2nd International Symposium on Future Mobility Safety Science and Technology

Pilsen, Czech Republic, Europe

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# Head Injury Protection by Engineering Design


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# Introduction

- ✓ **Head injury persistently declares itself as a worldwide health problem.**
- ✓ **It requires medical doctors and injury biomechanical engineers work together to mitigate/control this pandemic.**

# Introduction

- ✓ Medical doctors seek to develop sophisticated treatment methods to cure the disease.
- ✓ While injury biomechanical engineers explore injury mechanisms and develop advanced safety technologies to prevent the head from injury through engineering designs.

# Introduction

**Injury biomechanical researchers/engineers have postulated the theories of head injury as:**

- ✓ **Translational acceleration theory.**
- ✓ **Rotational acceleration theory.**
- ✓ **Combined Translational and Rotational Accelerations.**

# Introduction

## The Primary Head Injury

| Scalp Injury | Skull Fracture | Focal Injury | | Diffuse Injury |
|---|---|---|---|---|
| Bruise | Linear fracture | Contusion | Coup contusion | Cerebral concussion |
| Abrasion | Depressed fracture | | Contrecoup contusion | |
| Laceration | Basilar fracture | Hematoma | Epidural hematoma | Diffuse Axonal Injury |
| Avulsion | Comminuted fracture | | Subdural hematoma | |
| | Multiple fracture | | Intracerebral hematoma | |

# Introduction

- ✓ For several decades, bioengineers have incessantly investigated tools that can be used to assess the efficacy of safety technologies in engineering design .
- ✓ One of the tools is Head Injury Criterion or HIC for short.
- ✓ HIC has been adopted internationally as a safety regulation for vehicle design.

# Introduction

## Head Injury Criterion is defined by:

$$HIC = (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]_{\max}^{2.5}$$

where,

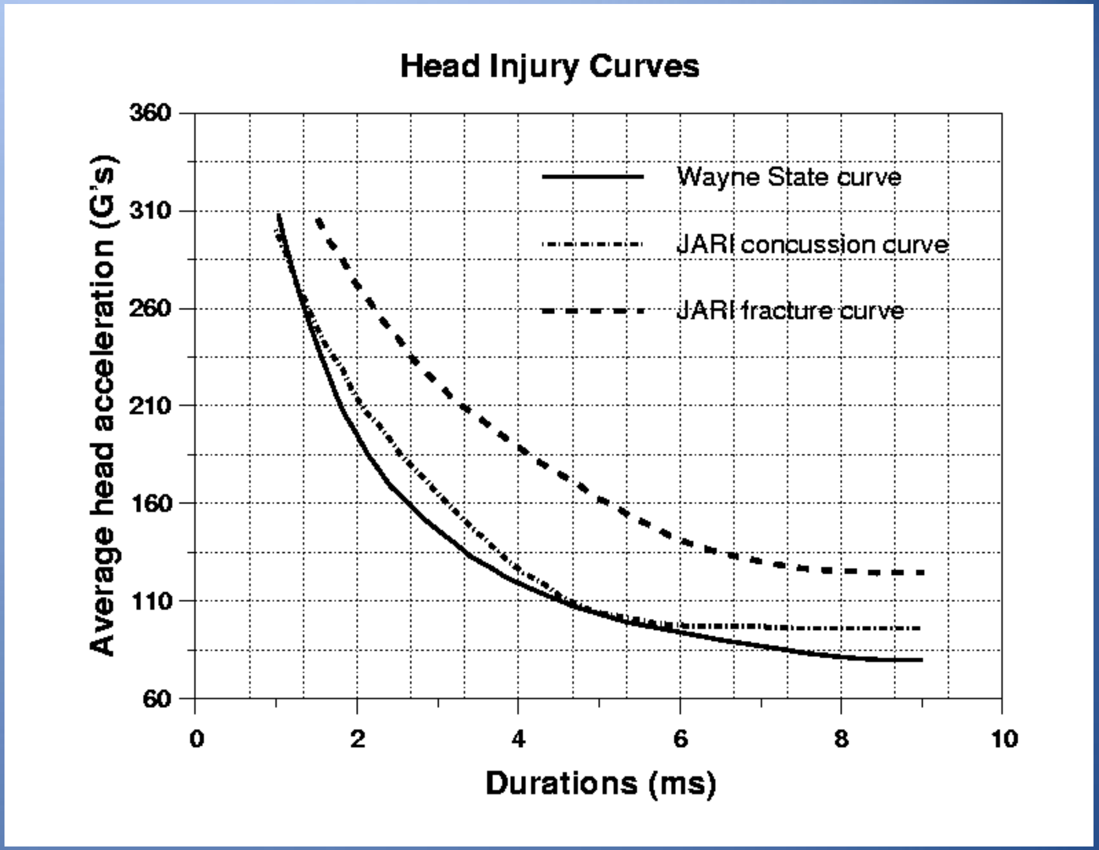
*a* is the resultant acceleration at the center of gravity of the head in *g*;
$t_1$ and $t_2$ is the time window in seconds.

HIC = 1000 was originally specified in FMVSS208

HIC is derived from The Wayne State Head Injury Tolerance Curve that shows that the head can withstand higher acceleration for short duration; and lower acceleration for longer duration. Any acceleration exposure above the curve is injurious.

When the Wayne State curve is plotted in a logarithmic paper, it becomes a straight line with a -2.5 slope.

This slope was used as an exponent by Gadd to develop Gadd Severity Index (GSI):

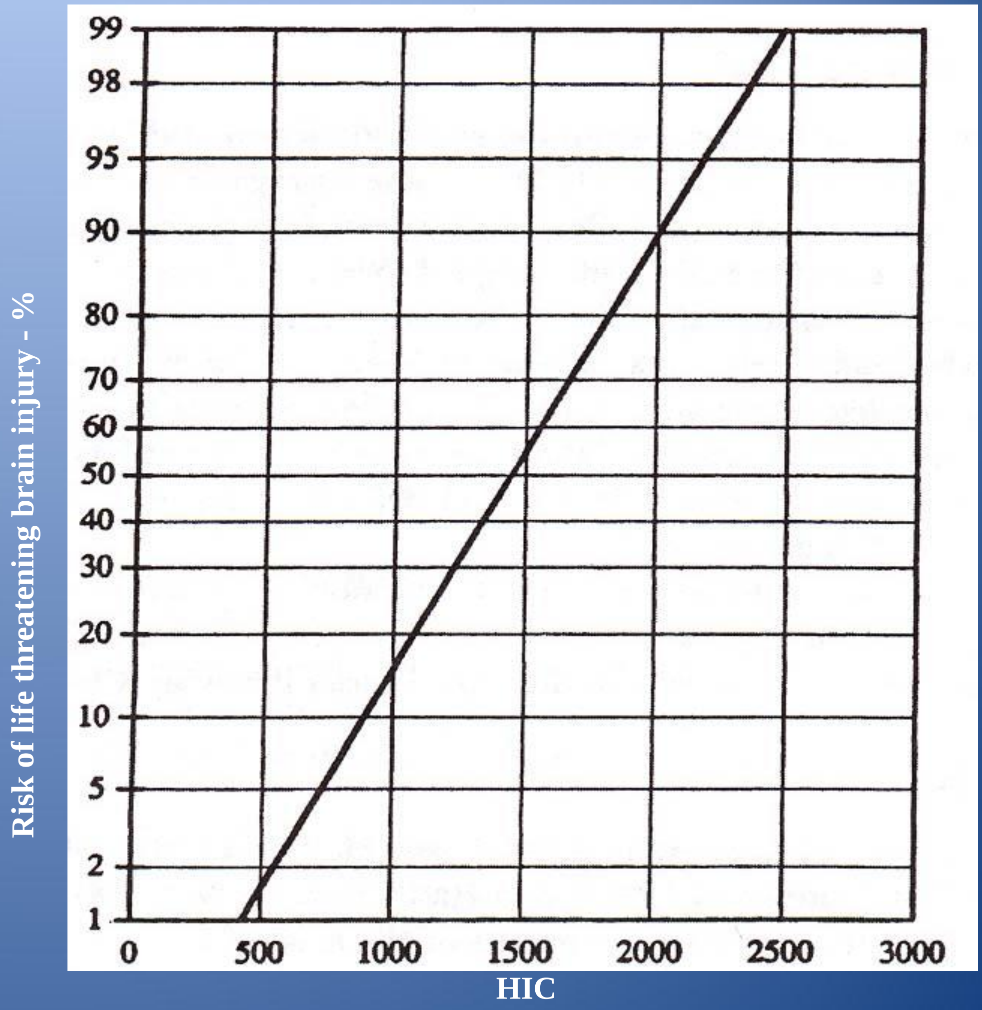



$$GSI = \int_0^T a^{2.5} dt$$

Where $a$ = instantaneous acceleration of the head
$T$ = duration of the acceleration pulse

The biomechanical connotation of HIC =1000 indicates that when a 50th percentile head is subject to a HIC value of 1000 it may still have a 16% of probability to sustain a mild head injury during impact.

Head injury criteria associated with other crash dummies within the Hybrid III dummy family (95th, 5th, 3, 6, 10 years-old dummies) were scaled from that of the 50th percentile dummy for the Injury Assessment Reference Values (IARVs) which were derived by scaling methods.




