Helmet Protection against Traumatic Brain Injury: A Physics Perspective

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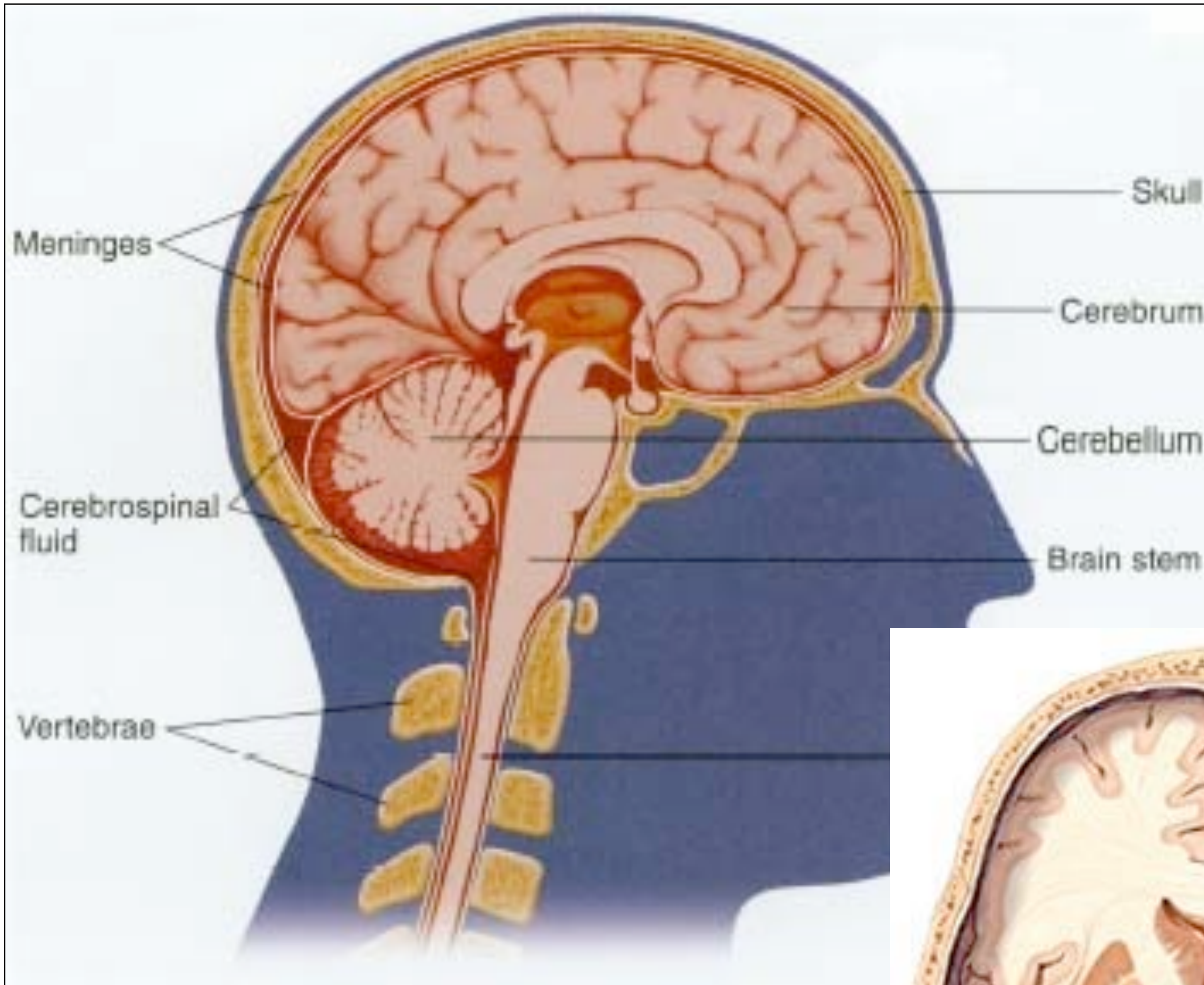
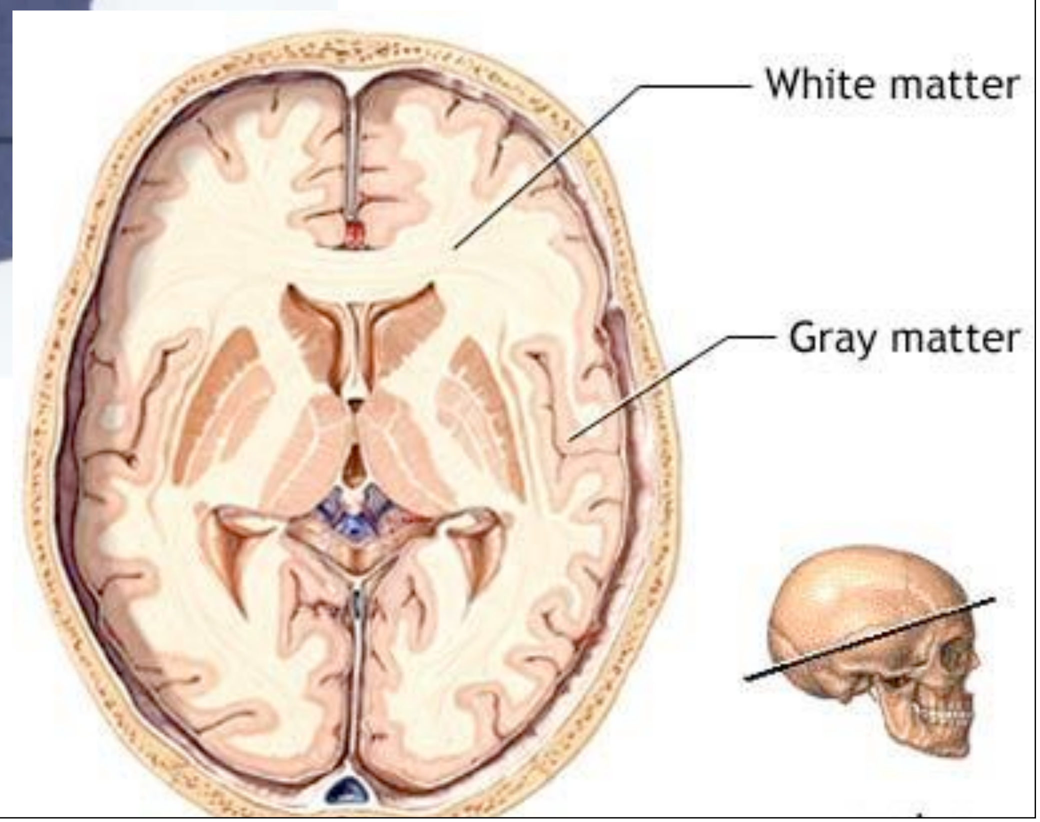
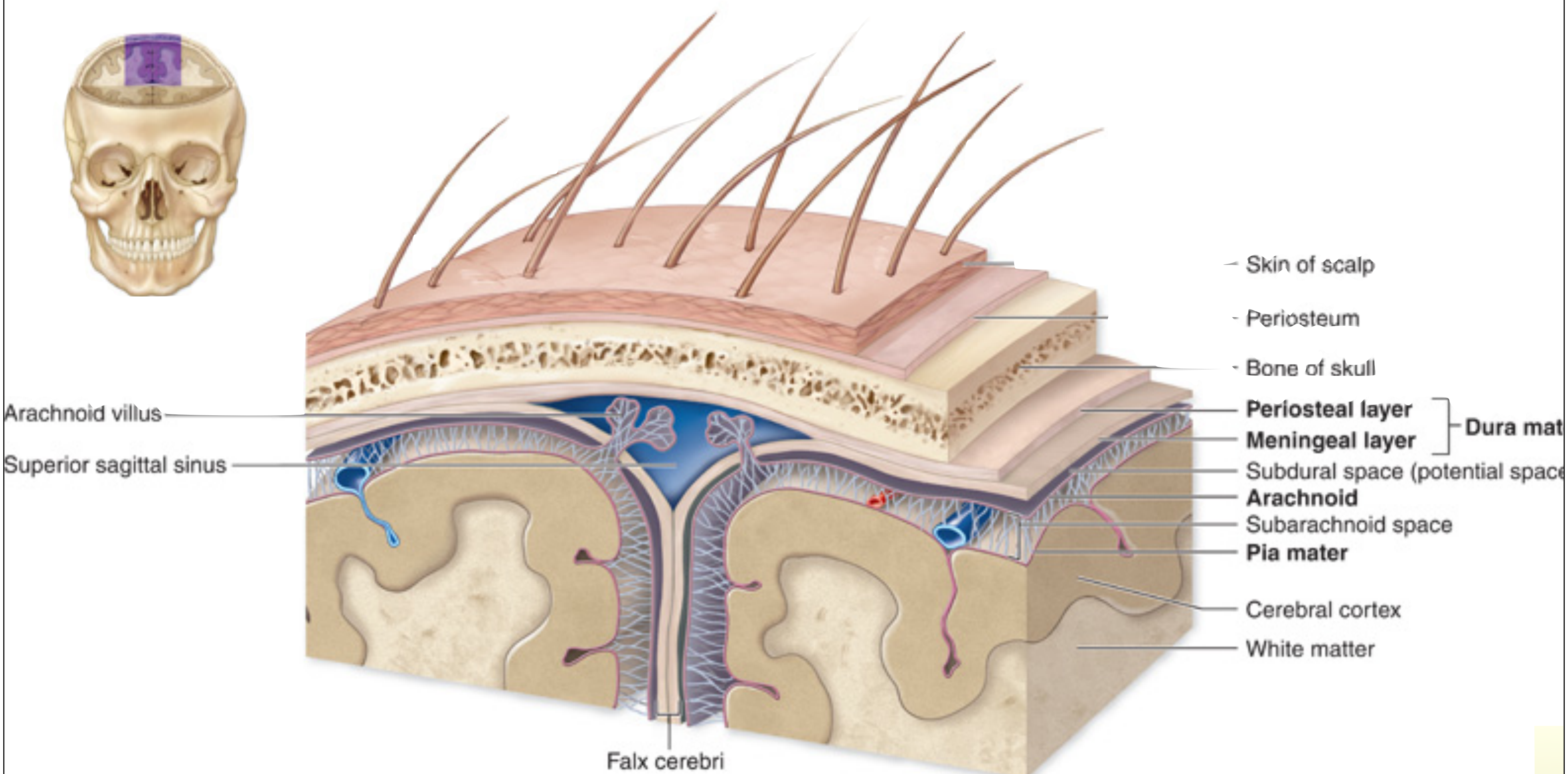
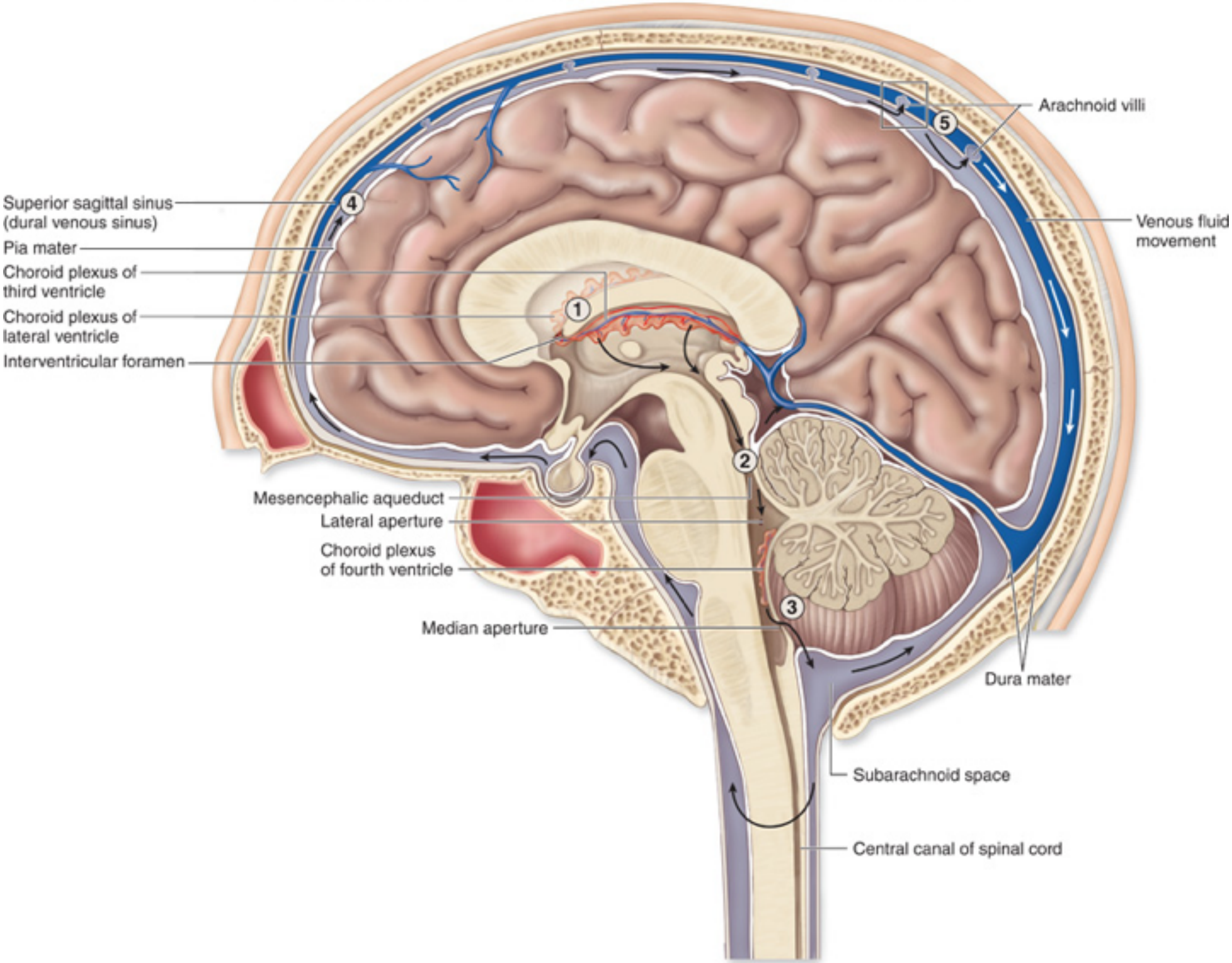
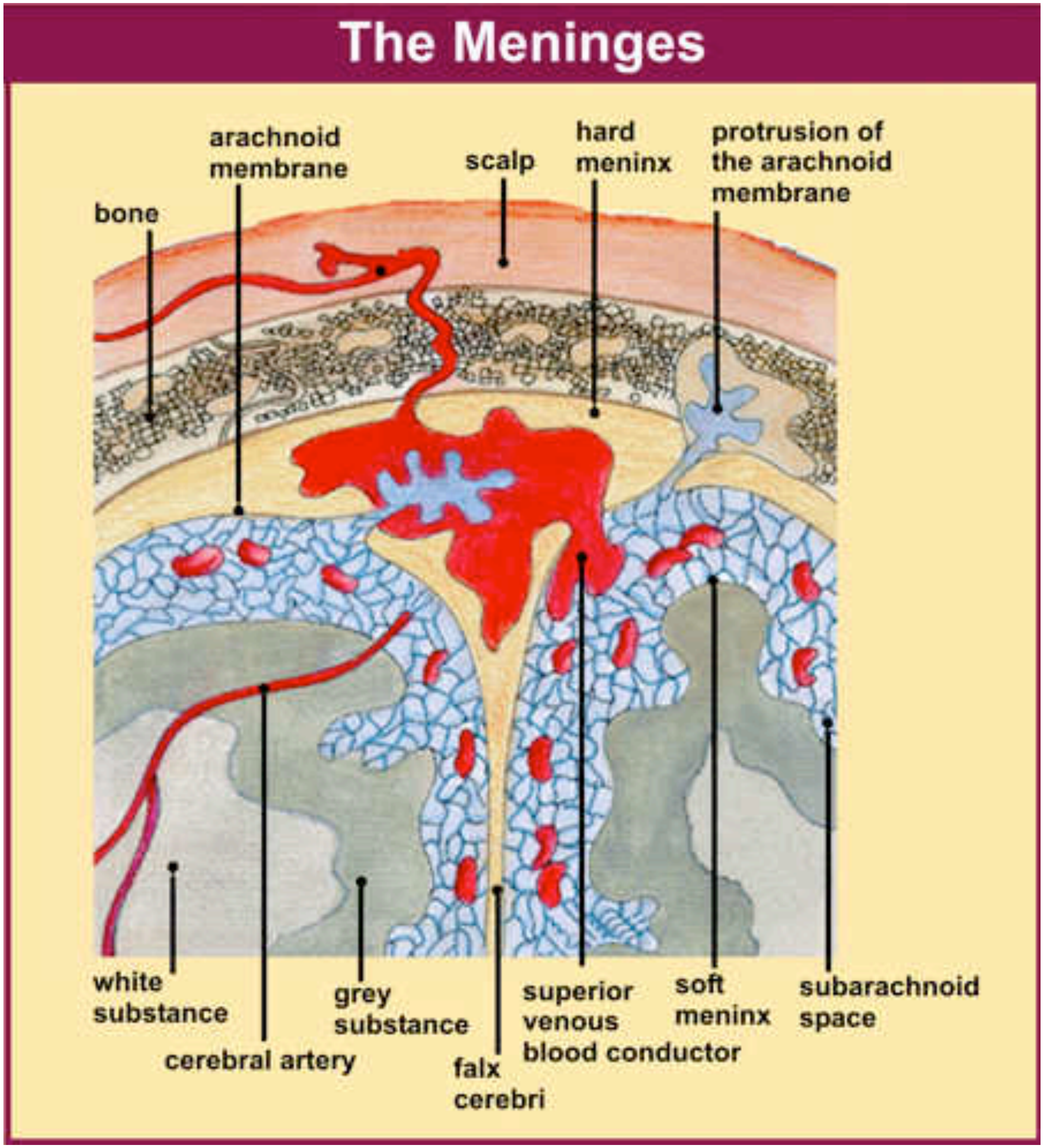

