Orthopaedic Blast Injuries

OTA Disaster Preparedness Committee

Christopher Born, MD (Chair)
Mark McAndrew, MD
Christiaan Mamczak, DO
Eric Pagenkopf, MD
Mark Richardson, MD
David Teague, MD
Philip Wolinsky, MD

Created: March 2015
Objectives

• Recognize the increasing threat of blast injuries
• Understand basic blast wave mechanics
• Understand blast wave wounding mechanisms
• Describe initial management of blast wave injuries
The Threat
Blast wave injury

• Blast forms when solid or liquid fuel is rapidly converted into its gaseous state

• Resulting detonations can produce injuries rarely seen outside of combat

• Severe, multi-system injuries are common

• Mass casualties are common
Sources of blast injury

• Accidental
  – Industrial accidents

• Non-accidental
  – Military combat operations
  – Acts of terrorism
Industrial accidents

- Coal mines
- Fertilizer and chemical plants
- Fireworks factories
West, Texas 2013

©AP Photo/Tony Gutierrez (used by permission)
Military combat operations

- High velocity conventional weapons
- Landmines
- Improvised Explosive Devices (IED)
Combat related blast injury

- Over 16,000 attempted IED attacks annually in Afghanistan

- U.S. casualties since 2001
  - > 6,800 deaths
  - > 50,000 wounded
  - > 1,500 amputations
Afghanistan injury mechanisms

- Other
- Helo crash
- Landmine
- Hand grenade
- Rocket
- Penetrating NFS
- RPG
- Other explosive
- GSW
- Mortar
- IED

US Army Surgeon General’s Report on Dismounted Complex Blast Injuries, Jun11
Improvised Explosive Devices

• Not confined to combat zones

• The weapon of choice for insurgents, terrorists, and home-grown violent extremists (HVE)
  – Inexpensive
  – Low tech
  – Materials readily available
  – Easily transported and concealed
  – Simple remote detonation
Improvised Explosive Devices

- Average > 260 IED incidents per month in 2010 globally, not including Iraq and Afghanistan.
Improvised Explosive Devices

- Maximizes casualty generation
- Maximizes lethality
- EMS easily overwhelmed with numbers and magnitude of wounding
Madrid, 2004
Terrorism trends

• A 5-fold increase in worldwide terrorism deaths, since 2000

• In 2013:
  – Nearly 10,000 terrorism attacks
  – 87 countries
  – 17,958 killed (63% increase vs 2012)

• Bombings the most common method of attack

Institute for Economics and Peace, 2014
Blast mechanics and injury mechanisms
Mechanisms of blast injury

1º - Blast injury
2º - Penetrating trauma
3º - Blunt trauma
4º - Associated injuries
5º - Contamination
1º Blast Injury: 
Blast wave / Blast wind
Magnitude of the blast wave

- Type of explosive
- Amount of explosive
- Distance from point of origin
Explosives classification

- High-order vs low-order explosive (HE vs LE)
- Solid vs Liquid
- Commercial vs Improvised
Explosives classification

• High-order explosive (HE)
  – TNT
  – Dynamite
  – C-4
  – Semtex
  – Nitroglycerin
  – Ammonium Nitrate Fuel Oil (ANFO)
Explosives classification

• High-order explosive (HE)
  – Generates shock wave (‘Blast wave’)
    • Supersonic
    • Over-pressurization impulse
  – Generates blast wind
    • Forced super-heated airflow
Explosives classification

- Low-order explosive (LE)
  - Gunpowder
  - Petroleum based bombs
    - ‘Molotov cocktail’
    - Aircraft improvised as guided missile (9/11)
Explosives classification

