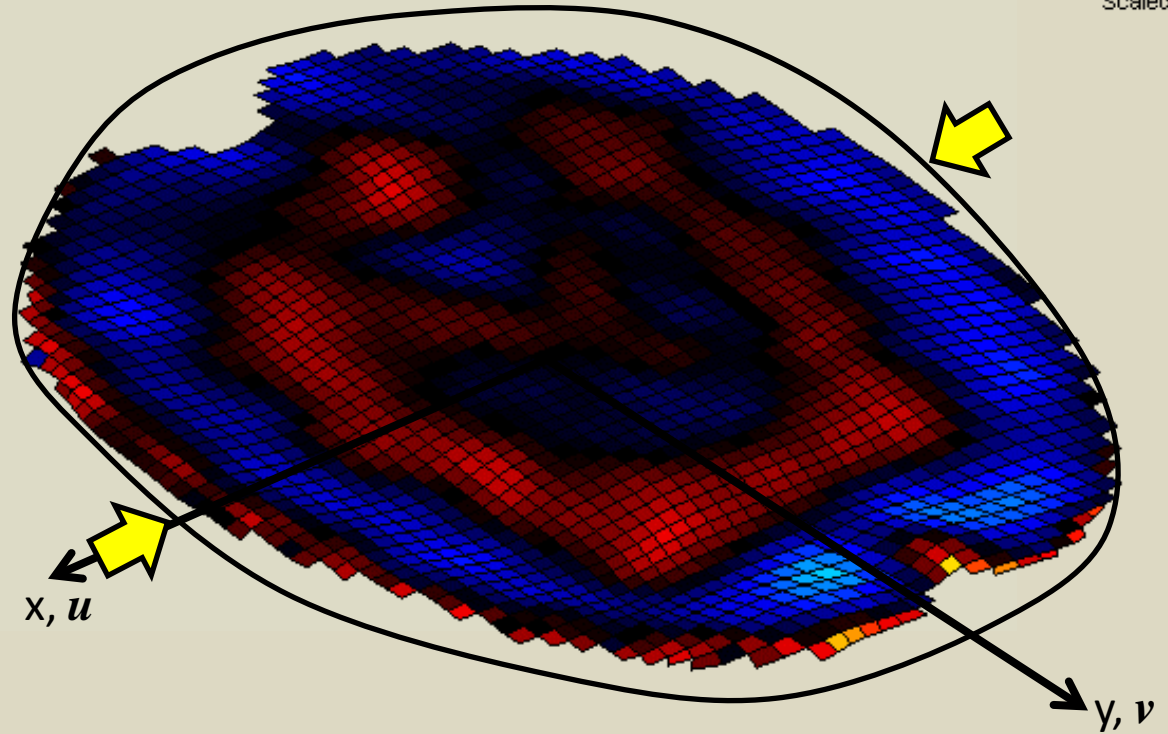
Shearing strain \rightarrow Diffuse axonal injury ?