Skull
Meninges
Cerebrum
Cerebellum
Cerebrospinal
fluid
Brain stem
Vertebrae


White matter
Gray matter


Skin of scalp
Periosteum
Bone of skull
Arachnoid villus
Periosteal layer
Meningeal layer
Dura mat
Superior sagittal sinus
Subdural space (potential space
Arachnoid
Subarachnoid space
Pia mater
Cerebral cortex
White matter
Falx cerebri



(a) Midsagittal section


The Meninges
arachnoid membrane
scalp
hard meninx
protrusion of the arachnoid membrane
bone
white substance
cerebral artery
grey substance
falx cerebri
superior venous blood conductor
soft meninx
subarachnoid space

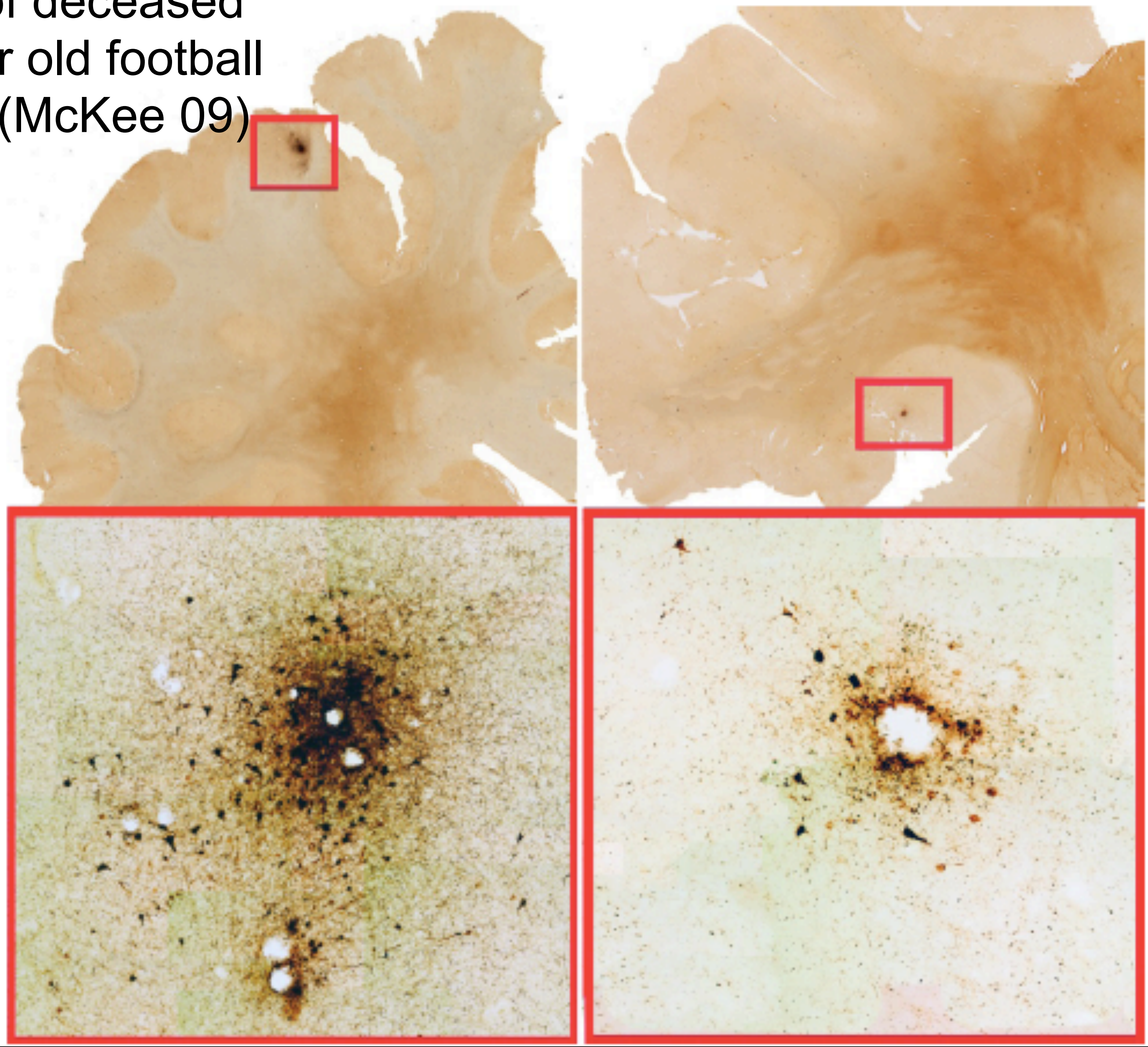
Closed Traumatic Brain Injury (TBI)

- physical injury to the brain without skull fracture
  - **concussions** (non-local; midbrain, brainstem, frontal lobe)
  - **diffuse axonal injury** (shear damage of axons; white matter grey matter linkage)
  - **contusions** (general bruising)
  - **subdural hematoma** (bridging vein damage)
  - **chronic traumatic encephalopathy** (CTE) (degenerative brain injury from repetitive head trauma)

Chronic Traumatic Encephalopathy (e.g. McKee 2009)

- CTE: toxic "tau protein" builds up in brain cells, preventing normal connections to other cells; cells die
- tau protein shows up as neurofibrillary tangles (NFTs) and glial tangles
- Tangles are formed by hyperphosphorylation of tau proteins in microtubules, causing tau to aggregate
- accompanies dementia though not itself a signature of Alzheimers (no beta amyloid)
- Prevalent in brain tissue of deceased football players and boxers, some even without clinical history of excessive concussions.
- Role of many low level impacts vs. few extreme impacts on CTE/ ITBI requires more work

Brain of deceased 18 year old football player (McKee 09)



Sources of TBI without skull fracture

- (1) head impact (ITBI)

- (2) blast overpressure (OTBI)

- (3) blast + impact: ITBI + OTBI combination must be common

Cost of TBI (in USA)

- **Human costs**

- **Civilian**: $2x10^6$ cases/yr; 50% auto; 25% sports (McArthur 04)
  - 20 deaths per 100,000: $20 billion/yr treatment

- **Military**:
  - before 2006; estimated 3% of soldiers have TBI (60% of hospital injured soldiers)
  - 0.6% of all soldiers serious TBI
  - New screenings: 2006-2009 ~20% of all troops have TBI; 1.5% of all troops unfit to return by current military standard
  - cost $2.7 million (Blimes 07) per 25 yr post-TBI life of soldier >$2 billion/year just for treatment of soldiers

- **Workforce / mission / security costs**

TBI is an Interdisciplinary Frontier

-Timely TBI: military, NFL

-Modern protection equipment has reduced fatalities, leaving previously hidden secondary injuries.

-NFL: 60% incur at least 1 concussion; retired players 19 times more likely to show symptoms of CTE (McKee 09)

-Many aspects of TBI science are nascent

- medical screening and correlation with trauma
- “macho” culture: TBI not always understood as physical
- PTSD vs TBI diagnosis and treatment
- physiology and biology of injury
- connecting external force to specific injury (impact vs. blast)
- basic physics of protection/ engineering protective equipment
- understanding deficiencies in protective equipment
- data collection

-Business, Politics, vs. Science

Head Impacts

- Gravity or explosion converts gravitational potential energy or chemical energy into bulk kinetic energy

- Rapid deceleration upon impact implies large force

- During impact, kinetic energy is converted into deformation energy
  - Brain damage from energy dissipated in brain rather than helmet or skull
  - tissue stress (force per unit area) threshold for injury
  - duration of force threshold for injury

TBI from Impacts

- As head impacts, brain keeps moving; it is coupled to skull by cerebral spinal fluid (CSF)

- Brain ‘crashes’ into skull displacing fluid; stresses brain tissue both by compression and shear

- Protecting skull from fracture is insufficient to protect brain from crashing into skull

