The Physics of Explosive Blast Traumatic Brain Injury

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Disclosures

Nothing as it pertains to this lecture
Speaker’s Bureau for Sanofi and Bristol-Myers Squibb

Disclaimer

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OIF (2007)
OEF (2009)
Explosive Blast Injury - Categories

Four categories of blast injury:

- **Primary** – Caused by the direct blast energy
  - Crush injuries, lacerations, hemorrhage common

- **Secondary** – Caused by projectiles and other hazards created by the blast
  - Rubble, building fragments, shrapnel, etc.

- **Tertiary** – Inertial injuries caused by personnel being propelled by the blast (being thrown)

- **Quaternary** – Inhalation, burns, and anything else not described by first three
Explosive Blast TBI

Wide spectrum of neurological effects have been described

Mild TBI
- Subtle cognitive deficits, neurobehavior changes, mood and affect issues
- Both can occur together

Moderate TBI
- Loss of consciousness, overt structural damage

Severe TBI
- Severe neurological deficits, subarachnoid hemorrhage, vascular changes (acute and chronic)
Mild TBI

- Pt suffered blast TBI from about 8 feet away
- Wearing helmet/armor
- No LOC but confusion/amnesia for at least 15min (Grade 2 concussion)
- CT: normal
- Persistent neuro cognitive deficits on Day #2 (transfer)
  - Frontal lobe based tasks (digit span, word list generation)
- Normal by Day 7, returned to duty
Moderate TBI
(low velocity shrapnel)

Pt exposed to mortar explosion and

Day #14, fully recovered
Pt suffered TBI from IED

- Pt underwent extensive surgery including hemicraniectomy
- 10-day ICU care, complicated course
- Recovered to awake, following commands, extubated --- tx to civilian rehab
Close to 50% of patients of cohort of WRAMC with severe blast TBI showed angiographic evidence of delayed vasospasm.
What is the mechanism of injury?

What is the physics?
Shock front formation

- Wave at point “a” is propagating into undisturbed media
- Wave at point “b” is propagating into a local zone of compressed media

point “b” eventually catches up to “a” steepening the wavefront

S. Parks, ORA, Inc
Air blast shock front

- Initial disturbance of media (air) caused by detonation
- Shock front is a discontinuous change in air properties
- Shock front heats the air to 1000’s of degrees
  - Primary cause of personnel burns from blast, not fireball
- Shock heating is a principle mechanism of blast energy dissipation

S. Parks, ORA, Inc
Blast Wave
Airblast signatures

Free field blast signature
- “Friedlander” shape
- Shock wave followed by decay of the pulse to a negative phase

Complex blast signature
- Many reflected components
- Quasi-static component
- Target loaded from multiple directions

All real-world blast signatures will have features of both

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Free-field ideal blast

Airburst of spherical, uncased explosives approach ideal case

Deviation from ideal – presence of ground, reflecting surfaces, multi-phase flow, ejecta, fireball, weapon casing

Friedlander equation

\[ P_S(t) = P_{SO} \left[ 1 - \left( \frac{t - t_A}{I_A} \right) \right] e^{-\left(\frac{t-t_A}{\theta}\right)} \]

Source: TM5-855-1

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Complex blast

- No closed form solution – many empirical equations to predict
- Multiple peaks from reflecting surfaces
- Empirical simulation software or CFD/hydrocodes
- Geometry is most significant factor defining the pressure profile

Sensor at this location

Non-responding concrete structure

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Crater Ejecta

- Delivers significantly more impulse and loading over airblast and fragments alone
- More destructive than simple blast prediction based on NEW

Show movie: Crater formation – OF-26 detonation (030107_01)

S. Parks, ORA, Inc
Blast / Ejecta Loading

- Soil ejecta imparts over twice the impulse of air-blast alone

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State of the Art
Bowen-Richmond Curves

Current metrics of blast injury are:
- Binary: alive or dead
- Evaluate pressure damage to the lungs
- Do not address TBI

Lethality vs Pressure

Some unstudied characteristics of explosions:
- Rapid temperature change
- Environmental chemical composition changes
- Electromagnetic pulse
- Kinetic energy transfer
## Typical damage thresholds

<table>
<thead>
<tr>
<th>Peak Overpressure (psi)</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4-1.0</td>
<td>Window glass breaks</td>
</tr>
<tr>
<td>1.5-5.5</td>
<td>Concrete shatters, wood splinters</td>
</tr>
<tr>
<td>2.9-8.7</td>
<td>Bricks shear</td>
</tr>
<tr>
<td>&gt;10.0</td>
<td>Lung damage</td>
</tr>
<tr>
<td>13.0-18.9</td>
<td>50% eardrum rupture</td>
</tr>
<tr>
<td>23.2-33.4</td>
<td>1% lethality</td>
</tr>
<tr>
<td>33.4-58.0</td>
<td>50% lethality</td>
</tr>
<tr>
<td>&gt;58.0</td>
<td>99% lethality</td>
</tr>
</tbody>
</table>

Without body armor
Paradox

- Many blast related TBI cases
- Few blast lung cases in isolation
- Few blast bowel cases
What is the mechanism of injury?
  – Is it more than pressure alone

What is the “continuum” of this disease?

