

Mediastinal injury is the strongest predictor of mortality in mounted blast amongst UK deployed forces



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ABSTRACT

Background: Blast injury has been the most common cause of morbidity and mortality encountered by UK forces during recent conflicts. Injuries sustained by blast are categorised by the injuring component of the explosion and depend upon physical surroundings. Previous work has established that head injuries and intra cavity haemorrhage are the major causes of death following exposure to under body (mounted) blast but has yet to explore the precise nature of these torso injuries nor the effect of particular injuries upon survival. This study examines the patterns of torso injury within the mounted blast environment in order to understand the effect of these injuries upon survivability.

Methods: This retrospective study examined the UK Joint Theatre Trauma Registry to determine precise injury patterns of mounted blast casualties within a 13 year period of UK military deployments. Survival rates of individual injuries were compared and a multivariable logistic regression model was developed in order to assess the effect that each injury had upon likelihood of death.

Results: 426 mounted casualties were reviewed of whom 129 did not survive. Median NISS and ISS for non-survivors was found to be 75. Torso injuries were significantly more common amongst non-survivors than survivors and high case fatality rates were associated with all haemorrhagic torso injuries. Multivariable analysis shows that mediastinal injuries have the largest odds ratio for mortality (20.4) followed by lung laceration and head injury.

Conclusions: Non-compressible torso haemorrhage is associated with mortality amongst mounted blast. Of this group, mediastinal injury is the strongest predictor of death and could be considered as a surrogate marker of lethality. Future work to link blast loading characteristics with specific injury patterns will inform the design of mitigating strategies in order to improve survivability of underbody blast

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Introduction

Recent military campaigns in Iraq and Afghanistan have seen the emergence of blast as the predominant mechanism of wounding and mortality [1].

Injuries caused by blast are dependent upon the surrounding physical environment. Marked differences are seen in the primary blast loading characteristics between explosions occurring within an enclosed space and in a free field due to reflection of waves and prolonged period of increased pressure [2]. Further differences in injury pattern are seen in response to explosions immediately

adjacent to enclosed spaces, in which the occupant is relatively protected from the primary blast wave but still subject to high rate loading. This loading environment does not conveniently fit within the classical description of tertiary blast and is best described as solid blast. This injury pattern is typified by vehicular under body blasts.

Specific injuries have been described in response to under body blast (UBB) loading. Characteristic calcaneal injuries (so called “deck slap”) are associated with poor functional outcome [3] and have influenced biomechanical research strategy [4]. Spinal injuries sustained due to UBB are of a unique distribution and may not be adequately described by current mechanical criteria [5,6].

Differences in blast mortality between mounted (in-vehicle) casualties and dismounted (on-foot) casualties within a UK military cohort were described by Singleton et al. [7]. A greater number of body regions were injured within the mounted group

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and can be attributed to solid blast. The likely cause of death within each group differed significantly. Within the dismounted group, extremity and junctional haemorrhage was the predominant cause of death. The dismounted complex blast injury pattern is well recognised with consideration required for the treatment of potentially devastating, abdominal, pelvic, perineal, and genito-urinary injuries along with proximal traumatic amputation [8,9]. Within the mounted group, head injury (50%) and intra-cavity haemorrhage (20%) were leading causes of death. Further examination of the torso haemorrhage group was not undertaken within this study.

Bleeding may be broadly classified into compressible haemorrhage (which is amenable to manual compression or tourniquet application) and non-compressible haemorrhage which due to anatomical position may not be manually controlled. Several studies have demonstrated poor outcomes from non-compressible torso haemorrhage (NCTH) within both UK and US military populations [10,11]. Explosions accounted for the majority of injuries within these groups although were not further specified as mounted or dismounted. Within the UK military population, NCTH was associated with 85.5% mortality with the majority of deaths occurring prior to reception at a medical treatment facility [11]. As such, improvements in outcome are likely to be achieved by prevention or mitigation, rather than improvements in treatment.