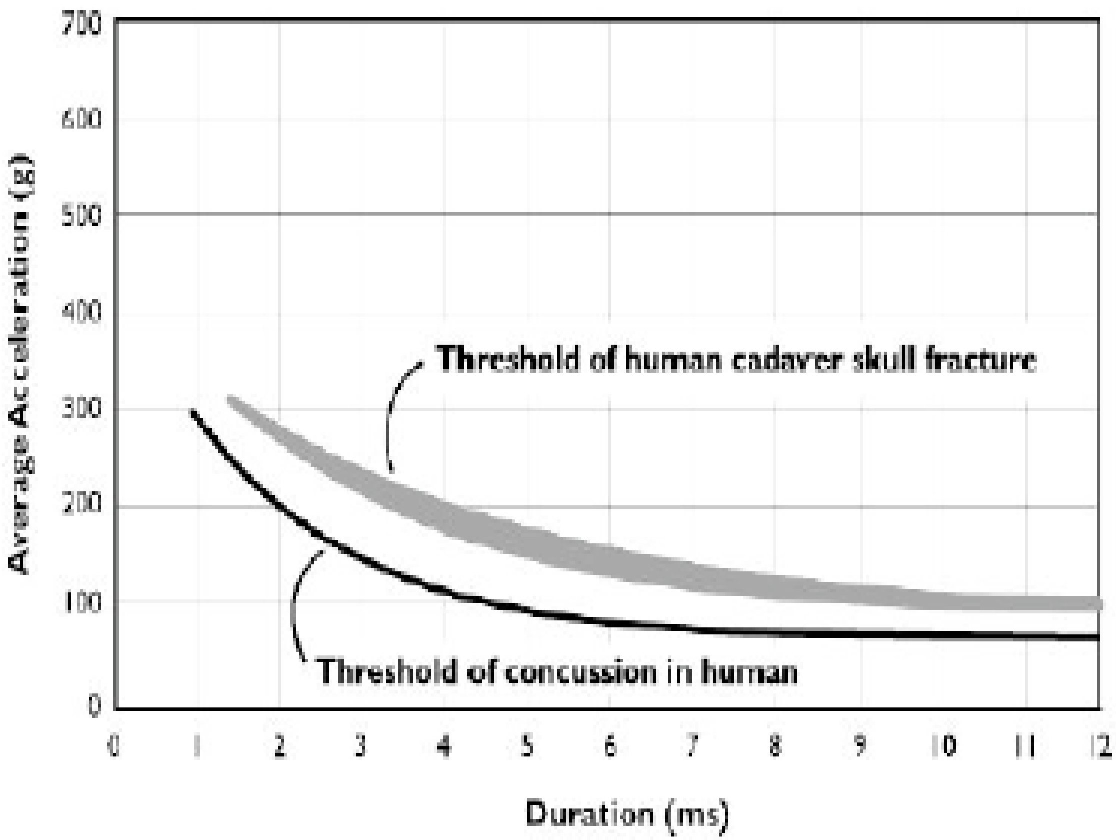
- Need to:
  - reduce head acceleration (reduces maximum force incurred by brain-skull crash)
  - reduce energy absorbed by brain (reduces energy available to sustain a distorted brain for extended period)

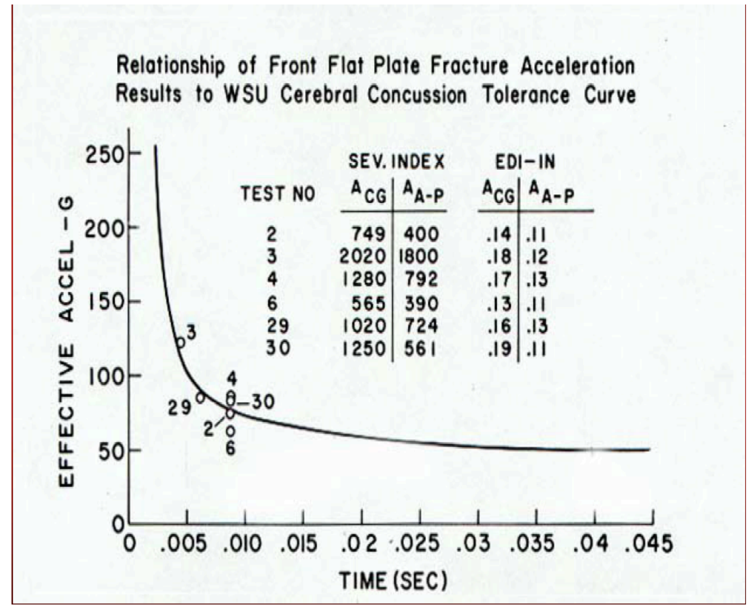
Role of Helmets for Impact TBI

- Hard shell alone is no good
- Need cushioning to reduce head impact acceleration and thus force on brain
- Cushioning standard must be more stringent to protect against closed TBI than to just prevent skull fracture
- subtleties in helmet/skull/brain/body force coupling

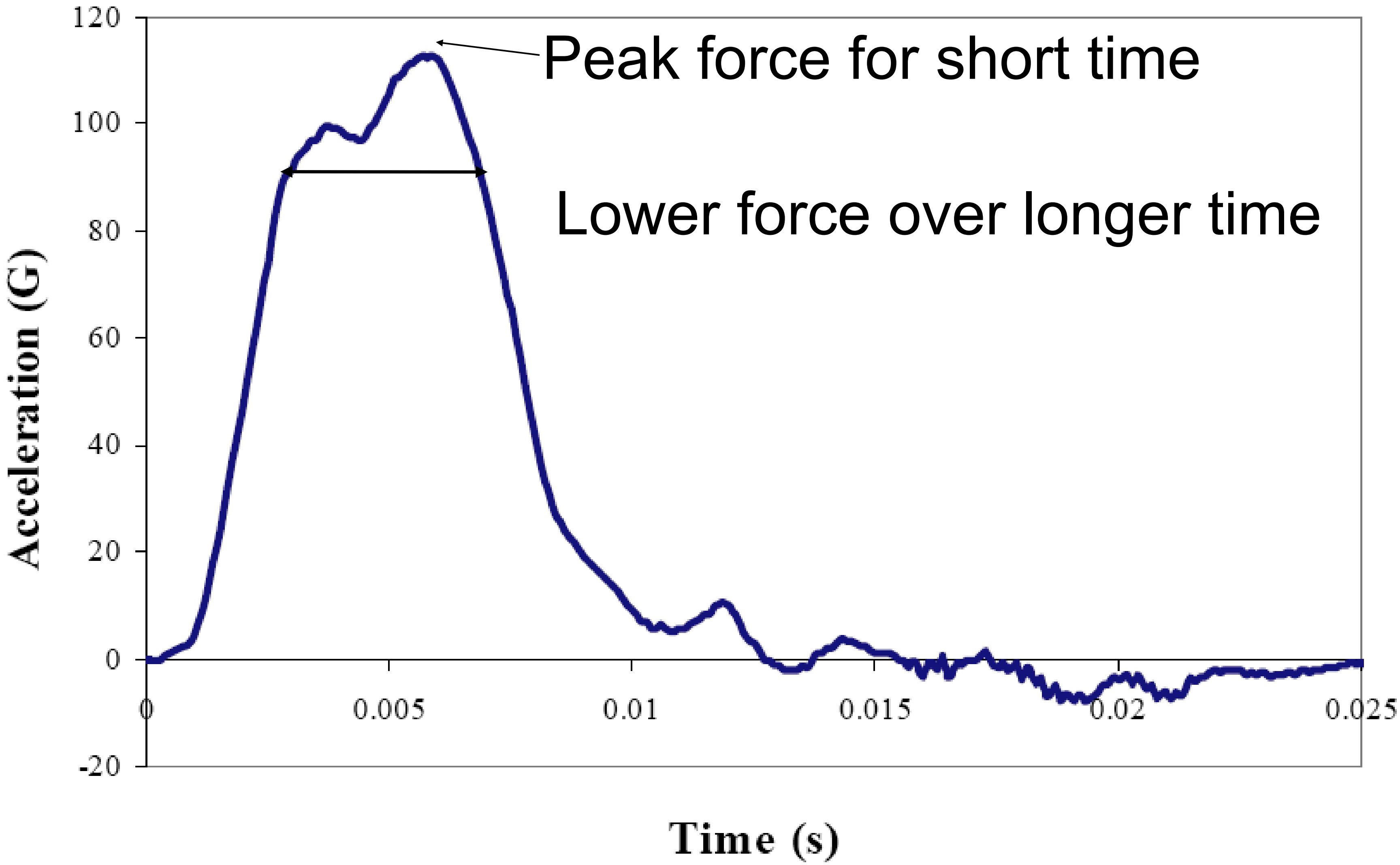
Origin of TBI/Blunt Impact Standards

Ono et al. 1980 (human cadaver and scaled monkey data)





Impact Acceleration Profile



Widely used Injury Measures

1. Peak g

2. $$\text{HIC} = (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{5/2} \quad \text{(around peak)}$$

3. $$\text{SI} = \int^{T} a^{2.5}dt \qquad (0 < t_1 < t_2 < T)$$

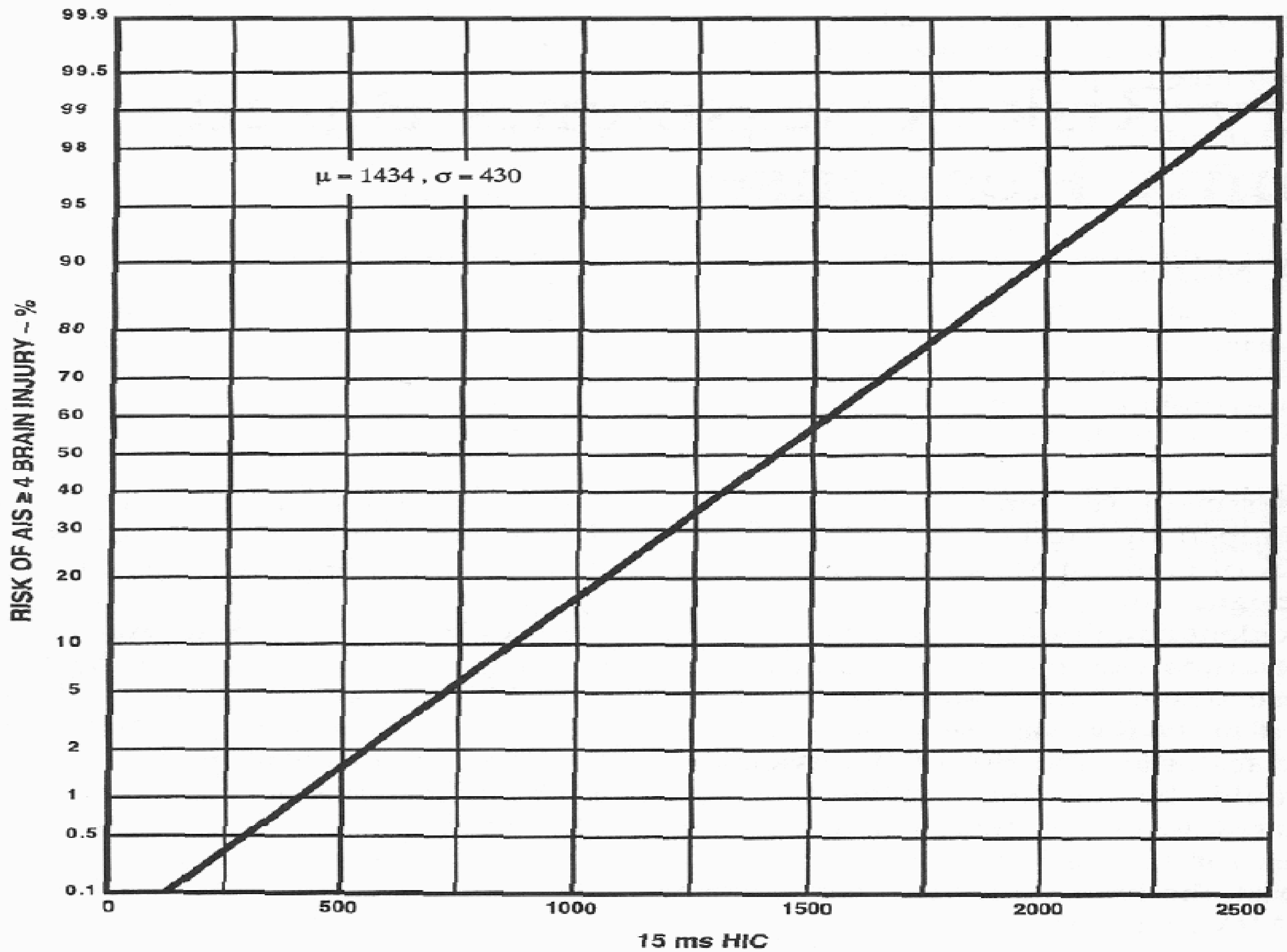
- SI (severity index) and HIC (head injury criterion) empirically accommodate acceleration and duration from cadaver and animal injury data
- Can create injury probability graph
- e.g.: Head HIC > 1000 (sec), 16% risk of life threatening TBI (Prasad & Mertz 1985) scaled monkey data; auto industry.

Classification of TBI Severity

(Hayes et al. 07)

Injury severity AIS	Severity code	Fatality rate (range %)
1	Minor	0.0
2	Moderate	0.1–0.4
3	Serious	0.8–2.1
4	Severe	7.9–10.6
5	Critical	53.1–58.4
6	Maximum (currently untreatable)	...

HIC15 AIS4 Injury Risk (Prasad & Mertz 85, data compilation)

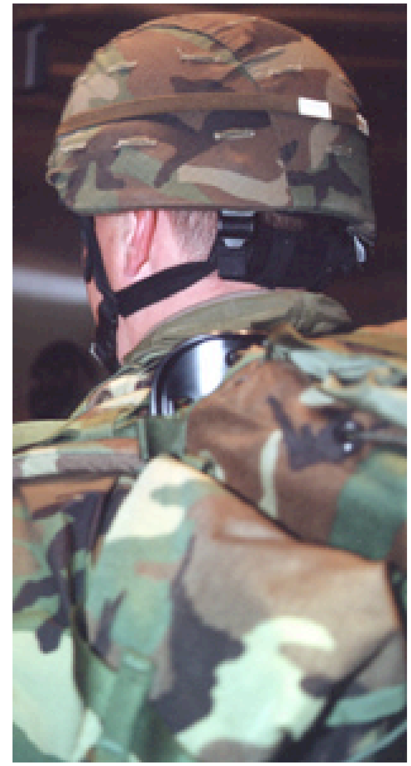


How are HIC and SI used?

