Orthopaedic Blast Injuries

OTA Disaster Preparedness Committee

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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

Military combat operations

- High velocity conventional weapons
- Landmines
- Improvised Explosive Devices (IED)

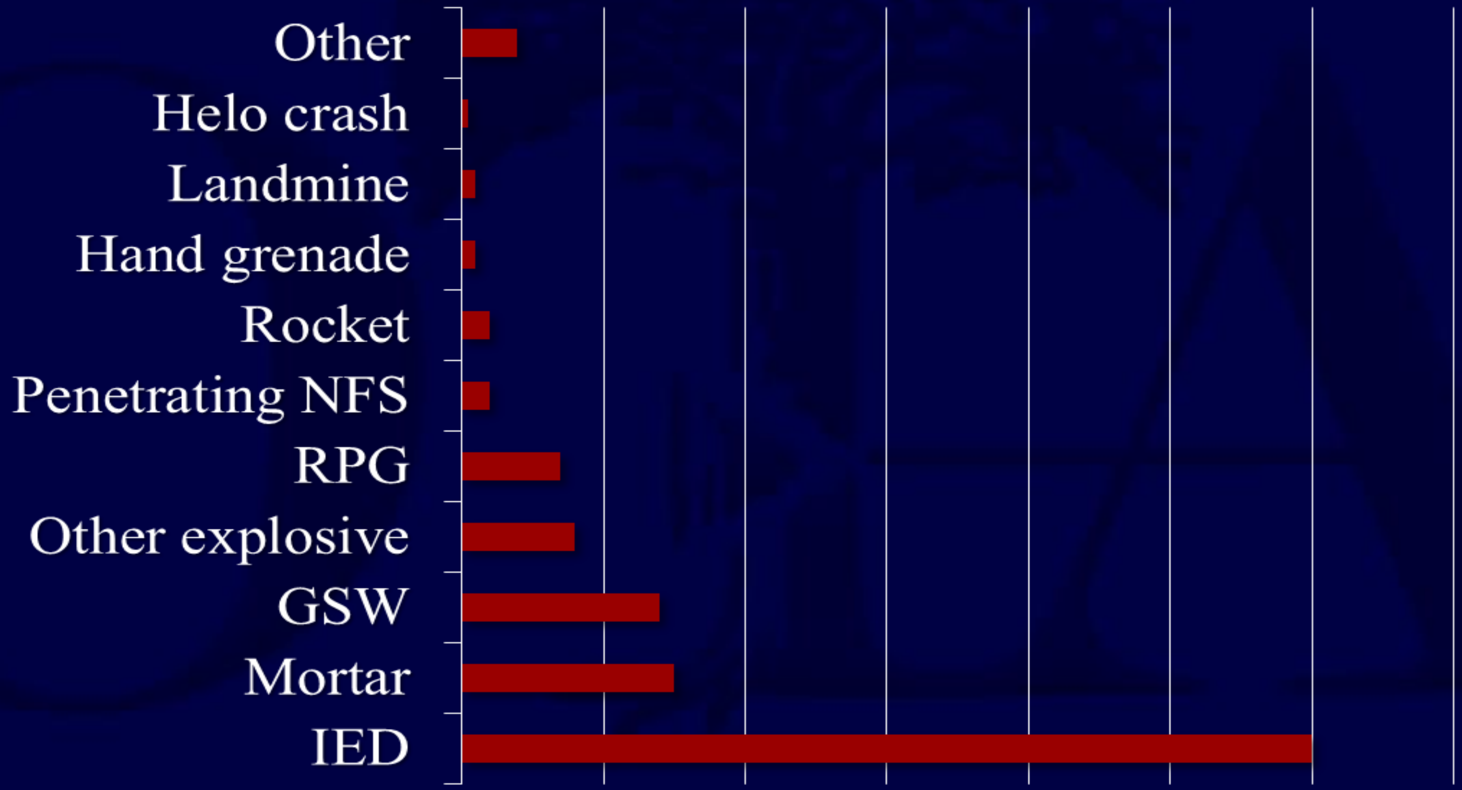
Combat related blast injury

- Over 16,000 attempted IED attacks annually in Afghanistan

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

www.defense.gov/news/casualty.pdf
Accessed : 09Mar15

Afghanistan injury mechanisms



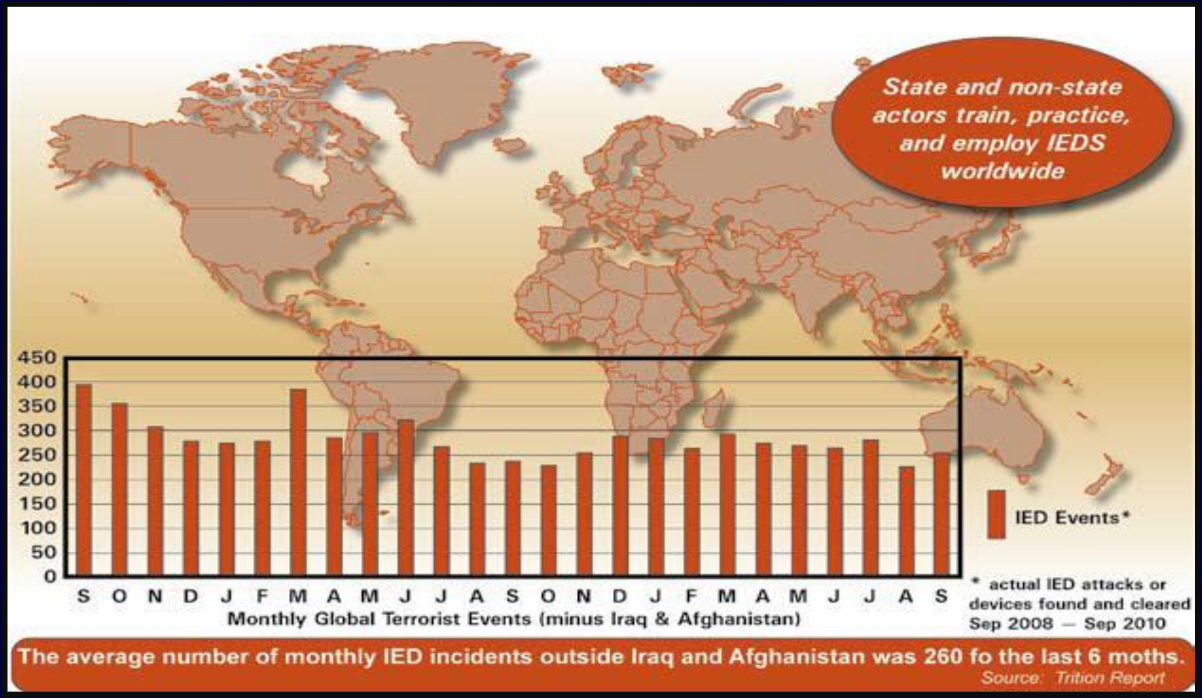
US Army Surgeon General's Report on Dismounted Complex Blast Injuries, Jun11

