The Impact of Blast Injury on Children

A Literature Review

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THE ROYAL BRITISH LEGION

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1 Glossary

Amblyopia	Eye that fails to achieve normal visual acuity
Apoptosis	Programmed cell death
Articular surface	Surface at the end of bones that form joints
Auditory cortex	Portion of the brain that interprets auditory input
Barotrauma	Injuries caused by increased air pressure on the lung
Cervical spine	Bones located in the neck. Spinal cord runs through it
Coagulopathy	Impairment of the blood's ability to clot
Depression	Low mood that affects thoughts and ability to function
Diaphysis	Shaft or central part of the long bone
Excitotoxicity	Over-activation of neurone receptors causing cell death
Fibrinogen	Protein required for blood clotting
Functional residual reserve	Air present in the lung at the end of expiration during normal breathing
Glasgow coma scale	Method of assessing an individual's conscious state.
Hair cell of the inner ear	Cells that transduce movement from sound waves to electrical signals
HE	High order explosives (e.g. Plastic explosive)
Hepatomegaly	Enlargement of the liver. Prolonged enlargement can cause impaired digestion, loss of energy, sepsis.
Heterotopic ossification	Soft tissue (muscle, ligaments) turning into hard tissue (bone)
Inotropic support	Medicines that alter heart action
International Classification of Disease (ICD)	International diagnostic tool for epidemiology, health and management
Interspinous ligaments	Ligaments connecting and stabilising spinal bones
Laryngeal oedema	Swelling of the upper airway. Can block the trachea
LE	Low order explosives (e.g. gunpowder)
Mediastinum	Central component of the thoracic cavity, including the heart and great vessels
Metaphysis	Portion of long bone containing the growth plate, which grows during childhood
Metabolic acidosis	Increased acid in the blood due to increased production of acidic substances
Middle ear ossicle	Small bones transmitting sound waves to inner ear
Neuroplasticity	Ability of the brain to reorganise neural connections
N-Methyl-D-Aspartate (NDMA)	Major receptor to neurotransmitters found in neurones
Optic nerve	Nerve transmitting visual signals from eye to the brain
Ossification	Laying down and remodelling of new bone
Periosteum	Layer of vascular connective tissue enveloping the bones
Pneumothorax	Air found within the pleural space (space between membranes of the lung)
Post-traumatic stress disorder (PTSD)	Anxiety disorder caused by stressful, frightening or distressing events

Pseudomonas aeruginosa	Opportunistic bacteria causing chronic infections in burn victims
Tissue factor	Protein released by damaged blood vessels
Traumatic axonal injury (TAI)	Tearing of connecting axons (pathways) in the brain
Tympanic membrane	Thin membrane transmitting sound waves to middle ear
Volutrauma	Injuries caused by over-distension (bloating) of the lung

2 Introduction

Children are not immune to the horrific injuries explosions inflict. While explosive exposure can occur from civilian sources such as fireworks or industrial accidents, the majority stem from conflict or terror related attacks across the globe (1,2). Despite an increasing recognition of the complex and unique patterns of injury sustained following blast exposure in the adult population (3), the physical and psychological impact on the paediatric population is less well understood.

For the purposes of this review, we define children as all humans under the age of eighteen years (as specified by the United Nations Convention on the Rights of the Child). The heterogeneity of these groups is acknowledged and most studies will further divide this group. These divisions differ and are somewhat arbitrary but can be approximated thus: <1 year are infants, 1-8 are young children; 9-15 are older children and 16-18 are adolescents.

It is essential to understand the epidemiology of blast injury within this overall group to demonstrate the effect of explosive weapons upon children and the burden that these injuries place upon both domestic and deployed health systems. Furthermore, insight into the mechanism of childhood blast insults will further efforts to prevent, mitigate, and treat these injuries (3,4). This review aims to provide an overview of the fundamentals of blast physics and injury and review how the injury patterns and biomechanical features of blast may differ between paediatrics compared to the adult populations. This will aid in defining future research needs for protection, mitigation, immediate medical treatment, and rehabilitation. This work is, of necessity, interdisciplinary and as such, covers material that is in both the biomedical sciences and engineering domains.

3 Blast physics

An explosive is comprised of a fuel, oxidiser and rapidly igniting material. Explosives are categorised based on their rate of oxidation (5). Low-order explosives (LE) rapidly burn or deflagrate, resulting in accumulation of product gasses if mechanically contained. Containment rupture allows a sudden release of over-pressure, seen in explosions. High-order explosives (HE) include unexploded military ordinance (UXO), improvised explosive devices (IEDs) and landmines, and produce internal high velocity shock-waves causing compression of the explosive material, therefore maximising subsequent gas expansion.

Rapid gas expansion produces a blast-wave of superheated, supersonic gases of exceptionally high-pressure. The theoretical pressure profile of a free-field explosion is classically described by the Friedlander wave form (figure 1).