Mitigation of injuries within the under-body blast environment is dependent upon characterising the relationship between the output of the explosive device and resultant loading upon the vehicle and occupant. The precise mechanism by which torso injuries and NCTH occur within this environment is not known. Therefore the objective of this study was to examine the injuries of mounted blast casualties in order to define the pattern of non-compressible torso haemorrhage and demonstrate the effect of these injuries upon outcome.

Further work will seek to link specific underbody loading characteristics with these injuries.

Methods

With the permission of the Medical Director (Defence Medical Services), and with the aid of the Clinical Information Exploitation team (CIET); the UK Joint Theatre Trauma Registry (JTTR) was

interrogated. The UK JTTR is a prospectively collected trauma database of every UK military casualty admitted to a medical facility or killed on deployed operations, and includes details of any surgery prior to death. In the case of fatalities, a military research nurse attends the formal autopsy performed once the body has been repatriated to the UK. The pathologist's findings are coded using Abbreviated Injury Scale (AIS) 2005-Military [12] and then entered into the JTTR.

Search terms included:

- operations in Iraq and Afghanistan 2003–2014;
- UK military personnel only; and
- explosive injury

The resultant number of cases was reduced by excluding explosive mechanisms other than underbody IED or mine. Injury severity was used as a further exclusion criterion. Any cases with no injuries graded AIS 2 or above were excluded since this implies very minimal injury.

Both Injury Severity Score [13] and New Injury Severity Score [14] were compared for each group. Both systems compile an overall score based upon three most severe AIS coded injuries. The ISS is based on the three most severe injuries from different body regions, NISS allows these injuries to arise from the same region.

The JTTR record was further interrogated for incident data, notably the location of each casualty. All in-vehicle casualties were grouped together as mounted, those on foot were described as dismounted. In-vehicle casualties were not separated by vehicle type for this study in order to avoid describing classified vehicle data.

The mounted group was split into two groups for the purpose of analysis, survivors and non-survivors. Non-survivors include both Killed in Actions (KIA) and Died of Wounds (DOW).

In order to describe the effects of individual injuries upon outcome, all injuries were examined and placed within one of 49 organ specific injury categories. The prevalence of torso injuries within outcome groups were compared.

All statistical analysis was performed using SPSS software (V24, IBM, New York, USA). Categorical data was analysed using chi-squared and Fisher's exact test depending on sample size. Mann-

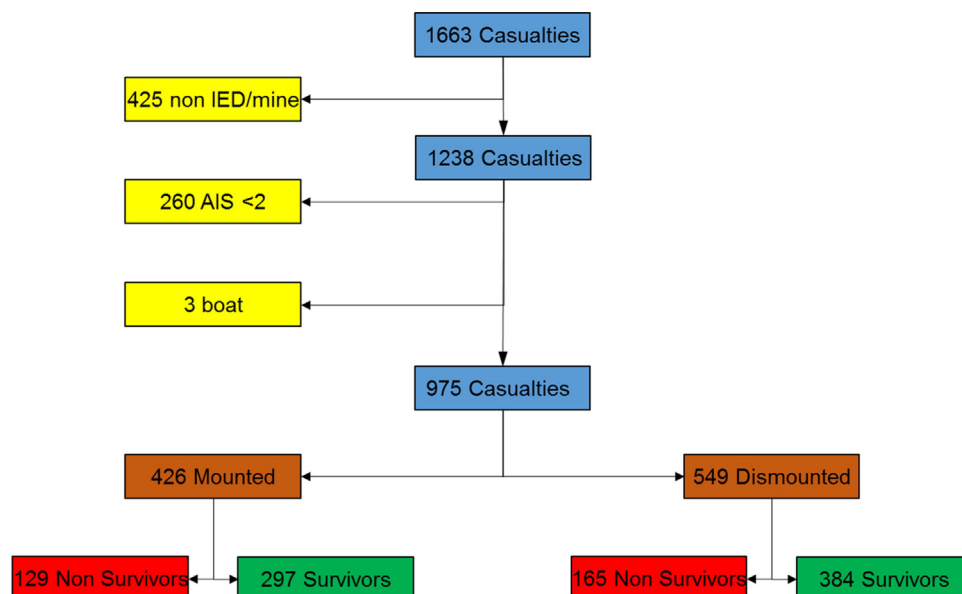


Fig. 1. UK Military Blast Casualties 2003–2014.