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

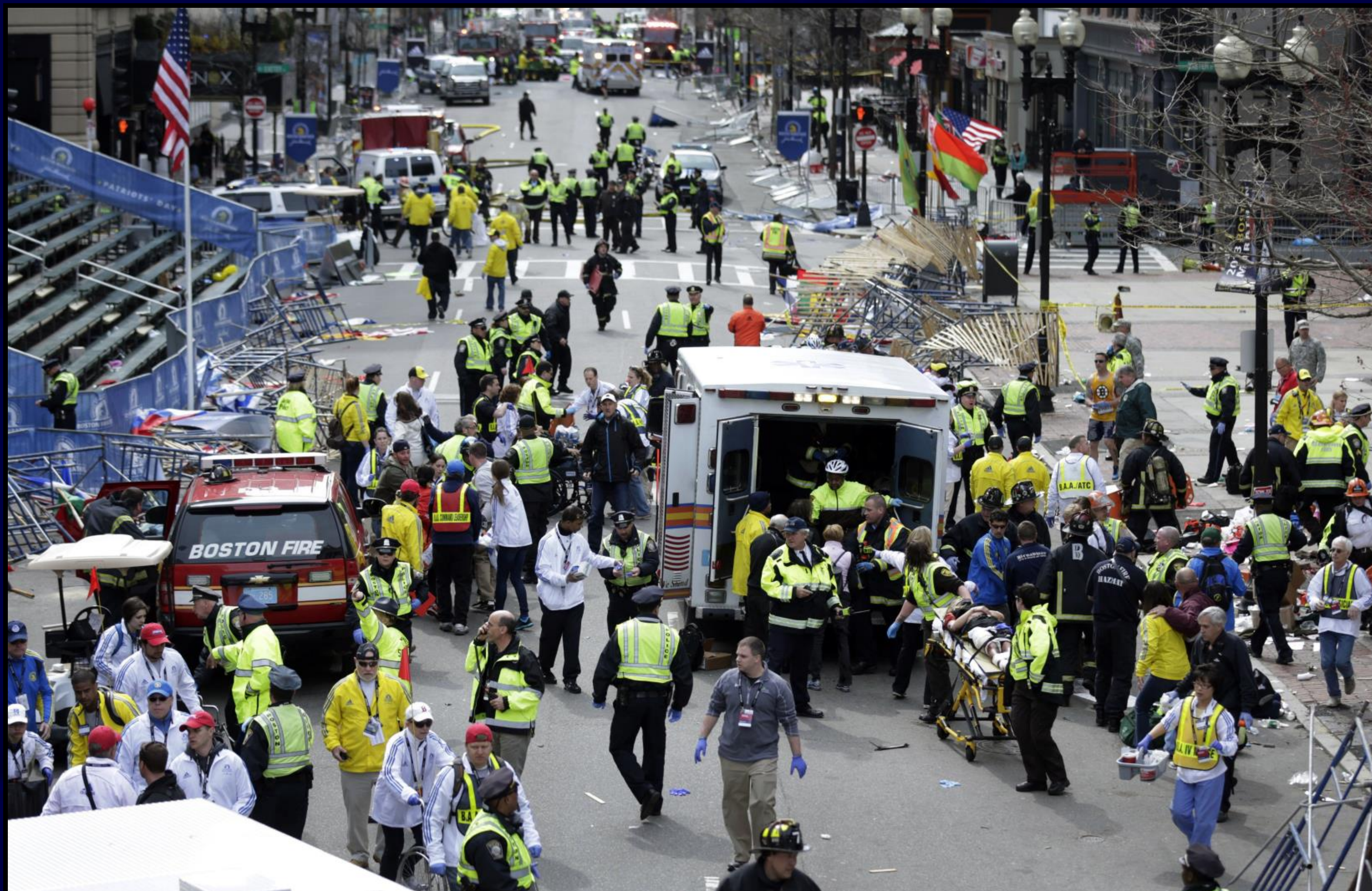
- Average > 260 IED incidents per month in 2010 globally, not including Iraq and Afghanistan



Improvised Explosive Devices

- Maximizes casualty generation
- Maximizes lethality
- EMS easily overwhelmed with numbers and magnitude of wounding

Boston, 2013

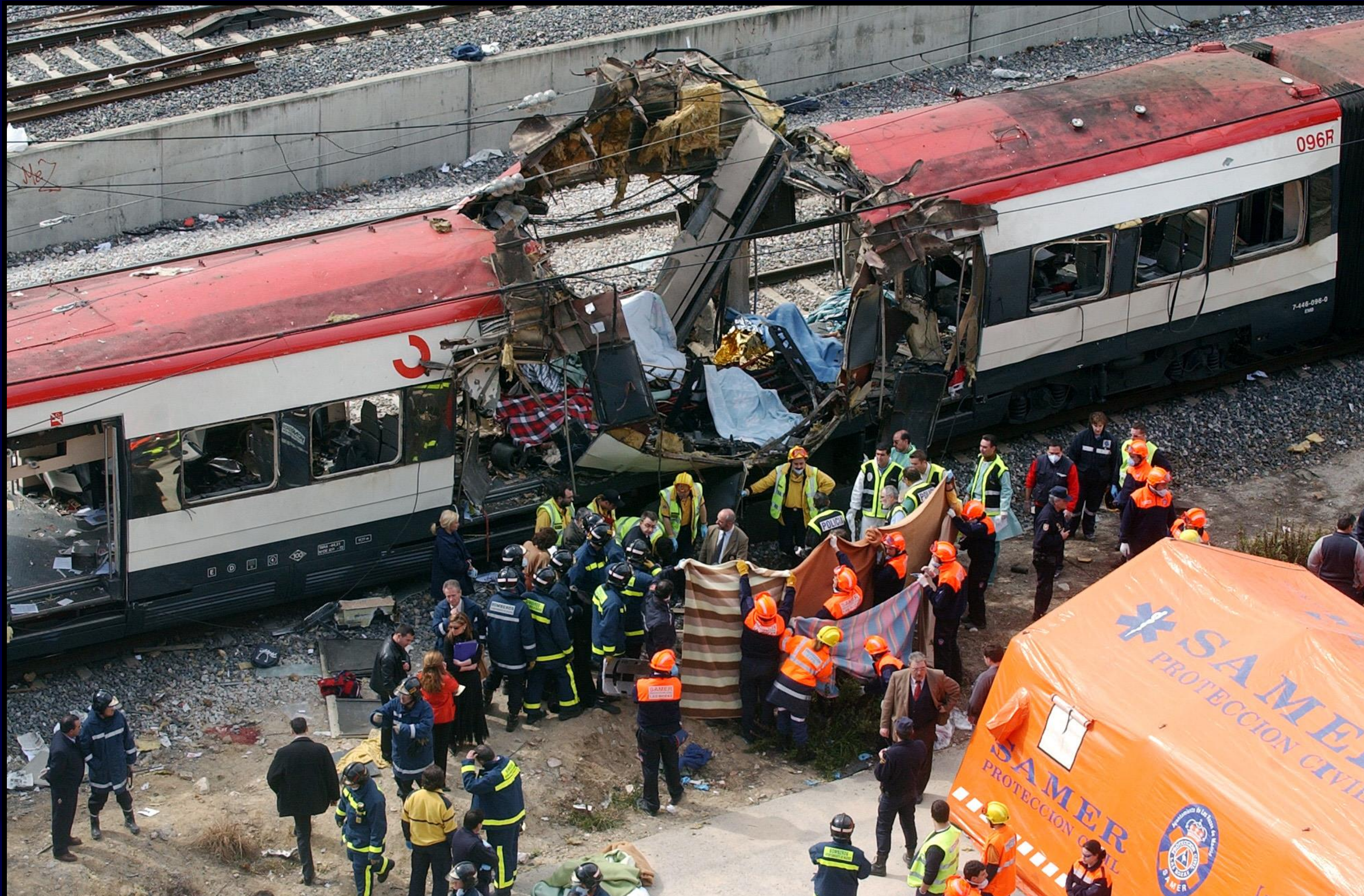


©AP Photo/Charles Krupa (used by permission)