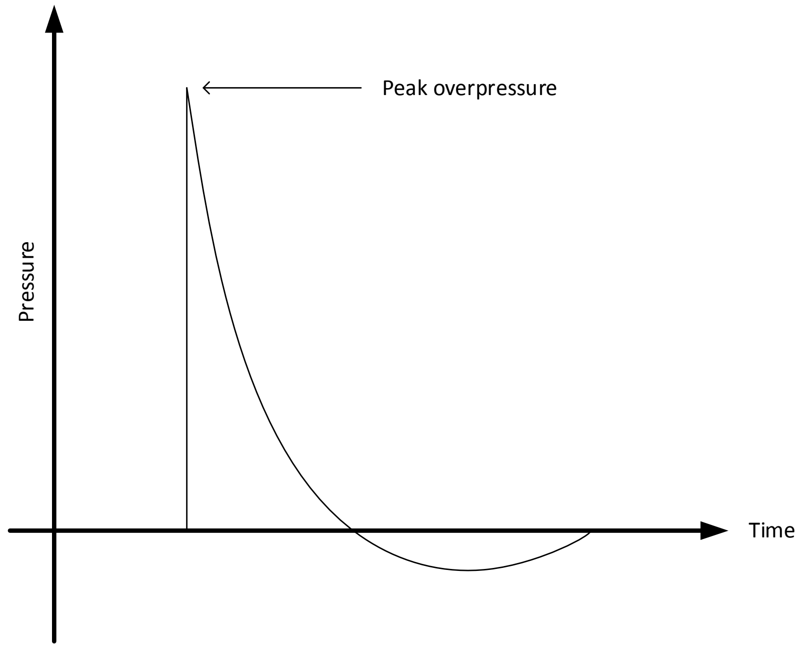

Figure 1: Simplified Friedlander wave form showing pressure changes over time in a free field explosion (6).

The peak positive pressure produced by the blast (blast-overpressure) is highly damaging to biological tissue (1). Subsequent decay of the pressure and transient negative pressure may cause a "push-pull" effect with increased movement of surrounding debris. This may account for some of the heavy tissue contamination typically seen in blast injury (7–9). Pressure variances result in rapid compression and re-expansion of delicate tissues, compounding subsequent injuries (10). Contact with superheated gases result in thermal burns, a major cause of mortality and morbidity in paediatric victims (11,12).

Complex interactions between the explosive, surrounding environment and the victim influence the blast-overpressure wave's ability to inflict injuries (10,13). These include distance of the victim from the blast epicentre, the relative impedance of the medium through which the blast travels (14,15) and the ability of the overpressure wave to reflect and amplify within a confined space (13). Beyond environmental factors, subtle changes to victim size and positioning result in clinically significant changes to energy loading within tissues, and subsequent anatomical distortion and injury (16).

Blasts produce a unique and devastating spectrum of injuries which differ from other forms of trauma, and are classically divided into primary, secondary, tertiary and quaternary blast injury (17). While this classification is useful for its simplicity in sub-dividing the principal harmful mechanisms within the blast injuries, the classification is based on Second World War data of open field bare explosives (18), and does not account for modern variations due to explosive type (Mine, IED, Suicide vest) or environmental factors (open-air, confined, buried). Furthermore, multiple mechanisms are normally involved, leading to overlap of injury types in the polytraumatised child (19). Nevertheless, the classification is a widely accepted theoretical model for understanding blast injury.

4 Blast injury mechanisms

4.1 Primary Blast Injury

Primary blast injury results from blast-overpressure damaging tissues through compression, expansion, spalling and shearing (10). Traditionally, primary blast injuries were thought to only impact air and solid tissue interfaces such as the lung, gastrointestinal tract, ear or sinuses (20). However it is increasingly recognised that blast overpressure may impact the brain, solid torso organs and musculoskeletal system. These organs are vulnerable to shearing stresses from overpressure waves accelerating the intrinsic heterogeneous tissue densities at different rates (21–23).

4.2 Secondary Blast Injury

Secondary blast injuries are due to the kinetic energisation of fragments from explosion (10). Fragmentation can be pre-formed (casing, shrapnel, ball-bearings, these are primary fragments) or environmental (soil, rubble, these are secondary fragments) and primarily has an antipersonnel effect (24,25). Fragmentation is the most common mechanism of blast injuries, capable of injury over large distance. There is consequently a high prevalence of penetrating injuries in children following blasts (25) compared to paediatric non-blast trauma (25% vs 10%) (26,27).

The lethality of fragmentation is dependent on direct penetration of vital structures. Fragmentation dispersion is indiscriminate and likelihood of fragmentation strike increased at shorter distances from the blast epicentre due to deviating trajectories (10). In a small standing child, the vital regions of the chest, neck and head will be closer to the epicentre of a buried explosive (mine, IED), increasing their respective fragmentation exposure. This may explain the increased incidence of thoracic, neck and head injuries in paediatric victims compared to adults (28) and increased requirement for operative procedures for these body zones (29).

The introduction of enhanced body armour to adult combatants provides partial protection from direct fragmentation strikes on the thorax, neck and head (30,31). Children are unlikely to receive this protection. Studies from Afghanistan showed high rates of fatal penetrating trauma in host-nation children when compared to deployed military forces, although the rate of injury in a comparable civilian (and un-armoured) adult group is unknown. It may be that explosion designed to maim in adults proves fatal in children (16,32).

4.3 Tertiary Blast Injury

Tertiary blast injury describes the spectrum of injuries sustained through bodily displacement or crush injuries. Blunt head injuries and fractures, similar to civilian trauma in circumstances not related to combat or conflict, dominate injury patterns, although at greater severity following blasts (10). Indeed, head injuries are the second most significant cause of mortality following blasts in the paediatric population (19). The relatively small body mass of paediatric patients increase their predisposition to bodily displacement and resultant blunt traumatic injuries (3). In addition to differences in size and shape, the tissues of injury have different material properties to adults. The mechanical behaviour of theses tissues in response to blast loading and impact may also differ. Paediatric bone has been shown to be less mineralised than adult bone. This reduction in ash content leads to a lower modulus of elasticity and lower bending strength such that a child bone will bend more than adult bone when subjected to the same force (33). The tendency of paediatric bone to absorb energy, bend more and deform plastically leads to the phenomenon of “greenstick” fractures. These are characterised by bending and unilateral fracture of the bone. This is in contrast to adult bone which fails and fractures completely following a lesser degree of bending (34). The potential of paediatric bone to absorb energy and deform has implications for musculoskeletal, head, and torso injury and will be discussed further.