S014 MREB016

45 Hz

Displacements
Scaled x2000



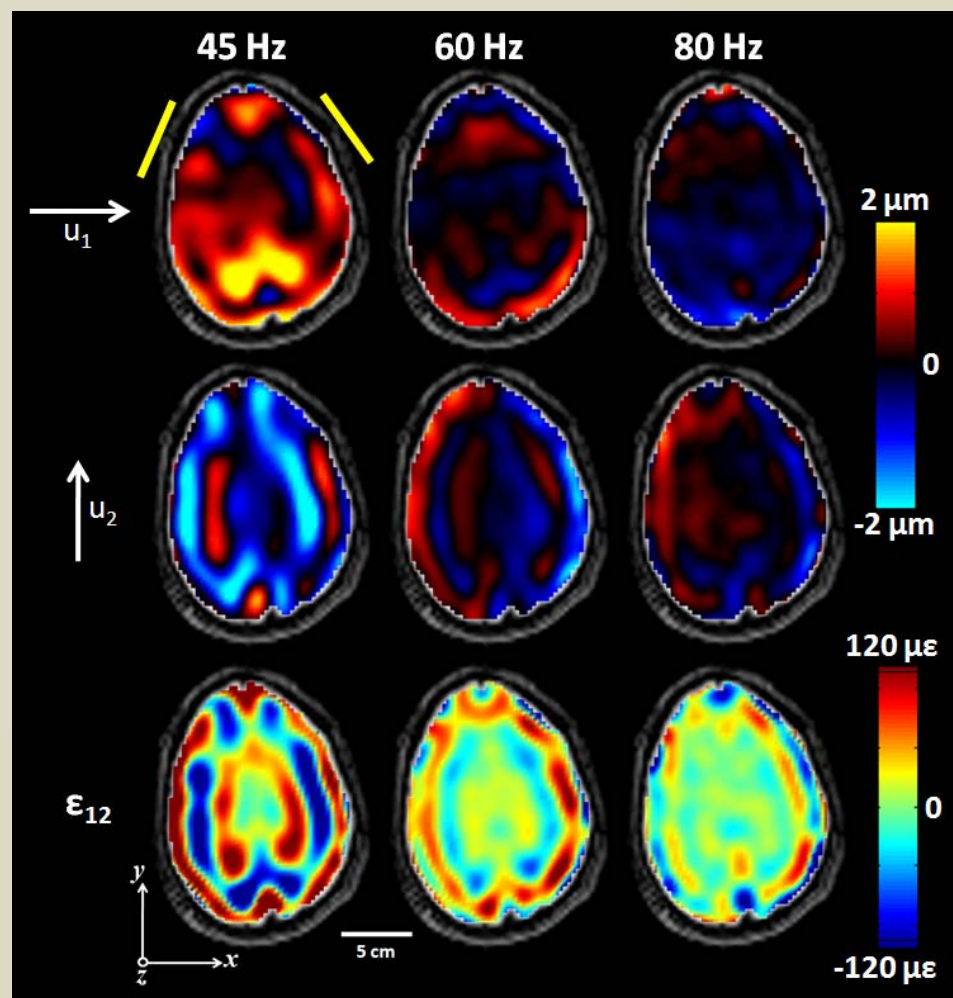
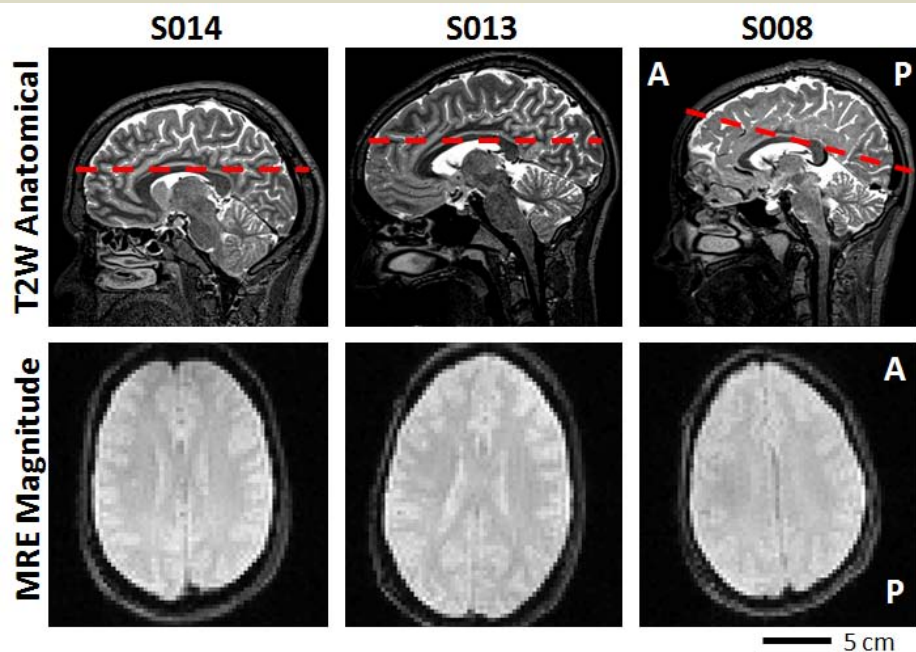
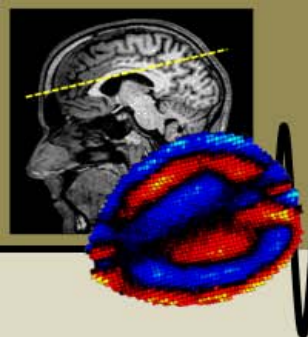
Contour: ϵ_{xy} (μ strain)