London, 2005

©Press Association via AP Images/PeterMacDiarmid (used by permission)

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

1° 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

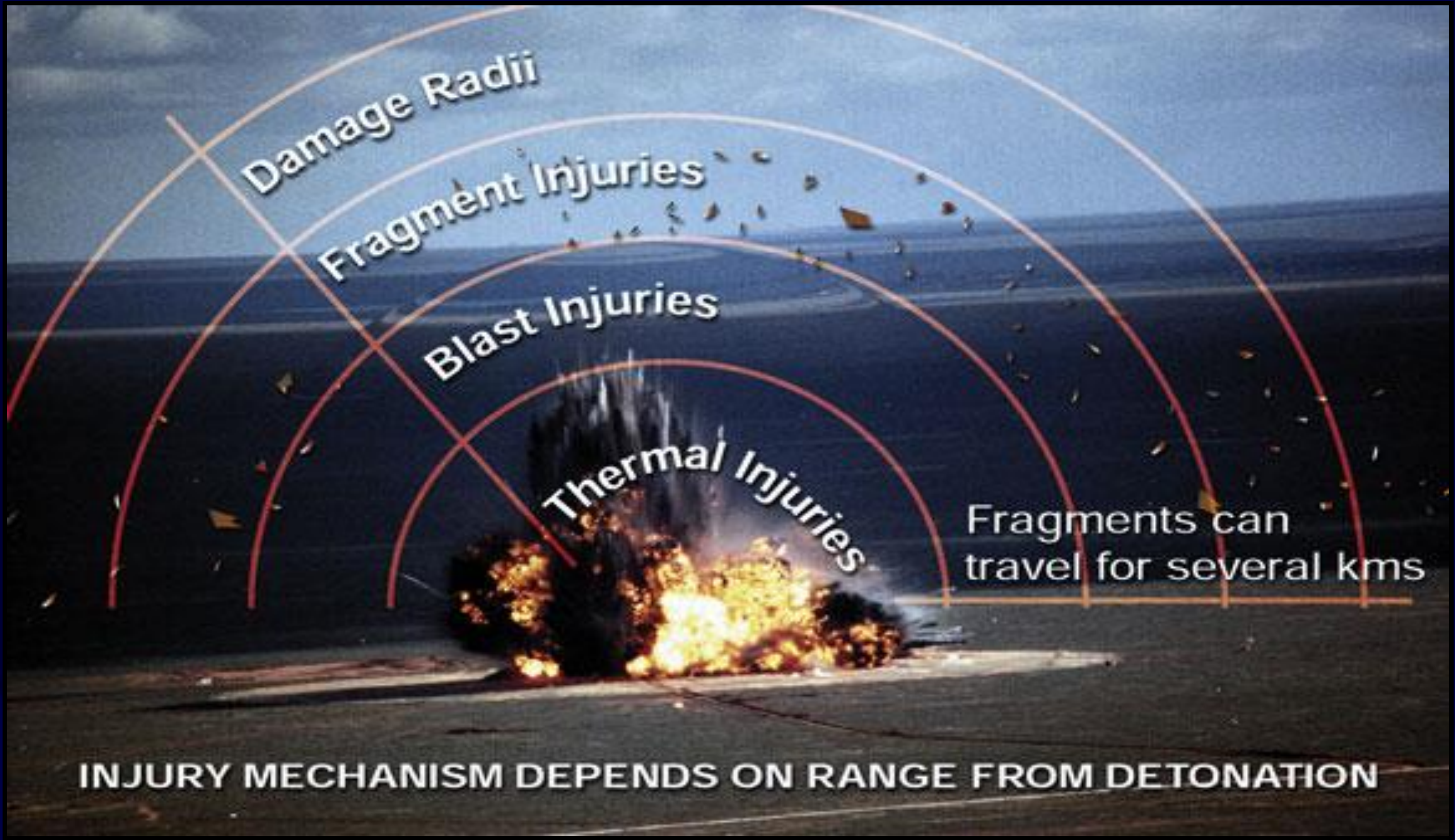
- Low-order explosive (LE)
  - Gunpowder
  - Petroleum based bombs
    - ‘Molotov cocktail’
    - Aircraft improvised as guided missile (9/11)

Explosives classification

- Low-order explosive (LE)
  - Subsonic explosion
  - No associated blast wave
  - Blast wind may be encountered with LE

	Common uses	Common form	Known IED use
HIGH-ORDER EXPLOSIVE			
Ammonium nitrate and fuel oil (ANFO)	Mining and blasting	Solid	Oklahoma City, 1999
Triacetone Triperoxide (TATP)	No common use – mixed from other materials	Crystalline solid	London, 2005
Semtex, C-4	Primarily military	Plastic solid	Irish Republican Army bombings
Ethylene glycol dinitrate (EGDN)	Component for low-freezing dynamite	Liquid	Millennium Bomber, intended for LAX, 1999
Urea nitrate	Fertilizer	Crystalline solid	World Trade Center, 1993
LOW-ORDER EXPLOSIVE			
Smokeless powder	Ammunition	Solid	Olympic Park bombings

