Computational Modeling and Injury Criteria for Motor-Vehicle Crashes

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Or
Brain Injury Mechanisms…. Simplified

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The views expressed here are my own and not necessarily those of DOT

Special THANKS to Vikas Hasija

Do we believe that STRAIN is “the devil” as far as brain injuries are concerned ?

If so, then how do high strains occur inside the brain?

If not, then what is “the devil”? Pressure?

Stress Tensor

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}$$

$$\boldsymbol{\sigma} = \underbrace{\boldsymbol{\sigma}_{HYD}}_{\text{Dilatational or Hydrostatic Component}} + \underbrace{\boldsymbol{\sigma}'}_{\text{Deviatoric Component}}$$

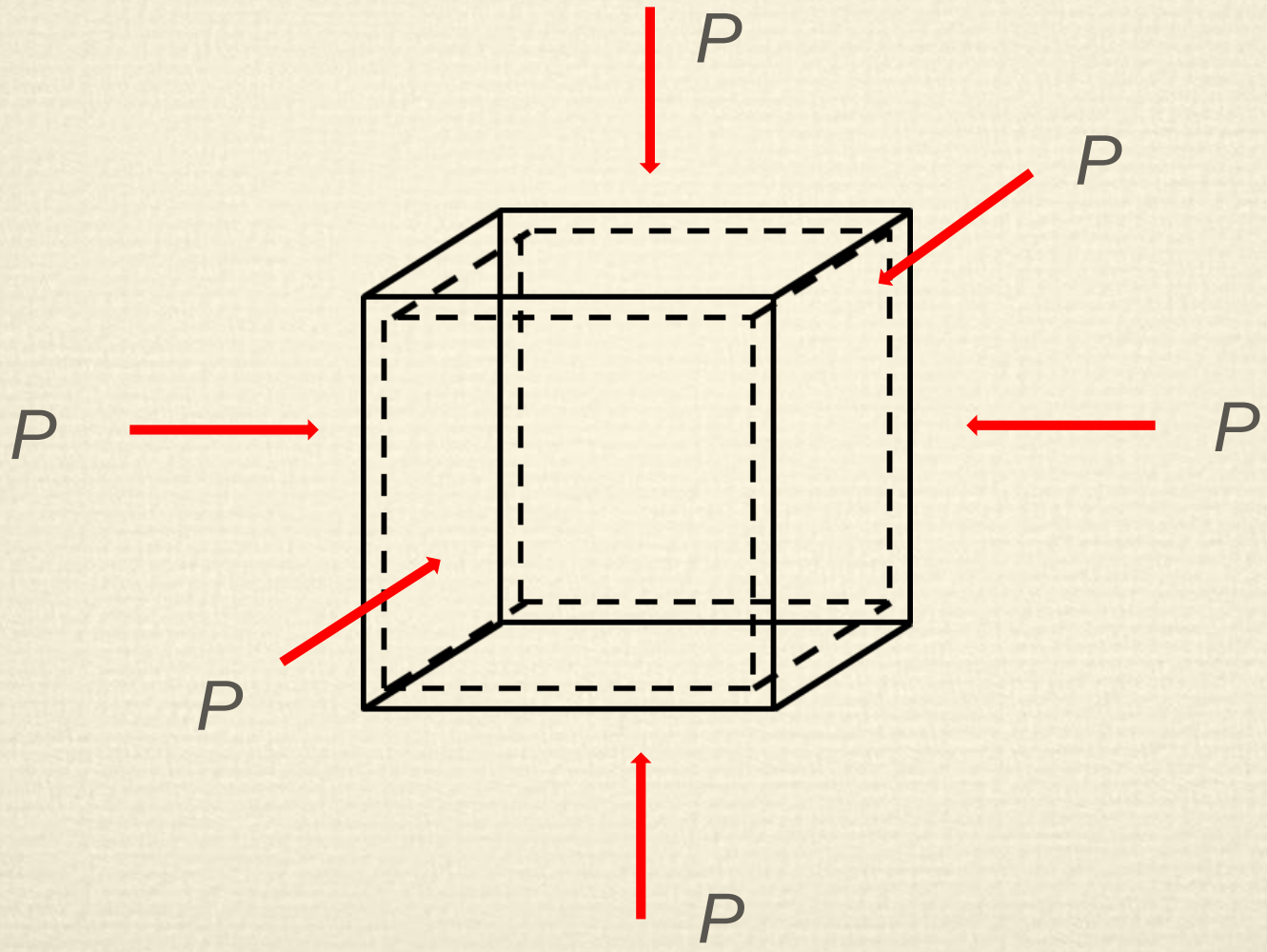
Dilatational/Hydrostatic Component of Stress Tensor: Pressure

$$\sigma_{HYD} = \frac{\sigma_{11} + \sigma_{22} + \sigma_{33}}{3}$$

$$\sigma_{HYD} = \begin{bmatrix} \sigma_{HYD} & 0 & 0 \\ 0 & \sigma_{HYD} & 0 \\ 0 & 0 & \sigma_{HYD} \end{bmatrix}$$

$$P = -\sigma_{HYD} = -\frac{(\sigma_{11} + \sigma_{22} + \sigma_{33})}{3}$$

Dilatational/Hydrostatic Component of Stress Tensor: Pressure



Hydrostatic stress/pressure are equal in all directions

They do NOT change under coordinate transformation – invariant

There are NO shear stresses and each direction is a principal direction

Hydrostatic stress/pressure tries to change the Volume of a material and is proportional to the BULK Modulus

The Bulk Modulus of the brain tissue is ~ 2.07 Gpa (McElhaney et al., 1976)

The Bulk Modulus for CSF and Blood is in the same order of magnitude

What if there is pressure gradient?

In this case, the deviatoric component of the stress tensor exists, i.e. it is not equal to zero

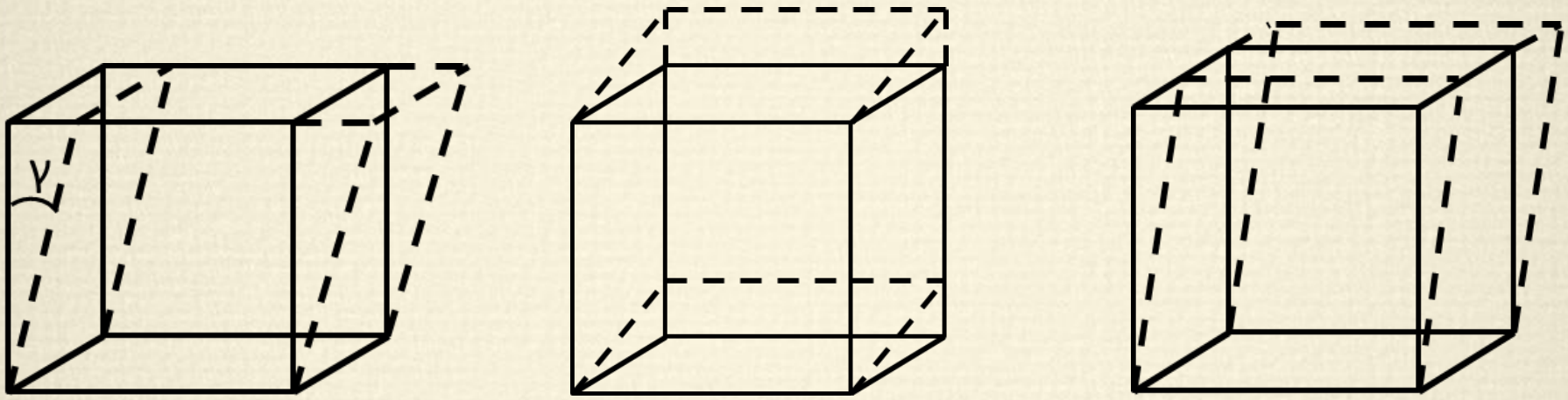
Deviatoric Component of the Stress Tensor