4.4 Quaternary Blast Injuries

Quaternary blast injuries encompass the wide spectrum of injuries not addressed by the previous three classifications (10). These include burns, inhalational injuries, toxic exposure and psychological trauma. Burns are the leading cause of death in <15 year olds, and alongside head injury, the greatest predictor of death in all age groups (11,12). Psychological trauma is a complex and underreported issue following paediatric blast injury. Recognition of a biological component and long term morbidity underlying psychological trauma is increasing interest in this type of injury.

5 Blast injury characteristics in the paediatric population

While acknowledging that blasts produce a heterogeneous injury pattern within adult and paediatric populations, epidemiological studies demonstrate certain injury patterns within the paediatric blast cohort.

Multiple body regions are involved in 65-70% of paediatric blast patients (19,28), with burns and penetrating injuries to the extremities present in between 70-80% of paediatric patients (11,12,19,35). Penetrating injuries to the face, head, neck, upper limb and trunk affect 80% of paediatric patients, markedly higher than the 31% in adults (29,36).

Children experience a high injury burden following exposure to blast, as assessed by the injury severity score (ISS - a widely used consensus based measure of injury severity (37)). 20-36% experience ‘severe’ injury (ISS >15), while 8-18% are “critically injured) (ISS >25) (11,19,28,32). Older children had the greatest ISS and the highest number of surgical interventions when compared to younger children (<9 years old). Of these, wound debridement and closure was most commonly performed, corresponding with adult data (38), followed by vascular interventions and exploratory abdominal surgical incisions respectively, reflecting penetrating trauma as a major mechanism of injury (39). Procedures in adults were similarly ranked, although a lower proportion of the adult cohort underwent each with only 8.5% of patients over 19 undergoing a laparotomy in contrast to 12.3% of under 19s.

Edwards et al described an all-cause mortality rate of 8% in under 15 year olds in Afghanistan over an 8 year period, significantly higher than older demographics (1-3%) (11). In-hospital mortality was independently increased in children of 8 years or younger compared to all patients over 8 years. (18% vs 4%) (28).

Paediatric victims affected by blasts constitute a disproportionately large resource burden on treatment facilities (39–45). Approximately 56% of paediatric blast victims require surgery (19), twice the proportion of surgical procedures required for non-blast paediatric trauma (42).

Despite paediatric patients comprising only 5-15% of admissions to UK military medical treatment facilities (MTF) in Afghanistan in 2003, this demographic constituted half of operative procedures conducted, and occupied beds in both general surgical and ICU ward for approximately twice as long as adults (46). A US study collating data from Iraq and Afghanistan found that paediatric patients represented 6% of total admission yet accounted for 11% of bed days, while coalition troops represented 74% of admissions but only 53% of bed days (40). Of these paediatric admissions, 79% were trauma related, compared to 46% of adult deployed force admissions. This is likely to reflect that admission criteria for host nationals to a coalition medical treatment facility typically require threat to life, limb, or eyesight. Interestingly however, children with mild to moderate traumatic injuries as defined by ISS were three times more likely than adults to be admitted to ICU (32). This may reflect a lack of certainty in initial assessment of injury severity. Table 1 compares recent epidemiological studies of paediatric blast injury.

Study	Age group	n	Male (%)	Burns (%)	Penetrating injuries (%)	ISS >15 (%)	Head/Neck Injury (%)	Torso Injury (%)	Extremity Injury (%)	Mortality (%)
	<8	38	22(58)	-	24 (63)	15 (39)	-	-	-	7 (18)
Matos et al. 2008	>8	1094	1050 (96)	-	778 (71)	214 (20)	-	-	-	42 (4)
	<10	49	29 (59)	9 (18)	27 (55)	13 (27)	26 (53)	21 (43)	17 (35)	1 (2)
	11 -- 15	65	33 (51)	9 (14)	45 (69)	9 (14)	39 (60)	21 (32)	43 (66)	2 (3)
Jaffe et al. 2010	>16	723	463 (64)	106 (15)	472(65)	85 (12)	434 (60)	316 (44)	410 (57)	35 (5)
	<18	7505	5629 (75)	905 (12)	2113 (28)	-	-	-	-	638 (9)
Borgman et al. 2012	>18	121077	110943 (92)	-	-	-	-	-	-	4677 (4)
Creamer et al. 2009	<18	2060	1627 (79)	274 (13)	1172 (57)	-	505 (25)	486 (24)	789 (38)	142 (7)
Villamaria et al. 2014	<18	155	122 (79)	-	-	-	16 (10)	47 (30)	122 (79)	-
	<7	497	354 (71)	12 (2)	-	205 (41)	148 (30)	161 (32)	97 (20)	42 (8)
	8 --14	708	594 (84)	29 (4)	-	284 (40)	186 (26)	241 (34)	212 (30)	52 (7)
	15-20	617	550 (89)	19 (3)	-	201 (33)	118 (19)	178 (29)	210 (34)	25 (4)
Edwards et al. 2012	>21	3091	2814(91	127 (4)	-	1077 (35)	736 (24)	857 (28)	987 (32)	216 (7)
Waissman et al. 2003	<18	160	84 (53)	13 (8)	-	46 (29)	78 (49)	75 (47)	128 (80)	8 (5)

Table 1: Studies which describe paediatric injury patterns and outcomes following blast

In summary, children are likely to sustain multiple injuries, have an increased ISS and risk of death following blasts compared to adults. Burns and penetrating trauma are common and impart high morbidity and mortality, with consequent consumption of hospital assets likely to place considerable strain on medical treatment facilities. The precise mechanism by which these injuries occur is difficult to ascertain from such studies. Several studies do not discriminate between penetrating and non-penetrating injuries and, to our knowledge, no study has accurately described the incidence of primary blast injury upon a paediatric population. Large variations are seen in the injury patterns across different studies. This may be due to the use of different ordinance amongst a variety of conflict zones.