- NHTSA uses HIC= 1000. (supposedly 1% chance of fatality 30MPH collision for restrained driver)
- NOCSAE uses SI=1200; (~ JHTC) but for NFL does not fully protect against TBI: should be <140 based on concussion data. Presently NO TBI standard. Moreover, the rigor of NOCSAE oversight committee needs to be challenged: http://www.nytimes.com/2010/10/21/sports/football/21helmets.html
- NO current SI/HIC standard for most military Helmets; peak g standard only and its NO GOOD.
  - Slobodnik (1980): need <150G at 1.5 meters drop
  - special forces helmets: standard is 150G at 1.5 feet(!)
  - Free falls of 3 feet for a ~5kg head form including PAGST or ACH helmets give 300G (McEntire et al.05)

Advanced Combat Helmet (ACH) is based on the MICH design and prov
PASGT. In addition to providing the Soldier ballistic and impact protection,
communication devices, and Night Vision devices. It provides increased 9m
although reducing area of coverage, will improve the field of vision and hea
components: The helmet shell, the pad suspension system, the retention s

Modular Integrated Communications Helmet (MICH) is a lightw
interface with most tactical communications headsets and microphon



Personal Armor System for Ground Troops (PASGT) helmet (also called the Kevlar, K-Pot and Fritz) wa: helmet, available in five sizes, provides ballistic protection for the head from fragmenting munitions. It is a c ballistic fiber and phenolic PVB resin. For a complete story, go to olive-drab.com

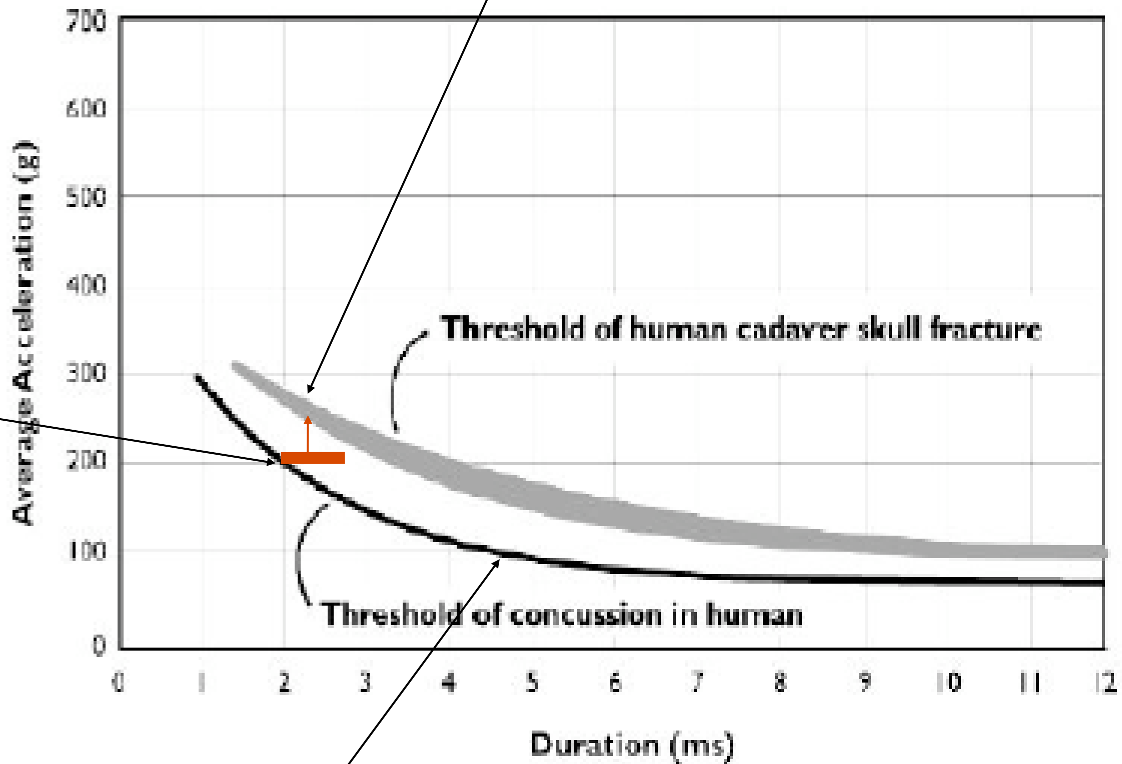
Ý This is the standard helmet above

Current Military Helmets Fail

Wayne State Head Tolerance (WSHTC) Gujdardan et al. 1966

Combat Helmets for 4.5 ft drop

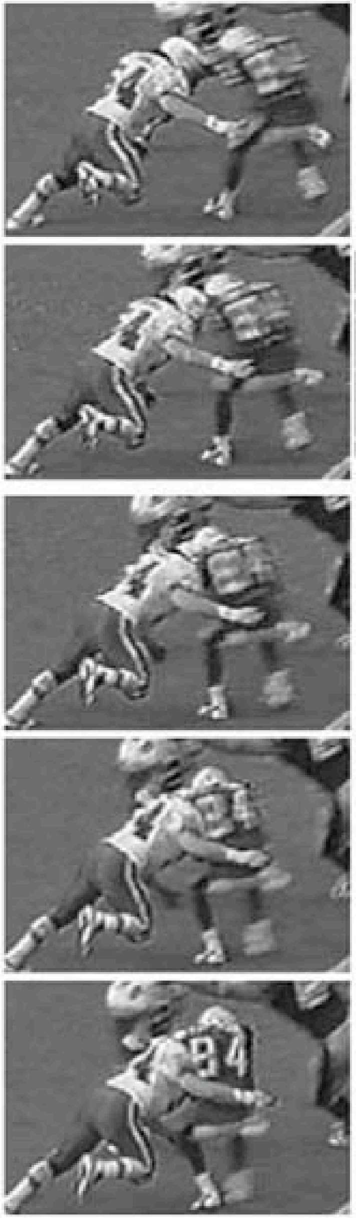
McEntire et al. 05

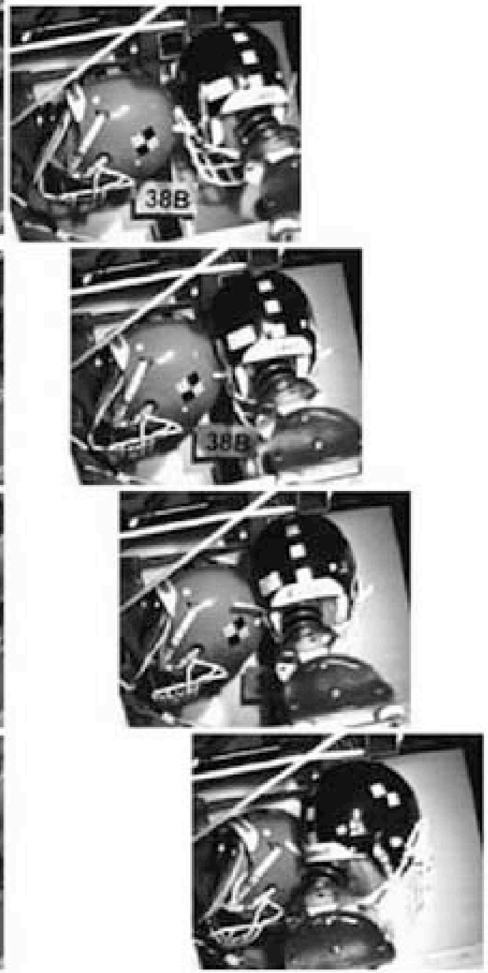


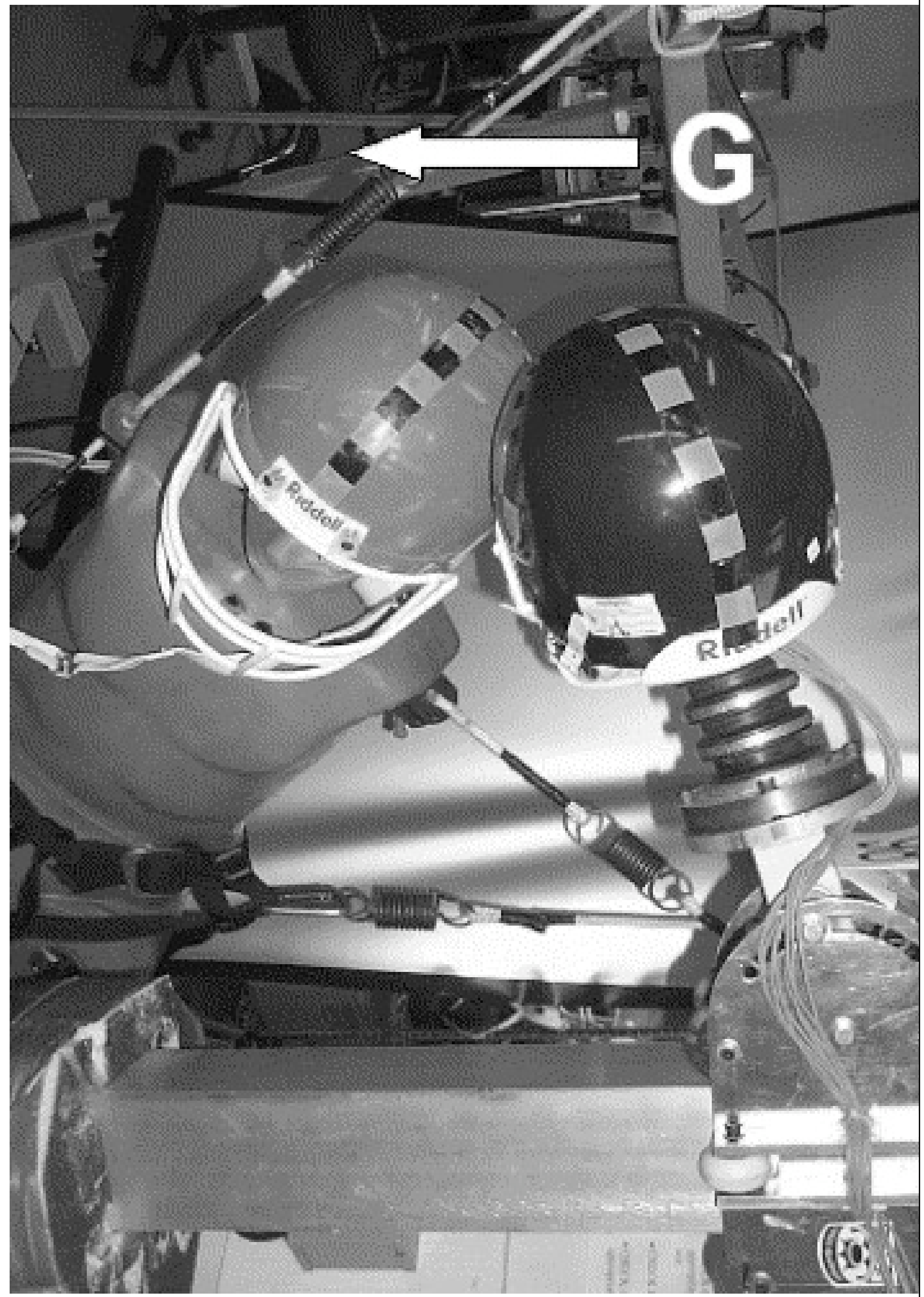
Japan Head Tolerance (JHTC); 25% prob. of concussion; HIC=1100) Ono et al. (1980)

Viano et al 2007

(Pellman et al. 03)







Innovative use of Accelerometers

FIGURE 2. Virginia Tech helmet with the player unit installed.

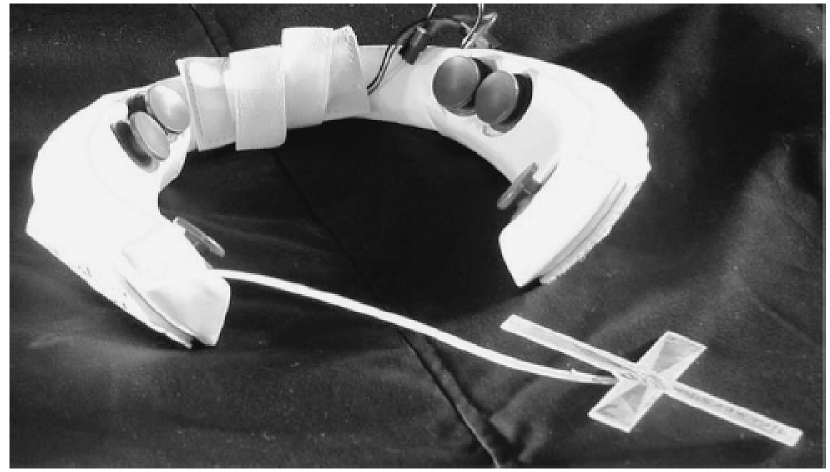


FIGURE 1. The player unit, consisting of 6 accelerometers in spring-loaded holders, frequency modulation antenna, and rechargeable battery pack.