**Head injury risk based on HIC**

***Courtesy: Prasad and Mertz (1985)**

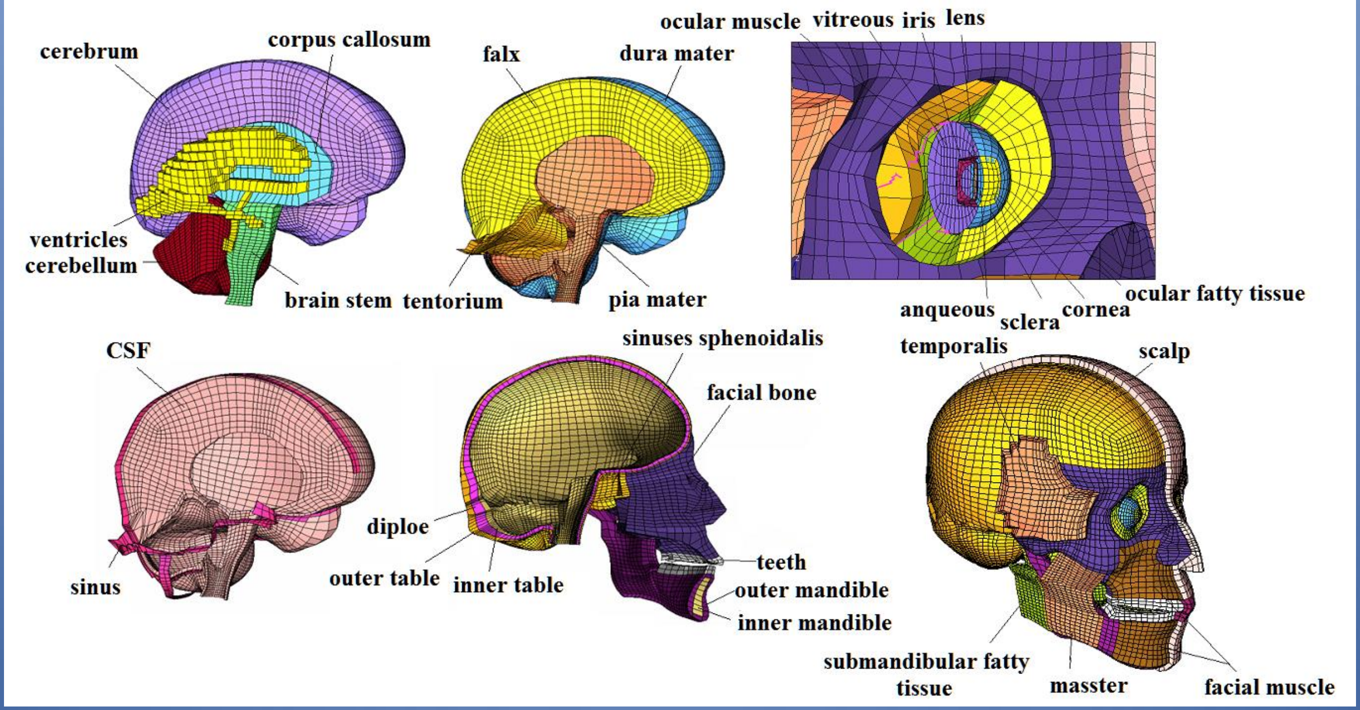
# Introduction

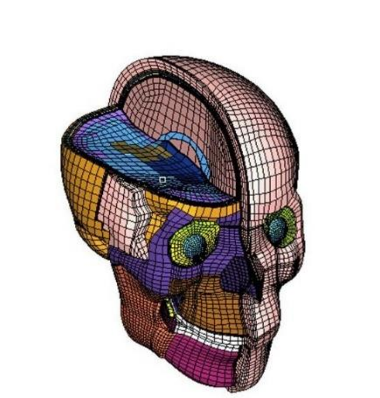
- ✓ **Although HIC exhibits the biomechanical principal component, controversy was surrounding it since its first introduction.**
- ✓ **Some criticized HIC as being fundamentally wrong (Newman, 1980).**
- ✓ **An angular acceleration criterion was needed (Mackay and Petrucelli, 1989).**
- ✓ **Other believed that in frontal impact, HIC appeared to work well (Backaitis et al, 1981).**

# Introduction

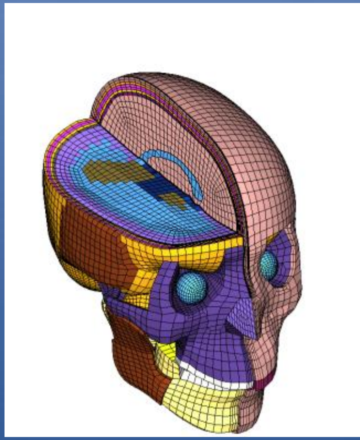
- ✓ HIC has led the automotive industry in the right direction that made the cars of up today more safer than those of the early sixties (Mellander, 1986).
- ✓ The formulations of GSI and HIC are plausible and fundamentally correct (Lockett, 1985).
- ✓ Despite its controversy, HIC is a widely accepted injury criterion for head protection in sports and vehicle safety design.
- ✓ The validity of the scaling techniques used to derive the IARVs for other dummies has not been proved.

# Finite Element Analysis of Human Head Impact

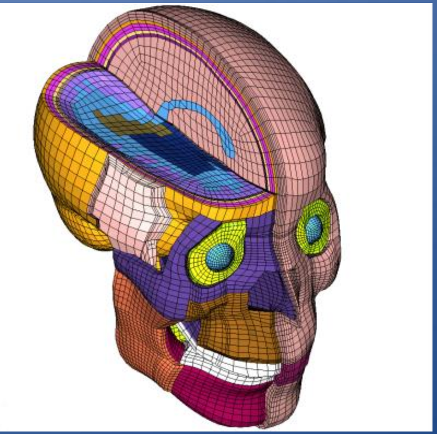


5th percentile model

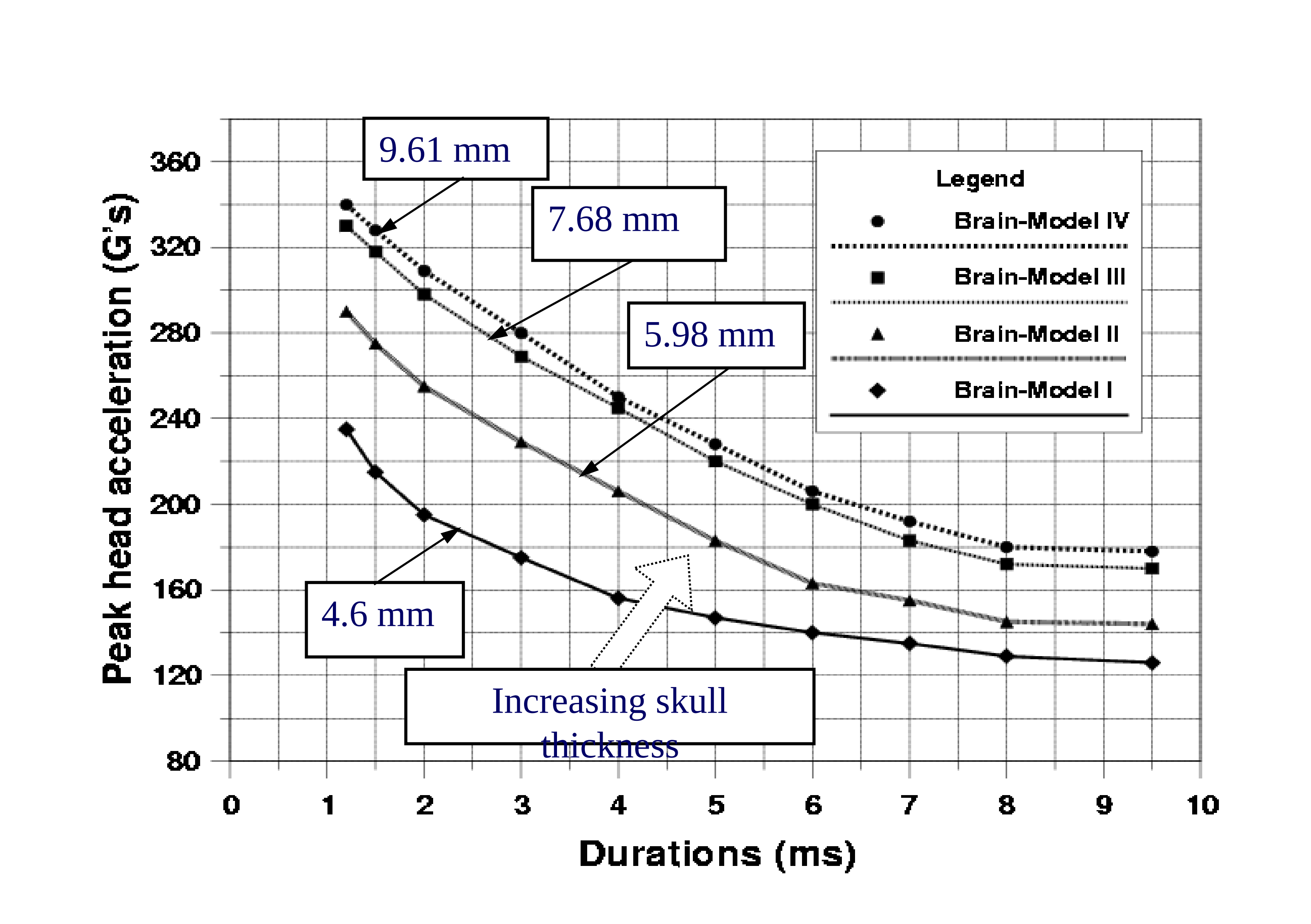


50th percentile model



95th percentile model

# Finite Element Analysis of Human Head Impact




**Head injury tolerance curves derived using FE human head models**

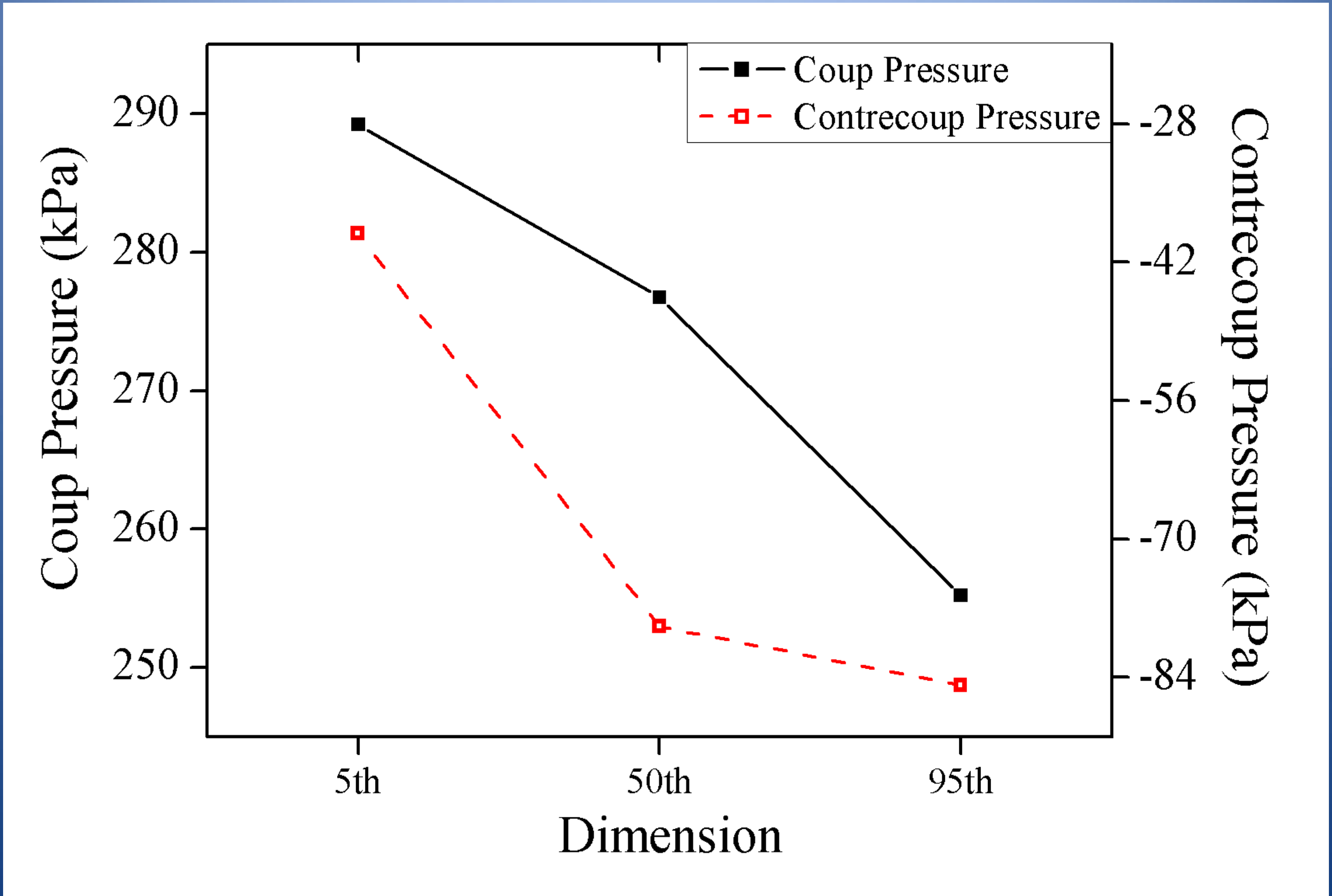
# Finite Element Analysis of Human Head Impact