Whitney *U* tests were performed for non-parametric continuous data.

In order to account for multiple injuries, a logistic regression model was constructed in which mortality was the dependent factor. In order to include them within the model, less common injuries, or injuries with only one outcome were grouped together. The mediastinal group includes aortic, cardiac, and other great vessel injuries. Presence or absence of NCTH injuries along with head injuries were listed as categorical independent factors

Given the lack of understanding of injury mechanism, chest wall fractures (rib or sternum) were included within the analysis as a possible marker for direct contact injury.

Results

The search parameters including exclusions and eventually included sample is shown in Fig. 1.

Demographic data is shown in Table 1. No significant difference was found in age between the two groups. Males accounted for the vast majority of casualties in both groups. A significant increase ($p < 0.001$) is noted in the proportion of survivors between operations in Iraq and Afghanistan. As expected, differences are seen in the injury severity of survivors and non-survivors.

The distribution of NISS amongst the mounted cohort is shown in Fig. 2. The maximum NISS of 75 has been sustained within the majority of the non-survivors, whereas a greater spread of lesser NISS is found amongst the survivors.

Non-compressible torso haemorrhage was defined in this study as injury to the heart, named blood vessel, or solid organ, in addition to haemothorax or lung laceration. These results, along with Case Fatality Rates (Non-survivors/total cases), a measure of injury lethality, are shown in Table 2.

Overall, NCTH was significantly more common in non-survivors ($p = < 0.001$) with 63% of non-survivors having sustained some form of NCTH and only 11% of survivors having sustained an NCTH injury. Multivariable logistic regression modelling was constructed to examine the relative effects of all injuries upon mortality and to allow for association of variables. Odds ratio of mortality was calculated as the exponent of *B*, the regression coefficient. The results of this analysis are shown in Table 3.

All injuries analysed have odds ratios greater than 1 and are associated with mortality. Mediastinal (including heart, thoracic aorta, SVC, and pulmonary vessel) injuries are the strongest predictor of death. Of this group, heart and aortic injuries predominated. Head injury account for the largest proportion of deaths but remains a weaker predictor of mortality.

Discussion

This study is the first to describe in detail the pattern of torso injury due to mounted blast casualties and the influence of particular injuries upon survivability. Previous work has highlighted the importance of non-compressible torso haemorrhage but has

not highlighted the importance of this injury complex due to a specific blast threat. Defining cause of death for service personnel killed in action is a difficult process and relies to some degree upon conjecture. The utility of the logistic regression model is to take into account all injuries sustained and the effect that a particular injury has upon mortality. A *p* value of greater than 0.118 and area under the ROC curve of 0.854 suggest a good fit for the model. Confidence intervals are wide, particularly for the effect of mediastinal and lung lacerations; these reflect the relative small numbers, particularly within the survival cohort.

Significant differences are seen between mortality rates in Iraq and Afghanistan. This may represent changes in vehicle use but may be related to use of different weapons. The use of Explosive Formed Projectiles, designed with the intention of defeating armoured vehicles, were more prevalent during the Iraq conflict [15].

Whilst head injuries have been documented as the most common cause of death, they were not found to be the strongest predictor of mortality. Thoracic aorta and heart injuries are the most statistically lethal injuries within this cohort. Chest wall injuries were also seen to be a significant indicator of mortality although similar injuries have been noted within experimental models of underbody blast and are not necessarily indicative of direct torso trauma [16].

These injuries do not occur in isolation and their statistical significance may be more useful as a measure of the total loading. The delineation of these injuries as measures of energy is perhaps more useful than a conventional injury score within this cohort. Both ISS and NISS have limited utility in the description of injury severity above a prescribed severity, given that any non-survivable injury results in a maximum score. Saturation of the scale by an AIS 6 injury means that these scores are not descriptive of the overall injury burden and are poor discriminators of survivability. This statistical model is useful in determining the effects of individual injuries upon survival amongst a cohort who have sustained extensive polytrauma.