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - \boldsymbol{\sigma}_{HYD}$$

$$\boldsymbol{\sigma}' = \begin{bmatrix} \sigma_{11} - \sigma_{HYD} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} - \sigma_{HYD} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} - \sigma_{HYD} \end{bmatrix}$$

$$\boldsymbol{\sigma}' = \begin{bmatrix} \sigma_{11} + P & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} + P & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} + P \end{bmatrix}$$

Deviatoric Component of the Stress Tensor



Deviatoric stress, when applied to a material, tries to change its shape

Deviatoric stress is traceless (it's first invariant or trace is zero) or hydrostatic stress of deviatoric stress tensor is zero

Deviatoric stress can be formed entirely from shear components, i.e. a coordinate system can be transformed such that only shear components exist

Deviatoric (or shear) stress is proportional to Shear Modulus

Shear Modulus of Brain Tissue is ~ 1 kPa

Mini Summary I

- Bulk Modulus of Brain Tissue is high (brain tissue is virtually incompressible) ~ 2.07 Gpa
- Shear Modulus of Brain Tissue is low ~ 1kPa
- There is ~ 2 Million times difference between the bulk and shear moduli for brain tissue (it is even greater for blood and CSF)
- It is ~ 2 Million times easier to change the shape of the brain than to change its size
- If stress is not hydrostatic, then deviatoric/shear component of stress tensor is non-zero

Stress Tensor

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}$$

$$\boldsymbol{\sigma} = \underbrace{\boldsymbol{\sigma}_{HYD}}_{\text{Dilatational or Hydrostatic Component}} + \underbrace{\boldsymbol{\sigma}'}_{\text{Deviatoric Component}}$$

Does dilatational component of the stress tensor or hydrostatic stress/pressure cause damage to brain tissue?

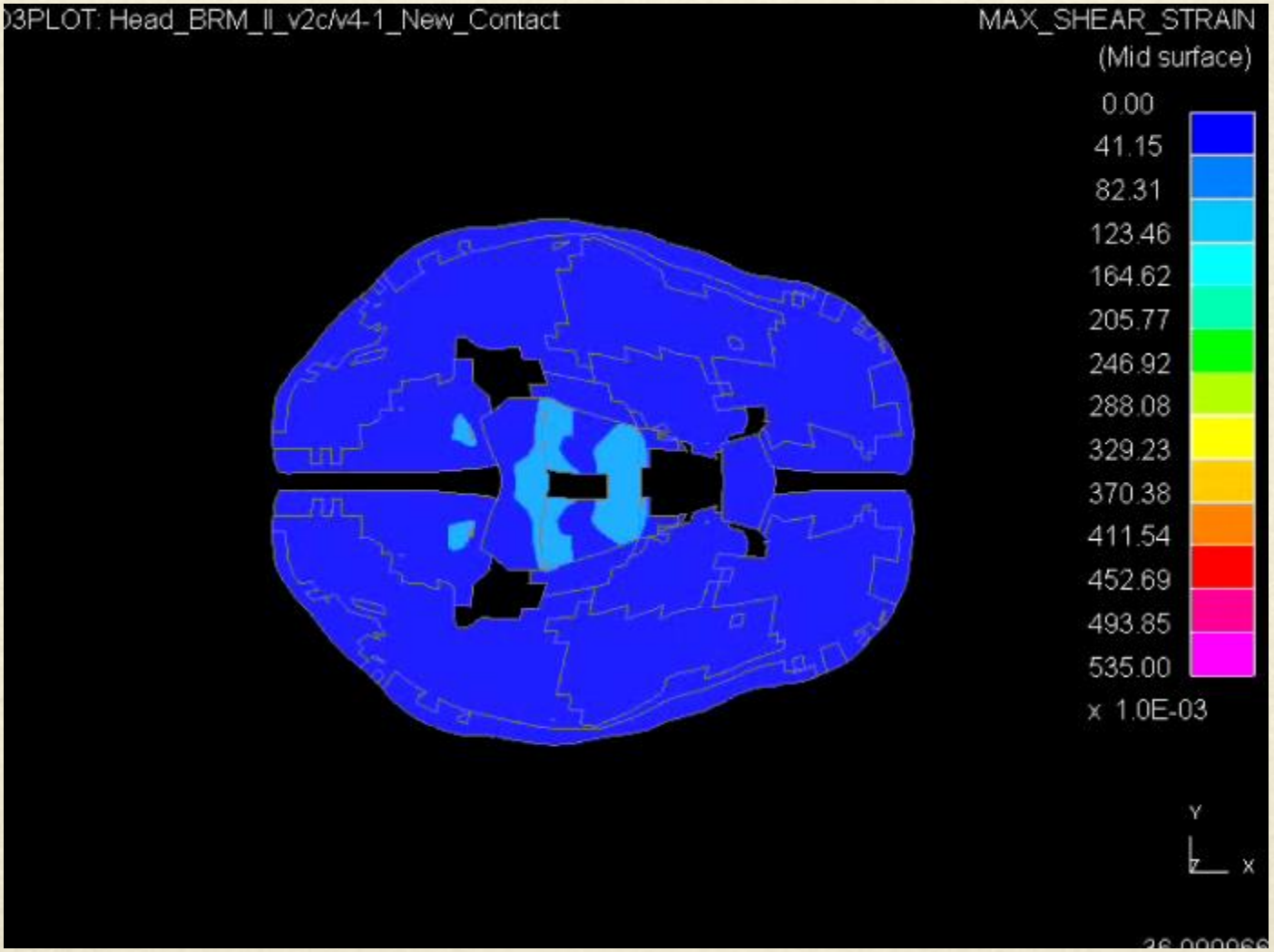
In 1936 Grundfest presented a study on the effects of different hydrostatic pressures upon the threshold of the frog sciatic nerve. There were minimal effects on nerve function for pressures up to 5,000 psi with only 10% decrease in the magnitude of the action potential and immediate recovery upon release of the pressure. When higher pressures up to 15,000 psi were applied, the potential reduced further, but was reversible even after being loaded for periods up to 20-30 minutes.

Wait a Minute. What about Linear Acceleration?

Logic:

Linear Acceleration causes Pressure Gradient causes Deviatoric Stress cause Shear Strain

GHBMC 50th Male FE Model
HIC = ~1,500



Okay, but what about Negative Pressure and Cavitation?

Logic:

Linear Acceleration causes
Pressure Gradient causes
Negative Pressure at Contrecoup
causing CAVITATION

- 1940. Goggio introduced the pressure gradient theory based on a simple hydrostatic theory, where negative pressure at the side opposite to impact was proposed as the mechanism of contrecoup injuries
- 1958. Gross experimented with partially fluid filled flask (simulating human brain) and attempted to explain various brain injury mechanisms including contrecoup injuries due to cavitation. He concluded that “it is violent collapse of the cavities that produces the tissue damage rather than effect of the negative pressure”; “coup cavitation occurs at the site of the impact because of the snap-back of the locally deformed skull”, etc.

Did anyone actually find/measure cavitation in brain tissue?