## Occupant responses from different barrier crash impact conditions

| Impact condition | Contact force (kN) | Shear stress (kPa) | Shear strain (mm/mm) | Peak accel. (G's) | Angular accel. (rad/s$^2$) | 15 ms HIC | 36 ms HIC |
|---|---|---|---|---|---|---|---|
| Airbag contact | 2.7 | 7 | 0.065 | 73 | 2,400 | 553 | 912 |
| No contact | 0.0 | 11 | 0.08 | 76 | 2,700 | 665 | 919 |
| Soft contact | 0.85 | 12 | 0.095 | 86 | 3,700 | 663 | 910 |
| Med-hard contact | 1.9 | 15 | 0.11 | 127 | 19,500 | 1543 | 1548 |
| Semi-rigid contact | 3.8 | 22 | 0.13 | 175 | 15,500 | 2359 | 2359 |

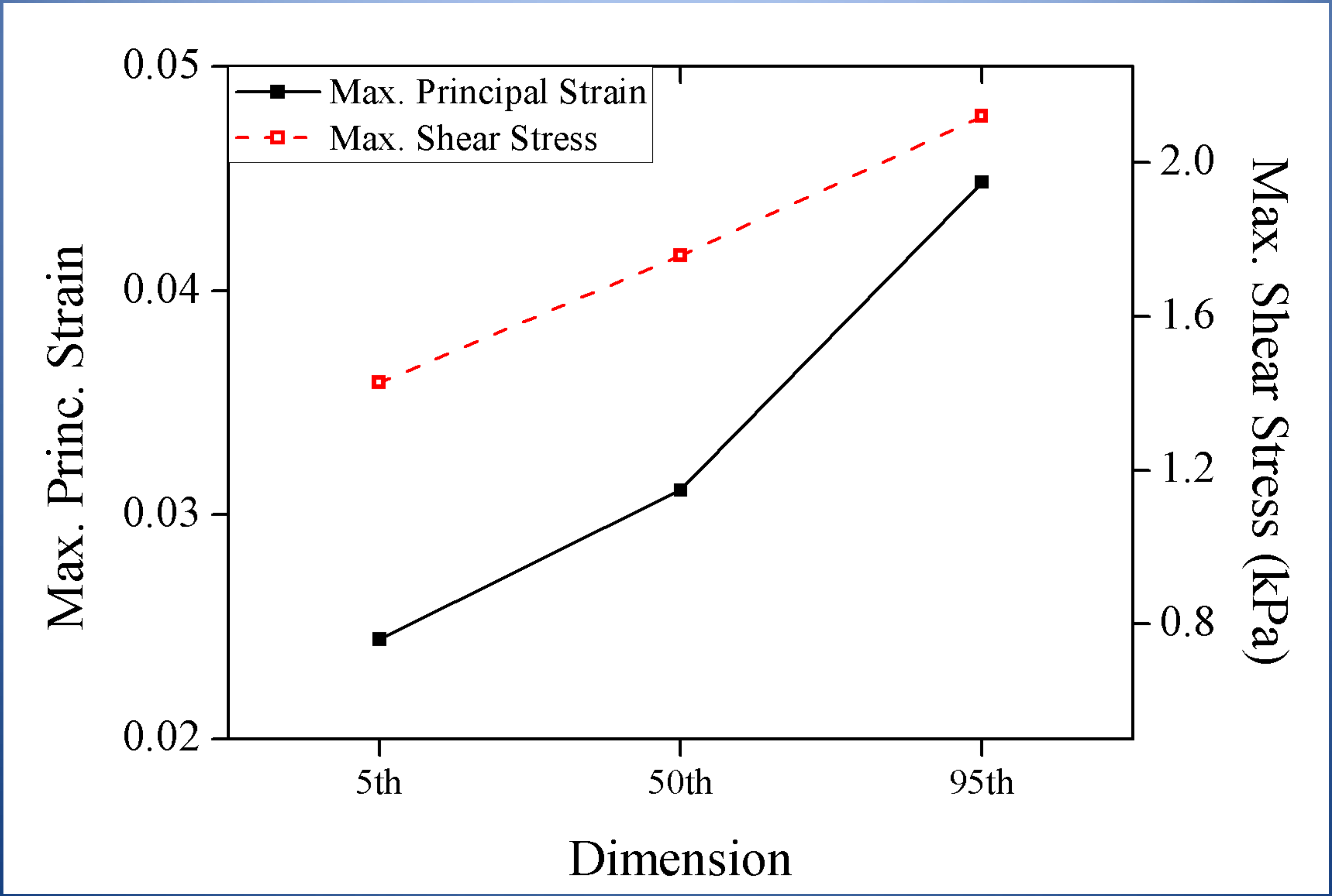
HIC is generally proportional to impact forces, brain pressures, maximum shear strains, maximum tensile strains, and even angular head accelerations in a direct impact situation.

# Finite Element Analysis of Human Head Impact

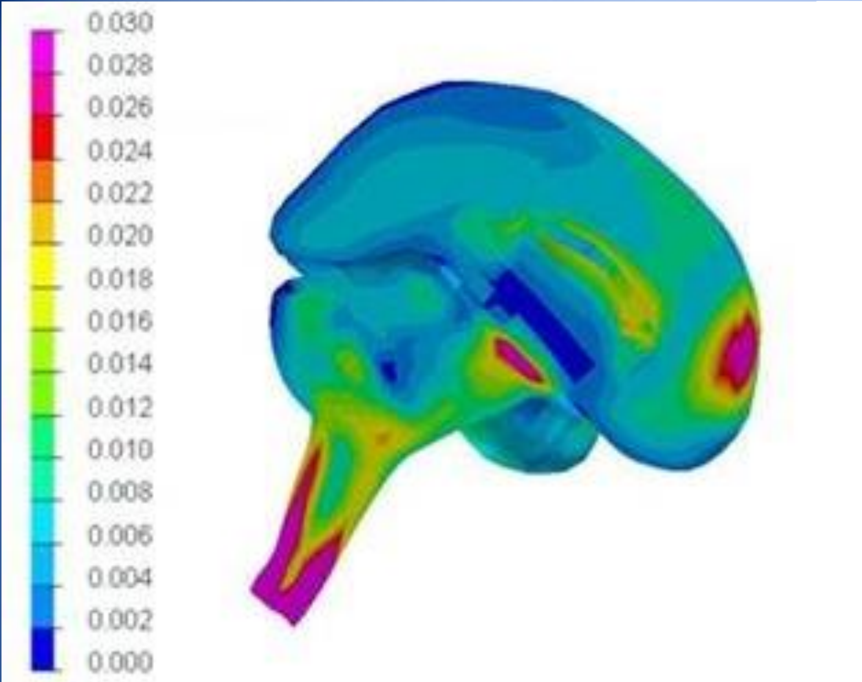


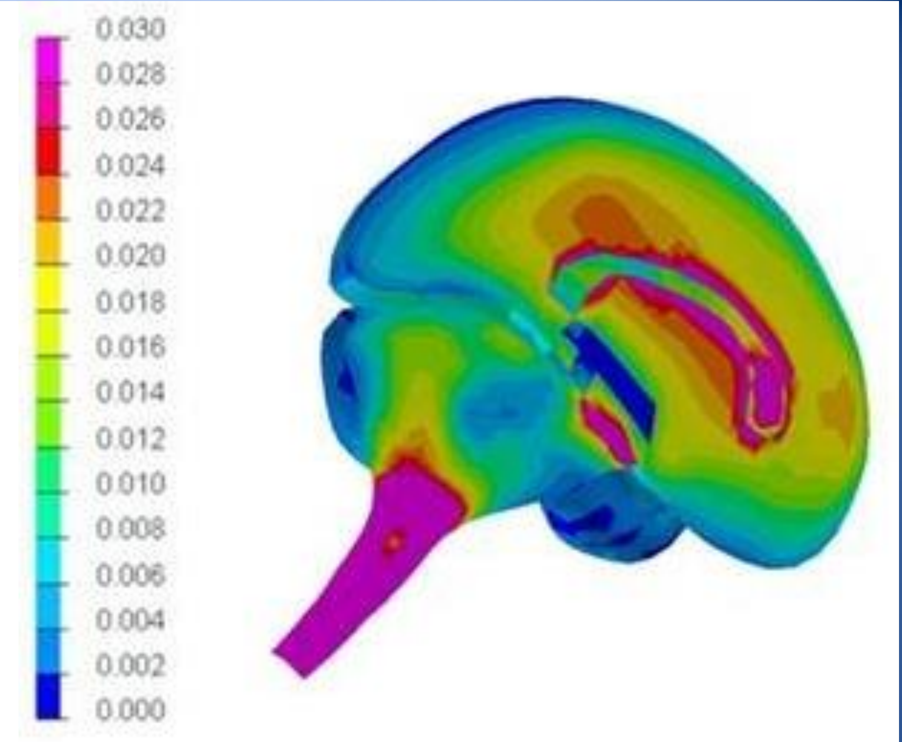

Dependence of intracranial pressure on head size under the same HIC value. (deformable skull)