• Low-order explosive (LE)
  – Subsonic explosion
  – No associated blast wave
  – Blast wind may be encountered with LE
<table>
<thead>
<tr>
<th>HIGH-ORDER EXPLOSIVE</th>
<th>Common uses</th>
<th>Common form</th>
<th>Known IED use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium nitrate and fuel oil (ANFO)</td>
<td>Mining and blasting</td>
<td>Solid</td>
<td>Oklahoma City, 1999</td>
</tr>
<tr>
<td>Triacetone Triperoxide (TATP)</td>
<td>No common use – mixed from other materials</td>
<td>Crystalline solid</td>
<td>London, 2005</td>
</tr>
<tr>
<td>Semtex, C-4</td>
<td>Primarily military</td>
<td>Plastic solid</td>
<td>Irish Republican Army bombings</td>
</tr>
<tr>
<td>Ethylene glycol dinitrate (EGDN)</td>
<td>Component for low-freezing dynamite</td>
<td>Liquid</td>
<td>Millennium Bomber, intended for LAX, 1999</td>
</tr>
<tr>
<td>Urea nitrate</td>
<td>Fertilizer</td>
<td>Crystalline solid</td>
<td>World Trade Center, 1993</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LOW-ORDER EXPLOSIVE</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Smokeless powder</td>
<td>Ammunition</td>
<td>Solid</td>
<td>Olympic Park bombings</td>
</tr>
</tbody>
</table>
Blast injury

INJURY MECHANISM DEPENDS ON RANGE FROM DETONATION

Damage Radii

Fragment Injuries

Blast Injuries

Thermal Injuries

Fragments can travel for several kms

Blast wave formation

• Solid or liquid fuel rapidly converted into gaseous state (detonation)

• High pressure gas expands at supersonic velocity into the surrounding medium (typically, air at atmospheric pressure)

• TNT denotes at ~ 7000 meters/second
Blast wave
Blast wave formation

- Nearly instantaneous increases in pressure, density and temperature occur across the shock, which cause tissue damage.

- Underpressure behind the blast wave creates a suction effect, generating blast wind.
Typical blast wave
Blast wave behavior

• As the blast wave expands, its strength decreases, until it eventually dissipates

• Like sound waves, blast waves:
  – Can reflect off solid surfaces (‘bounce back’)
  – Can ‘turn corners’
  – Travel faster in fluids than in gases
Blast wave injury

- Pressure gradients generate high tensile and shear stresses
  - Sufficient to traumatically amputate limbs

- Thermal damage near point of origin
Blast wave injury

- May cause immediate death with full body disruption
  - Near the point of origin

- May cause immediate death without apparent injury
  - Damage to internal hollow or solid organs
Blast wave injury

• Hollow organs most susceptible
  – Lungs, gastrointestinal tract, TM

• Solid organs may lacerate / rupture
  – Liver, spleen, kidney

• Central nervous system susceptible
  – Traumatic Brain Injury (TBI)
  – Altered/disrupted EEG pattern
<table>
<thead>
<tr>
<th>System</th>
<th>Injury or Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory</td>
<td>TM rupture, ossicular disruption, cochlear damage, foreign body</td>
</tr>
<tr>
<td>Eye, Orbit, Face</td>
<td>Perforated globe, foreign body, air embolism, fractures</td>
</tr>
<tr>
<td>Respiratory</td>
<td>Blast lung, hemothorax, pneumothorax, pulmonary contusion and hemorrhage, A-V fistulas (source of air embolism), airway epithelial damage, aspiration pneumonitis, sepsis</td>
</tr>
<tr>
<td>Digestive</td>
<td>Bowel perforation, hemorrhage, ruptured liver or spleen, sepsis, mesenteric ischemia from air embolism</td>
</tr>
<tr>
<td>Circulatory</td>
<td>Cardiac contusion, myocardial infarction from air embolism, shock, vasovagal hypotension, peripheral vascular injury, air embolism-induced injury</td>
</tr>
<tr>
<td>CNS Injury</td>
<td>Concussion, closed and open brain injury, stroke, spinal cord injury, air embolism-induced injury</td>
</tr>
<tr>
<td>Renal Injury</td>
<td>Renal contusion, laceration, acute renal failure due to rhabdomyolysis, hypotension, and hypovolemia</td>
</tr>
<tr>
<td>Extremity Injury</td>
<td>Traumatic amputation, fractures, crush injuries, compartment syndrome, burns, cuts, lacerations, acute arterial occlusion, air embolism-induced injury</td>
</tr>
</tbody>
</table>
Blast wave injury

• Blast Lung
  – Most common cause of death
  – Alveolar membrane damage results in pulmonary edema
  – Clinically similar to ARDS
Blast wave injury