Blast injury

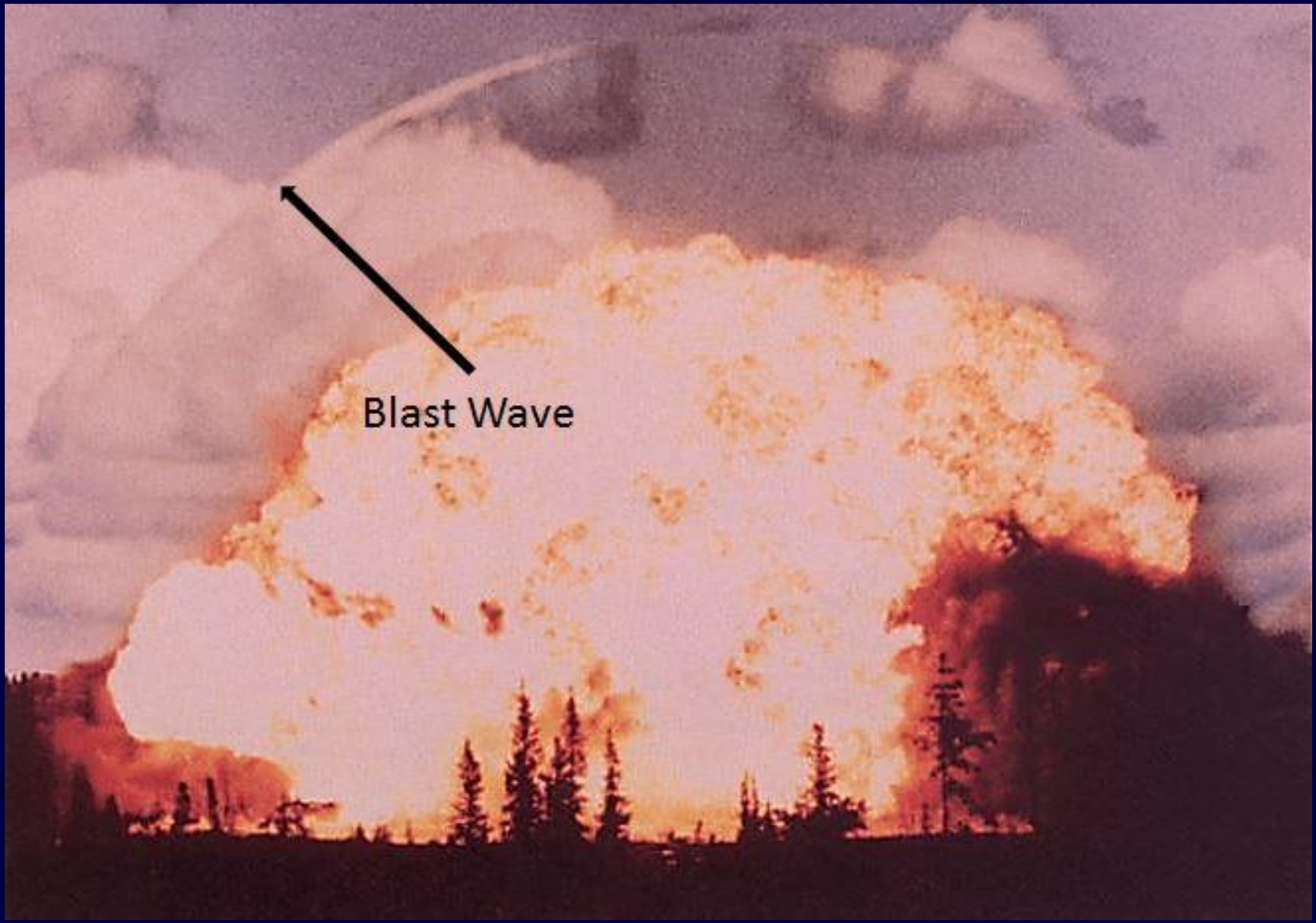


www.defence.gov.au/health/infocentre. Accessed: 13May13

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

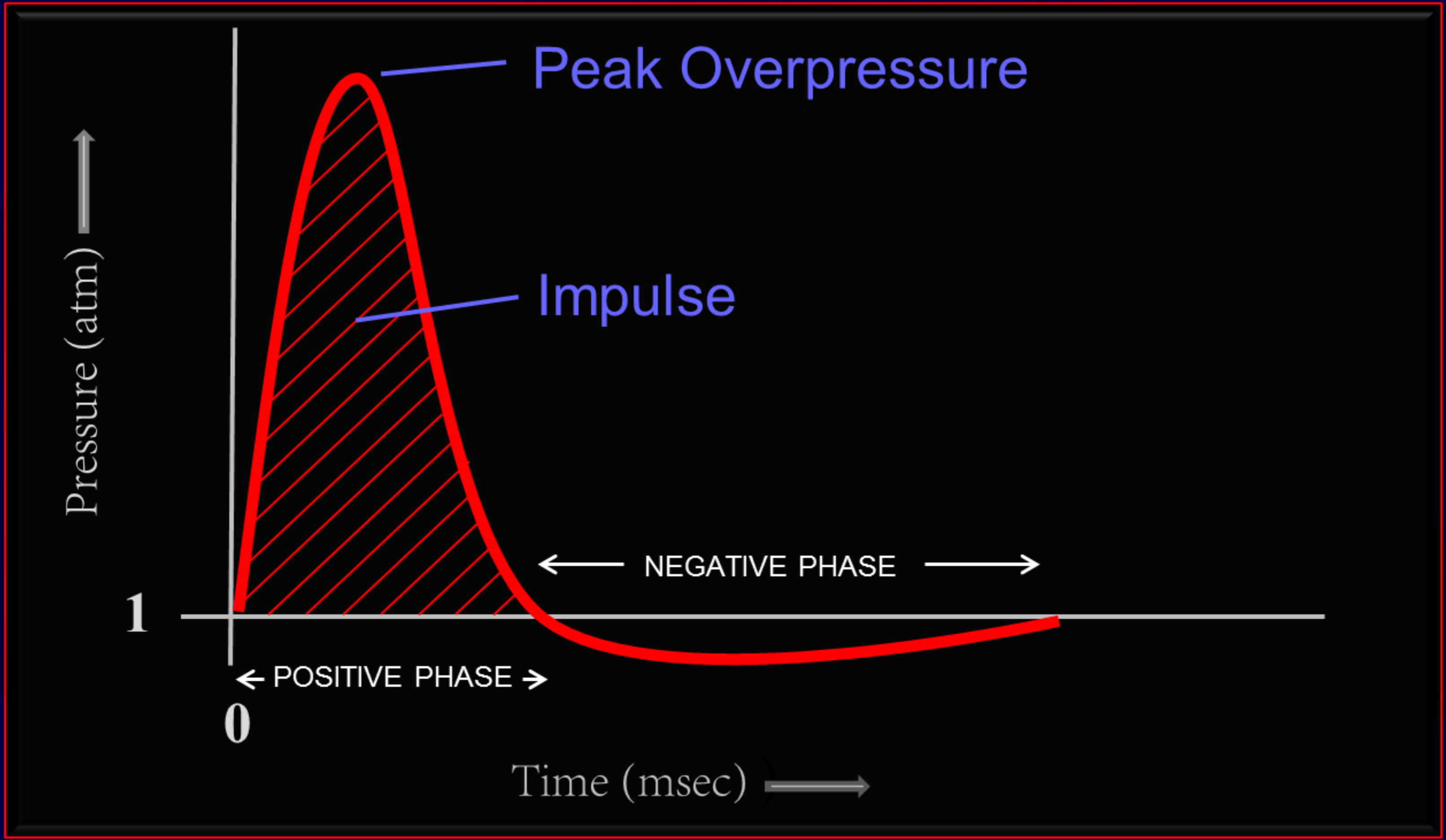


Blast wave formation

- 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

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

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

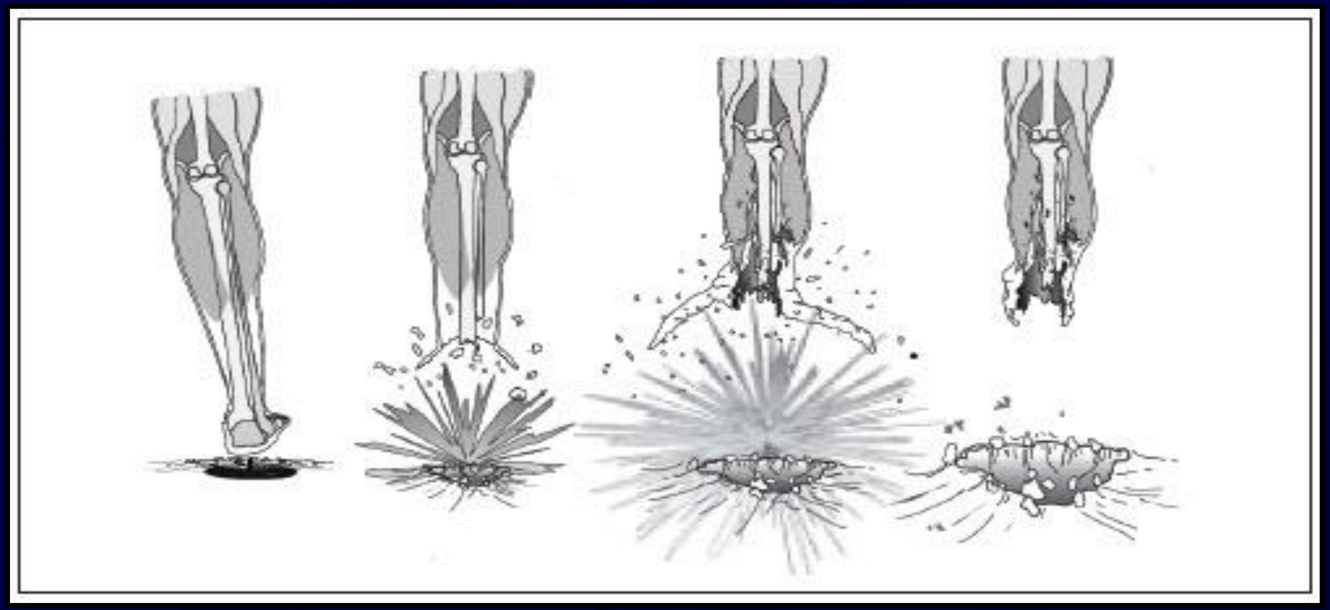
- Tympanic membrane rupture
  - Occurs in 1% at 5 psi overpressure
  - Occurs in 99% at 45 psi overpressure
  - <u>Not</u> a reliable marker for other primary blast injuries (Sensitivity ~ 30%)