Nusholtz et al., 1984

- Used live anesthetized and post-mortem Rhesus monkeys and repressurized cadavers in impactor tests. Measured 3D skull kinematics and epidural pressure
- Concluded that skull deformation and angular acceleration of the head are potentially important parameters on brain injury
- “For live Rhesus subjects, negative pressure peaks during an impact event equal to or greater than ***one atmosphere*** do NOT appear to produce injury”

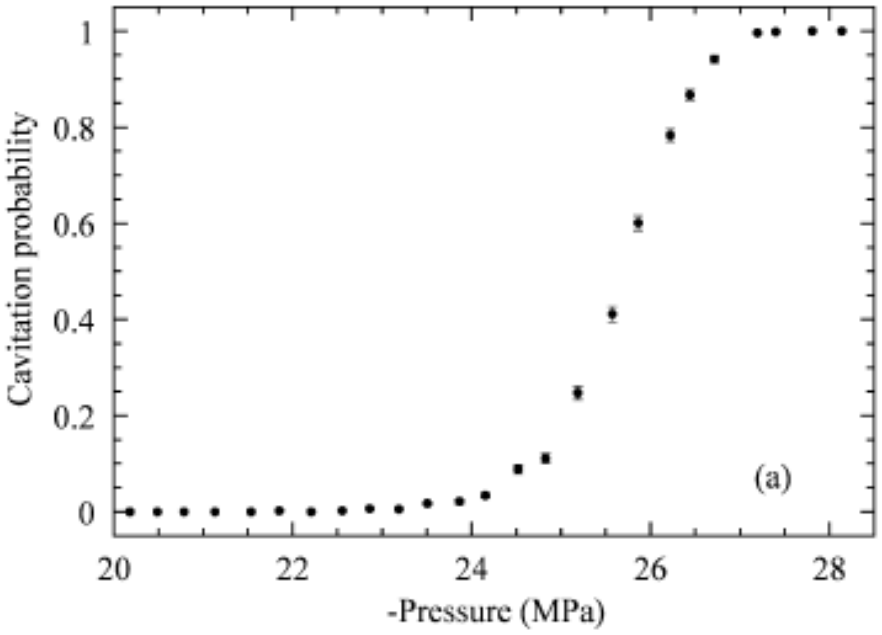
Takhounts et al., 2003

- DDM – dilatational damage measure
- “The DDM monitors the volume of the brain experiencing specified negative pressure levels... For the purposes here, this pressure threshold is set at ***–14.7 psi (~100 Kpa)***, the vapor pressure of water.”

Note: 14.7 psi = ~ 1 atmosphere

What really is the “vapor pressure of water” or cavitation pressure of water?

Caupin and Herbert, 2006
"Cavitation in water: A review"



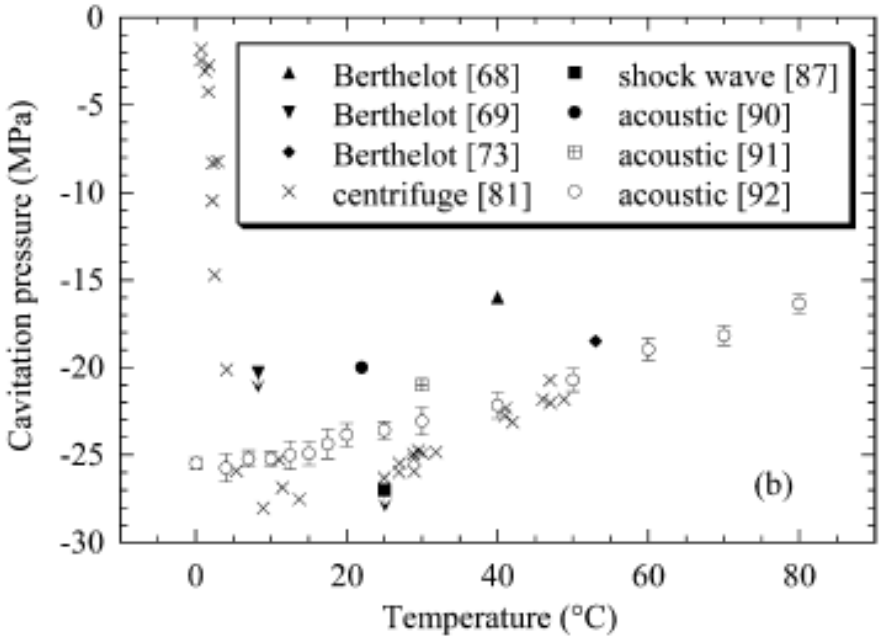


Fig. 3. (a) Cavitation probability as a function of pressure at 4 °C. Each data point was obtained by repeating 1000 acoustic bursts. The error bars are calculated from the binomial law. (b) Cavitation pressure as a function of temperature for different experiments: the corresponding method and reference are given in the legend. Only the experiments with the most negative cavitation pressures were selected, except the inclusion work, for sake of clarity. An arrow means that cavitation was not observed. The error bars on the empty circles represent the uncertainty on the pressure calibration.

What are the magnitudes of negative pressure usually measured in impact tests?