Morrison and Rasmussen [17] examined the incidence of NCTH within UK forces over a recent 10 year period and identified that 75% of those with this injury pattern were killed in action. Whilst the majority of these injuries were attributed to explosions, there was no detailed study of the injury mechanism. The authors proposed that mitigation strategies for head injury are important, but mitigation and prevention of torso injuries were not considered. Morrison and Rasmussen [17] included evidence of physiological compromise within their definition of NCTH but excluded mediastinal injuries. This approach may be valid when examining cases amenable to surgical intervention but less so for determining mechanism of injury and the potential for improving survivability of blast events

Cardiac and great vessel injuries are already known to have poor outcomes. They have been described as unsurvivable within the combat setting [18]. This study is the first to identify the importance of these injuries within the underbody blast setting. By examining the lethality of individual injuries, we have sought to identify targets for future experimental research.

It is hypothesised that these injuries arise due to high rate axial loading and generation of inertial stress within tissue and tissue interfaces. The importance of aortic injuries as markers of survivability is already described within an automotive context in which these injuries are seen within only 0.06% of incidents but account for 11% of deaths [19]. The aetiology of aortic injury typically seen within road traffic collisions is still uncertain but is likely multifactorial and dependent upon chest impact causing craniad displacement of the heart with possible potentiation due to intraluminal pressure changes. [20]. These mechanisms are however dependent upon direct frontal or lateral impact.

Table 1

Demographic data and trauma scores for mounted UK blast casualties.

		Survivor 297	Non-Survivor 129	<i>p</i>
<i>n</i>				
Male, <i>n</i> (%)		293 (98.7%)	126 (97.7%)	0.359
Operation	Iraq, <i>n</i> (%)	27 (44.3%)	34 (55.7%)	
	Afghanistan, <i>n</i> (%)	270 (74.0%)	95 (26.0%)	<0.001
Age		24 (21–29)	24 (21–29)	0.987
Injury Number, median (IQR)		4 (3–8)	14 (7–23)	<0.001
Injury Severity Score, median (IQR)		9 (5–17)	75 (75–75)	<0.001
New Injury Severity Score, median (IQR)		12 (8–22)	75 (75–75)	<0.001