$$\epsilon_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i})$$

Brain Motion Captured via MR Elastography

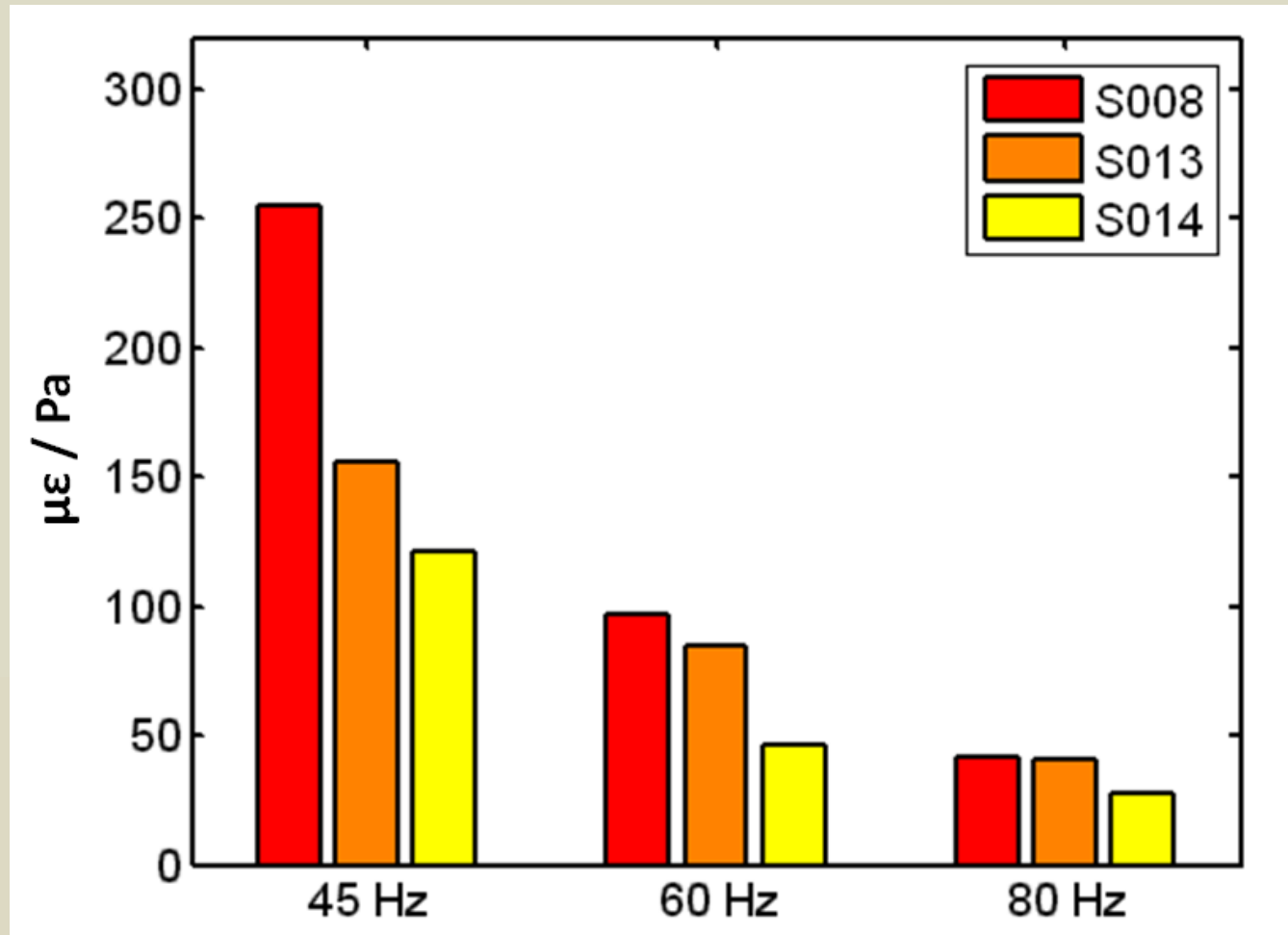
Brain response to acoustic load at various frequencies