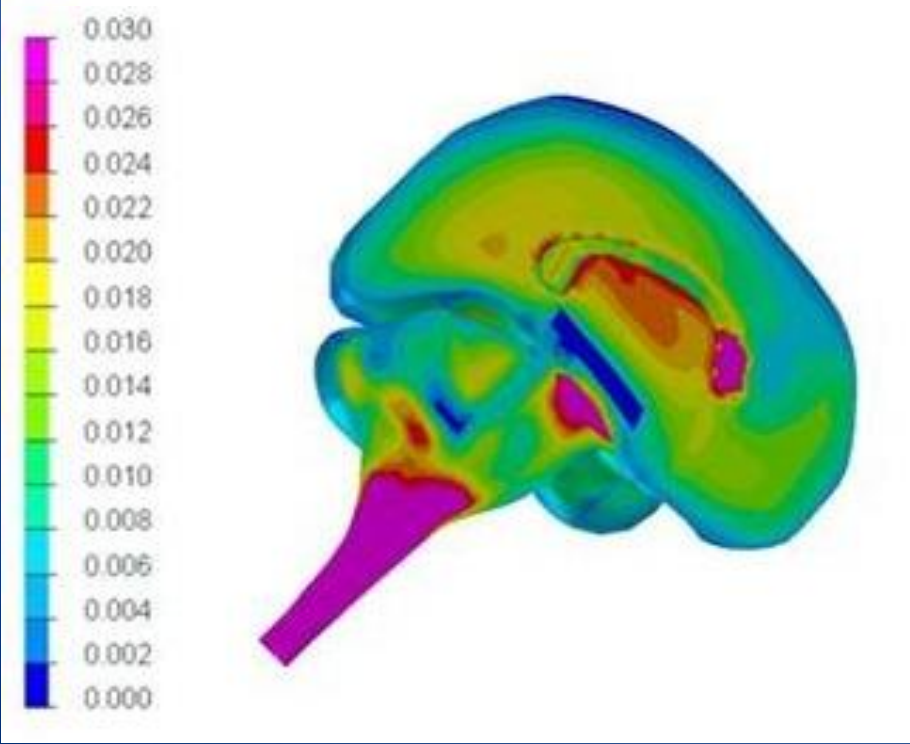
# Finite Element Analysis of Human Head Impact




**Dependence of maximum principal strain and maximum shear stress on head size under the same HIC value. (deformable skull)**