6 Injury specific considerations in Paediatrics

6.1 Thermal Burns

Thermal burns are a common injury following blasts, with prevalence ranging from 56-70% in paediatric patients regardless of age (11,46). Thermal energy release from blasts can result either directly from the explosion, through superheated gas production or by secondary fires igniting surrounding vehicles and buildings (47). Burn severity has been suggested as a prognostic marker for paediatric blast models and their respective outcomes (48), and severe burns exceeding 30% of the burn surface area are the principal cause paediatric deaths in under 15 years old (11,12,40).

Children are predisposed to increased burn severity (49). Anatomical disproportionality increases the lethality of certain burn patterns. A burn to the face and scalp of an adult comprise only 9% of the total body surface area (TBSA), not requiring IV fluid therapy, while the same injury in a paediatric patient translates to 19% TBSA, and necessity for fluid management (50).

Children younger than 2two years have reduced subcutaneous layers and skin thickness compared to older children and adults. Full thickness burns, and the resulting rapid fluid, protein and heat loss, can occur at relatively lower thermal energy levels. Consequently, assessment of clinical severity by burn depth has been shown to be less accurate in young children (51). Subsequent dehydration, nutritional deficiencies and hypothermia from full thickness burns increase morbidity significantly (49).

Thermal inhalation injuries in paediatric victims are difficult to assess, and clues to inhalational injuries such as increased respiratory rate may be incorrectly interpreted in the context of physiological age discrepancies. The paediatric subglottis represents the narrowest section of the upper airway, and deteriorates rapidly from burn-induced laryngeal oedema, especially in the context of failed intubation attempts (49). Rapid desaturation following upper airway obstruction occurs due to increased oxygen utilisation combined with limited functional residual reserve (52).

Burns are a multisystemic insult affecting not only the dermis, but the pulmonary, cardiovascular, inflammatory and metabolic systems (1). Insulin resistance, increased fracture risk, hepatomegaly, cardiac dysfunction, reduced immune function and hypermetabolic changes, common in burn patients, have been demonstrated to persist for up to three years following burn exposure in adults (53). Through impairment of wound healing, nutritional deficits and infection risk, these systemic alterations are associated with increased risk of hospitalisation, morbidity and mortality long after the initial insult (53–56).

Children are rarely left without functional sequelae, with limited joint mobility and impaired tactile sensation presenting significant future challenges for rehabilitation (57,58). Prolonged rehabilitation and visible aesthetic disfigurement can produce psychosocial morbidity long after the event (59). Nosocomial infection of the burn eschar, in particular from *Pseudomonas aeruginosa*, is greatly reduced by aggressive debridement and meticulous anti-microbial wound dressings (60). However, sub-optimal facilities, delays in wound cleaning and prolonged transfer times increase burn infection incidence (61).

A common conclusion arising is the requirement for sustained monitoring, treatment and rehabilitation of these at-risk patients. Long term recovery with good functional outcome is improved with early return to pre-burn activities and regular multi-disciplinary follow-up. (53,56). The degree to which these services are available within conflict zones and Lower to Middle Income Countries (LMICs) is uncertain. Ethical questions naturally arise when performing interventions where health systems are unlikely to address a child’s long term needs. Examination of existing paediatric burn services within zones of interest and longer term follow up of paediatric blast burn patients are required to determine the problems and needs for this cohort.

6.2 Head and Spinal Injuries

The reported prevalence of paediatric head injuries following blasts varies greatly between

15%-60% (11,32). Patients under 7 years are almost twice as likely to present with head injuries to older children (28% vs 15%) (11) and neurosurgical decompression is the most common surgical intervention overall in under 3 years olds (39). Blast-induced traumatic brain injury (bTBI) is more common in victims under 10 years of age compared to adolescents (32). Head and cervical spine injury was the second most common cause of death in all age groups (11), with one retrospective study conducted on post-mortem data noted skull fractures in 90% of paediatric patients who died (36).

There is a paucity of experimental and clinical data available into the pathophysiology of bTBI in the paediatric patients. Available data stems from adult studies into bTBI or paediatric non-blast TBI (nbTBI), such as following automotive accidents. While there is clinical overlap between bTBI and nbTBI resulting from severe blunt or repetitive low-impact head trauma, the underlying mechanisms are likely to differ (62,63).

The increasing survival of adults experiencing bTBI has prompted extensive research into this field (64), with effects of bTBI including a spectrum of injury, from mild to fatal injury (21). The mechanism of bTBI following primary blast injuries is still incompletely understood and often contradictory (22,65); the main experimental data originates from laboratory or computer models (22,66–69). The overall view is that the brain injury can occur following overpressure oscillations from the primary blast, penetrating fragments to the cranium from the secondary blast and blunt traumatic or coup-countercoup injuries from the tertiary blast injury mechanism (70). Post-mortem pathoanatomical data provides the majority of evidence for the pathophysiological effects of blast, which include oedema, contusions, vasospasm of the internal carotid and anterior cerebral arteries, diffuse axonal injuries and haematomas (71–75). Following blast, cerebral concussion is common, with increasing evidence of association with post-traumatic stress disorder (PTSD) (63,66,76,77).

Shear stress thresholds in cadaveric brain samples are increased by increasing skull thickness, reducing exposure of underlying structures to shear stress at higher accelerations (78,79). Studies have demonstrated that infants and young children undergo proportionally higher number of neurosurgical interventions following blasts compared to older children, adolescents, and adults, and younger patients are more likely to sustain bTBI (32,39), suggesting an underlying susceptibility. Anatomical immaturity in skull composition may increase risk of bTBI from the primary blast wave. The infantile skull is a thin structure, incompletely ossified at birth, possibly leading to greater shear stress and subsequent injury to the underlying brain structures (79). Reduced calvarium thickness is also likely to afford less protection from penetrating and blunt traumatic injuries following secondary and tertiary injury (78,80). Whilst the material properties of adult calvarium and suture are similar, the infantile calvarium is considerably stiffer than the infantile suture. Both are considerably less stiff than the adult skull. As a result, high rate loading of the immature skull causes much greater deformation prior to fracture. This deformation will apply greater proportional shear and compressive stress upon the underlying brain (81).