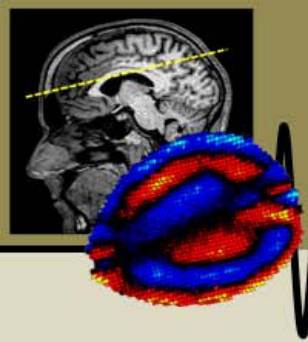


$$\epsilon_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i})$$

Frequency response of brain matter

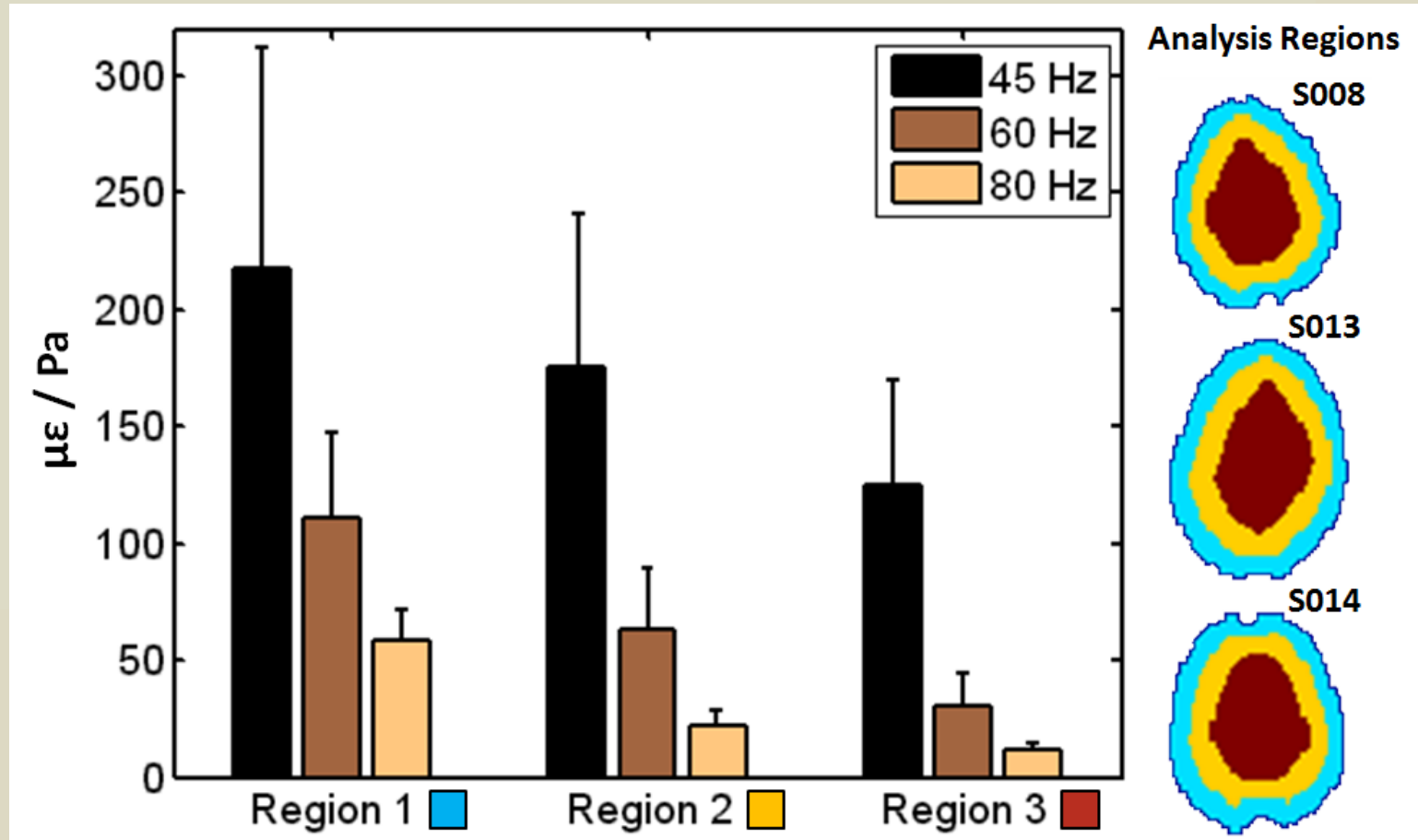
RMS strain normalized by pressure load

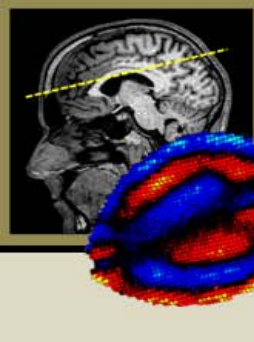




Energy absorption by brain tissue

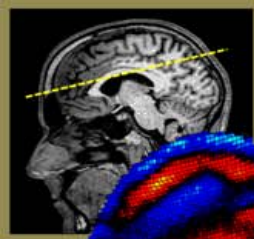
RMS strain normalized by pressure amplitude





Summary & Conclusions

- MRE performed on human subjects
 - Shear waves in brain imaged *in vivo* & non-invasively
 - Input pressure load quantified
 - Displacement and strain response measured/calculated
- **First quantitative calculations relating experimental pressure load on skull to measured strains *in vivo***
- Future work
 - Acquire multi-slice data (complete 3D strain tensor)



Questions?

ACKNOWLEDGMENTS

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