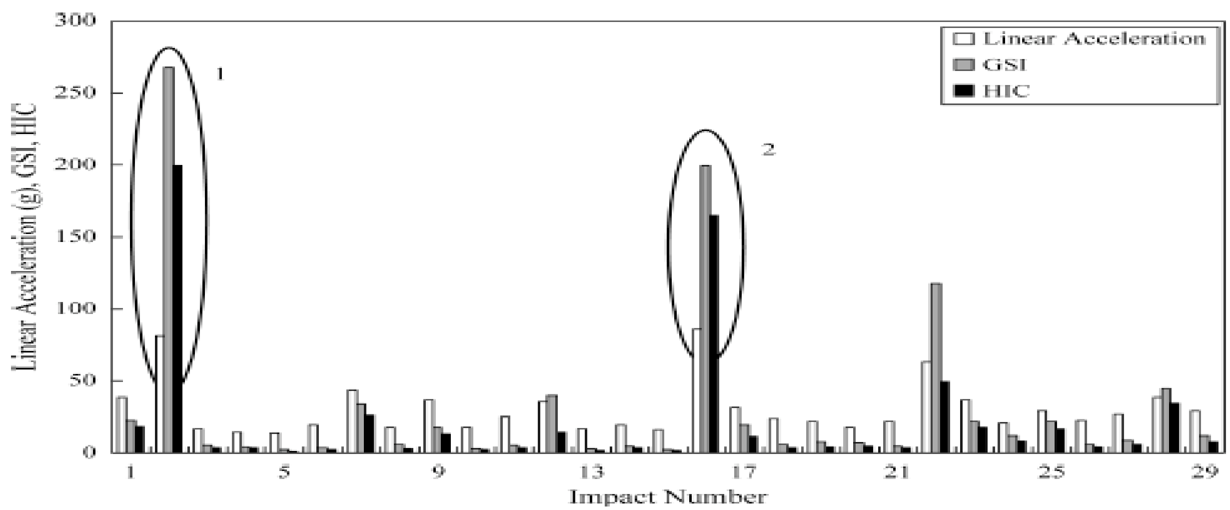


FIGURE 7. One player's head impacts for 1 game in which he sustained a concussion (1) and stayed in the game, and a neck stinger (2) for which he came out briefly before playing the remainder of the game.

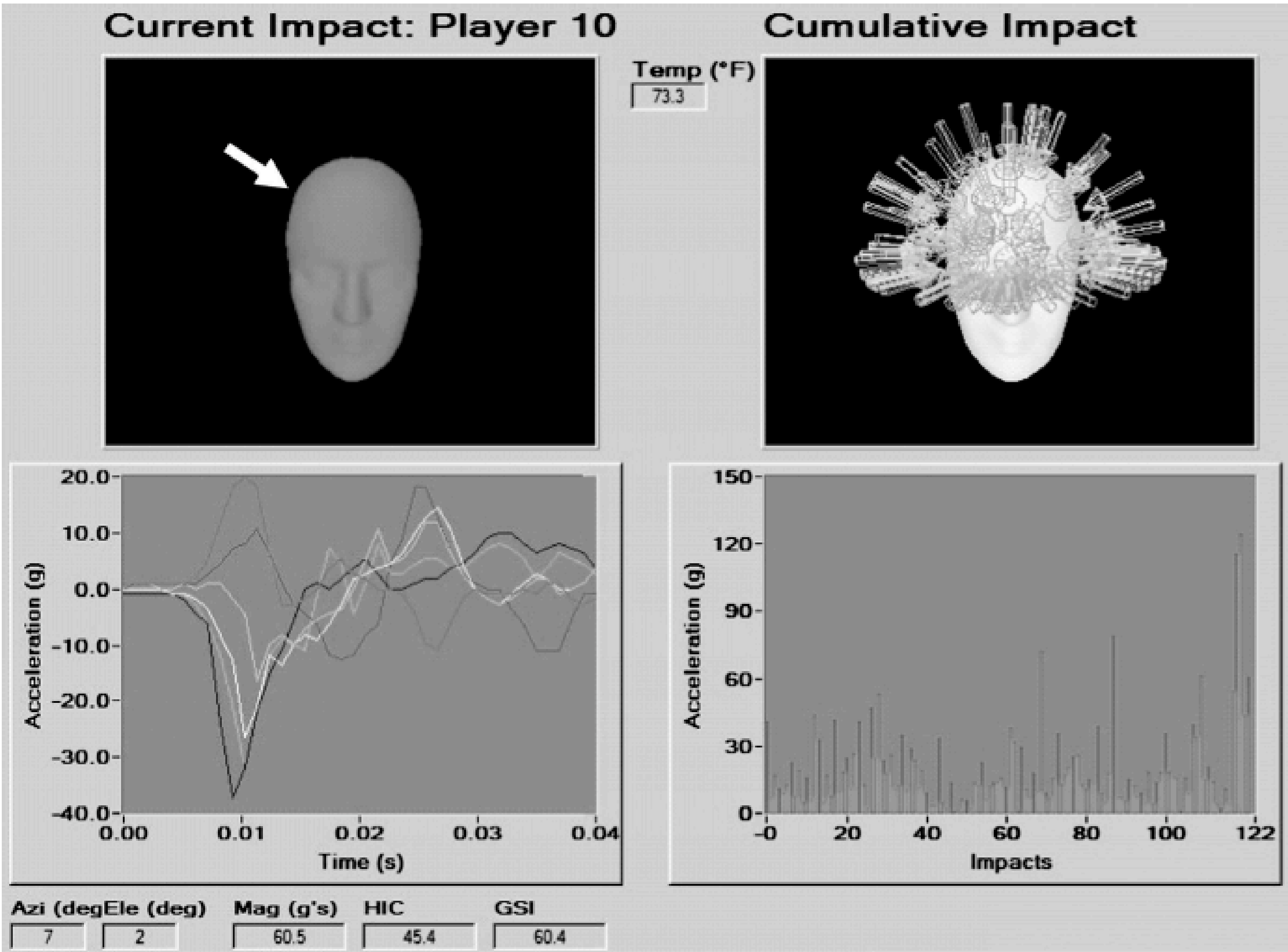


FIGURE 3. Sideline
screen. A, A direct
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Directional vectors f
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accelerometer trace
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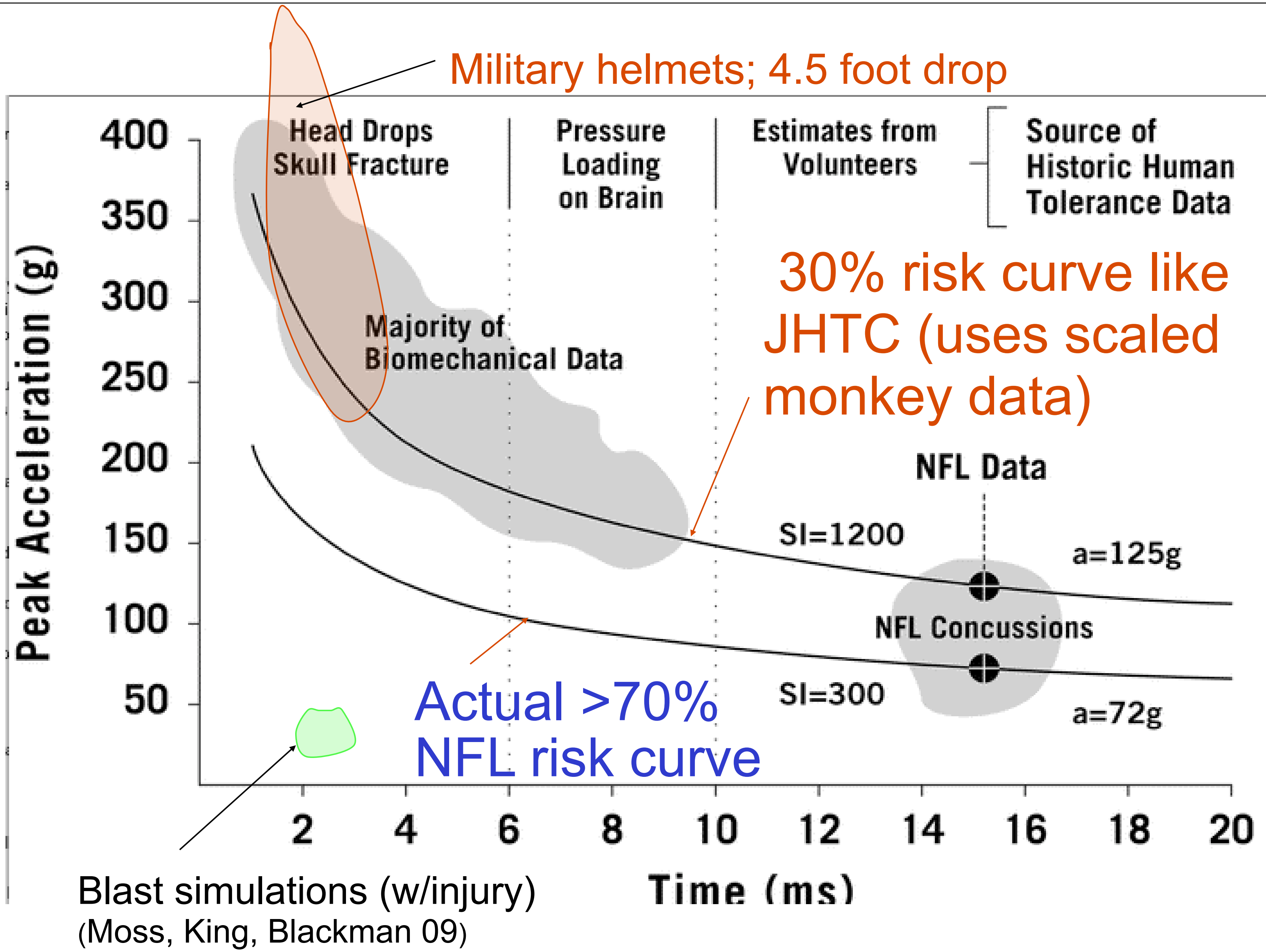
magnitude history i
chart format.

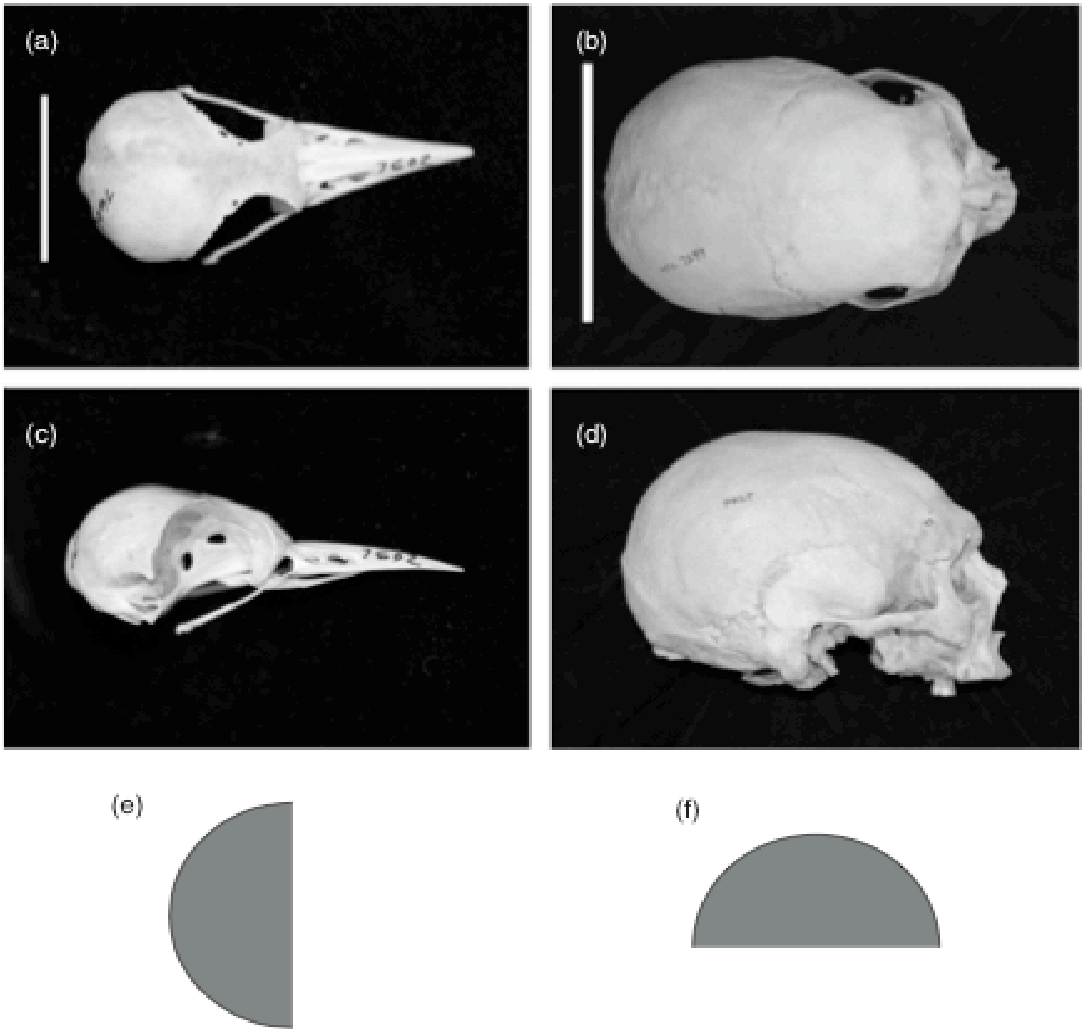
FIGURE 3. Sideline controller laptop



augmented from Pellman et al (03,06)

ITBI protection standards AND measures are flawed

- measures: HIC, SI based only on (limited) experimental data; body mass and impact angles not included, have little theoretical foundation, not even the best indicators...
- even if measures were correct: standards in military and NFL are inadequate
- Different material properties needed at different accelerations
- ITBI measures are useless for OTBI (later)
- newer paradigms for ITBI: many low acceleration impacts vs. few high acc. impacts may cause CTE



woodpecker brain against the skull is approximately πr_w^2 whereas that of the human brain, A_h, is $\pi r_h^2/2$, where r_w and r_h are the radii of the woodpecker and human brains, respectively. Assuming that brain injury occurs at the same stress, σ, in both the woodpecker and the human, then