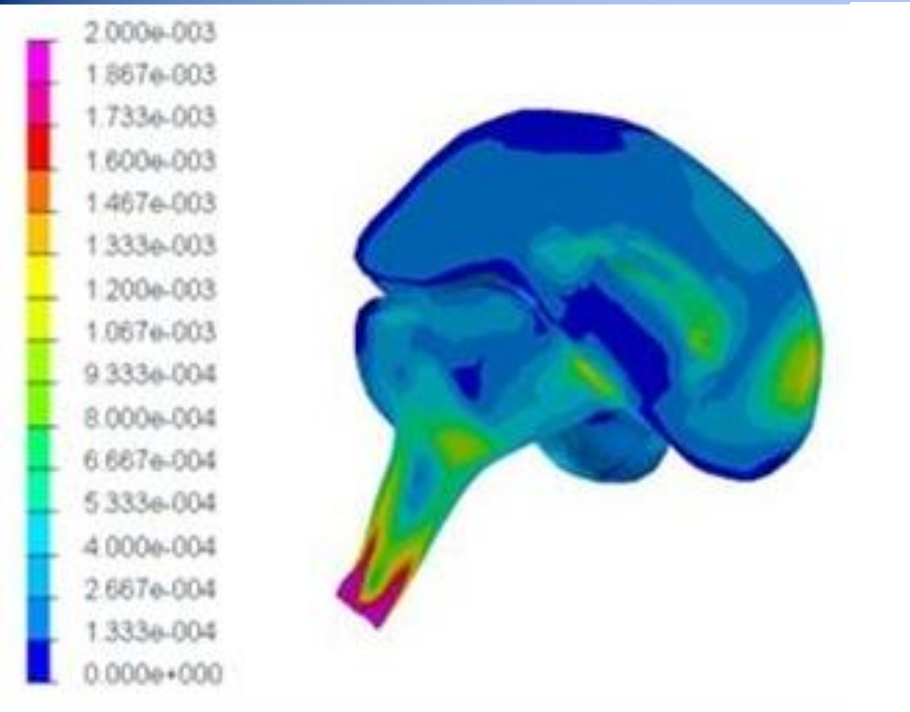



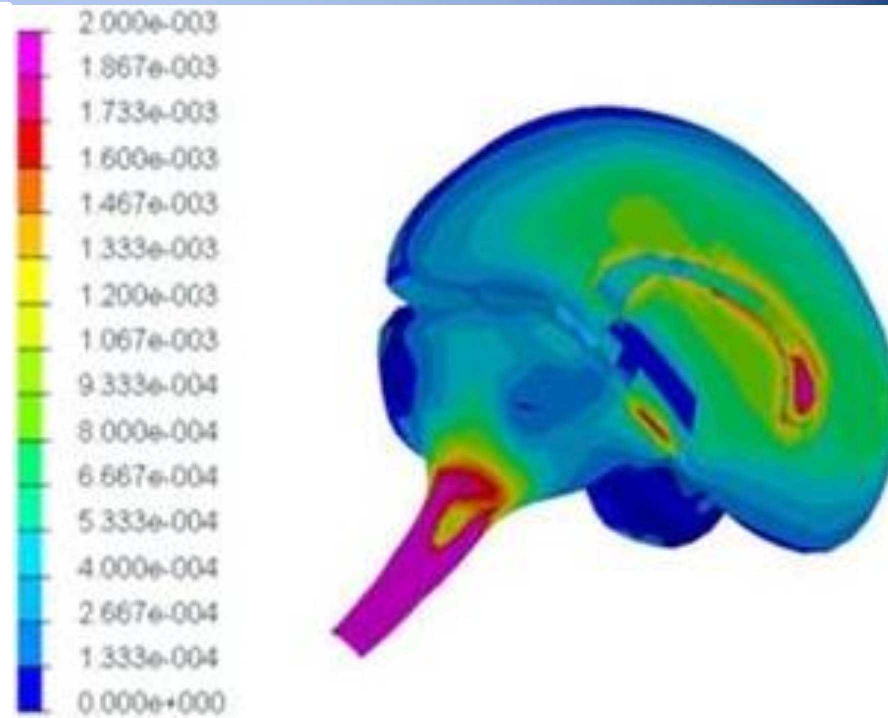

**Maximum principal strain contours following different head size under the same HIC value (deformable skull):**

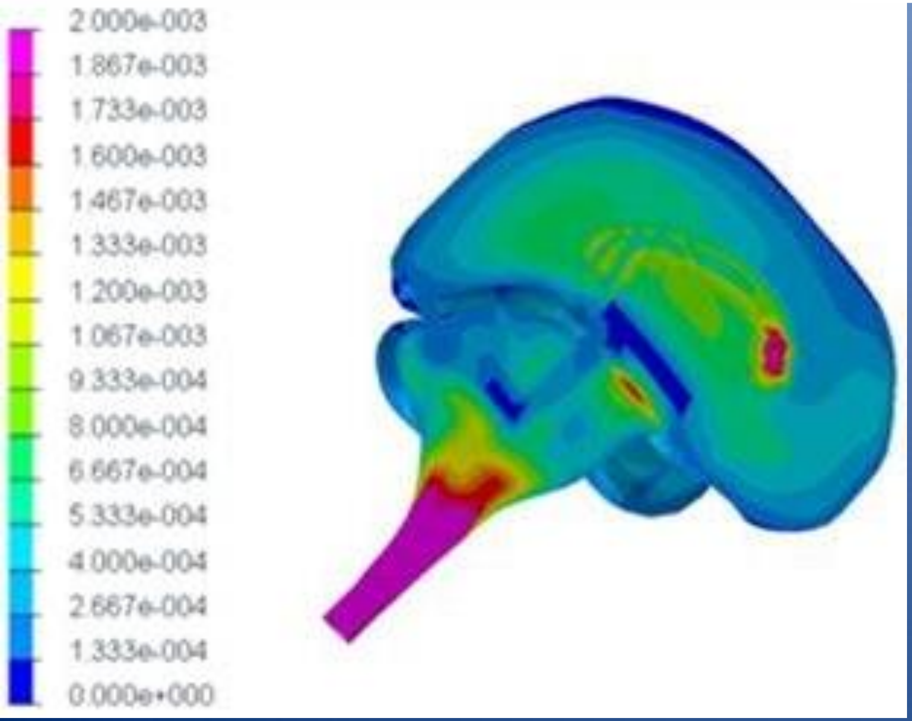
**(a) 5th percentile head model**

**(b) 50th percentile model**

**(c) 95th percentile mode**

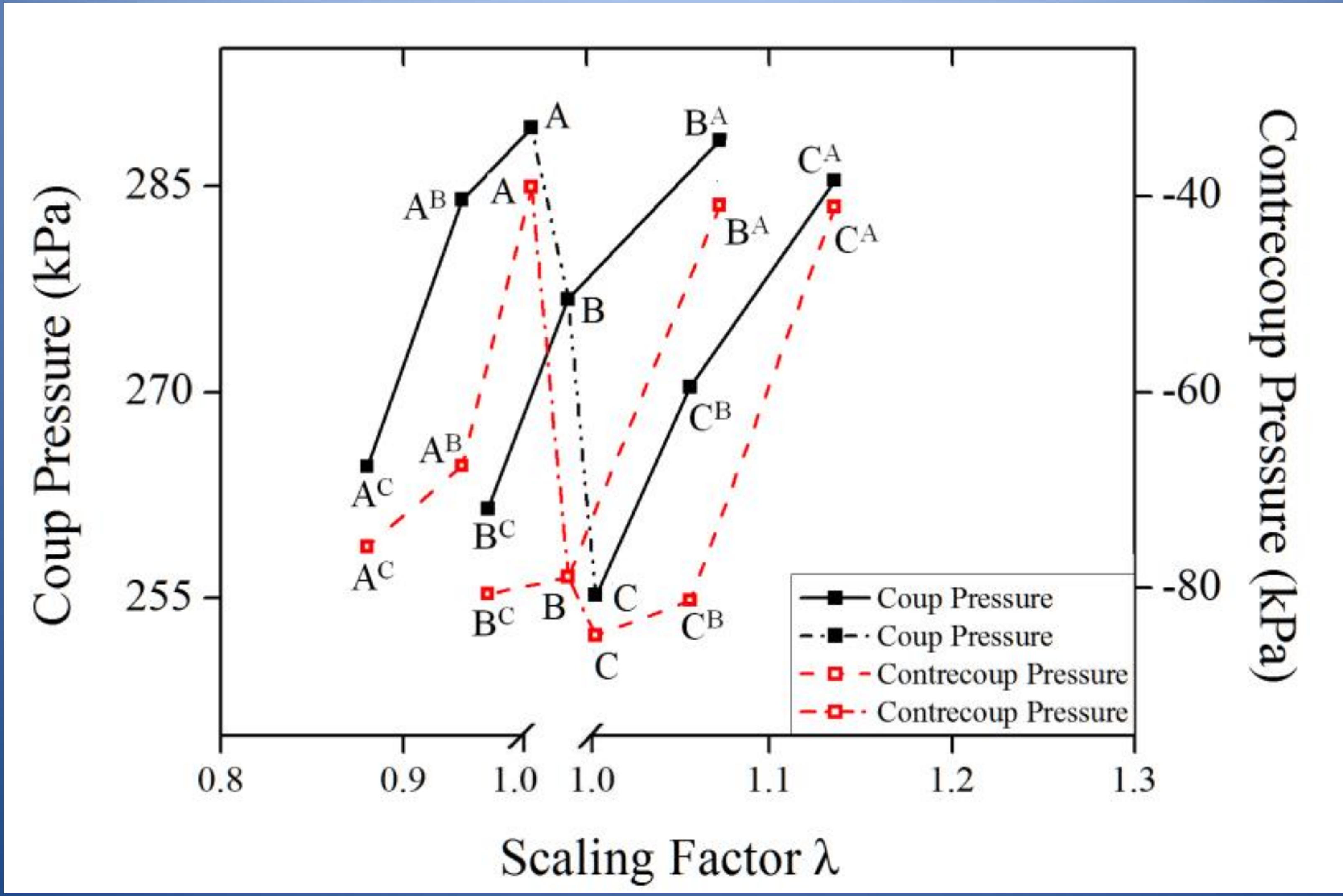


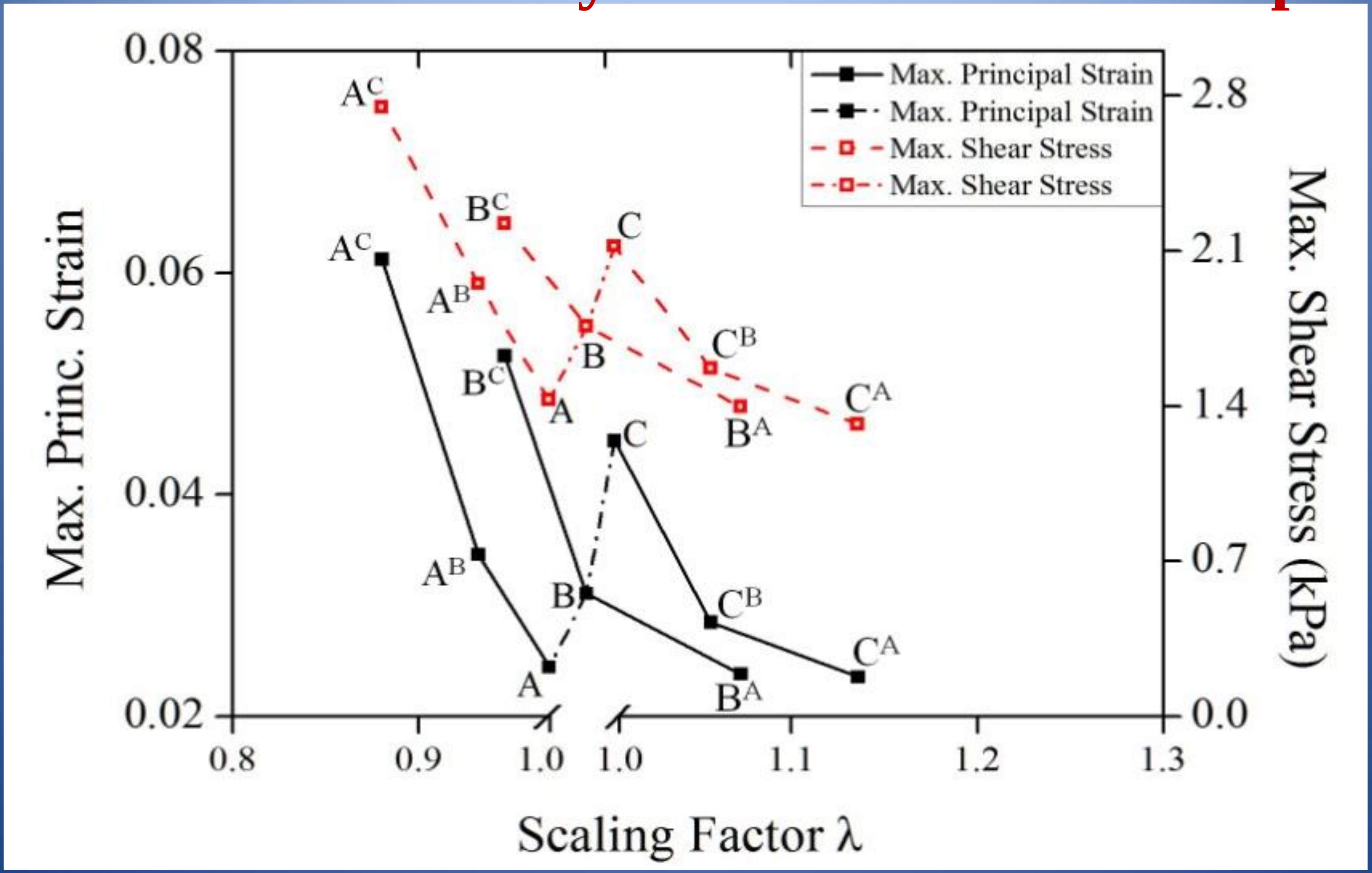

**Maximum shear stress contours following different head size under the same HIC value. (deformable skull):**
**(a) 5th percentile head model**
**(b) 50th percentile model**
**(c) 95th percentile model**

# Finite Element Analysis of Human Head Impact



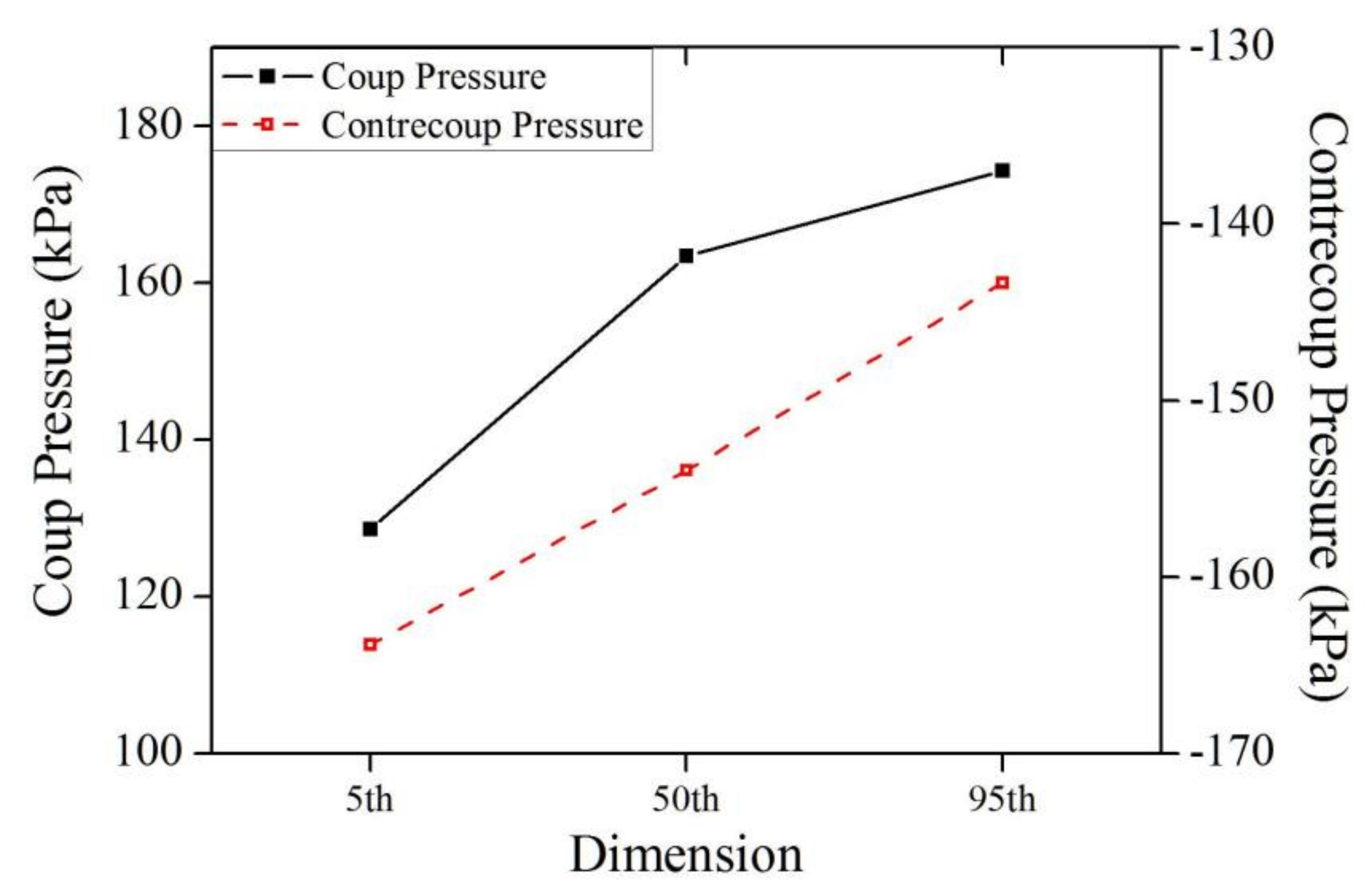

**Comparison of intracranial pressure between scaled models and realistic models under the same HIC value. (deformable skull). The left side is the pressure in smaller heads. The right side is the pressure in larger heads**