Nahum et al., 1977

1 mmHg = 133.3 Pa

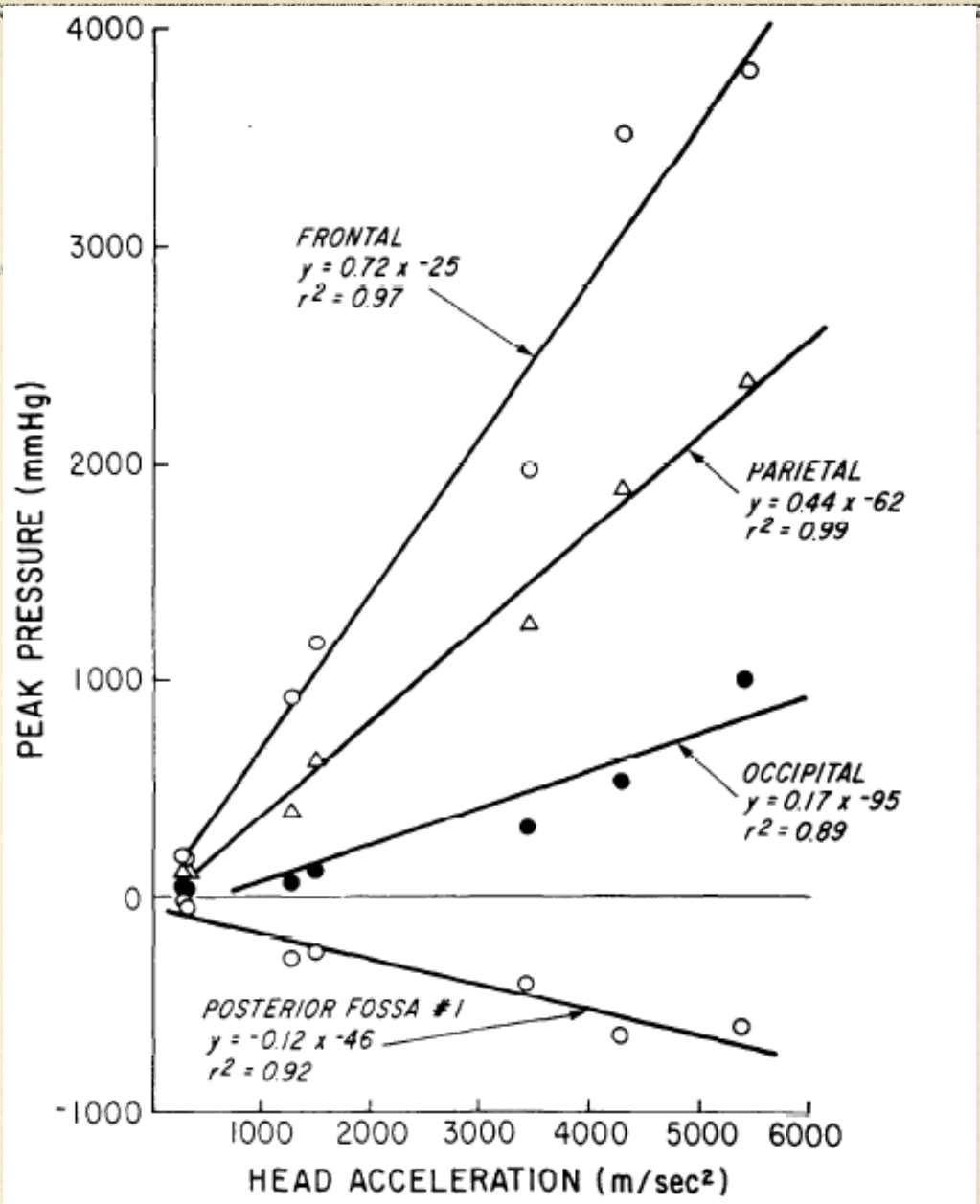


Fig. 7 - Regression analysis of peak pressure-head acceleration relationship

Mini Summary II

- Hydrostatic stress/pressure does NOT cause nervous tissue damage
- Linear acceleration does cause shear strains, but they are small
- Brain injuries due to negative pressure have never been demonstrated
- Negative pressure does cause cavitation, but these negative pressures are in order of -25 Mpa at room and body temperature, much lower than -150 kPa that are seen in impact tests
- In order to cause brain injury due to cavitation two conditions have to be satisfied: (1) cavitation has to be present at the body temperature, and (2) sufficient time has to pass for the vapor nuclei to cause tissue damage – neither has been demonstrated experimentally
- Cavitation as a mechanism of brain injury is NOT supported by the existing experimental data

Stress Tensor

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$$\boldsymbol{\sigma} = \underbrace{\boldsymbol{\sigma}_{HYD}}_{\text{Dilatational or Hydrostatic Component}} + \underbrace{\boldsymbol{\sigma}'}_{\text{Deviatoric Component}}$$

Does deviatoric or shear stress component of the stress tensor cause damage to brain tissue?

Recall:

Deviatoric or shear stress component of the stress tensor tries to change the shape of a material and is proportional to shear strain

How to change the shape of the brain?

Or

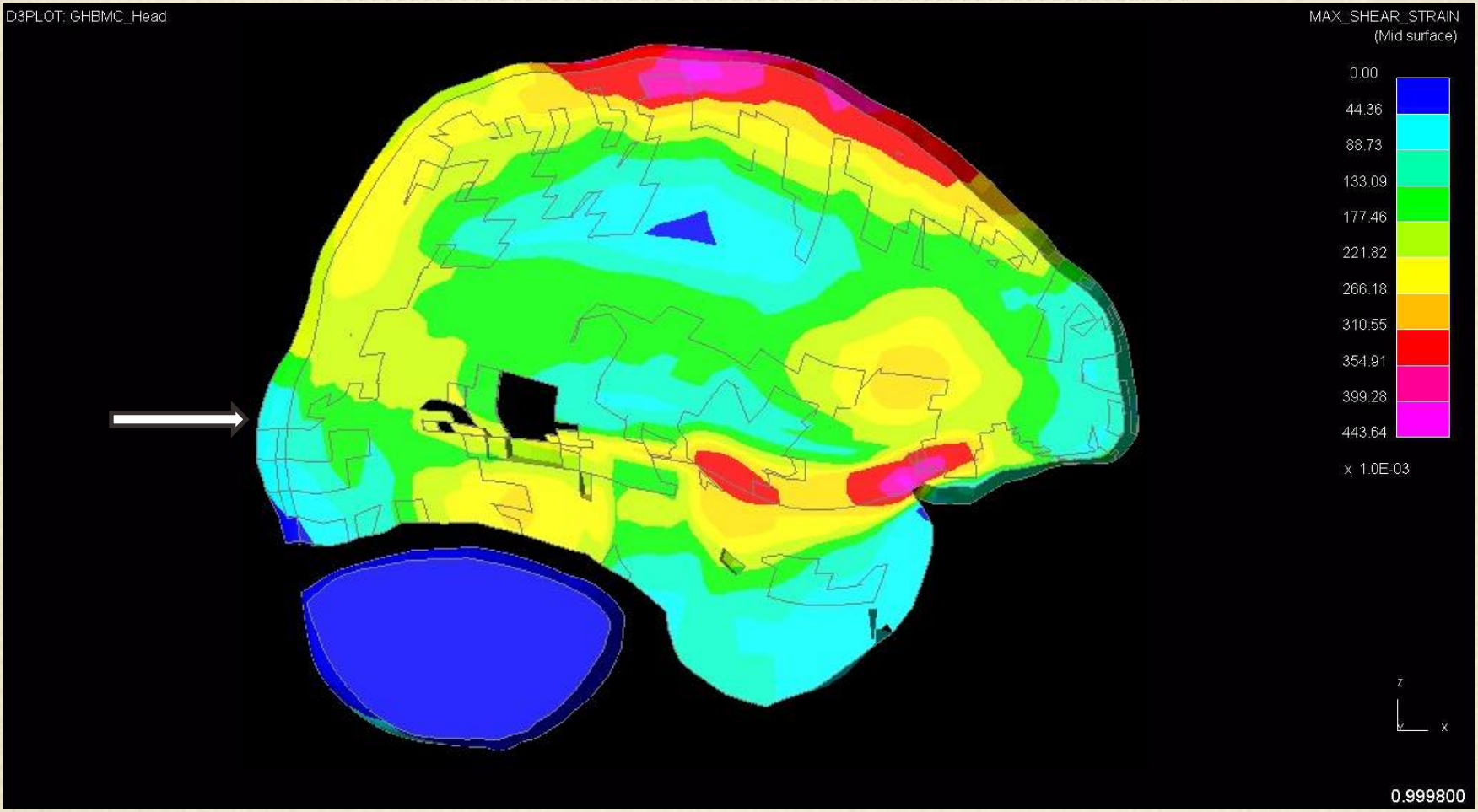
What is the easiest way to change the shape of the brain?