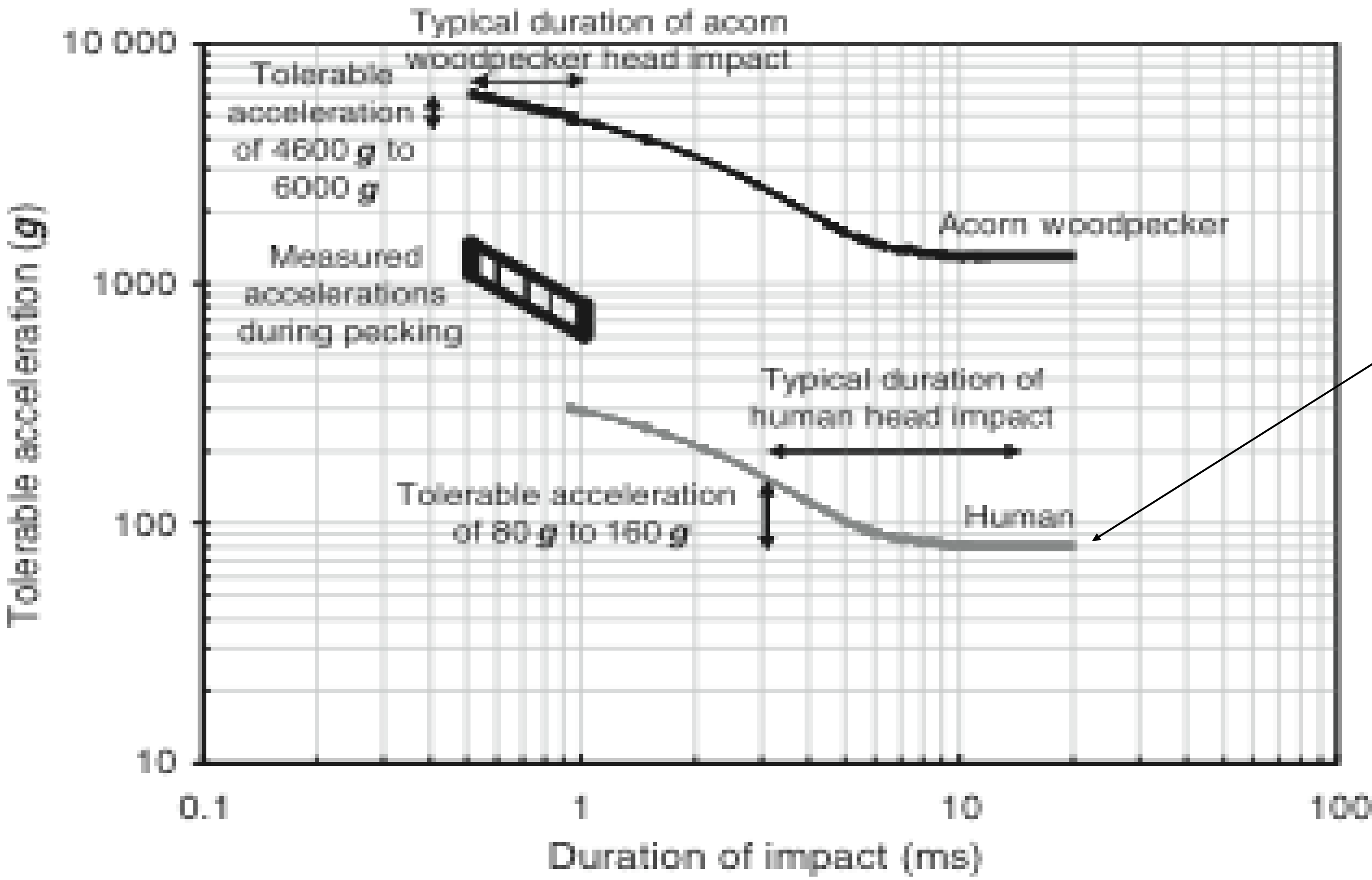
$$\frac{\sigma_w}{\sigma_h} \propto \frac{F_w}{A_w}\frac{A_h}{F_h} \propto \frac{\rho_w r_w^3 a_w}{r_w^2}\frac{r_h^2}{2\rho_h r_h^3 a_h} \qquad (2)$$

imaging experime
impact rather thar
head accelerations
The maximum
withstand without
the acceleration. T
Ono *et al.*, 1980) s
impact: acceleratio

Gibson (2006)

Woodpeckers probably don't get TBI:

HIC relies on fixed brain mass and surface area
but "stress" ~ mass times acceleration/area

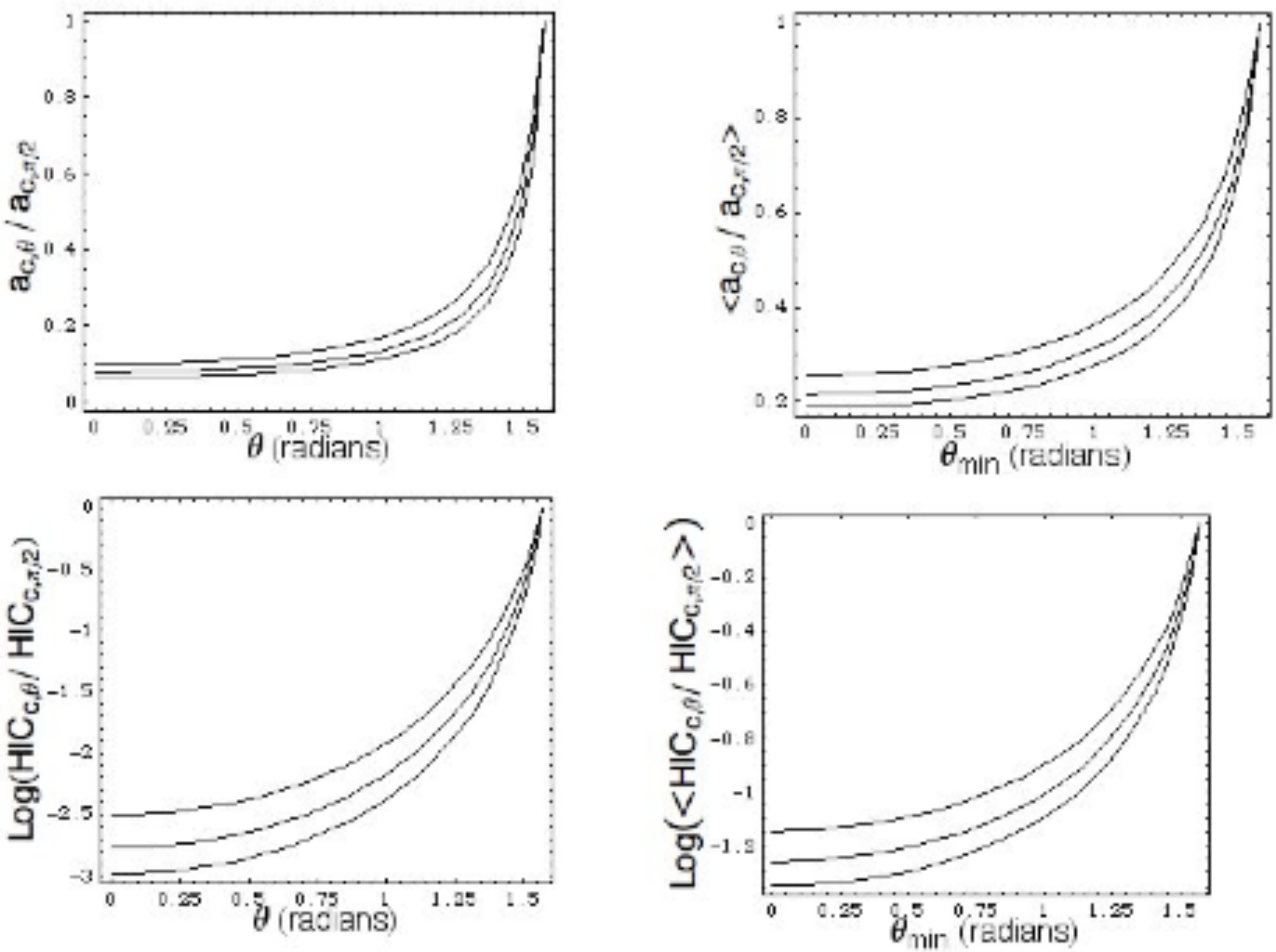


JHTC

Gibson 06

Figure 1 Tolerance curves for human and acorn woodpecker *Melanerpes formicivorus* head impact. The lower curve gives the threshold

Role of Body Mass and Impact Angle on Injury Thresholds (Blackman 2010)



Physical Quantities that TBI measures should correlate

- External
  - linear force (mass x linear acceleration)
  - total energy and energy input rate
  - torque (moment of inertia x rotational acceleration)

- Internal
  - brain tissue stress or pressure maximum
  - brain tissue rate of elastic energy change (localized)

Numerically Simulating Impact + Head Models: TBI Thresholds based on Internal Stresses

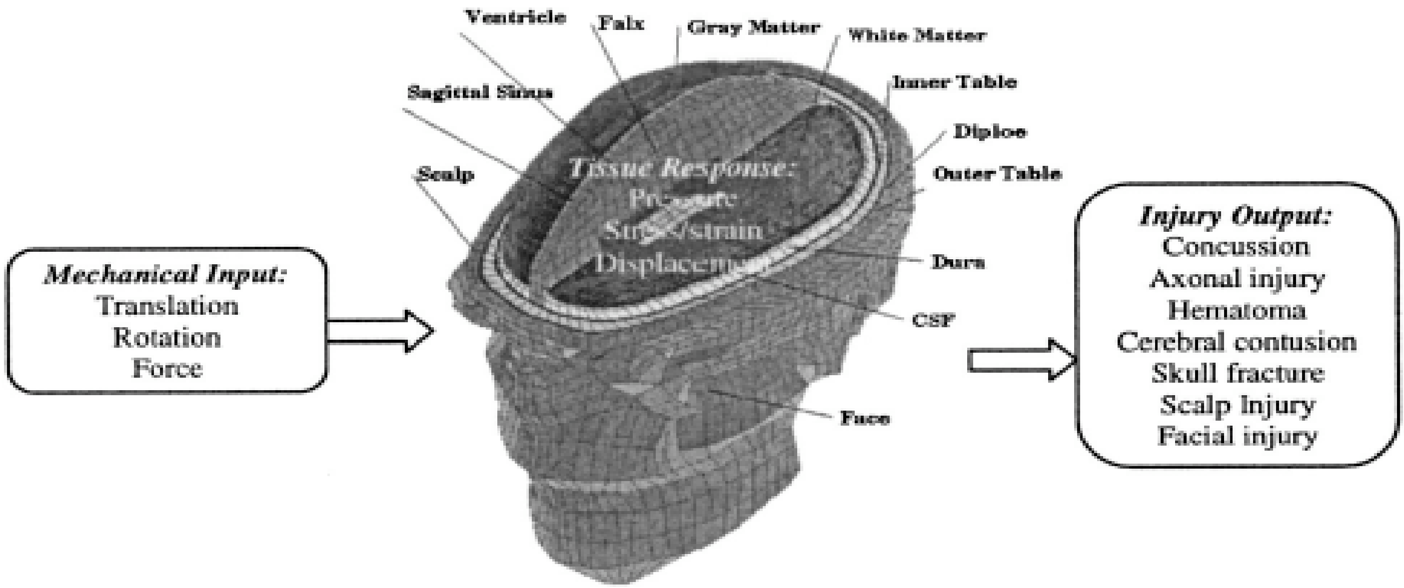


Fig. 2 Block diagram illustrating the tissue-injury response to traumatic input loading as a biomechanical analysis process using a computer surrogate

- Zhang et al. 04; reproduced NFL collisions with Wayne State Head Model
- WSHM: gray matter (cell) white (fibrous): shear moduli 20% larger for white; white is 2-D isotropic, grey is 3-D isotropic; brain stem shear mod 40% higher than cerebrum etc..
- Data on these properties differ, but codes can incorporate what the data require

TBI "internal" measures from simulations

- Zhang et al 04: reproduce NFL game video impacts with head forms in lab, then use lab data as input for numerical simulations to calculate internal stresses
- Maximum stress at core (diencephalon, upper brain stem)
- rate of maximum strain (= rate of elastic energy change) and peak stress were best correlators with injury
-