# Finite Element Analysis of Human Head Impact



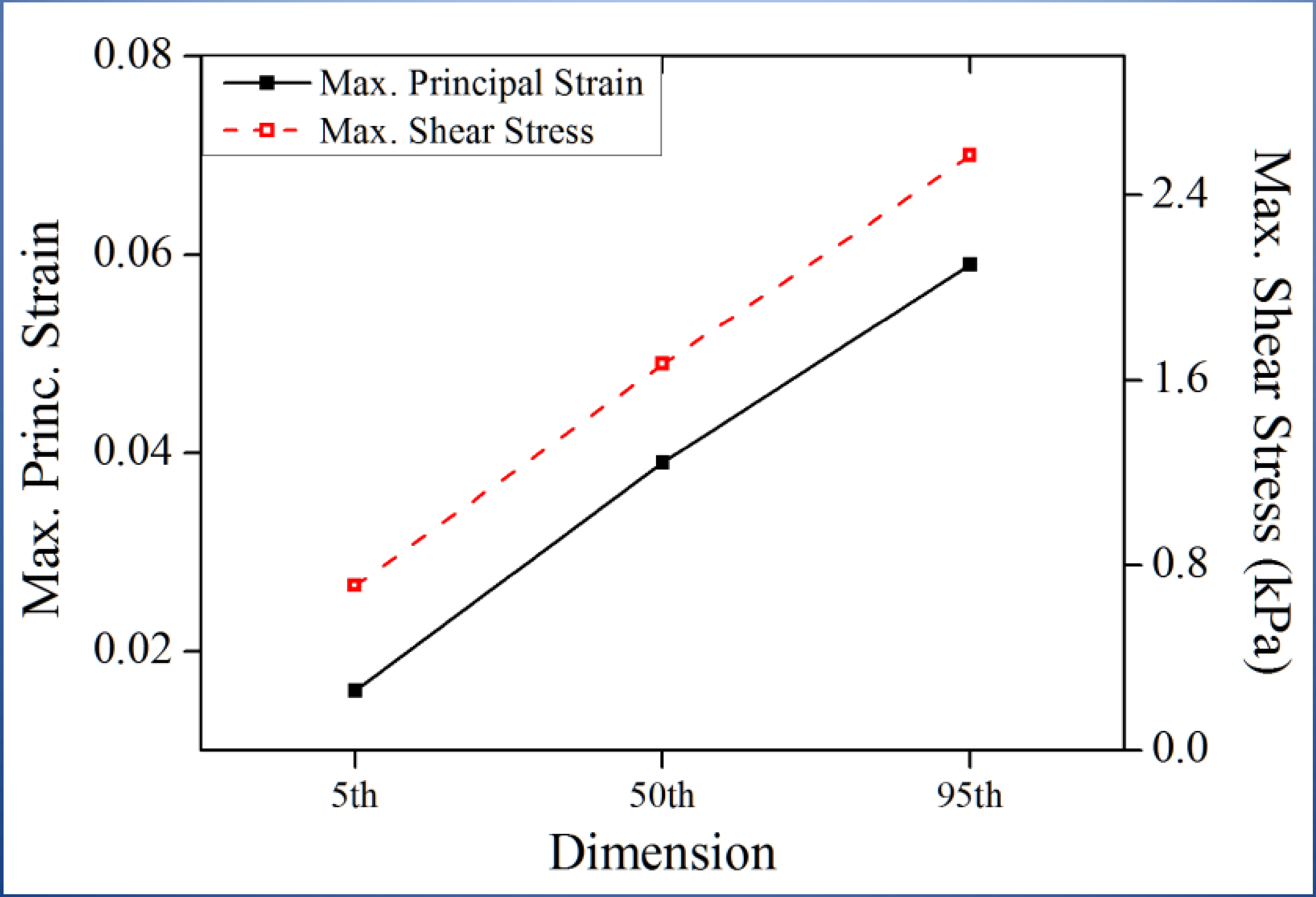

**Comparison of maximum principal strain and maximum shear stress between scaled models between scaled models and realistic models under the same HIC value. (deformable skull). The left side is the pressure in smaller heads. The right side is the pressure in larger heads**

# Finite Element Analysis of Human Head Impact

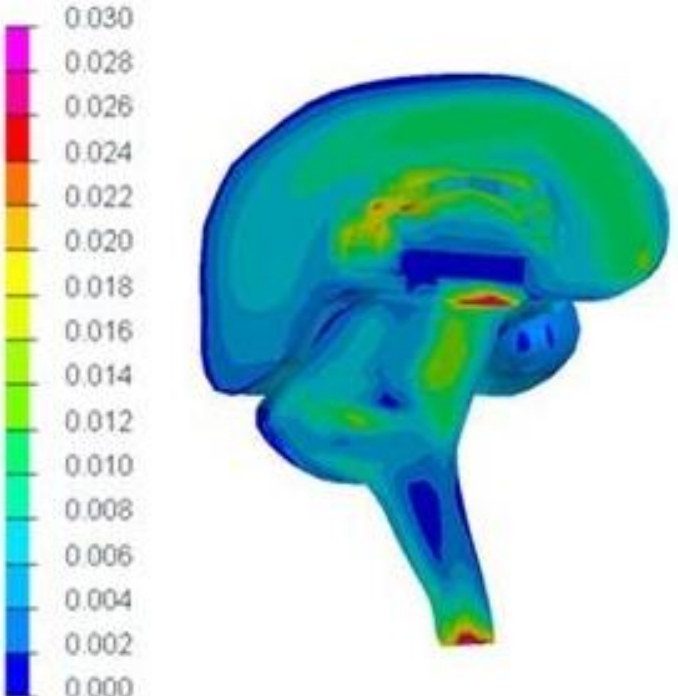


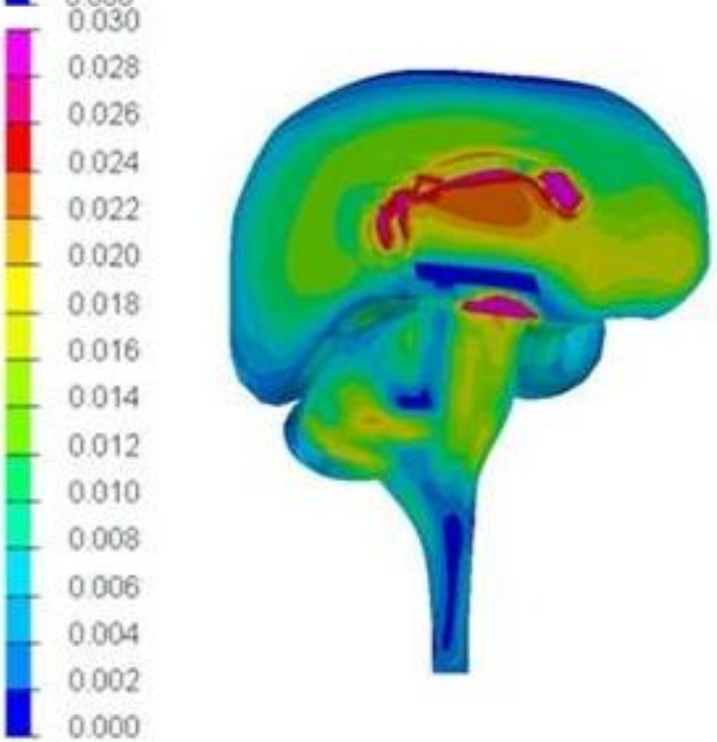

**Dependence of intracranial pressure on head size during the same acceleration pulse. (rigid skull)**

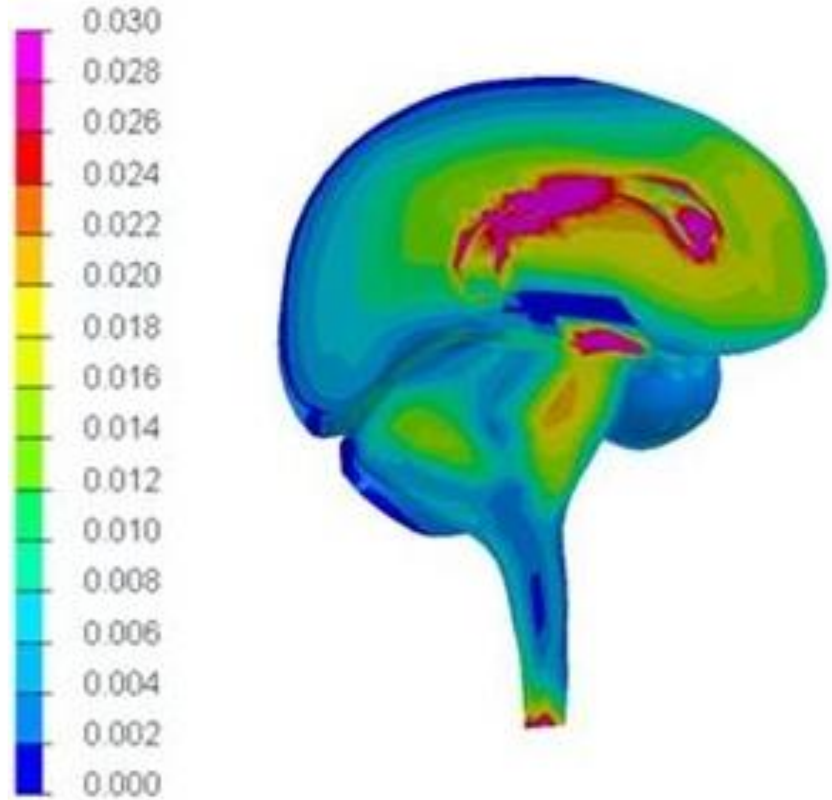
# Finite Element Analysis of Human Head Impact