Leibovici, et al. Ann Emerg Med, 1991

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***

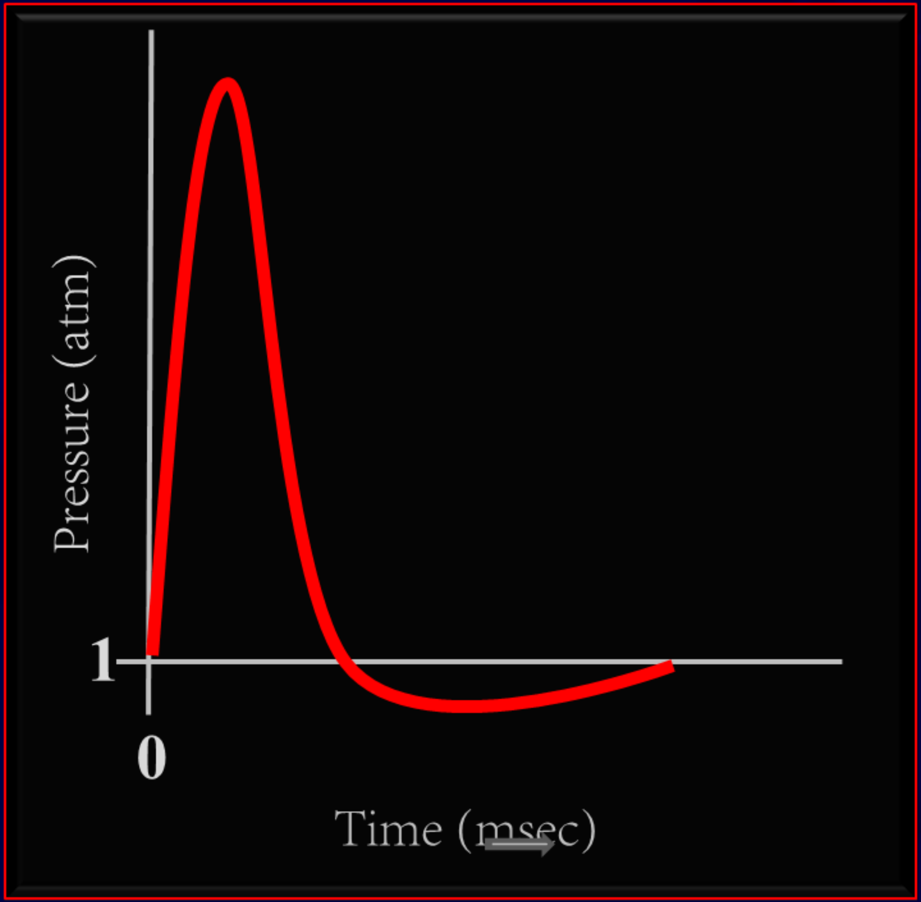
Hull, et al. J Trauma 1996

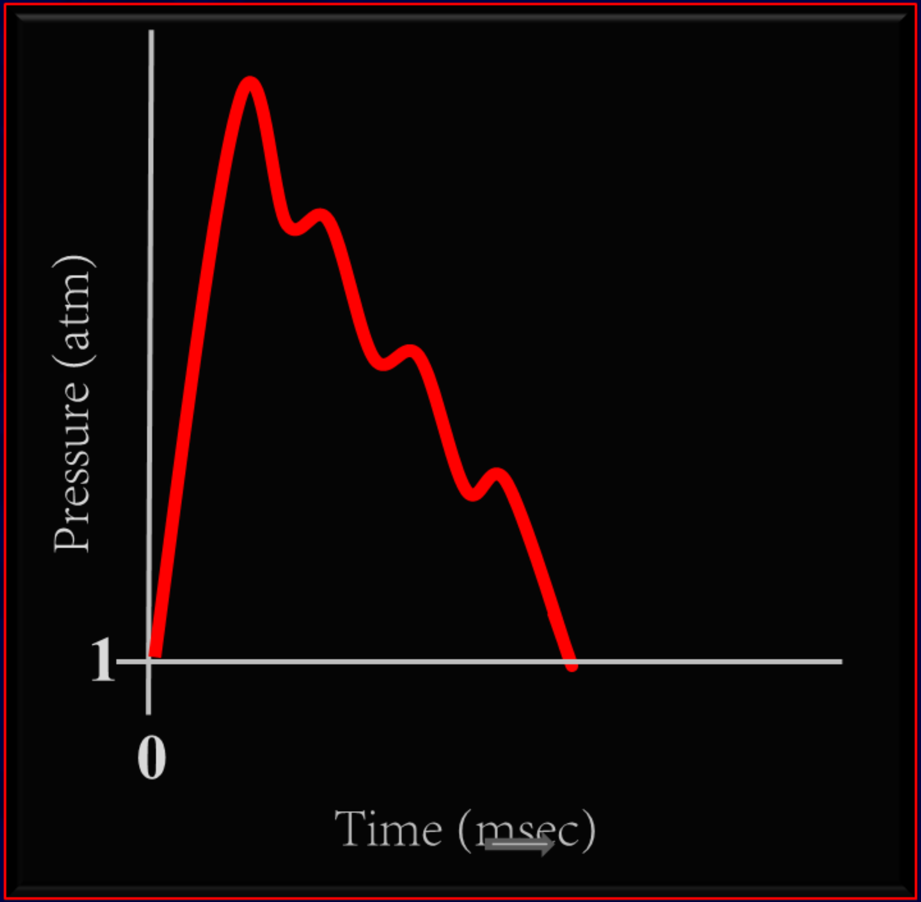
Reflected blast waves

- 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

Reflected blast waves

	Open air explosion	Bus explosion
Mortality	8%	49%
Survivor mean ISS	4	18
Primary blast injury	34%	78%