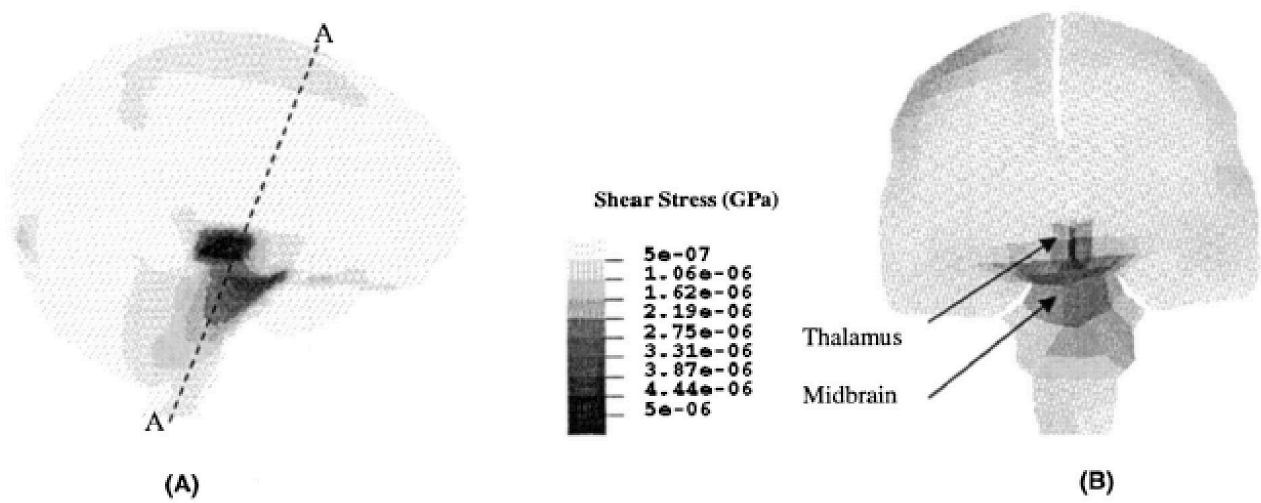
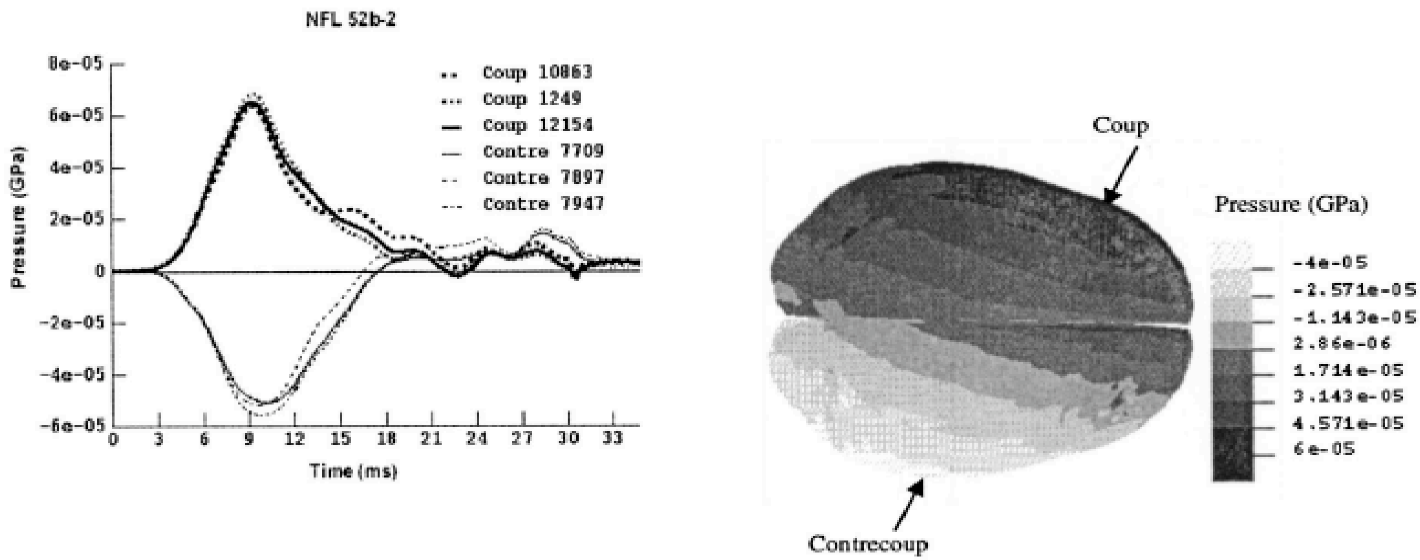


Fig. 6 Shear stress contours predicted by the model at 16 ms for: (*A*) a parasagittal section; (*B*) Sectional view through A-A which represents a section through the mamilothalamic tract

Coup + Contrecoup pressures



(A) **(B)**

Fig. 4 (*A*) Predicted peak positive and peak negative intracranial pressure-time histories; (*B*) Predicted intracranial pressure distribution 9 ms after the impact

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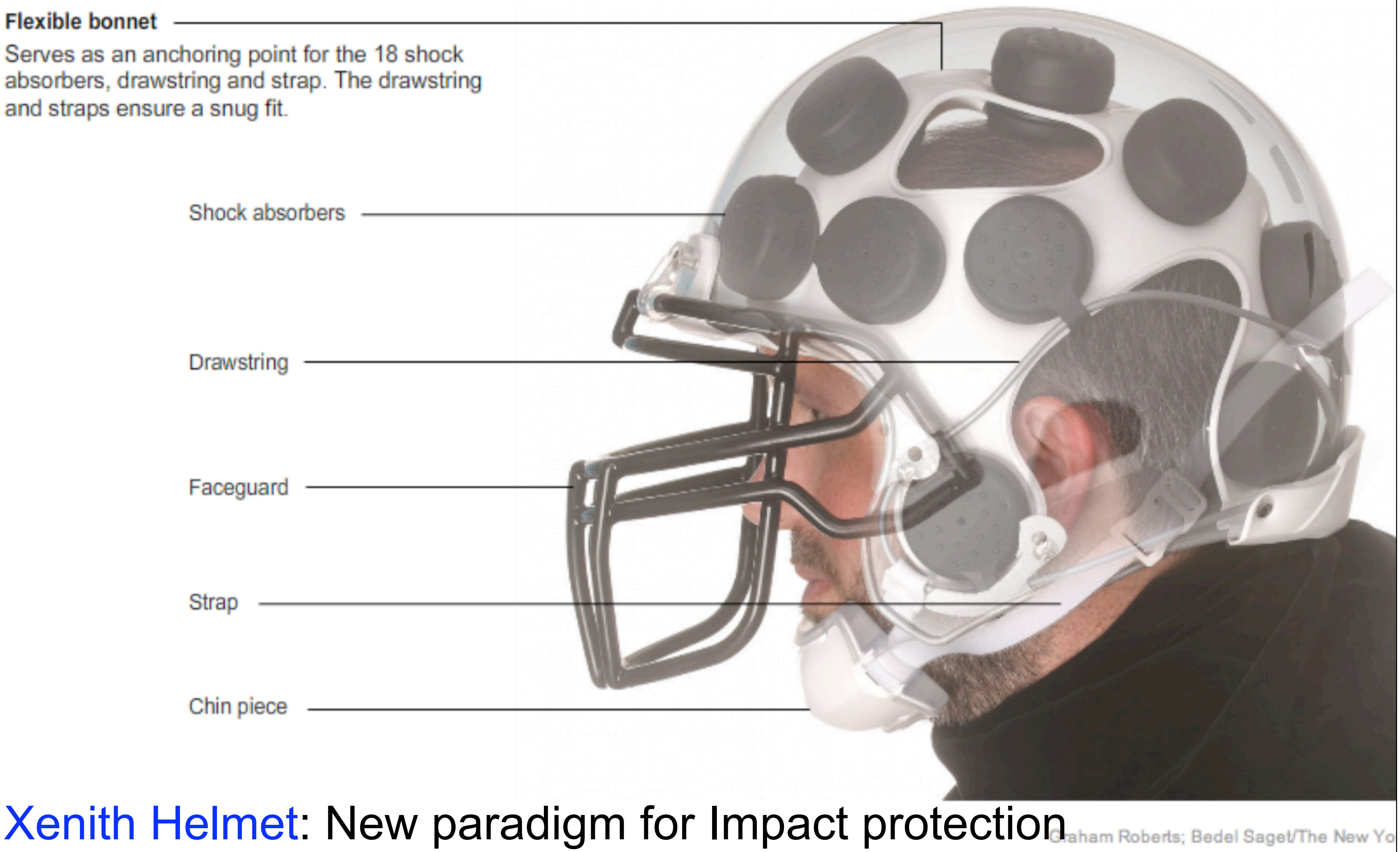
Liyiang et al (04)



Xenith Helmet: New paradigm for Impact protection

“Air Cushions” with a hole that hyrdrodynamically adjust stiffness depending on impact acceleration

Newer Cushioning (2010)

- “Phatcushion” TPU (Thermoplastic polyurethane) elastic rather than dissipative (not yet in helmets)

- Schutt TPU cushions:
  – claim to reduce impact deceleration by 15-20% compared to Ridell and Xenith

- **Impact TBI (ITBI) protection suffers from:**
  - -inadequate measures and standards
  - -insufficient data
  - -lack of first-principles modeling
  - -insufficient interdisciplinary research

- **Overpressure TBI**: an even newer frontier

- **Blast produces pressure + impact injury**

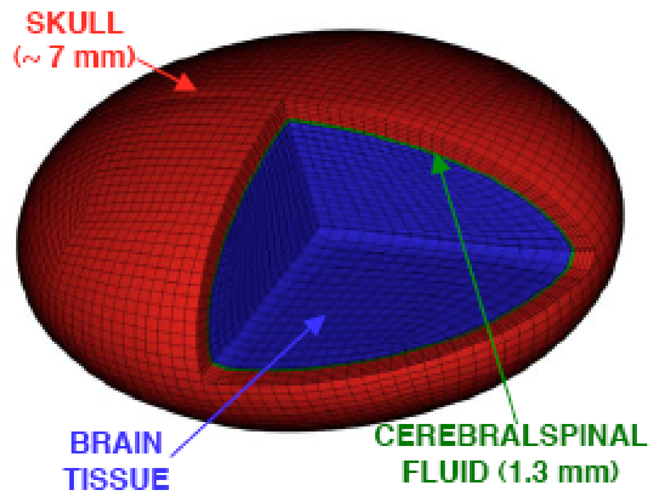
Simulations of Blast vs. Impact:

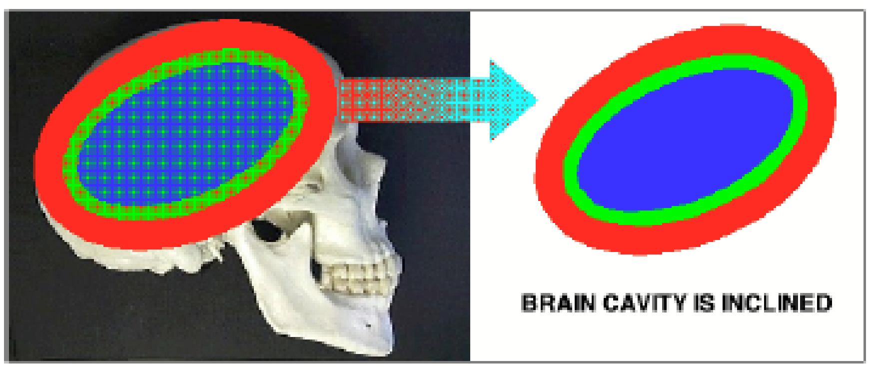
Moss, King, Blackman (2009)

ALE3D: LLNL's blast analysis code

- Originally developed to support the nuclear weapons complex
- 3D Arbitrary Lagrangian-Eulerian Hydrocode
  - Advection capabilities
  - Built in methods for coupling fluid and structural interactions
  - Complex geometries
  - Massively parallel capabilities ← analysis with supercomputers
  - Rich material library
  - Thoroughly tested
- ALE3D is specially designed for studying the response of complex structures to blast