Head

ROTATION

GHBMC 50th Male FE Model

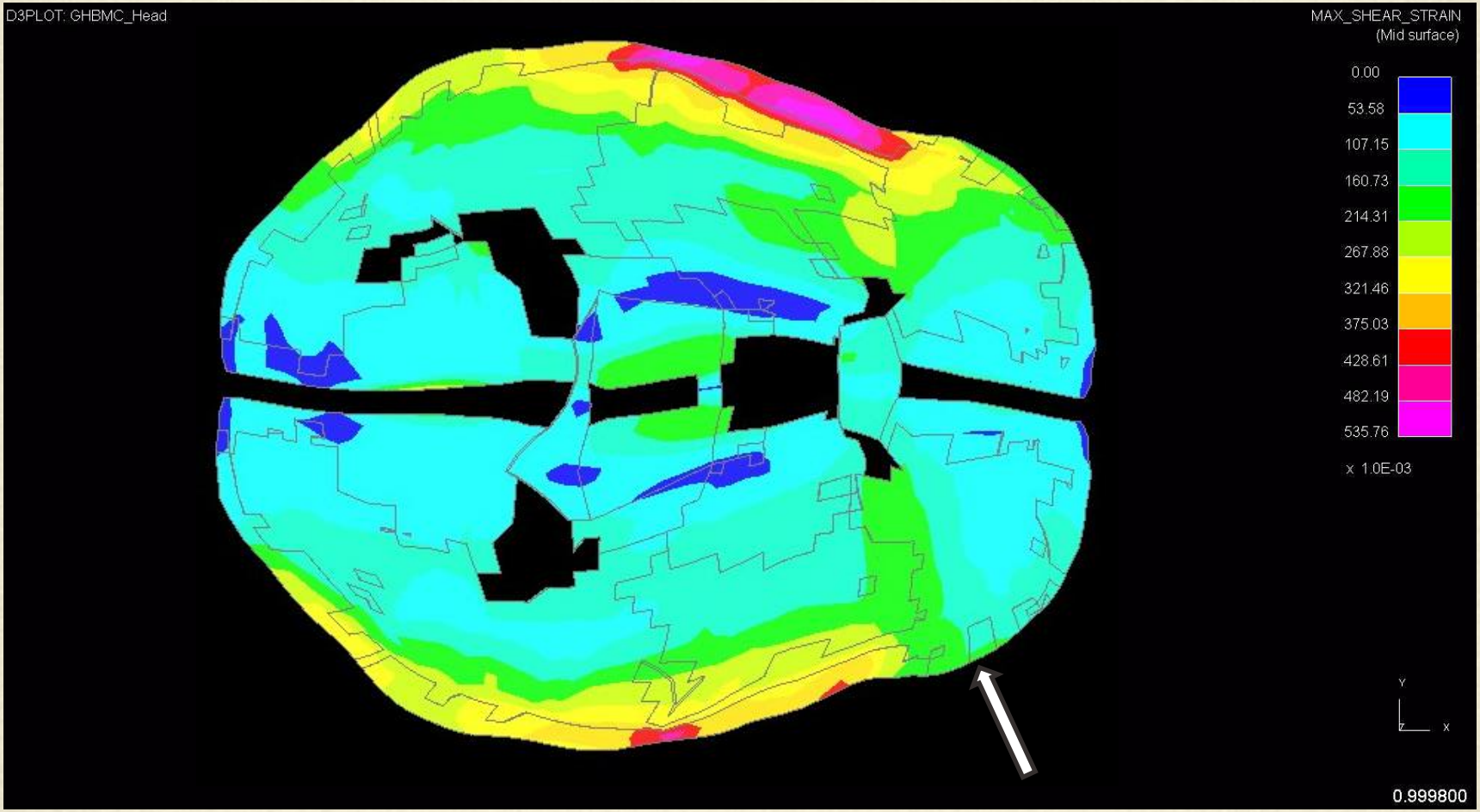
Angular Velocity = 40 rad/s; Sagittal Plane



Max shear strains simulating impact at the occiput (see arrow)

GHBMC 50th Male FE Model

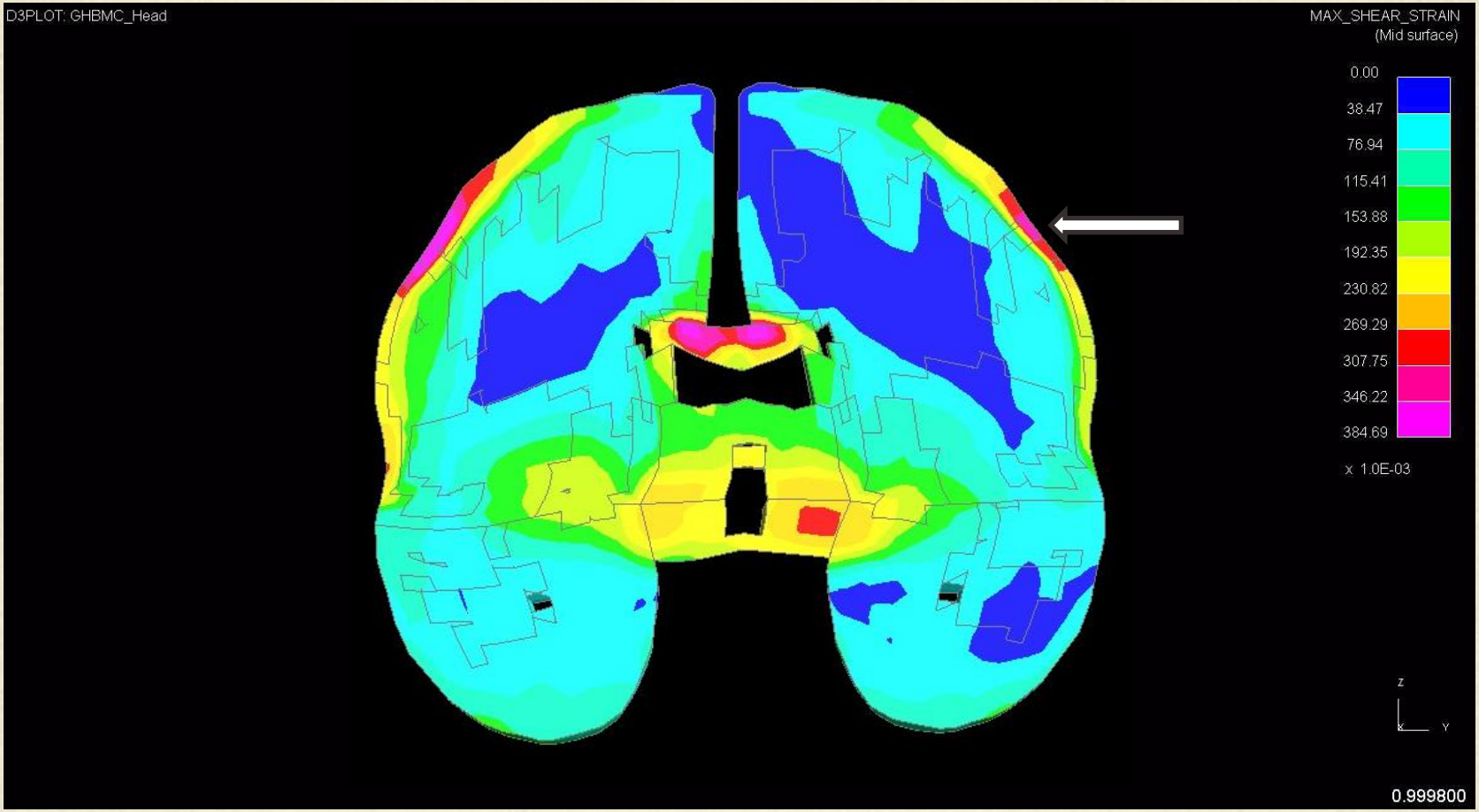
Angular Velocity = 40 rad/s; Horizontal Plane



Max shear strains simulating impact at the temporal lobe (see arrow)