- Blast Gut
  - Colon is the most commonly injured visceral structure
  - Mesenteric infarct from shear, acceleration-deceleration
  - May present as late bowel perforation
Blast wave injury

• Tympanic membrane rupture
  – Occurs in 1% at 5 psi overpressure
  – Occurs in 99% at 45 psi overpressure
  – Not a reliable marker for other primary blast injuries (Sensitivity ~ 30%)

Traumatic amputation

- **Blast wave / blast wind related amputation**
  - HE / near point of origin
  - High energy blast wave

- **Penetrating trauma related amputation**
  - HE or LE / near point of origin
  - High concentration of projectiles

- May be difficult to distinguish mechanism
Traumatic amputation

Mortar / Landmine / Dismounted IED
Blast wave amputation

- Amputation level through bone, not the joint
Northern Ireland, 1969-1998
Blast wave amputation

• Most blast-related traumatic amp victims die on scene from other blast injuries

• In survivors: blast-related traumatic amputation is a marker for other life-threatening injuries

Reflected blast waves

• Blast waves reflect off solid surfaces

• Multiple reflections in enclosed spaces

Settles. American Scientist, 2006 (Photo used by permission of the author)
Reflected blast waves

Wolf. Lancet, 2009
Jerusalem

©AP Photo/Brian Hendler (used by permission)
Reflected blast waves

<table>
<thead>
<tr>
<th></th>
<th>Open air explosion</th>
<th>Bus explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortality</td>
<td>8%</td>
<td>49%</td>
</tr>
<tr>
<td>Survivor mean ISS</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>Primary blast injury</td>
<td>34%</td>
<td>78%</td>
</tr>
</tbody>
</table>

Leibovici. J Trauma, 1996
Blast wind

- Occurs with HE, some LE
- Follows blast wave
  - High velocity
  - High temperature
- Reverses direction during under-pressure phase
Blast wind

Figure 3-III. Variations of Blast Effects Associated with Positive and Negative Phase Pressures with Time
Blast wind

• Causes additional wounding
  (penetrating trauma from debris)

• Causes additional contamination

• May help complete partial amputations
2º Blast Injury: Penetrating Trauma
Secondary blast injury

• The predominant mechanism causing orthopedic injuries related to blast
  – Open fractures
  – Traumatic amputations
  – Severe soft tissue injuries
  – Multi-organ penetrating injury
Secondary blast injury

• Injury severity significantly greater than typically encountered in urban trauma setting
  – Kinetic energy 1 to 2 orders of magnitude greater
  – Local shock wave associated with some projectiles
  – Increased mass of some projectiles
  – Increased number / concentration of projectiles
IED projectiles

• Primary Fragmentation – related to device
  – Casing material
  – Embedded: nuts, nails, ball-bearings

• Secondary Fragmentation – external to device
  – Rocks, gravel, building materials, vehicle parts, glass
  – Body parts (other victims or suicide bombers)
Kinetic Energy

\[ KE = \frac{1}{2} m V^2 \]
Kinetic Energy

Muzzle Velocity (fps)

Hand Gun  M-16  IED

Speed of sound in air
Projectile shock wave

Muzzle Velocity (fps)

Settles. American Scientist, 2006 (Photo used by permission of the author)
Projectile shock wave

Settles. American Scientist, 2006  (Photo used by permission of the author)
A Perforating missile crushes and lacerates tissue

B Expanding temporary cavity stretches surrounding tissue

C Aspiration of foreign material into collapsing temporary cavity

D Potentially contaminated and devitalized tissue lines permanent wound tract
Cavitation effect
Zone of injury

- Not immediately obvious
- Maintain a high degree of suspicion
- Wound progression results in interval necrosis over several days
- **Do** open and explore fascial planes
  **Do not** close traumatic wounds
Kinetic Energy

KE = \frac{1}{2} m V^2
IED projectiles

- Can be large
- Asymmetric geometry
  - More rapid deceleration than bullets
  - Can result in greater soft tissue damage
IED projectiles

• Near explosion point of origin
  – Highest concentration of fragments
  – Multiple, high velocity wounds
  – Can result in traumatic amputation

