Evolving mechanisms and patterns of blast injury and the challenges for military first responders

CPL C. Stevenson

Introduction

Explosions cause more military casualties (65.5%[1]), than any other combat mechanism of injury [1-9, 14, 16, 18]. Injury patterns have evolved as a direct result of developments in personal protective equipment and insurgent tactics techniques and procedures (TTPs) [8, 15, 17, 18]. The purpose of this paper is to outline emerging blast mechanisms of injury (MOI) directed against coalition troops in Iraq and Afghanistan, resultant patterns of injury (POI), and prehospital challenges which first responders encounter with this unique group of casualties.

Mechanisms of injury

Blast injuries are categorized by mechanism into primary, secondary, tertiary and quaternary injuries [1-10, 17, 18, 23].

Primary injury

Primary injuries are the consequence of the rapidly expanding blast wave which follows a detonation [2, 3, 10, 16, 17, 18, 23]. The blast wave quickly exerts blast overpressure (BOP) outwardly from the centre of the blast [4]. Underpressure rapidly follows [10 16]. The abrupt pressure change stretches then contracts human tissue beyond normal limits. Consequently it is referred to as barotrauma (literally 'pressure injury') [21]. The peak physiological effect is experienced by air filled organs; the middle ear, lungs and colon [10, 16, 18, 22, 23].

Secondary injury

Secondary injuries involve penetrating trauma. Projectiles are driven indiscriminately from the detonation site into humans at up to 1800 metres per second [1, 2, 16, 17, 18, 23]. Projectiles can be incorporated into the design of the device such as: metal casing (classically termed 'shrapnel' after its 1784 inventor Major-General Henry Shrapnel [19]), nails, nuts, bolts, or glass coated in faeces designed to maximize secondary infection [17, 29]. Other missiles can be energized by the blast wind including rocks, dirt, bone fragments of other casualties, and clothing [17, 29]. The velocity and irregular profile of blast missiles cause haemorrhage and localized crush injuries which are more extensive than gunshot wounds (GSWs) [16].

Tertiary injury

Tertiary injuries are a consequence of blunt trauma, as humans are propelled into stationary objects, or along the ground [18 23].

Quaternary injury

Quaternary injuries are an assortment of miscellaneous insults encompassing respiratory compromise, thermal burns, and crush injuries [18, 23]. To summarize these effects primary is movement of air pressure, secondary is movement of projectiles, tertiary is movement of humans, and quaternary are miscellaneous injuries.

Casualties are likely to experience multiple blast effects and multi system injuries [17, 29] depending on: proximity to the epicentre of the explosion, protective equipment employed [6], whether the explosion occurred in a confined space and the size and shape of missiles energized by the blast [4, 18, 23]. The blast energy to time and distance relationship is inversely proportional, i.e. as time and distance increase from detonation, blast wave energy decreases [4]. The result is that casualties situated three metres from the blast are subjected to nine times more blast effect than casualties situated six metres from the blast [4].

Blast enhancement

Blast waves are enhanced by environmental factors such as confined spaces, underwater detonation and

focused detonation [4 18]. The walls of a room, bus or train confine and reflect the blast wave, increasing the extent of injuries experienced by casualties trapped inside [4]. The world witnessed a diabolical example of multiple confined blasts in the July 2005 London bombings. Fifty were killed and seven hundred injured by improvised explosive devices (IEDs) placed on three trains and one bus [11]. After an underwater detonation, the blast wave and sound are transmitted faster and further than a surface detonation [4, 12]. A focused blast occurs when all of the kinetic energy is channelled along the path of least resistance, in the same way a bullet is propelled directly through a rifle barrel.

Concealed IEDs

A characteristic concealed IED employed by insurgents in Iraq consists of a camouflaged bank of 155mm artillery rounds (up to seven) [25] packed behind rows of conical copper discs. The IED is remotely armed by mobile phone, and initiated when a vehicle breaks an infrared beam. On detonation the concave faces of the discs are forced inside out to form a molten hot projectile capable of penetrating armoured vehicles. The IED can be aimed horizontally at specific crew members of a vehicle with devastating accuracy. As this penetrating device is created post detonation it is referred to as an explosively formed projectile or penetrator (EFP) [18]. Other IEDs consist of an artillery round, homemade explosives (HME) concealed underground and initiated remotely by one of a number of commercial available electronic transmitting devices [3]. Anti personnel and anti tank mines are used in isolation or to initiate IED's. Convoys that maintain strict inter vehicle spacing are able to minimize concealed IED casualties [25].