GHBMC 50th Male FE Model

Angular Velocity = 40 rad/s; Coronal Plane



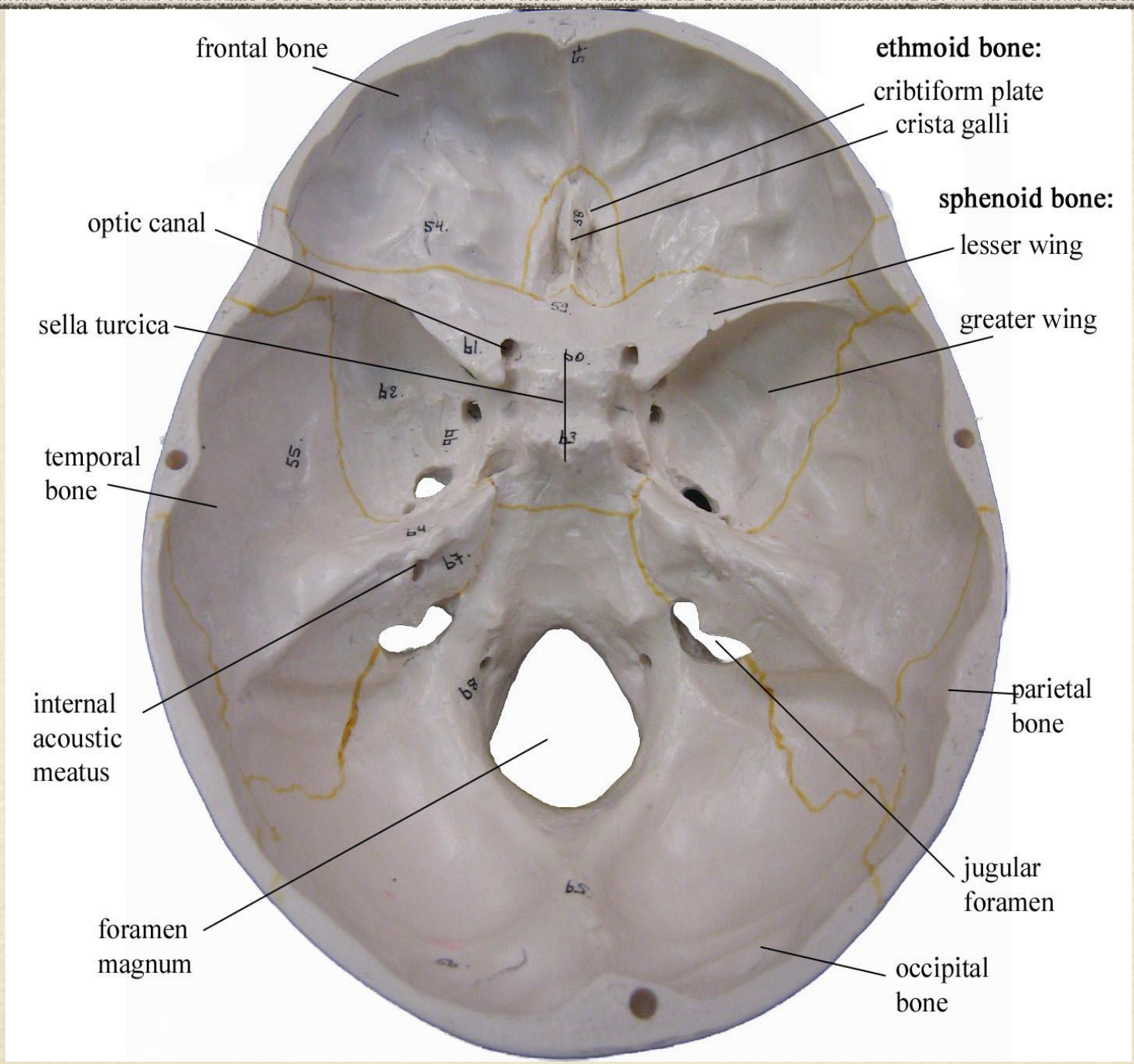
Max shear strains simulating impact above the ear (see arrow)

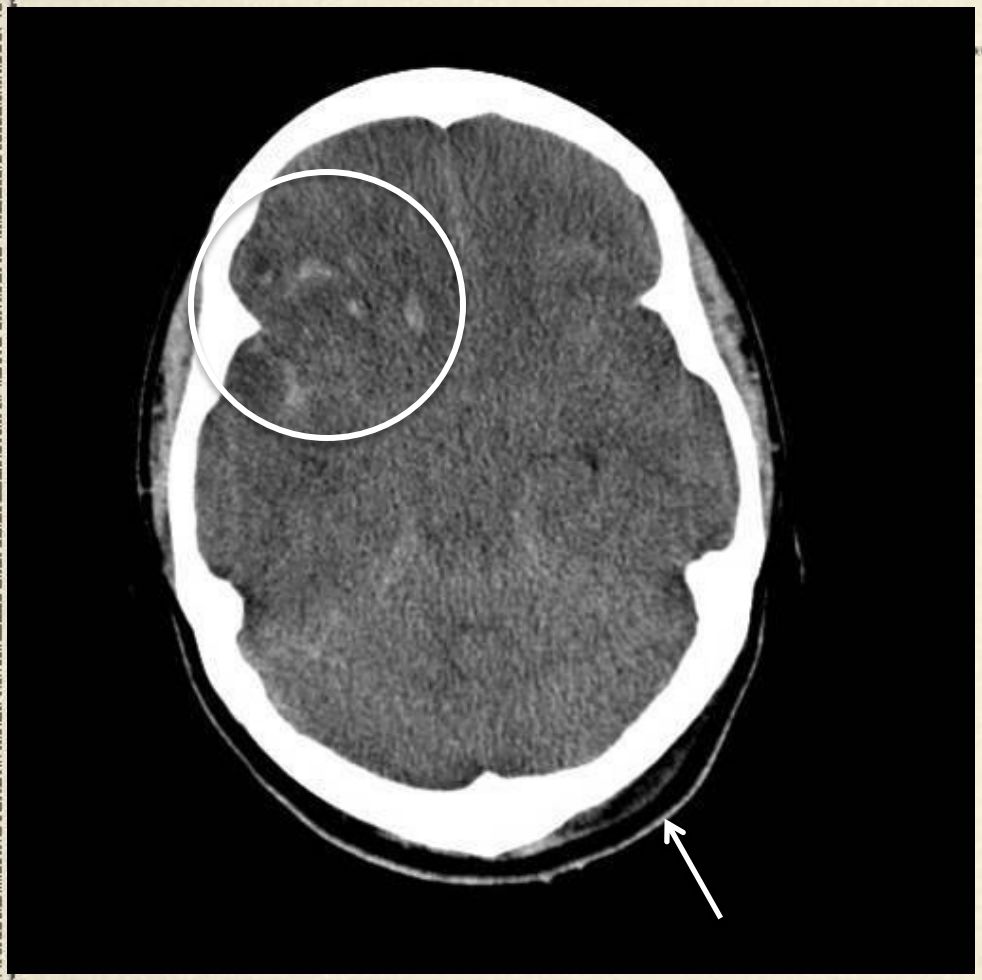
Can Contrecoup injuries be explained with the shear strain/rotation theory?

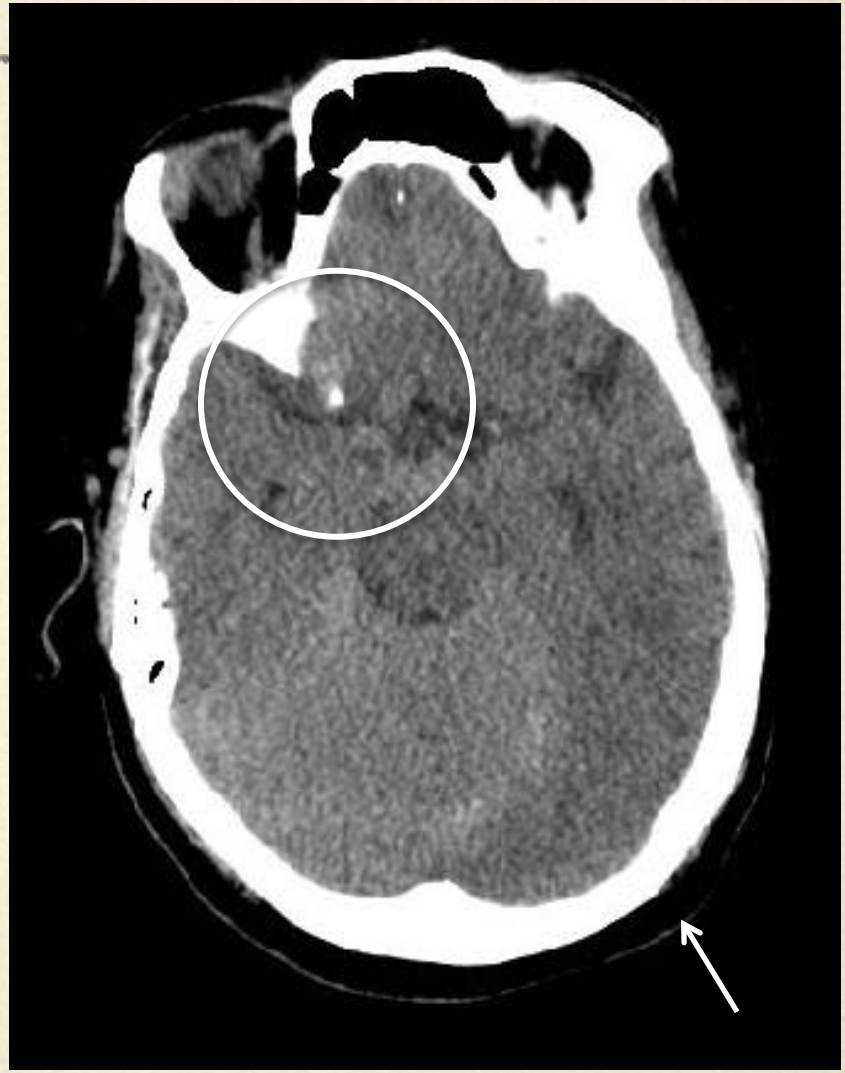
YES. See slides above.