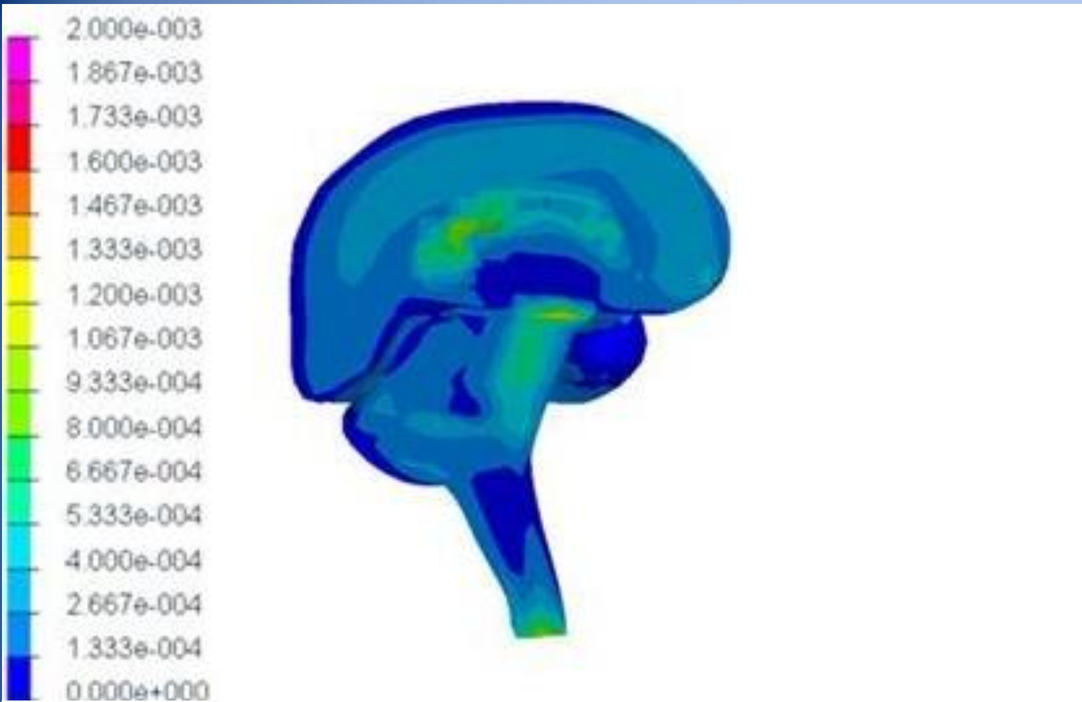

**Dependence of maximum principal strain and maximum shear stress on head size during the same acceleration pulse. (rigid skull)**

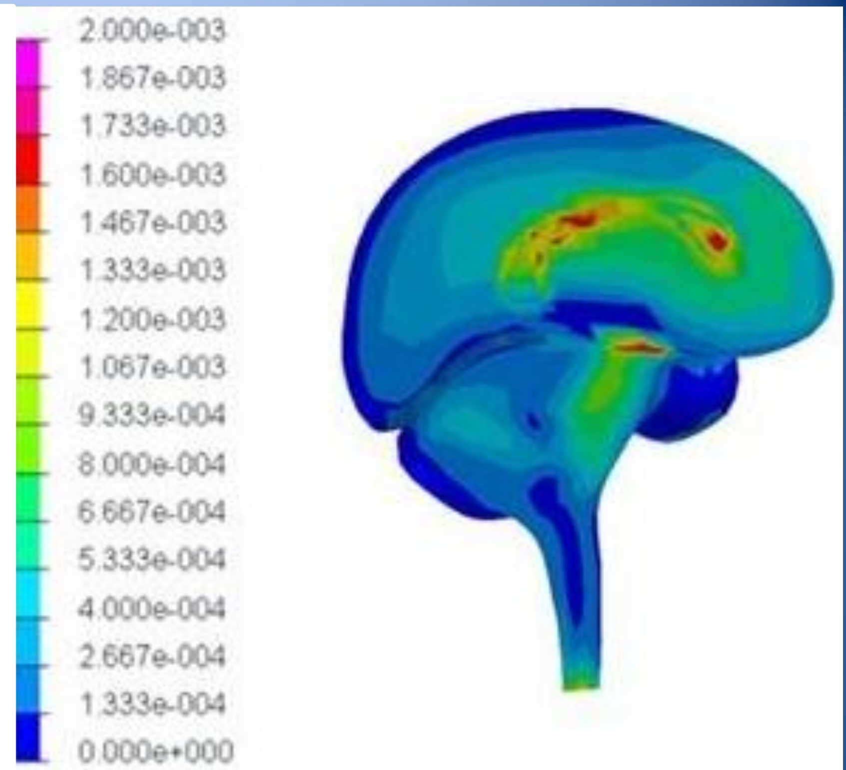


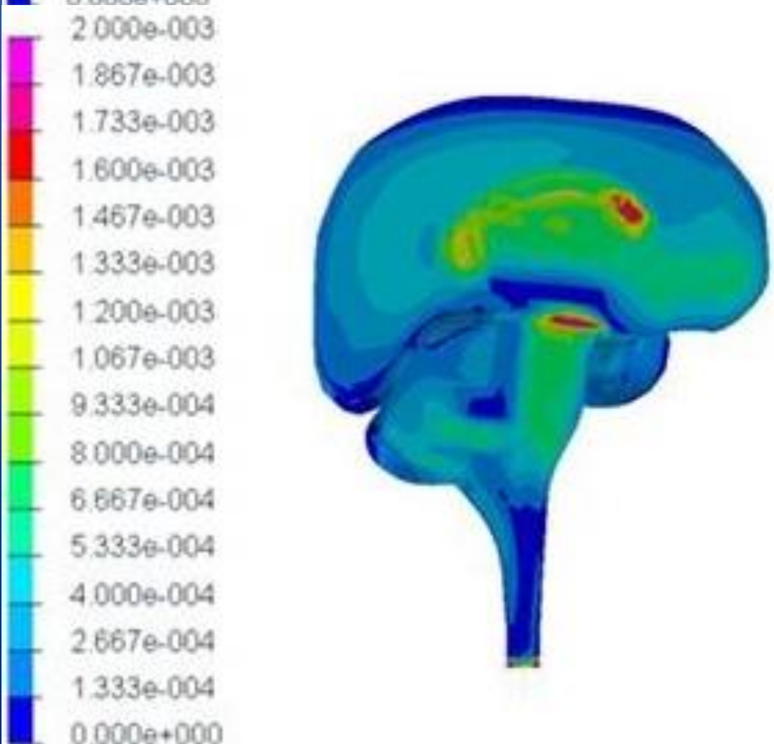




**Maximum principal strain contours following different head size under the same HIC value (rigid skull):**
**(a) 5th percentile head model**
**(b) 50th percentile model**
**(c) 95th percentile mode**