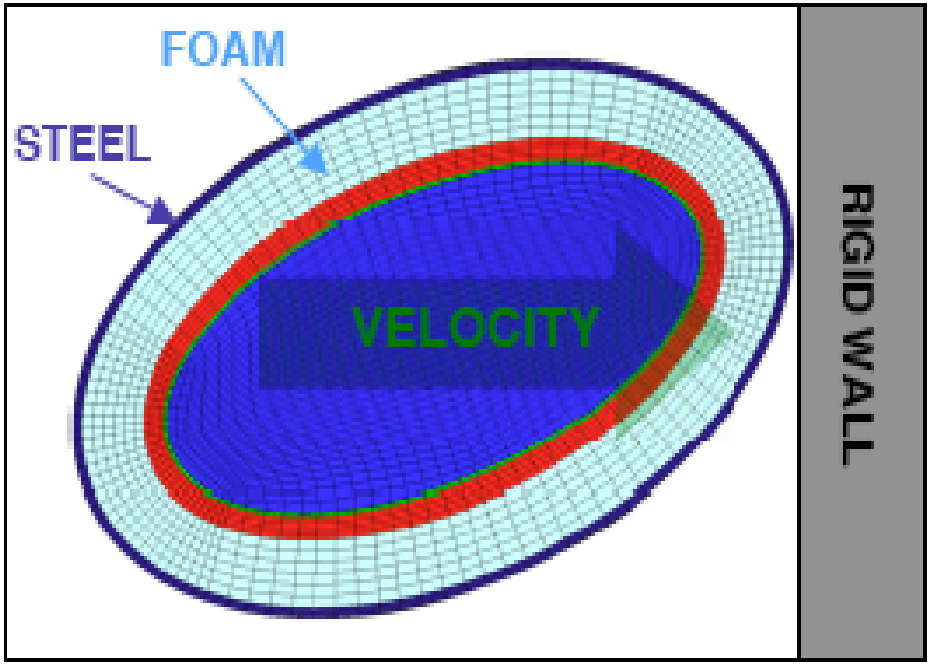
The “Head” in the simulations





Brain cavity model

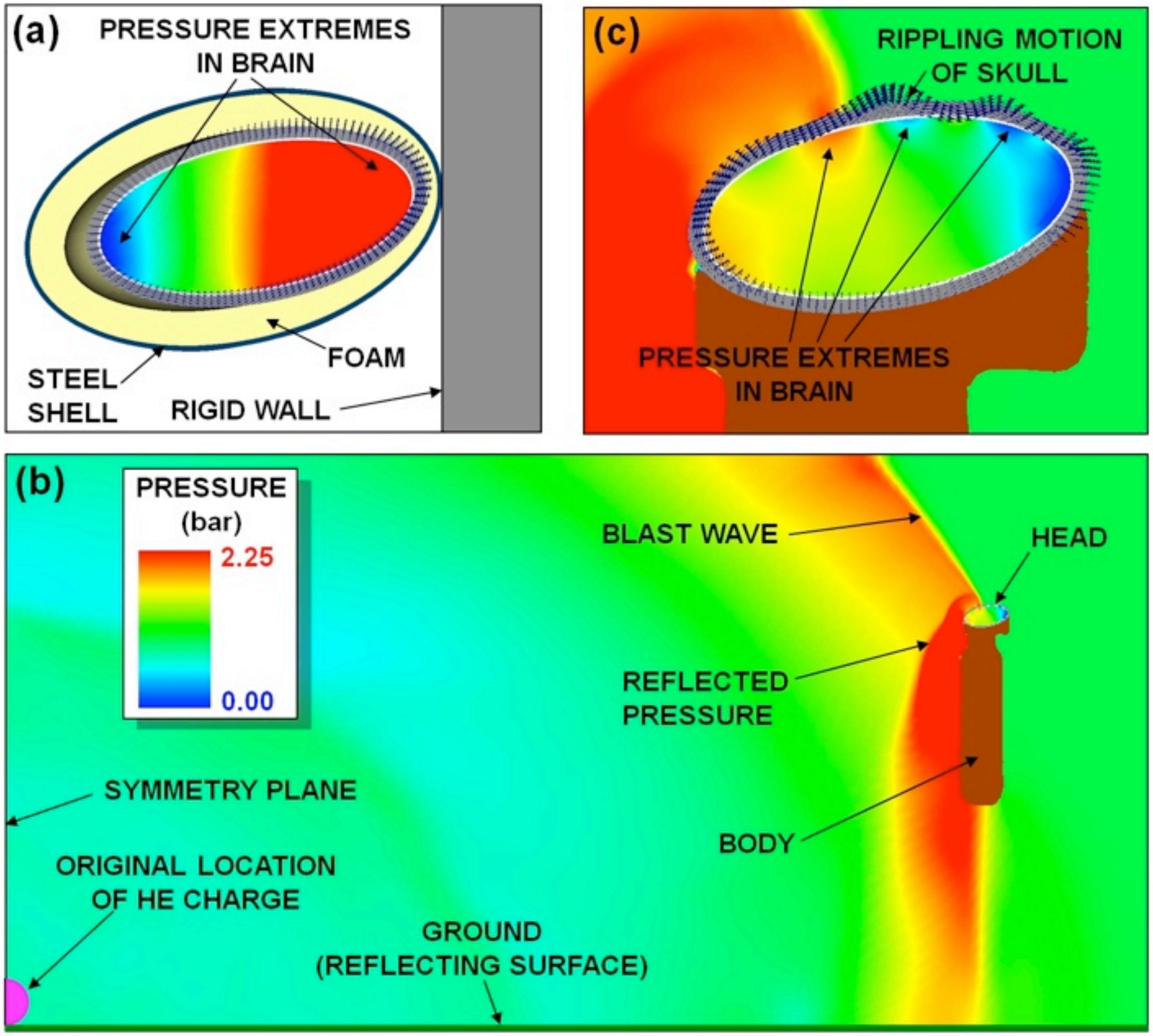
Model for Impact



Impact model with padded helmet (angled)

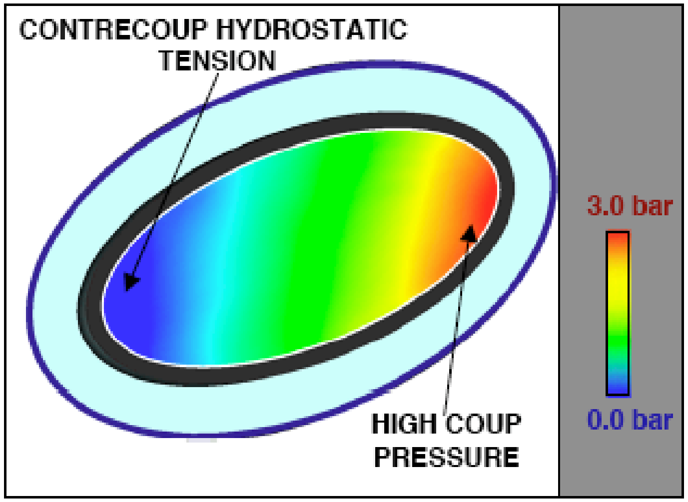
- HIC = 1090
- peak g 194 g
- impact duration 2.1 ms

Snapshot of Impact vs Blast Pressures

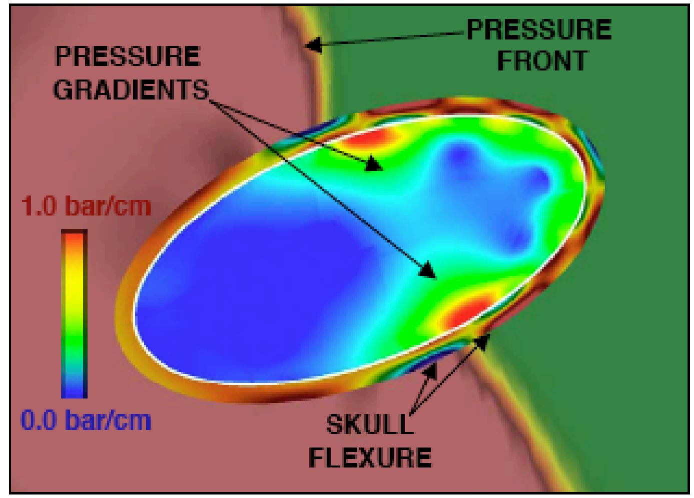


Blast wave at 5.6 ms after detonation

Impact versus blast



PRESSURES DURING IMPACT



PRESSURE GRADIENTS DURING BLAST

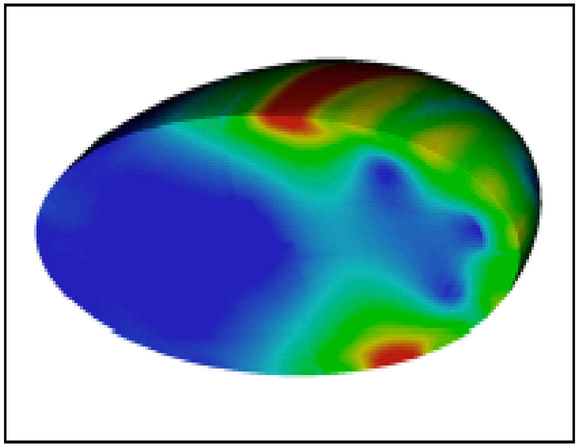
Impact

- Large linear accelerations
- Angled→large rotations
- Moderate skull flexure at ends
- High coup pressure
- Contrecoup tension → cavitation
- Small pressure gradients
- Rotation→large shear strains, bridging vein stretching

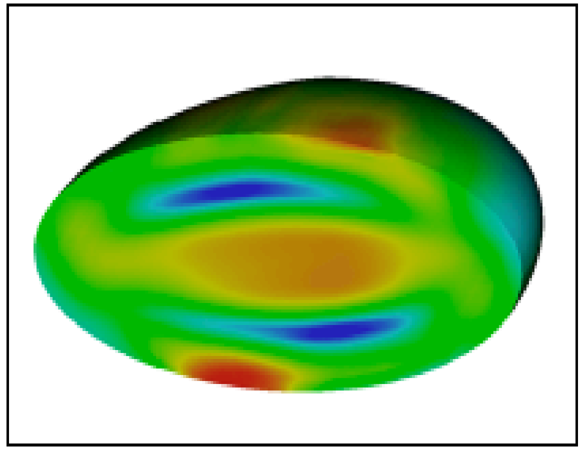
Blast

- Negligible linear acceleration
- Small rotations (more with whiplash?)
- Pressure wave → large lateral skull flexure
- Moderate coup/contrecoup pressure
- Hydrostatic tension → cavitation
- Skull flexure → large pressure gradients
- Rotation, pressure gradients → moderate shear strains

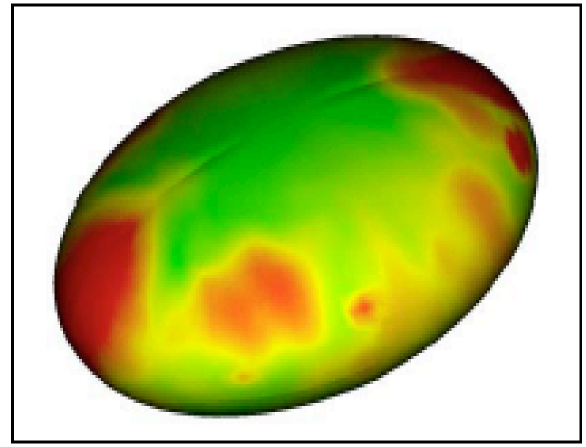
POTENTIAL DAMAGE METRICS FROM VARIOUS SIMULATIONS



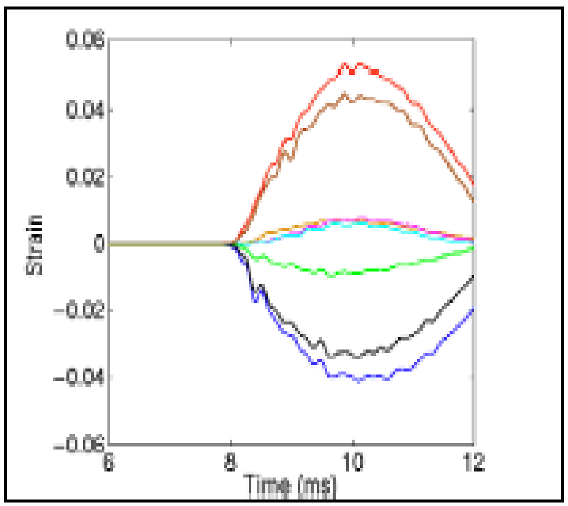
Pressure gradients in brain
HEMORRHAGING, DIFFUSE AXONAL INJURY



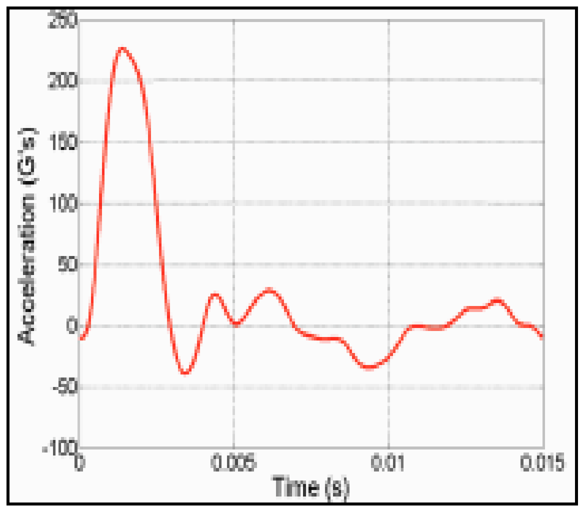
Shear strain in brain tissue
DIFFUSE AXONAL INJURY



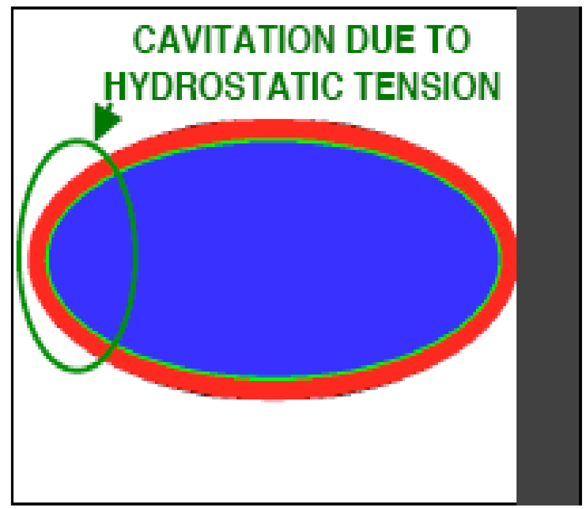
Peak pressures at brain surface
CONTUSIONS



Strain in bridging veins between brain and skull
SUBDURAL HEMATOMA



Acceleration of skull during impact
INDUSTRY DAMAGE METRIC



Hydrostatic tension, cavitation
CONTUSIONS/HEMORRHAGING

Moss et al. 09 .

Future Studies

- BLAST over-pressure (OTBI)
  - Add more realistic head model
  - compare to other pathways that couple blast to brain (e.g. Cernak 01,05)
- IMPACT (ITBI)
  - consider impacts of different durations
  - include effect of body attached to head for the impact and vary impact with angle extract effective mass
- For BOTH:
  - correlate specific external forces with specific internal stresses
  - simulate helmet shells and cushioning to develop “intuition” and “principles” that guide material design to mitigate the internal stresses
  - run impact simulations for pre-injured brain from overpressure
  - correlate specific blast vs. impact history with with medical symptoms
  - correlate stresses with biological/biochemical changescorrelate stresses with biological/biochemical changes
  - integrate/test simulations with clinical studies where injury history, symptoms, and pressure acceleration data are available

Need Interdisciplinary Effort

- Pinning down quantitative thresholds for injury requires better in vivo measurements of tissue properties and correlation with clinical data
- Also need better material measurements
- BUT: let us not confuse “principles” with “parameters”: e.g. simulations are powerful tools and its easy to change the parameters
- Need iterative interplay between simulations and experiment to “benchmark” simulations

END