Courville, 1942

Reviewed 206 cases of fatal brain injuries that were results of automotive collisions and falls. Made a few valuable observations: (1) frontal impacts – only coup contusions occurred on the basilar surface of the frontal lobe; (2) occipital impacts – only contrecoup contusions occurred at the same site as frontal impacts; (3) in side impact to the temporal or parietal regions the major contusion is the contrecoup one (smaller coup lesions are also found in some cases). Observed that the more irregular the bony walls of the skull are the more likely it is that that part will sustain coup or contrecoup contusions


frontal bone
ethmoid bone:
cribtiform plate
crista galli
sphenoid bone:
optic canal
lesser wing
sella turcica
greater wing
temporal bone
internal acoustic meatus
parietal bone
jugular foramen
foramen magnum
occipital bone





Head rotation causes high shear strains inside the brain.

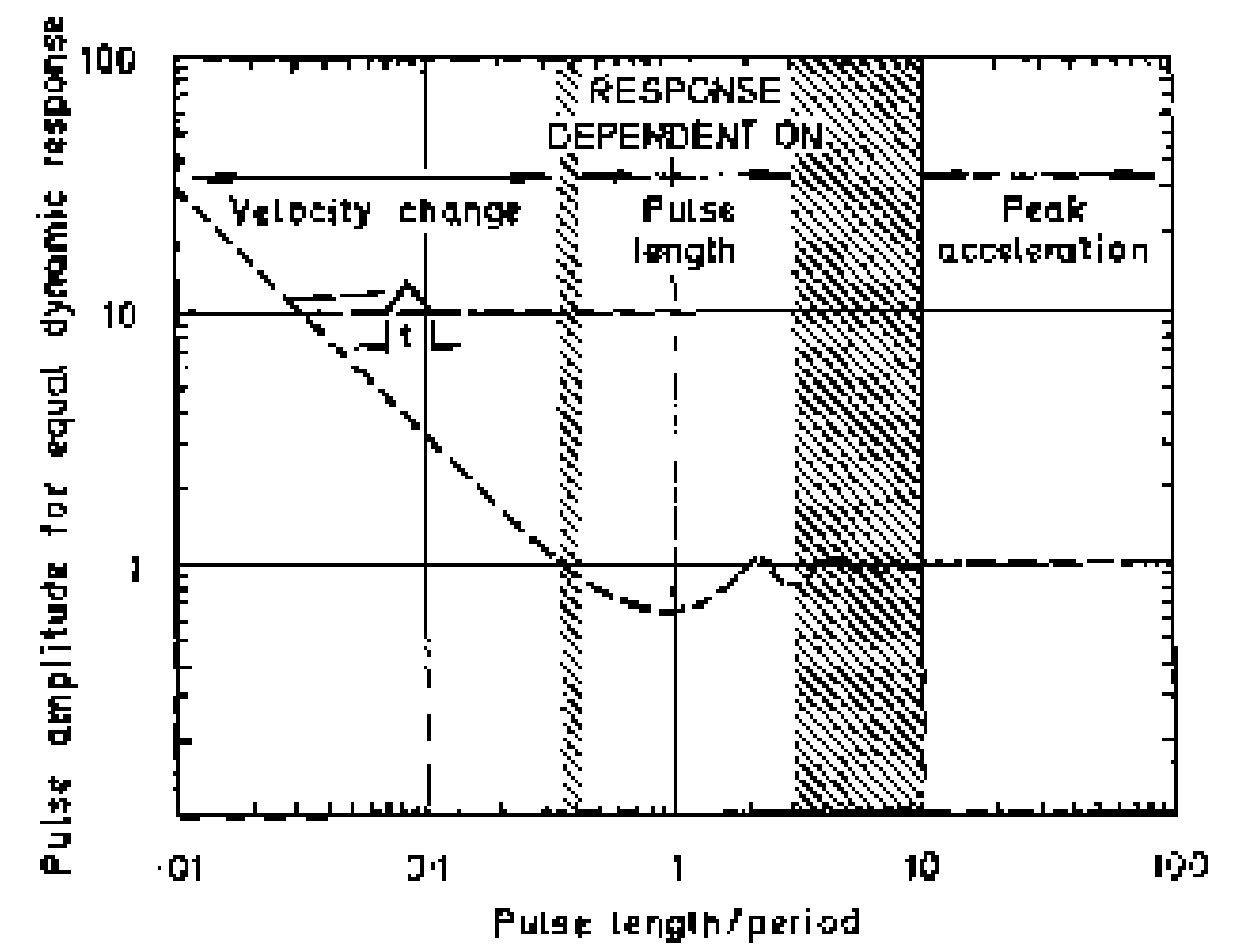
Are these shear strains proportional to head rotational angle, velocity, or acceleration?

Holbourn, 1943

Takhounts et al., 2013

The best correlate to max principal or shear strain in the brain is the head rotational/angular velocity

Glaister (1975) after H.E. von Gierke (1964)