• Distant to explosion point of origin
  – Lower concentration of fragments
  – Less wounds, lower velocity
IED projectiles

• Penetrating injury to 4 or more sites highly predictive of blast lung injury

• Long bone fractures indicative of higher ISS, morbidity and mortality

IED projectiles
IED projectiles
Injury progression
3° Blast Injury: Blunt Trauma
Blunt trauma

- Victim propelled into objects by blast wind
- Objects propelled by blast wind into victim
- Crush injury
  - Structural damage
  - Building collapse
Blunt trauma
Blunt trauma

Schematic: ©LWW (used by permission)
Blunt trauma

- Mounted IED injuries
  - 16/19: LE fractures
  - 12/19: Spine fractures
    - T-L junction
    - 38% Chance fractures

Image: ©LWW (used by permission)
Crush injury

• With structural collapse of a building:
  – High casualty rate
  – High mortality figures
  – Crush is the predominant mechanism
Oklahoma City, 1995

©AP Photo/Bill Waugh (used by permission)
New York, 9/11

©AP Photo/Jim Collins (used by permission)
4° Blast Injury: Associated Injuries
Associated injuries

• Increased with confined-space explosions
  – Burns
  – Toxic gases and inhalation injury
  – Environmental contamination
  – Biologically active tissue: suicide bombers
    • Hep B/C, HIV from body fluids, tissues
5° Blast Injury: Contamination
Contamination

• “Dirty bombs” – a potential threat
  – Chemical
  – Biological
  – Radiological
  – Nuclear

• High-yield explosives remain the primary weapon of choice for terrorists and extremists
Initial Treatment Principles
Initial treatment principles

- Implement institutional disaster response plan
- Multi-disciplinary team approach required
- Apply Damage Control Orthopedics
Appreciate the spectrum of wounding

• Blast trauma has higher ISS, morbidity and mortality than blunt or penetrating trauma

• Survivors with blast wave amputations usually have associated life-threatening injuries

• Victims with amputations from penetrating trauma commonly have other life-threatening penetrating wounds
Appreciate the magnitude of wounding

- Shock waves cause significant soft tissue damage
  - Blast wave from the explosive
  - Local shock waves from supersonic projectiles

- Projectiles can be large, multiple and highly concentrated
Appreciate the full zone of injury

• Usually larger than initially anticipated

• Not immediately obvious

• Shock waves and blast wind cause ST damage and contamination adjacent to the obvious wounds

• Proximal tissues planes must be opened and explored during the initial debridement

• Remain alert for onset of compartment syndrome
Anticipate injury progression

• Demarcation of wounds takes longer than typical penetrating or blunt trauma (days to weeks)

• Do not close traumatic wounds primarily

• Serial interval debridements required

• Increased risk for further early injury progression:
  • History of delayed revascularization
  • Requirement for vasopressor therapy (head-injured)
  • Infection
Limb damage control

• Hemorrhage control
• Provisionally re-perfuse the limb
• Thorough, aggressive initial debridement
• Consider fasciotomies
• Provisionally realign the limb
  – External fixation, splints as appropriate
• Apply sterile dressings
• Continue resuscitation, antibiosis, etc
Additional Considerations

• Remember:
  – Severe primary blast injury will also affect internal organs including abdomen, lungs and CNS
  – Observation for at least 24 hours is mandatory for victims of PBI to look for signs/sx of late bowel necrosis, lung dysfunction, hemorrhage, etc
Resources

• Clinical Practice Guidelines
  U.S. Army Institute of Surgical Research

• Combat Extremity Surgery Course - Lecture archive
  https://sites.google.com/site/combatextremitysurgerycourse/

• JAAOS Special Issue (August 2012)
  Extremity War Injuries: Current Management and Research Priorities
Conclusions

• Blast-related trauma is fundamentally different from typical blunt or penetrating trauma

• Blast-related trauma is increasing in frequency

• Orthopedic surgeons must prepare for the eventuality of treating blast-related trauma

If you would like to volunteer as an author for the Resident Slide Project or recommend updates to any of the following slides, please send an e-mail to ota@ota.org