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

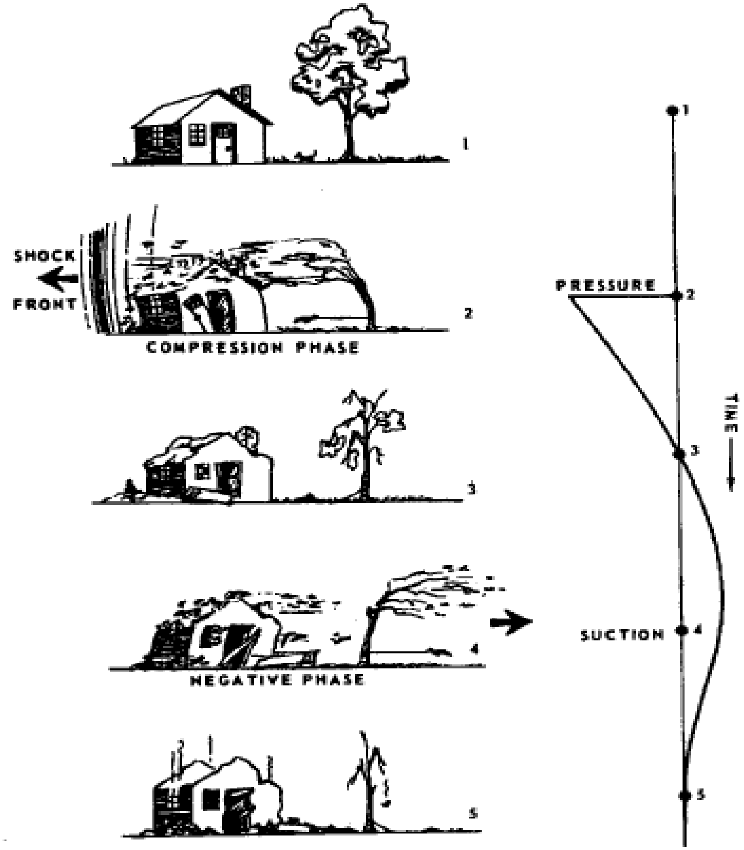


Figure 3-III. Variations of Blast Effects Associated with Positive and Negative Phase Pressures with Time

Blast wind

- Causes additional wounding (penetrating trauma from debris)
- Causes additional contamination
- May help complete partial amputations

2° 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

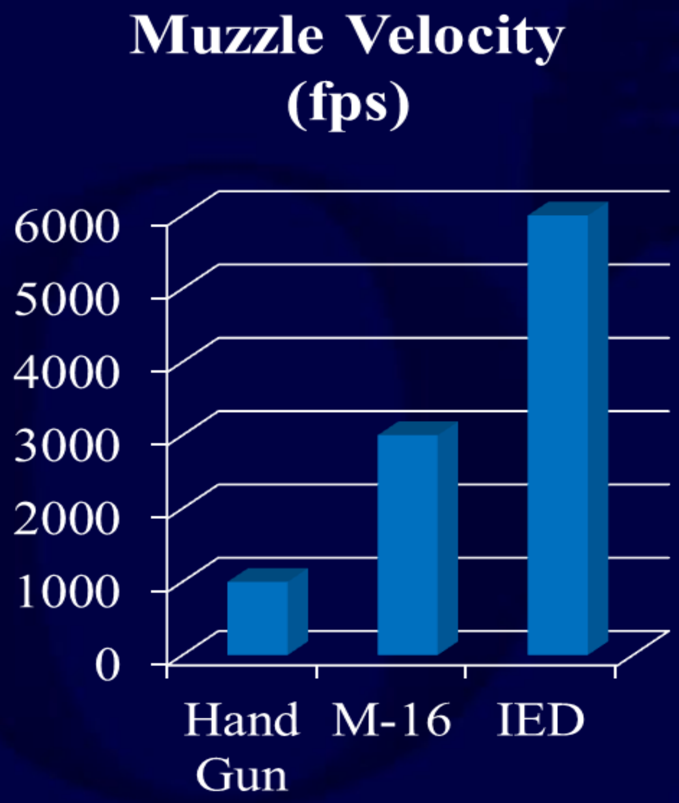
- Primary Fragmentation – related to device
  - Casing material
  - Embedded: nuts, nails, ball-bearings

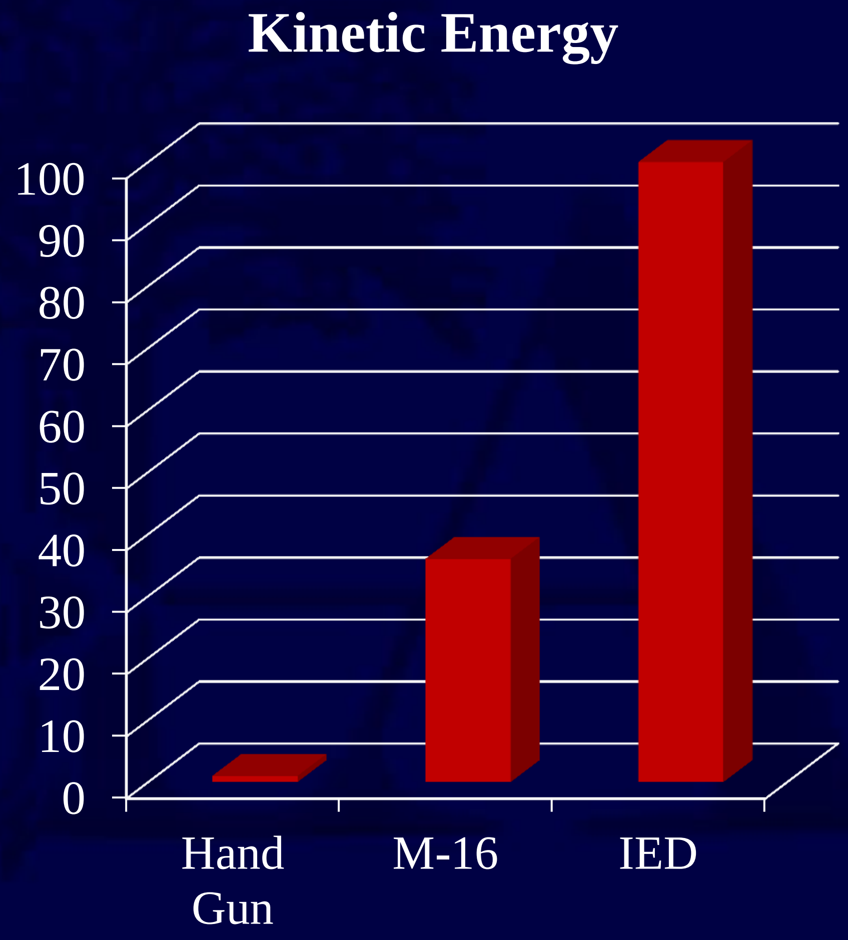
- Secondary Fragmentation – external to device
  - Rocks, gravel, building materials, vehicle parts, glass
  - Body parts (other victims or suicide bombers)