Vehicle borne IEDs

Attacks on infrastructure and convoys are achieved with vehicle borne IEDs (VBIEDs) [3]. VBIEDs are capable of delivering considerable quantities of explosives [2]. An average sized car can deliver 200kg of explosives, and a light truck 27000kg [2]. A current TTP which maximizes casualties is to dispatch a truck to breech a roadblock [2]. As first responders arrive on scene, a VBIED approaches and detonates [2]. A second VBIED may follow after 30 to 100 minutes [23].

Building contained IEDs

A static IED which accommodates a significant quantity of explosives and propellants is a building contained IED (BCIED) [13]. A BCIED can be remotely detonated or victim initiated. The blast effects are enhanced by the confined space.

Human borne IEDs

Human borne IEDs (HBIEDs) also known as suicide vest IEDs (SVIEDs) bring to bear less explosive than VBIEDs and BCIEDs [2]. Generally the quantity of explosives which can be carried is limited to the amount which can be concealed in a vest or belt under clothing or inside a backpack. Women and intellectually handicapped people are increasingly being used as SVIEDs. Cultural sensitivities in Afghanistan generally prevent women wearing the burqa (a traditional head to toe garment which conceals the wearers face behind a cloth mesh screen) from being searched by coalition forces [35]. In Eastern Afghanistan males and females armed with SVIEDs and assault rifles concealed in burqas attacked government buildings killing 12 in July 2009 [35]. In April 2009 two female SVIED's killed 60 people in Baghdad [34]. Backpack IEDs can be thrown at or attached by magnet to vehicles as they pass through choke points or retained by the wearer (as seen in the 2005 London railway and bus bombings) [2, 11].

Indirect blasts

Indirect fire blasts are delivered by Katyusha rockets. A Katyusha (Russian for 'little Katherine') rocket comprises an artillery round launched along an improvised rail or tube which is indirectly aimed at a target. 107mm or 122mm rounds are commonly used [3, 20]. In Iraq and Afghanistan, multiple rockets are ground launched or mounted on enclosed trucks utilizing a timing device so insurgents are not exposed to return fire [20].

Direct blasts

Direct fire blasts are delivered by rocket propelled grenades (RPGs) [3]. The RPG consists of a 1.4 kg high explosive (HE) warhead launched from a shoulder mounted tube [24]. The firer is positioned in line of sight of the target at distances of up to 500m [24].

Patterns of injury

Demographics

It is pertinent at this point to explore the demographics of coalition military casualties in Iraq and Afghanistan. These are males with a mean age of 26-28 years [5, 6]. This is significant for recovery because soldiers in this age group are generally healthy, with good physiological reserves. Blast injury has been described as the "signature injury" of the current conflict in Iraq [2, 18]. The current casualty survival rate is 88-96%, which is a significant increase since the Vietnam War (76.4%) [2, 3, 17, 18]. Injuries which had poor outcomes in previous conflicts are now survivable but with devastating life changing consequences [2, 6, 17, 18]. This is a result of improvements in personal protective equipment (e.g. body armour, ballistic helmets and ballistic eyewear) and medical care (forward definitive care, rapid critical care, aeromedical evacuation and expert rehabilitation) [2, 6, 15, 17, 18, 29].

Immediate death

Immediate death is expected in casualties situated in the immediate vicinity of the detonation due to massive tissue destruction. This occurs despite prehospital resuscitation and is an incredibly confronting reality for first responders [16, 23].

Primary injuries

In Iraq, IED's characteristically produce a BOP greater than 60 pounds per square inch (psi) [6]. To put this into perspective, rupture of the tympanic membrane (TM) can occur following exposure to five psi of BOP [4]. A Hellfire II air to ground missile delivers 5 000,000 psi of BOP [33]. One third of casualties experiencing TM rupture will suffer from permanent hearing deficit [4]. Young healthy ears containing cerumen experience the most favourable outcomes following BOP exposure [10]. Ear injuries require no specific prehospital treatment [4, 23]. Pulmonary contusion ('blast lung') occurs following exposure to 15 psi of BOP [4]. TM rupture was previously thought to be an indicator of underlying 'blast lung'. It is now known that there is no correlation between the two insults; one can occur in the absence of the other [4, 10]. Historically only a small number of casualties experience intestinal contusions ('blast abdomen') (1.2%) [10]. The region of the gastrointestinal tract most likely to suffer the ill effects of BOP is the large intestine. Blast abdomen is difficult to diagnose in the field [23]. Onset of sequelae for blast lung and abdomen can be 12-48 hours after the initial insult [4]. Traumatic brain injury (TBI) or blast brain occurs in 50% of blast casualties and is frequently undiagnosed until the rehabilitation phase of care [1, 6, 7, 18, 27, 29]. The causes of late TBI diagnosis are multifactorial. Ear injury and hearing deficit are common (64% of blast casualties) [1, 6]. Confused casualties experiencing TBI may be assumed to be suffering from hearing deficit [6, 18]. Due to unconsciousness and more immediate concerns such as massive haemorrhage, damage control surgery and rapid strategic aeromedical evacuation, neurological investigation is often assigned a lower priority and may not occur until the rehabilitation phase of care [1, 6, 18]. There is a direct correlation between TM rupture and TBI following blast exposure [27]. Ballistic helmets and eyewear are ineffective against BOP [2]. Spinal injuries can occur when vehicles strike concealed IEDs [16]. The upward blast results in excessive axial loading, particularly when the victims head strikes the ceiling of the vehicle [16].