The relative compliance of the skull means that absence of skull fracture may prove a poor indicator of underlying brain injury (82). Traumatic axonal injury (TAI), commonly occurring within the basal ganglia, corpus callosum and periventricular white matter (83) is a commonly observed pathology following nbTBI and responsible for considerable morbidity (84,85). Animal studies have suggested increased susceptibility of TAI in blast due to increased transmission of shear stress through the skull of infantile pigs (86), potentially due to a similar mechanism.

It has also been suggested that following brain injury, paediatric patients are at greater physiological risk of brain injury from enhanced excitotoxicity and impaired cerebral blood flow. Excitotoxic effects may lead to increased neuronal apoptosis (87). Experimental data using paediatric neurones undergoing nbTBI demonstrated that extra-synaptic N-methyl-D-aspartate (NDMA) channels were excited, leading to increased calcium channel influx (88,89). Calcium influx is associated with pro-apoptotic phenotype of neuronal cells, enhancing intracellular cascades and neuroapoptosis (90). Furthermore, severe nbTBI in children has been associated with impaired cerebral autoregulation and subsequent poor outcome (91,92). In a later study, those under 4 years were found to be at risk of impaired autoregulation, regardless of nbTBI severity, suggesting enhanced susceptibility. This correlates with animal studies demonstrating prolonged reductions in cerebral blood flow in newborn pigs compared to juvenile pigs following diffuse nbTBI (93).

As significant cognitive, intellectual and functional sequelae arising from paediatric nbTBI have been described (94–99), there is a clear need for specific studies on the long term prognosis of paediatric bTBI. Controversy exists as to whether mild nbTBI is analogous to bTBI in adults (100), and the paucity of paediatric data means this comparison is even more problematic. Extrapolation of results from nbTBI suffer from differing follow up times, variation in paediatric ages, developmental milestones and the variability of mechanism of TBI. Early nbTBI data suggest paediatric patients benefit from increased neuroplasticity in the developing brain, allowing recovery of cognitive and intellectual function (94). However conflicting studies demonstrated reduced educational performance, increased impulsivity, hyperactivity and learning problems after 2 to 5 years in children with brain injury (95–98). A recent study by Shaklai et al (99) assessed 77 children of ages 2-17 over 10 years following moderate to severe nbTBI and found 69% were able to fully reintegrate back into regular education following extended duration of rehabilitation. The remaining 31% required additional help (19%) or special education (12%). Previous studies report reintegration of between 24-59% (101,102). Higher Glasgow Coma Scale at admission and shorter loss of consciousness correlate with a positive outcome, consistent with nbTBI studies (103–105).

Paediatric spine injuries are present in a modest percentage of children following blast injury (1-3%) (12,19), with its presentation being almost ubiquitously associated with concurrent head injuries (11). No blast specific paediatric spinal injury data exists, however, non-blast spinal trauma reveals the cervical spine receives between 60-80% of total paediatric spinal injuries (106), as oppose to adult cervical spine injury (15-45% of spinal injuries) (107–109). Thus in a paediatric patient, and a high degree of clinical suspicion is warranted. Prior to the age of 10, the relatively large head places the fulcrum of flexion and extension injuries at the upper cervical region, potentially increasing injury. Cervical spinal fractures are rare, while ligamental dislocations due to underdeveloped neck musculature, lax interspinous ligaments and incomplete vertebral ossification dominate. The absence of fractures may partially explain the high rate of spinal cord injury without radiographic abnormality (SCIWORA) in infants (17%) compared to adolescents (5%) (110). Neurological sequelae are highly dependent on the degree of spinal cord injury (SCI) sustained. While several reports have suggested children have reduced neurological sequelae compared to adults (111,112), a recent retrospective review found minimal recovery following complete and incomplete spinal cord injury (113). With intensive rehabilitation in developed healthcare systems, adult outcomes from paediatric-onset SCI demonstrate that 42-70% live and drive independently (113). A substantial unmet need for both long term health care and rehabilitation for those living with SCI has been described, even within higher income countries (114–116). SCI imposes a complex burden upon patients who commonly suffer with physical, psychological and reproductive needs. Rehabilitation and reintegration into the work or educational environment requires the input of a multi-speciality team. The availability of such a robust resource may be lacking in LMICs or disrupted in those with conflict.

Paediatric data from non-blast related trauma suggests an anatomical, physiological and developmental susceptibility to both head injury, TBI and SCI, both in the short and long term. However, given mechanistic differences, caution must be taken with translating data to the blast exposed child.

6.3 Torso injuries

Following blasts, chest and abdominal trauma is common, with incidence varying between 32%-50% and peaking in children aged between 5-10 years of age (19,32). Primary, secondary and tertiary blast injuries may impact the structures and viscera present in the chest and abdomen. A comparison to unarmoured adults (28) suggests that the torso is far more commonly injured in children following landmine and UXO explosion. This may be due to anatomical susceptibility or unintentionally high risk behaviour.

Primary blast lung injury (PBLI) is the most common fatal injury following exposure to overpressure waves (1). The air-tissue interface of the pulmonary system is vulnerable to spalling, compression and shear forces (10). Barotrauma and volutrauma leads to alveolar haemorrhage, pulmonary contusions and widespread oedema and pneumothoraces (1,31). Paediatric specific data on PBLI is lacking, with documented occurrences coming primarily from case series and reports (117,118). Pneumothoraces from blast injury are at increased risk of tensioning in infants due to the inherent mobility of the paediatric mediastinum, adding to additional mortality (52).