Kinetic Energy

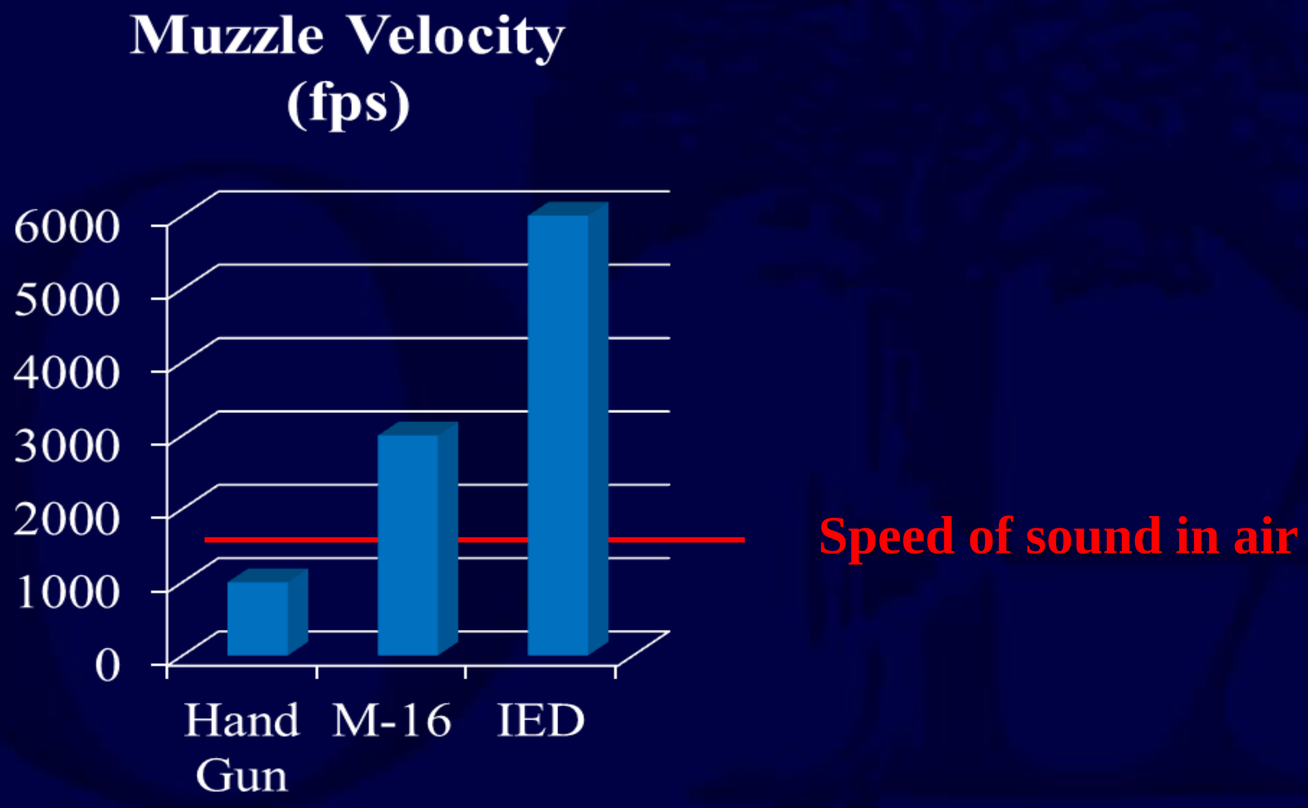
$$KE = \tfrac{1}{2}mV^2$$

Kinetic Energy

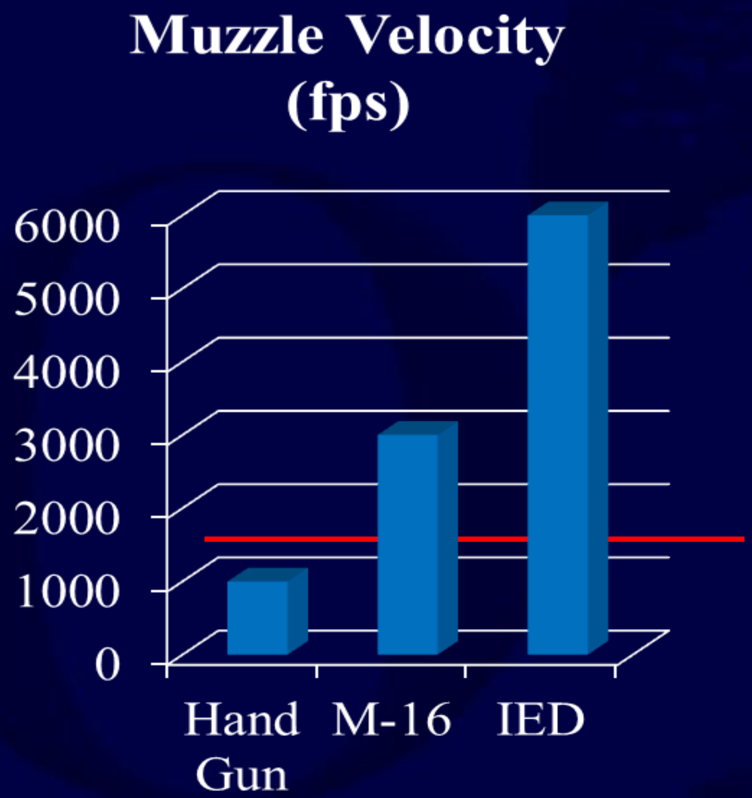




Kinetic Energy



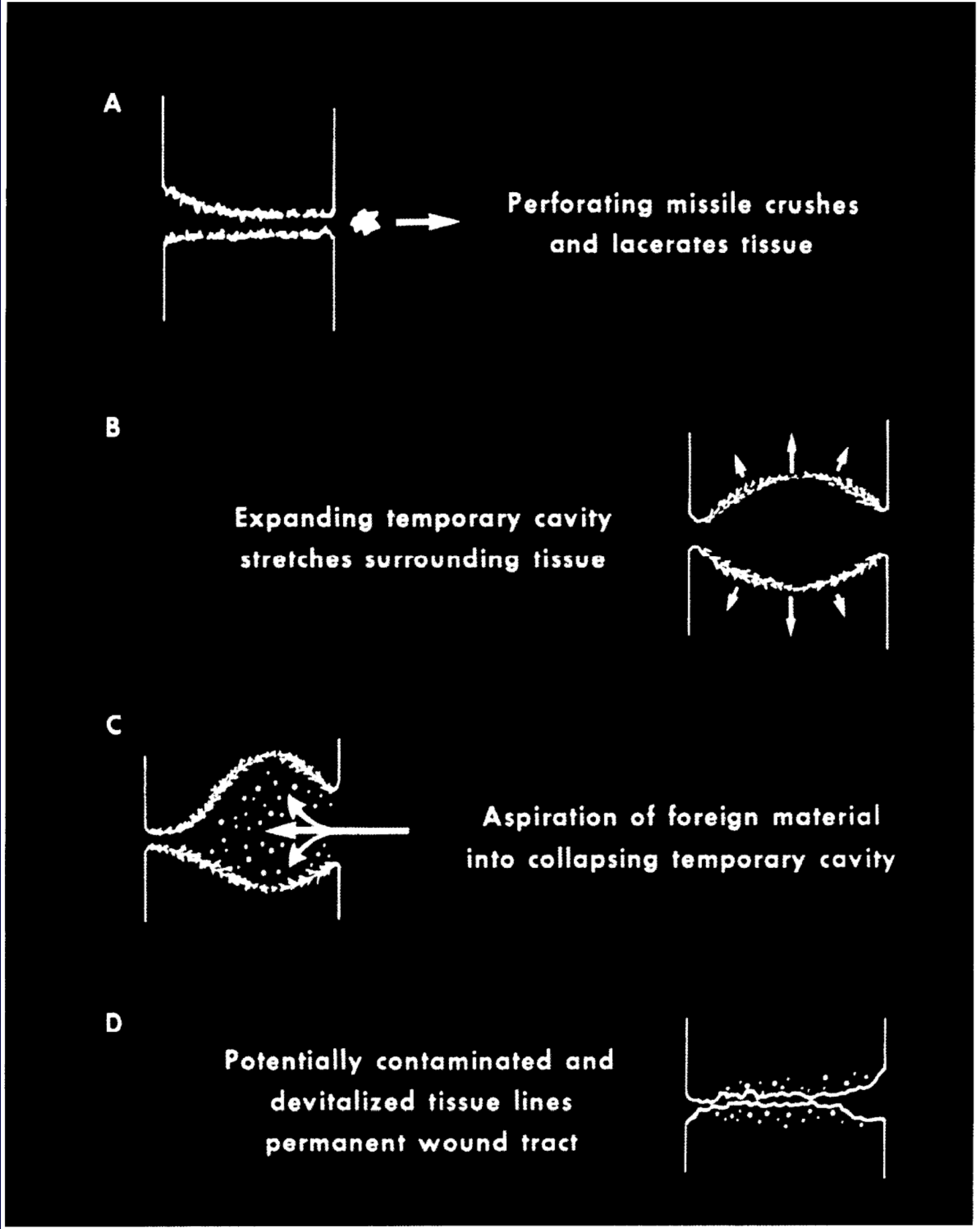
Projectile shock wave



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
- <u>Do</u> open and explore fascial planes
  <u>Do</u> <u>not</u> close traumatic wounds

Kinetic Energy

$$KE = \frac{1}{2}mV^2$$

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

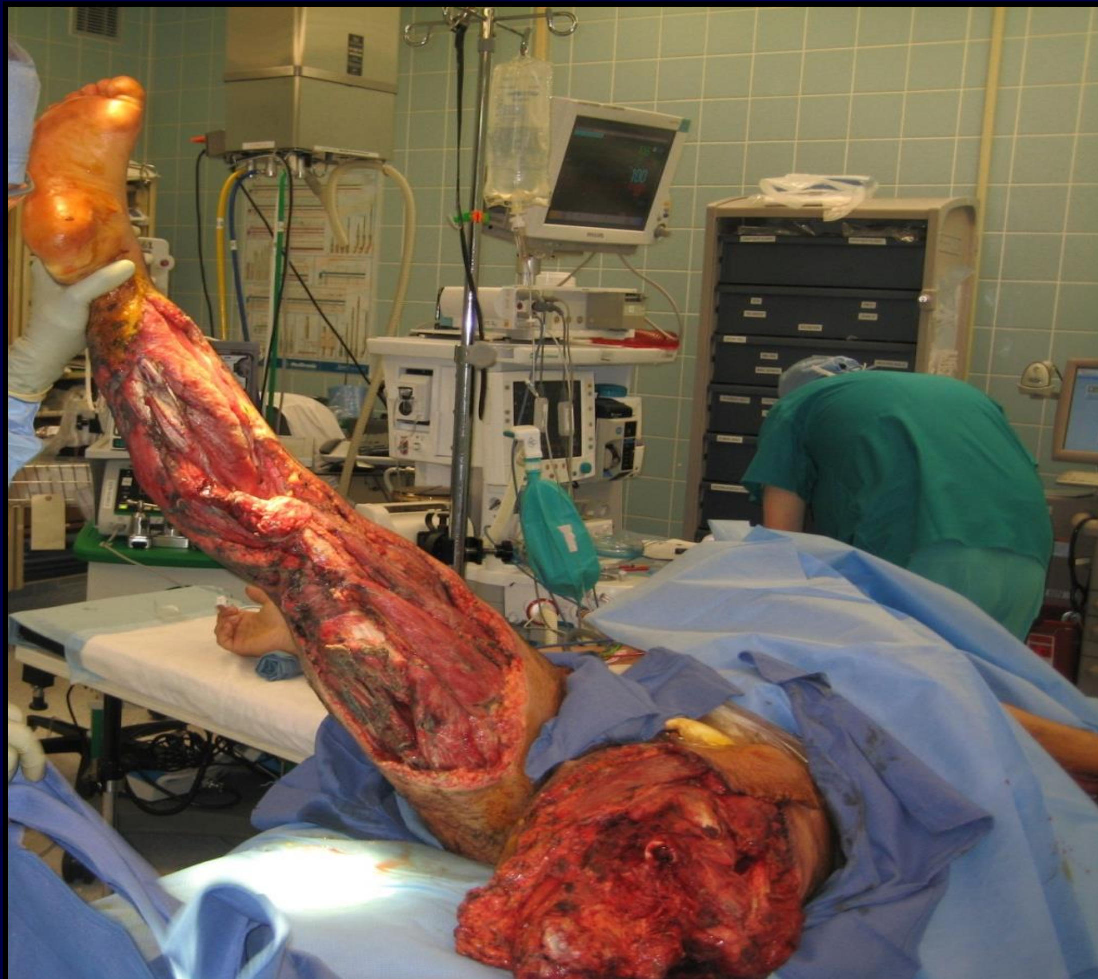
- Long bone fractures indicative of higher ISS, morbidity and mortality

Almogy, et al. Ann Surg, 2006
Weil, et al. J Trauma, 2007

IED projectiles

IED projectiles

Injury progression



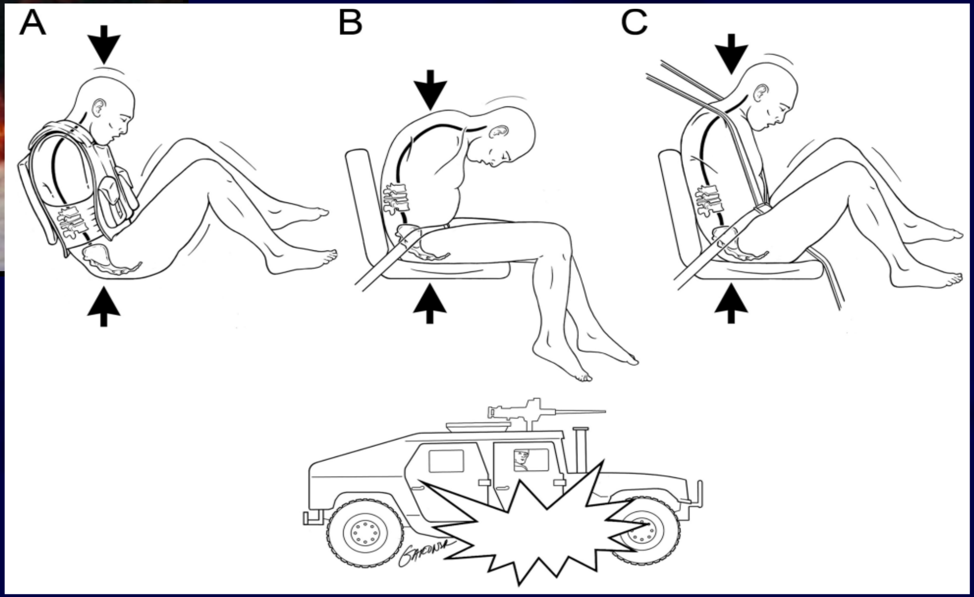
3° Blast Injury: Blunt Trauma

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



Ragel, et al. Spine, 2009
Schematic: ©LWW (used by permission)

Blunt trauma

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

Ragel, et al. Spine, 2009

Crush injury

- With structural collapse of a building:
  - High casualty rate
  - High mortality figures
  - Crush is the predominant mechanism

Oklahoma City, 1995

New York, 9/11

©AP Photo/Jim Collins
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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
  http://www.usaisr.amedd.army.mil/clinical_practice_guidelines.html

- 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

E-mail OTA about Questions/Comments

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