Secondary injuries

Fifty per cent of combat deaths result from exsanguination [30]. Body armour, ballistic helmets and ballistic eyewear are particularly effective in preventing secondary blast injuries [17, 18, 29]. However the unprotected body regions (face, neck, axillae, groin, buttocks and limbs) are vulnerable to insult. Chest injuries which were previously associated with a high mortality rate are now minimised with the use of body armour [3, 17, 29]. Injuries to the face and neck account for 21% of combat injuries and 64% of combat deaths [8, 15, 29]. The kidneys are reasonably well protected by body armour, and the frequency of genitourinary injuries is the same as other wars [28]. Insurgents are using increasingly sophisticated directional blasts to target the groin and axillae [17].

Extremity injuries comprise 60-75% of blast injuries [3, 16]. Typically these include: large lacerations, multiple small 'peppered' wounds, and mangled extremities [17, 29]. In isolation these injuries are generally not fatal when treated promptly [8, 15]. Peppered wounds are the product of multiple high velocity blast energized missiles [16, 18]. Projectile pathways penetrate deep within the body forcing foreign bodies and contaminants into those regions [16, 18]. Traumatic amputation is the result of BOP and the secondary shearing effect[16]. The consequences are catastrophic haemorrhage, mutilation and heavy contamination. This group of casualties have a poor prognosis due to the exposure to significant destructive forces [6, 16].

Tertiary injuries

Tertiary injuries are classic acceleration deceleration blunt insults. Head injury, TBI and fractures are common in blast casualties [1, 10, 18].

Quaternary injuries

Quaternary injuries include respiratory compromise from an array of inhaled pollutants (ranging from carbon monoxide and minute particulates to toxic by-products of the combustion process) and airway burns, external thermal burns from the superheated blast wind pursuing the blast wave, and crush injuries following structural collapse [18, 23, 29].

The challenges

Number of casualties

A typical ratio of dead to injured following a blast is 4:35 [32], i.e. for each immediate death there are approximately eight injured, a considerable number of casualties for first responders [4]. The language barrier makes assessment of multiple civilian casualties complex.

Haemorrhage control

Combat related haemorrhage is difficult to control. Effective management is the product of training and experience. Small entry wounds can conceal significant internal injuries with resultant massive haemorrhage [16, 17, 29]. Intra abdominal haemorrhage can result from missile wounds to the thigh, buttocks or perineum [16]. Small entry wounds can be filled with packing gauze or a similar improvised product. In the presence of massive haemorrhage, mutilated extremities and traumatic amputations, an appropriately applied tourniquet is an excellent method of haemorrhage control. Catastrophic tissue devitalisation is invariably confronting for first responders.

Evacuation time

The time from combat injury to evacuation is easily prolonged by severe weather, tactical constraints and terrain [30, 31]. This is particularly relevant in the mountainous Hindu Kush in Afghanistan where rotary wing airframes experience power limitations at elevations greater than 10 000 feet [31]. Access to casualties can be complicated when first responders are targeted by insurgents. Knowledge of evacuation procedures is essential for all team members as key personnel can become victims. The mode of evacuation (surface/aeromedical or a combination) must be an early consideration.

Wound contamination

Extensive environmental contamination of wounds causes significant risk of secondary infection. Cephalosporins are recommended particularly in the case of open fractures [16]. In the delayed evacuation scenario, the early administration of Ceftriaxone (carried by Advanced Medical Technicians) is feasible.

Diagnostic dilemma

Confused casualties encountered during the prehospital phase may be experiencing a TBI, hearing deficit, or both [18]. Performing a neurological assessment in the field on civilian casualties is complicated by the language barrier.

Hypothermic coagulopathy

Preventing hypothermia and the resulting coagulopathy is extremely challenging in trauma casualties [29]. When a casualty's core temperature decreases beyond 32 degrees Celsius, clotting factors become ineffective. In the absence of effective clotting factors, concomitant bleeding is exacerbated. Hypovolaemic shock and clothing removal are probable causes of hypothermic coagulopathy [29]. Clothing may be blown off as a result of primary and quaternary blast effects, or removed during the primary survey.