Return to first principles
Swine are exposed to blast in three environments
- **Large scale blast wave generator**: Creates operationally relevant levels of blast overpressure
- HMMWV blast test surrogate: Allows for study of complex blast in high interest small enclosed environment
- Urban warfare blast test arena: Replicates blast effects from detonation in enclosed spaces

Large scale blast wave generator:

- Creates free-field blast wave exposure to high levels with minimal explosive weight
- Free-field blast exposure occurs with any open-air detonation of an IED – free-field is relevant for study
- Explosive = 90/10 mix of nitromethane/triethylamine (TNT equivalent of 1.0)
Swine are exposed to blast in three environments

- Large scale blast wave generator: Creates operationally relevant levels of blast overpressure
- **HMMWV blast test surrogate**: Study complex blast in high interest small enclosed environment
- Urban warfare blast test arena: Replicates blast effects from detonation in enclosed spaces

**HMMWV surrogate:**

Charge set under surrogate, simulates blast breach into driver side floorboard

- Creates complex blast with multiple reflected peaks characteristic of exposure to IED blast inside up-armored HMMWV
Swine are exposed to blast in three environments

- Large scale blast wave generator: Creates operationally relevant levels of blast overpressure
- HMMWV blast test surrogate: Study complex blast in high interest small enclosed environment
- **Urban warfare blast test arena**: Replicates blast effects from detonation in enclosed spaces

Urban warfare blast test arena
(under construction – operational 15 July 2008)

Charge set around corner

- Creates complex blast with multiple reflected peaks characteristic of exposure to IED blast inside or between buildings
  - Generally a larger volume with more vent paths than encountered in vehicles
  - Distinctly different power spectrum than vehicle blast

Complex blast wave created by similar structure (blue)
OUTCOMES

Gait Analysis

EEG

Histopathology

Cognitive

Spatial Memory

Bioreactor with 3-D tissue constructs

General and neurophysiology
Cerebral autoregulation
Serum and CSF Protein Analysis

Cerebral Angiography

Arena: capture volume

near infrared strobe (NIR)

DMS

sample

delay

Ascending pharyngeal artery

Auricular artery
**IRA Protocol/Schedule**

**IRB Protocol Approved:** subjects and controls

- **June course**
  - Four pressure gauges, one inertial cube, and one air sampler per subject, personnel-borne
  - Two free-field pressure gauges

- **September course:**
  - Same as above and:
  - Four free-field thermal flux sensors
  - EMP sensors still being refined for implementation without disruption of tests
Evaluation Techniques and Insights

Quantico, VA: Breacher Training Facility
- Personnel-worn pressure gauges, inertial cubes and air samplers, and free-field pressure gauges
- September measurements will add thermal flux sensors, EMP sensors

Human – ALL STUDIES ARE NON-INVASIVE

Vestibular/Auditory
- Standard USMC Breacher training exercises

Neuro-Imaging
- T1/T2 weighted, FLAIR
- fMRI
- Diffusion tensor

Environment

Toxic Gas

Neuro-Behavior
- Computer based TBI testing
  - Reaction time
  - Mood affect
  - Cognitive processing
- Clinical testing
  - Clinical interviews
  - PTSD/Brain injury scale scoring
Pre-Clinical

- **Blast thresholds** associated with increasing severities of injury are identified
- **Limited* TBI**: predominantly inflammation with no neuronal damage, can persist for many days/weeks, neurobehavior effects resolve over time
- **Moderate TBI**: neuron damage, functional deficits
- **Severe TBI**: widespread neuronal death, vasospasm, diffuse cerebral edema, significant deficits and death

Clinical

- Standard USMC breacher training does not lead to TBI
- Below a threshold, repeated exposures can be tolerated without leading to TBI

*Limited TBI may or may not be equivalent to “mild” TBI, as it is defined clinically.
Conclusion

- Explosive blast related TBI covers a wide spectrum
- The coupling of pressure waves to the brain is, in part, the cause
- The long term sequelae of explosive blast TBI has yet to be fully characterized