Abdominal injury following primary blast injury can be life threatening, resulting from compression and decompression trauma leading to separation of the mucosal layers, haemorrhage and infarction (119) and present days after initial insult (20). The delayed presentation necessitates repeated examinations and radiographic input, while communication and developmental milestones complicate assessment of the acutely unwell child, particularly by healthcare providers unaccustomed to dealing with this demographic (52). Children frequently swallow air when frightened or in pain, resulting in gastric dilation. As well as increasing vomiting risk, this may erroneously suggest abdominal injury (120).

While rarely seen in civilian paediatric trauma, vascular injury following penetrating trauma is significant in the blast patient (4% of total trauma surgeries compared to 0.3% in civilian centres) (121,122). The increased incidence of vascular torso trauma in paediatrics compared to adults (25% vs 12%) is likely to reflect the protection afforded by body armour. Vascular surgery to control haemorrhage following penetrating torso wounds carry a significant mortality of 71% in children (121) comparable to civilian vascular injury (123,124).

Blunt trauma is a significant mechanism for paediatric torso injury following bodily displacement (41). In the chest, incomplete ossification of the thoracic cage permits compression without bony fracture. Whilst this compliance confers partial protection from rib fractures and flail chest, the thoracic cage's compressibility allows blunt force transmission directly to underlying structures, thus increasing pulmonary contusion despite the absence of overlying rib fractures (120). Underdeveloped musculature and reduced subcutaneous fat in the abdominal wall provides reduced protection for underlying structures. The proportionally large size and close proximity of the liver and spleen increase likelihood of injury from penetrating or blunt trauma (52). While there is increasing consensus for conservative management of blunt abdominal trauma in paediatrics (125), laparotomies were the third most common surgical procedure performed on paediatric patients (39).

Penetrating torso trauma is far more common in children following blast exposure than in adult civilian trauma. Additionally, greater compliance of the child torso and proportionally larger abdominal organs may make them more susceptible to the high rate primary and tertiary blast loading.

6.4 Extremity injuries

Extremity injuries are one of the defining injury patterns observed in adult victims of explosive devices (126). In the paediatric population, the prevalence of extremity injuries vary greatly from 11-85% (19,32). Analysis shows these injuries to be highly age dependent, with only 11% of infants and 20% of children less than 7 years old experiencing limb injuries, contrasted with over 50% of older children (32). Younger children were at increased risk of upper limb injuries, while adolescents had predominantly lower limb injuries mirroring the adult population (29). Primary, secondary and tertiary blast injuries result in a spectrum of extremity wounds, including vascular injuries, long bone fractures and traumatic amputation. Vascular injuries to the extremities were more common than vascular torso injuries in <15 years old (66% vs 25%), and associated with lower mortality (25% vs 71%) (121).

Long bone fractures were present in 45% of paediatric patients (19), and more common in the upper limbs (36). The skeletal periosteum is highly active throughout the skeleton up to the age of four. Increased osteogenic potential aids fracture healing through callus formation, while malunioned fractures can remodel by 1^{o} per month (52). it is suggested (although not evidenced) that a thicker periosteum provides some protection from comminution, while producing buckle, greenstick and bowing fracture patterns (127). Immature bone contains a proportionally lower mineral and higher collagen content compared to adults. While the composition gives the immature bones enhanced elasticity relative to adults, there is reduced strength to the tensile and compressive forces typically seen following blasts, which may explain the high prevalence of fractures in this demographic. Immature bones continue to grow from metaphyseal plate. As the last area to ossify, the plate is vulnerable to injury; such injuries are associated with significant morbidity depending on the degree of disruption, including growth arrest leading to limb length discrepancies, reduced range of motion and deformity (128).

Traumatic amputation (TA) following blasts may occur through two mechanisms: diaphyseal stress leading to fracture, flailing of the joint and transosseous amputation or intra/periarticular stress leading to articular failure, flailing of the joint and through joint amputation (129). Prevalence of TA in paediatric patients varies from 11-31%, and were mainly of the lower limbs (36,39). Upper limb TA was commonly associated with upper torso, neck and head injuries, and rarely seen in survivors (130).

The long term physical, psychosocial and financial repercussions of amputation cannot be underestimated. Physical complications are greatest following TA and below knee amputations, and include anterior and varus bowing, heterotopic ossification and osseous overgrowth requiring future operative or prosthetic revision (52,131). Whilst the paediatric population is capable of considerable resilience to psychological and physical stressors (132), US data suggests depressive and anxiety symptoms are present in between 28-36% of children (133), with post-traumatic stress disorder impacting both the child and caregiver (134). Psychological maladaptation to disability is proportionally higher in adolescents undergoing TA compared to non-traumatic indications (e.g. malignancy) (135), possibly due to pre-amputation counselling. Social acceptance of the child amputee is culturally specific, with stigmatisation in certain cultures negatively impacting the childs' psychological, social and educational status (136,137). The requirement for physical, psychological and educational support is often prolonged, and the skeletal growth of children require multiple prosthesis changes (137). The financial burden of rehabilitation and prosthesis on the children and host country's health system is considerable, in the US on average equating to $116,000 until the age of 18 for a single lower limb amputation (138). There is a paucity of outcome and long term costing studies in LMICs, complicating assessment of unmet health needs (136). However, despite the addition of low cost prosthetics and community-based rehabilitation (139), the social and financial burden is likely to be considerable.

Extremity injuries are common following blast exposure in children (as they are in adults). Paediatric bones are more compliant and therefore less likely to fracture for an appropriately scaled insult. Injury to the growth plates may lead to long term growth disruption. Children are known to be resilient to amputation but expensive long term rehabilitation and regular prosthetic changes may be unavailable in LMIC. Complications of blast related amputation including heterotopic ossification and infection are likely to play a role in paediatric recovery but adequate follow up data is not to our knowledge available.