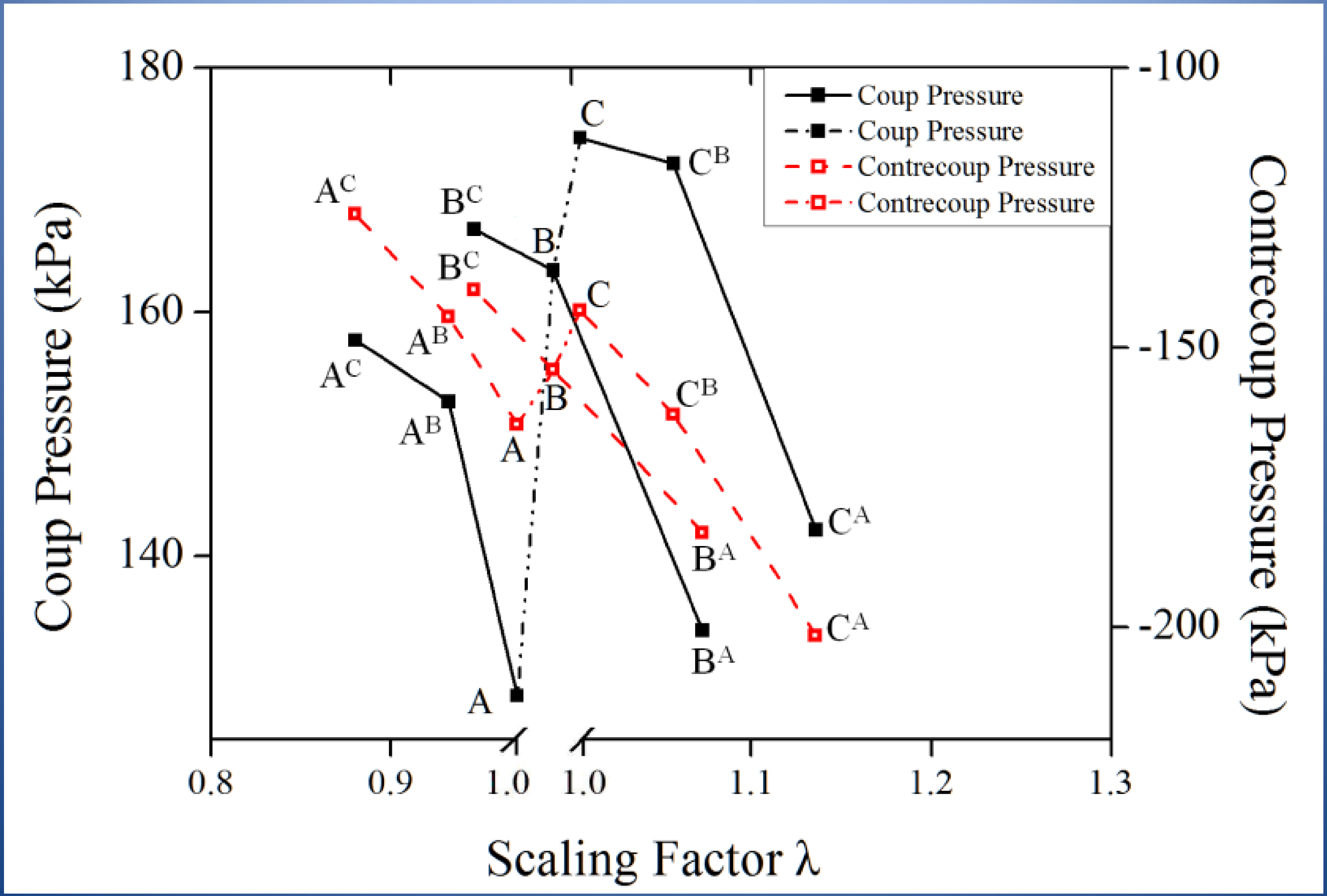


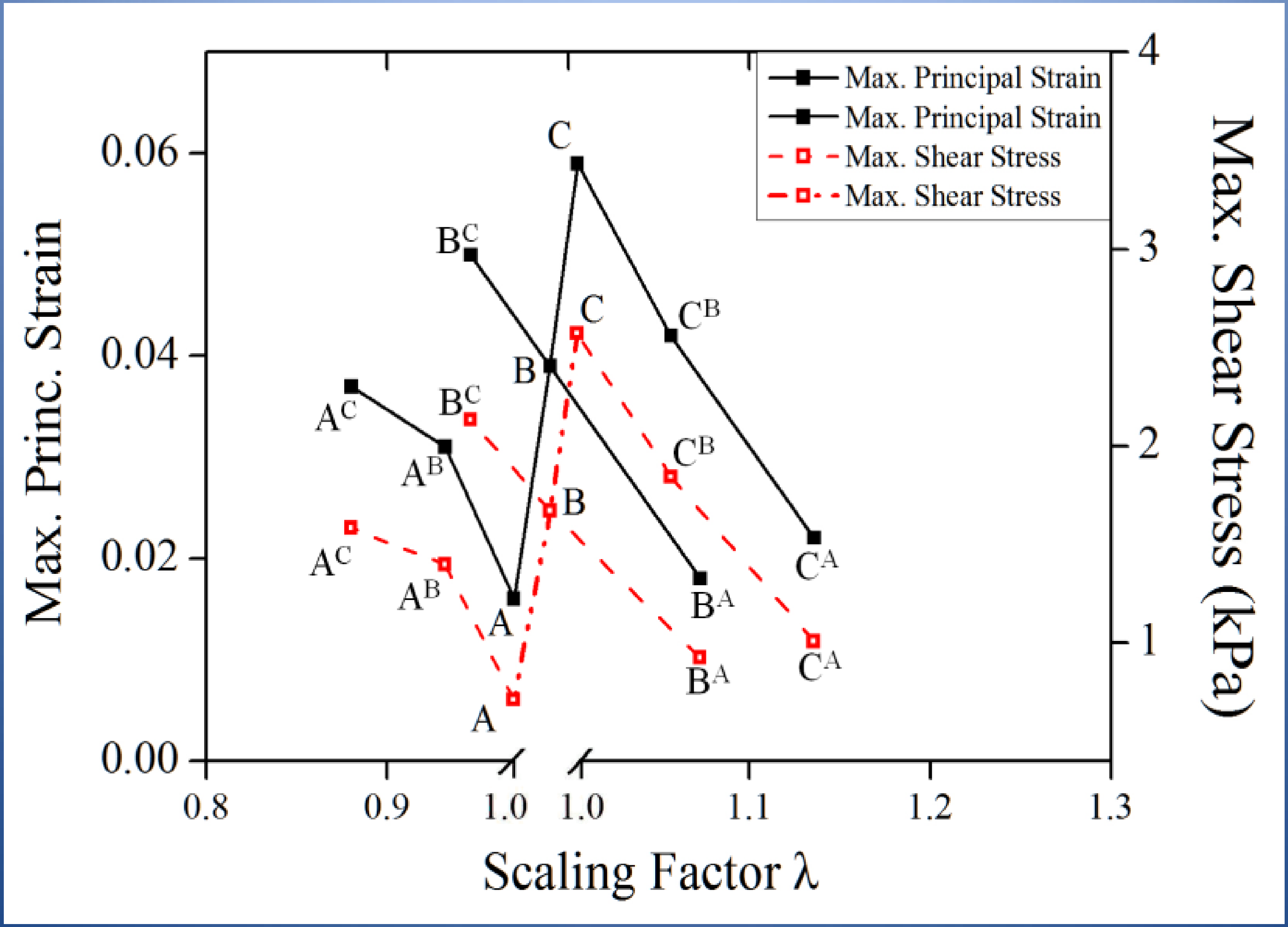

**Maximum shear stress contours following different head size under the same HIC value (rigid skull):**
**(a) 5th percentile head model**
**(b) 50th percentile model**
**(c) 95th percentile model**

# Finite Element Analysis of Human Head Impact




**Comparison of intracranial pressure between scaled models and realistic models during the same acceleration pulse. (rigid skull) The left side is the pressure in smaller heads. The right side is the pressure in larger heads**

# Finite Element Analysis of Human Head Impact




**Comparison of maximum principal strain and maximum shear stress between scaled models between scaled models and realistic models during the same acceleration pulse. (rigid skull). The left side is the pressure in smaller heads. The right side is the pressure in larger heads**

# Intracranial responses of realistic models.

| Definition of skull | FE Model | Coup pressure (kPa) | Contrecoup pressure (kPa) | MPS (-) | MSS (kPa) |
|---|---|---|---|---|---|
| Deformable | A | 289.232 | -39.093 | 0.024 | 1.428 |
| | B | 276.742 | -78.871 | 0.031 | 1.760 |
| | C | 255.197 | -84.824 | 0.045 | 2.120 |
| Rigid | A | 128.545 | -163.837 | 0.016 | 0.710 |
| | B | 163.403 | -153.974 | 0.039 | 1.669 |
| | C | 174.292 | -143.336 | 0.059 | 2.570 |

# Output intracranial responses of scaled models

| Definition of skull | FE Model | scaling factor | Coup pressure (kPa) | Contrecoup pressure (kPa) | MPS (-) | MSS (kPa) |
|---|---|---|---|---|---|---|
| Deformable | $A^C$ | 0.880 | 264.579 | -75.769 | 0.061 | 2.747 |
| | $A^B$ | 0.932 | 283.984 | -67.536 | 0.034 | 1.950 |
| | $C^B$ | 1.057 | 270.347 | -81.252 | 0.029 | 1.568 |
| | $C^A$ | 1.136 | 285.404 | -41.129 | 0.024 | 1.317 |
| Rigid | $A^C$ | 0.880 | 157.701 | -126.132 | 0.037 | 1.582 |
| | $A^B$ | 0.932 | 152.676 | -144.540 | 0.031 | 1.396 |
| | $C^B$ | 1.057 | 172.183 | -161.987 | 0.042 | 1.841 |
| | $C^A$ | 1.136 | 142.124 | -201.561 | 0.022 | 1.007 |

# Introduction to BrIC

- ✓ **One of the criticisms of HIC is that it does not effectively take into account the rotational acceleration of the head while rational acceleration causes more harm to the brain than translational acceleration.**
- ✓ **Therefore, Brain Injury Criterion or BrIC was proposed (**Takhounts et al, 2013**).**

# Brain Injury Criterion (BrIC)

$\omega_x$:

- Belt & lateral movement
- Head slips off bag

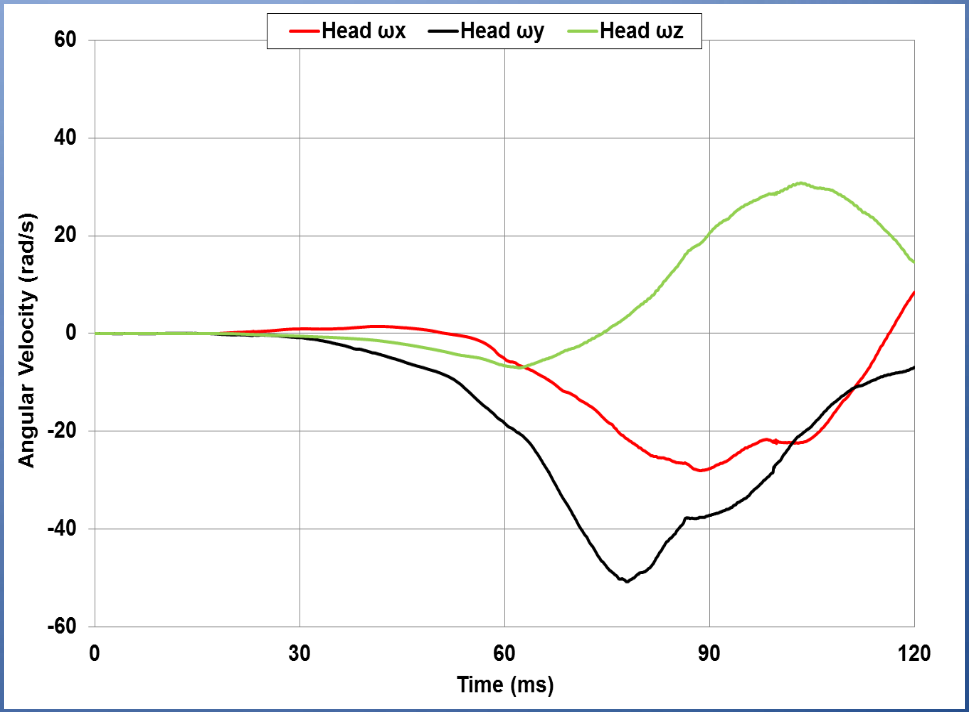
$\omega_y$:

- Belt & forward movement
- Head lacks bag support

$\omega_z$:

- Initial belt & lateral movement
- Head interacts w. bag
- Head slips off bag

$$BrIC = \sqrt{\left(\frac{\omega_{x\max}}{66.3}\right)^2 + \left(\frac{\omega_{y\max}}{53.8}\right)^2 + \left(\frac{\omega_{z\max}}{41.5}\right)^2}$$




- BrIC is determined from maximum head rotational velocity components
- Maximum determination is independent of time
- The weighting factors are not equal for the three components
- Causes of the three components are different, and might be in conflict

# HIC vs. BrIC

| Claims | HIC | BrIC |
|---|---|---|
| Expression Form | Math Formula | Math Formula |
| Injury Mechanisms | Translational<br>Direct Impact<br>Contact | Rotational<br>Indirect Impact<br>Non-contact |
| Biomech. Basis* | Deformable Skull | Rigid Skull |
| Cause of Injury | Skull bending<br>Brain pressures | Brain strains |
| Injury Types | Focal/Diffused | Diffused |
| Injury Assessments | Skull Fracture<br>Concussion Sub-dura Hematoma | Concussion<br>DAI |

# Remarks on BrIC

- Finite element models of head injury haves showed that both the magnitude and duration of head angular acceleration affect brain strain responses.

- Since rotation is always one component of head motion in the real world, higher rotational head acceleration will result in higher resultant head acceleration

# Remarks on BrIC

- Rotation is not the only injury mechanism to cause brain injury, BrIC may be inadequate for brain injury assessment in all kind of impact cases.

- In general, the peak values of biodynamic parameters such as force, acceleration and displacement are not good indicators for assessing human body tissue dysfunction, their durations are also counted.

# Conclusions

- HIC is applicable to a direct impact situation, and it works well in protecting head injury in automotive safety design and helmet design for sports.
- HIC behaviors differently from a deformable skull and a rigid one.
- Scaling laws used in biomechanical injury reference value calculation are not accurate enough and their usage could be limited.

# Conclusions

- BrIC means to be used to assess brain injury in a rotational loading condition, it cannot be used for assessing the effects of skull fracture.
- The efficacy of BrIC may need to be more thoroughly evaluated before it can be used as a design tool in vehicle safety design.
- Finite element modeling of human head could be a more comprehensive tool in engineering safety design.

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# Thank You for Your Attention

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