Conclusion

The critical message for first responders to take home from the coalition experience in Iraq and Afghanistan is the value of haemorrhage control and blast injury training. To be merely familiar with blast injuries is inadequate. Buddy aid must be instinctive to be effective. All troops must be proficient in haemorrhage control, as buddy aid saves lives before clinicians arrive on scene. The onus for this training cannot fall on commanders. First responders at all levels from the combat first aider upwards must proactively seek to train their dependants to respond decisively to blast injuries.

Contact author: CPL C. Stevenson (Advanced Medical Technician) Royal Australian Army Medical Corps
Email: charles.stevenson@defence.gov.au

References

1. Scott S, Belanger H, Vanderploeg R, Massengale J, Scholten J. Mechanism of injury approach to evaluating patients with blast related polytrauma. JAOA. 2006; 106 (5):265-270
2. Weybright C. Surviving the injuries of war. veteransvoice.wordpress.com/2007/04/08/surviving-the-injuries-of-war/. 08 April 2007
3. Hyer R. Iraq and Afghanistan producing new pattern of extremity war injuries. www.medscape.com. 27 March 2006
4. Lavonas E. Blast injuries. emedicine.com. 30 Dec 2003
5. Kauvar D, Wolf S, Wade C, Cancio L, Renz E, Holcomb B. Burns sustained in combat explosions in Operations Iraqi and Enduring Freedom. Burns. Nov 2006 32 (7):853-857
6. Chandler D. Blast-related ear injury in current U.S military operations. *The ASHA Leader*. July 2006; 11 (9):8-9, 29
7. Taber K, Warden D, Hurley R. Blast related traumatic brain injury: What is known? *J Neuropsychiatry Clin Neurosci*. May 2006; 18 (2):141-145
8. Xydakis M, Casler J, Delwood. Analysis of battlefield head and neck injuries in Iraq and Afghanistan. *Otolaryngology head and neck surgery*. August 2004
9. Tien H, Farrell R, Macdonald J. Preparing Canadian military surgeons for Afghanistan. CMAJ. 2006; 175 (11):1365-1366
10. Mayo A, Kluger Y. Blast-induced injury of air-containing organs. ADF health. April 2006; 7:40-44
11. Minute by minute account. cnn.com. 11 May 2006
12. Elliott D, Bennett P. The physiology and medicine of diving 4th ed. Saunders. 1993; 245
13. Bellavia D. House to house. Simon & Schuster. 2007; 121
14. Fearful asymmetry. *The Economist*. 01 May 2008
15. 1 in 6 injured in Iraq, Afghanistan need treatment by Otolaryngologists. www.medicalnewstoday.com. 19 September 2004
16. Covey D. Blast and fragment injuries of the musculoskeletal system. *J Bone Joint surg*. 2002;84A (7):1221-34
17. Gawande A. Casualties of War- Military care for the wounded from Iraq and Afghanistan. *NEJM*. 2004; 351 (24):2471-2475
18. Gean A. Battlefield brain injury: the lessons from Iraq. medicexchange.com. 6 Dec 2007
19. www.britannica.com/EBchecked/topic/541996/Henry-Shrapnel
20. www.globalsecurity.org/military/world/russia/katyusha.htm
21. Dorland's illustrated medical dictionary. 2003; 30: 201-2 22. www.bordeninstitute.army.mil/published volumes/ophthalmic/ophthalmic.html
23. Stewart C, Nixon R. When Things Go Boom: Blast Injuries. www.fireengineering.com/articles/article_display.html?id=204602. 01 May 2004
24. www.defense-update.com/products/r/rpg-29.htm
25. Fennell K. Warrior brothers, my life in the Australian SAS. Random House. 2008; 221-234
26. Iraq coalition casualty count. icasualties.org. 03 Oct 2007
27. Robbins A. Tympanic-Membrane perforation as a marker of concussive brain injury in Iraq. *NEJM*. August 2007; 357 (8):830-831
28. Paquette E. Genitourinary trauma at a Combat Support Hospital during Operation Iraqi Freedom: The impact of body armour. *The Journal of Urology*. June 2007; 177 (6):2196-2199
29. Rosenfeld J, Rosengarten A, Paterson M. Health support in the Iraq War. *ADF Health*. April 2006; 7:2-7
30. Kragh J, Baer D, Walters T. Extended (16-hour) tourniquet application after combat wounds: A case report and review of the current literature. *J Orthop Trauma*. April 2007; 21 (4):274-278
31. Hirsh M. None braver: US Air Force pararescuemen in the war on terrorism. NAL Caliber. 2003; 7-8, 12, 14, 24, 161, 192.
32. Soldiers killed in car blast. *The Sunday Mail*. 18 January 2009; 47
33. Macy E. Apache: The man the machine the mission. *Harper Press*. 2008;31