6.5 Eye injuries

Despite the eye comprising only 0.3% of the anterior body surface area, the eye is sensitive to injury and thus a prevalent injury seen following blasts (as great as 60% of blast casualties performing mine clearance operations) (12,36,140). Damage to the eye can result from overpressure waves reflecting off the bony orbit causing optic nerve and anterior/posterior segment disruption, secondary injury from fragmentation, tertiary facial trauma and chemical or thermal burns (141,142). Mine blast is thought to cause particularly high incidence of eye injuries due to its high directionality of the explosive particles towards the face in children (140,143,144). Like torso and upper limb injuries, the curiosity of children may predispose them to facial and ocular injuries.

Vision loss confers significant long term morbidity in children. In infants, visual processing plasticity and binocular vision develop in the first year of life. Monocular visual impairment can lead to further morbidity through amblyopia and visual defects (145,146). Without adequate social support, developmental and educational deficiencies occur. Indeed 75% of early learning occurring through vision, and visual impairment will translate to future social and economic challenges to both the individual and society (145,147).

6.6 Otologic injuries

Hearing loss following blast exposure is the most prevalent primary blast injury (148,149) persisting well after the initial insult, with 55% of adults and child victims of the 2005 London bombings experience dysfunction after four weeks (150). Blast overpressure exceeding 104 kPa, approximately 1/5th the pressure required for lethal injury, damages the air-tissue interface of the tympanic membrane with a 50% chance of membrane rupture, middle ear ossicle damage and subsequent conductive hearing loss (151,152). Sensorineural hearing loss is normally permanent, and occurs following excessive mechanotransduction of pressure to the sensitive hair cells of the inner ear, or through bTBI damaging the auditory cortex (152).

Auditory input is essential to early development of language, literacy and social development (153–155) and paediatric hearing deficits are associated with poor outcomes in these parameters (153,156). The cost of hearing aid maintenance, healthcare follow-up and tailored education often exceed the host countries ability to finance (157–159). Children suffering hearing impairment are therefore vulnerable to academic and social underachievement, impacting future employment opportunities while predisposing children to psychological morbidity including depression and social isolation (160–162).

6.7 Physiological considerations

Children are remarkably resilient to extreme traumatic insults resulting from haemorrhage, maintaining systolic blood pressure despite loss of 30-45% of circulating volume (163); however, certain physiological insults are associated with increased mortality in this population. Catastrophic haemorrhage from penetrating injuries is the primary cause of preventable death in both children and adults following blasts (38,164). Although children are somewhat different physiologically, basic physiological parameters may act as prognostic indictors of trauma outcome. A retrospective review by Matos et al on 1,132 patients following penetrating trauma compared prevalence of physiological derangement in children under 8 who went on to die compared to those who survived. Children who died were more likely to have hypotension (22% vs 4%), tachycardia (65% vs 39%), hypothermia (53% vs 18%), as well as an elevated base deficit, low pH and GCS ≤8 (28) . Similar variables are prognostic within the adult penetrating trauma cohort (165).

Decreased total circulating blood volumes in young paediatric patients accentuates bleeding severity and likelihood for hypovolaemic shock, supported by the increased prevalence of base deficits and acidosis in those paediatric patients died. 14%-17% of paediatric patients injured by blast were likely to require a blood transfusion, compared to 10% of children traumatically injured through non-blast mechanisms (11). Paediatric patients requiring over 40ml/kg of blood products were also more likely to have suffered a blast injury, have a higher ISS, be clinically shocked and die in the first 24 hours (166). A separate study found 6.3% required massive transfusions (>10 units of blood), and 14% required ionotropic support (43).

Refractory coagulopathy following trauma would seem to be a major cause of deaths in the first 24 hours in both adults and children (26,167), due to an initial hypercoagulability followed by a consumptive hypocoagulable state and haemorrhagic shock (168,169). Increasingly recognised is the role of blast specific mechanisms and the now well-recognised multifactorial processes involved in trauma-induced coagulopathy (TIC). In porcine models, a pure primary blast wave prolonged hypercoagulopathy when not complicated by haemorrhage (169). While interesting, its clinical applicability is debateable in the polytraumatised child where haemorrhage is invariably involved (170). Infants under 12 months have reduced fibrinogen reserves; with 52% developing hyperfibrinogenaemia following trauma (171–173) although specific data for blast has not been examined.

Amplified tissue factor release leading to a consumptive coagulopathic picture has been associated with TBI (174,175). With head injuries prevalent in paediatric blast victims, this may be an interesting aetiological factor to consider in TIC development (167).

Predisposing factors to the development of TIC include iatrogenic dilution, hypothermia, acidosis, platelet dysfunction and exaggerated fibrinolysis (171). Children are vulnerable to hypothermia due to increased surface area to mass ratio and high metabolic rate. Furthermore infants have an immature thermoregulatory system meaning inability to mount a shivering response. Increased non-shivering thermogenesis in response to cold increases glucose and oxygen consumption and anaerobic metabolism, risking hypoglycaemia and anaerobic metabolic acidosis, and worsening TIC (176).

The implications of these complex blast related physiological challenges are daunting within a well-equipped trauma facility or field hospital. Resuscitation strategies for battlefield trauma in adults has evolved considerably over recent years with a shift in the use of blood products (177,178), whole blood (179) and antifibrinolytics such as tranexamic acid (180). The role of these strategies for paediatric trauma has not been extensively investigated although Tranexamic acid has been shown to convey similar benefits within a small paediatric trauma cohort (181). Development and performance of novel resuscitation strategies within LMIC is undoubtedly challenging given the need for robust supply chains, a suitably large blood pool and thorough screening process.