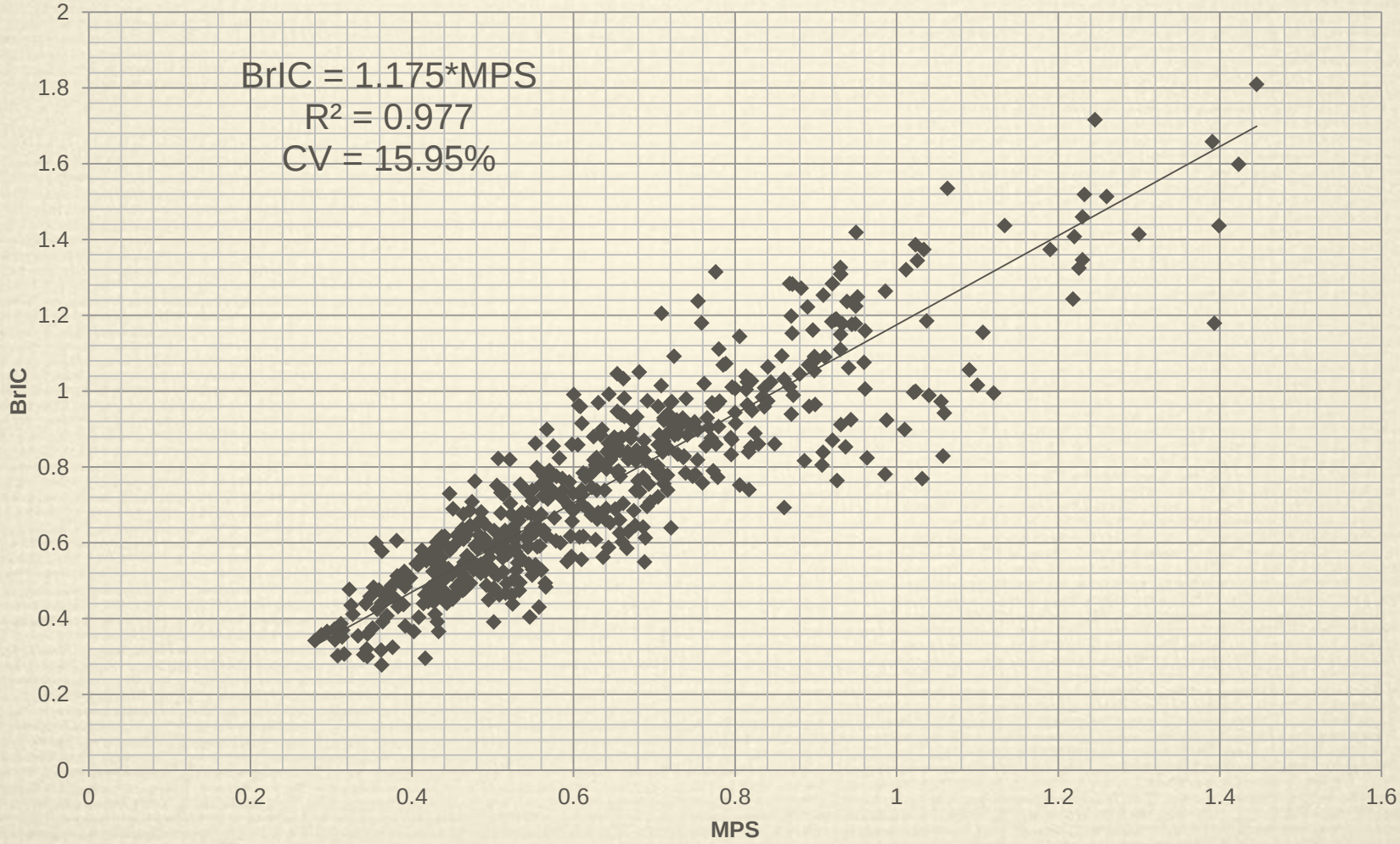
Mini Summary III

- Deviatoric component of shear stress tensor is proportional to shear strains
- The easiest way to create high shear strains inside the brain is via head rotation
- Contrecoup (and coup) injuries can be explained with the shear strain injury mechanism
- Max shear and principal strains inside the brain are proportional to the magnitude of rotational/angular velocity

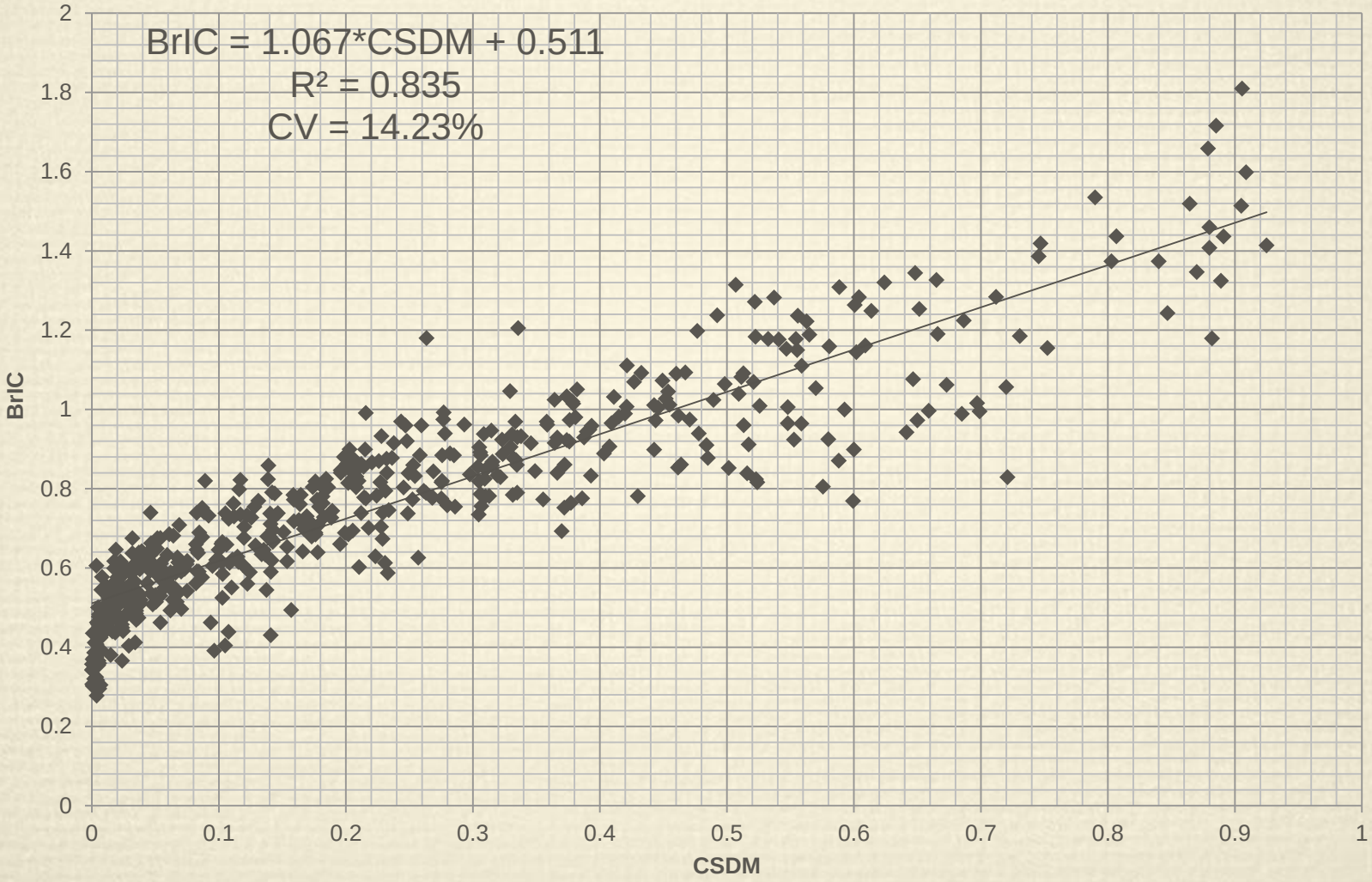
Takhounts et al., 2013

Even better correlate to max principal strain is BrIC

“Original BrIC” is a Correlate for MPS (543 tests)



“Original BrIC” is a Correlate for CSDM (543 tests)



Current Formulation

$$BrIC = \sqrt{\left(\frac{\omega_x}{\omega_{xC}}\right)^2 + \left(\frac{\omega_y}{\omega_{yC}}\right)^2 + \left(\frac{\omega_z}{\omega_{zC}}\right)^2}$$

ω_{xC}	**66.25 rad/s**
ω_{yC}	**56.45 rad/s**
ω_{zC}	**42.87 rad/s**

Conclusions

- Dilatational component of the stress tensor (pressure) does NOT appear to cause brain injuries
- Cavitational theory of brain injury is without experimental foundation
- Linear acceleration doesn’t results in high strains inside the brain
- The easiest way to create high strains inside the brain is via head rotation – rotational velocity
- Rotational velocity is proportional to the strains inside the brain
- BrIC correlates better to the strains inside the brain than any other kinematic parameter

The End

Questions?

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