6.8 Psychological considerations

Blasts subject children to feelings of uncertainty, insecurity and terror by disrupting the child's basic assumption of safety and security (182). These emotions can occur through direct exposure where children are directly affected, interpersonal exposure where there is loss of a loved one and second-hand exposure through the climate of fear and perceived threat from others (183,184). These disrupt daily routines and stability, leaving the child vulnerable to developmental and psychological disorders (184). The child's ability to adapt to the aftermath of the traumatic event is highly dependent on their perceived level of social support, primarily from family and school (185). The loss of carers and friends may therefore not only expose the child to educational, financial and social morbidity, but trigger pathological mourning leading to depression, anxiety and behavioural problems (186,187).

PTSD was the most common presentation in children (186) followed by internalising symptoms including depression, anxiety and agoraphobia (188–190). Studies investigating the prevalence of externalising symptoms such as behavioural disorders and substance abuse are lacking despite being well documented in adult responses to traumatic events (191,192). Evidence suggests both internalising and externalising symptoms exhibit an exposure-response relationship, with greater exposure resulting in increased psychopathology (183,189). While PTSD was most frequently encountered, only a limited number of studies have investigated non-clinical consequences of mental health disorders (184,193). However, these have demonstrated a high prevalence of psychosocial difficulties, including at home and school (190,193). Children are less likely to self-present and talk about the traumatic experience, increasing the likelihood of being overlooked with unmet needs (194). Regression habits can arise in response to stress and pain, manifesting social, behavioural and educational reclusion in older children (195).

Pathological responses following blast exposure should be considered against what constitutes a normal response to this emotionally stressing event (196). Children are capable of remarkable resilience to psychopathological problems, with the majority able to recover from terror exposure (including explosions) with minimal and transitory effect on their functionality (197–199). Assessing the functional impact, however, is complex and dependent on the child's age, developmental stage, sex, social and support framework (200). There is a need for individualised appraisal of psychological symptoms in the heterogeneous cohort that children represent, and long term studies into the social and educational morbidity arising from exposure to the traumatic event that blasts represent.

Psychological support systems within LMICs may not be adequate. In addition to the ability of a local healthcare system to accommodate such services, cultural variations in the attitude towards psychological health may impact on the desire to seek or deliver help.

7 Challenges remaining in paediatric blast injury management

Article 3.3 of the UN Convention on the Rights of the Child (UNCRC) states that medical care of the child be delivered and supervised by providers competent in that field (201). However, paediatric care in conflict zones is often delivered by personnel with whom paediatric experience is unusual or not mandated (202). Historically, paediatric specific training was viewed as 'mission creep' beyond the primary role of MTF's, whose services were tailored to the military population. As such, many providers lacked confidence in management of children (203). However, increasing recognition of the significant workload and unique challenges presenting in paediatric patients has highlighted the need for further training (39,43,202). Indeed, incidences of deployed UK medical services urgently requesting acute paediatric textbooks to be delivered were not uncommon in the early stages of Operation Herrick in Afghanistan, emphasising the unique demands and training gaps with this demographic (204). Paediatric training is now incorporated into pre-deployment simulations of UK forces, in addition to increase availability of paediatric specific medical equipment and guidelines (43).

One of the key challenges is providing sustainable health services in the host country. MTFs may be capable of delivering exceptional paediatric care in the acute phase following blasts, but recovery from morbidity is dependent on long term rehabilitation (205) normally provided by host country services. Not only can this place exceptional strain on local health authorities, but if provisions are not available, the child is likely to undergo a protracted decline (202,205). While clearly an emotive subject for those directly involved, consideration of the host country's ability to support the child's long term recovery is essential. Furthermore, delivery of advanced medical management can distort the local health structure, leading to reliance on services provided by foreign sources and subsequent service gaps once the foreign aid departs (205).

Limitations of available data regarding paediatric considerations in blast injuries are multifactorial. Most of the recent blast injury data is acquired by deployed military services. These services may only admit local children with life threatening or changing injuries where beds are available This leads to a selection bias towards the most severely injured children (41). Furthermore, study data are mainly collected from combat support hospitals and may not include children who failed to reach these hospitals, either through death or triaging to alternative hospitals. Those children who are admitted and treated by deployed military systems are unlikely to be followed up by the same system beyond discharge. Where civilian data was available it was incorporated in this review. However the problem of disjointed data collection has been recognised, with studies suggesting only 30-40% of total morbidity is recorded (25). Finally, the characterisation of injuries utilised the International Classification of Disease (ICD). While useful for standardisation of injuries, it is liable to capture incorrectly the varied spectrum of injury, unique following blasts. The result of these combined issues may be an under-representative sample of paediatric injuries following blasts.

A recurring theme when exploring long term challenges of blast injuries in children is that of follow-up. Children are a complex cohort to monitor with geographical displacement, particularly in the context of a conflict, and are liable to being lost to follow-up. This can impact not only the child's rehabilitation and coordination with local health authorities, but also causes difficulty in assessing long-term functional outcomes which are needed to detect future health needs (206). Increasingly there is recognition of the need for formalised trauma registries accessible in the host country, assisting the follow-up of this vulnerable demographic (39,41,207,208).

8 Conclusion and recommendations

This review highlights key deficits in the long-term follow-up and rehabilitation of this vulnerable population. Children differ physiologically, anatomically and psychologically from adults in their biological responses to injury. While children remain the unintended victims of explosive injuries, age specific research into the effects of blast injuries are urgently required. Recurrent themes are the lack of long term follow up for blast injured children and the difficulties in translating any lessons learned to the health systems of LMICs.

Specific knowledge gaps and recommendations include:

- The establishment of robust registries for paediatric blast. The ideal registry would include a detailed examination of incident information (including explosive type and scenario), all injuries, physiology, and management. Follow up would include in-hospital journey (including complications and mortality) and long term data to include physical, psychological, and educational recovery.
- The establishment of ongoing research trials using the above registries to establish evidence based treatments.

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