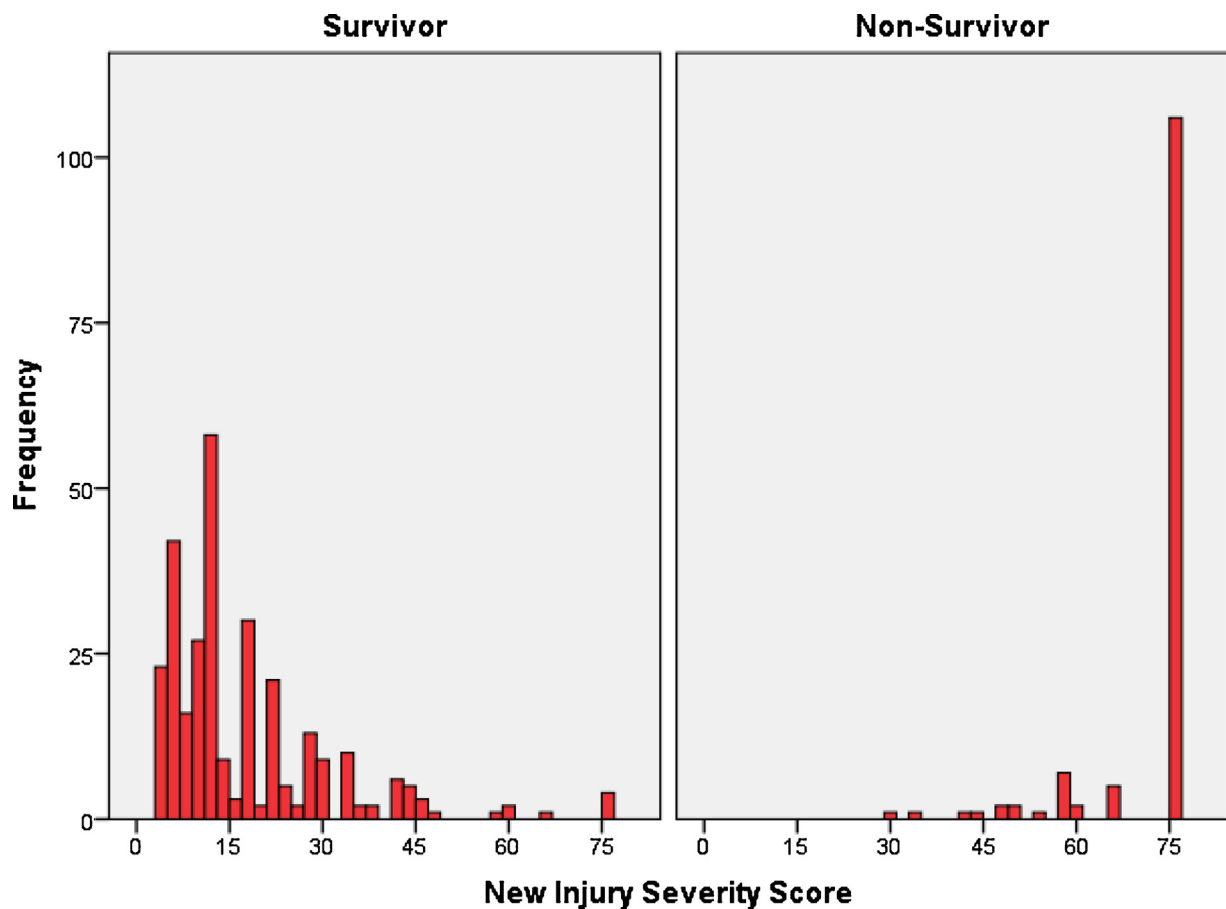


Fig. 2. Histogram showing NISS (New Injury Severity Score) of mounted blast casualties.

Table 2

Torso injury patterns of mounted casualties. (CFR – case fatality rate).

	Survivor (n = 297)	Non-Survivor (n = 129)	CFR	p
Cardiac Injury	1 (0.3%)	31 (24.0%)	96.9%	<0.001
Thoracic aorta Injury	0	17 (13.2%)	100.0%	<0.001
Pulmonary artery Injury	0	1 (0.8%)	100.0%	0.303
Pulmonary vein Injury	0	4 (3.1%)	100.0%	0.008
SVC injury	0	2 (1.6%)	100.0%	0.091
Haemothorax	8 (2.7%)	32 (24.8%)	80.0%	<0.001
Pneumothorax	11 (3.7%)	2 (1.6%)	15.4%	0.192
Lung Contusion	20 (6.7%)	34 (36.4%)	63.0%	<0.001
Blast Lung	10 (3.4%)	13 (10.1%)	56.5%	0.006
Lung Laceration	2 (0.7%)	24 (18.6%)	92.3%	<0.001
Other Thoracic Vascular Injury	1 (0.3%)	4 (3.1%)	80.0%	0.031
Liver Injury	6 (2%)	53 (41.1%)	89.8%	<0.001
Splenic Injury	16 (5.4%)	47 (36.4%)	74.6%	<0.001
Kidney Injury	3 (1.0%)	35 (27.1%)	92.1%	<0.001
Abdominal Aorta Injury	0	2 (1.6%)	100.0%	0.091
IVC Injury	0	2 (1.6%)	100.0%	0.091
Other Abdominal Vascular Injury	3 (1.0%)	19 (14.7%)	86.4%	<0.001
GI Injury	8 (2.7%)	33 (25.6%)	80.5%	<0.001
Rib/Sternal Fractures	19 (6.4%)	70 (54.3%)	78.7%	<0.001
Head injury	43 (14.5%)	81 (62.8%)	65.3%	<0.001

The degree to which pure axial loading will contribute to visceral injury is disputed [21] but has been demonstrated in previous experiment models. A canine model of rapid headwards [22] deceleration produced aortic injury amongst a small sample size. Hanson suggested an inertial mechanism in which the cardiac mass displacement generated sufficient tension within the aorta to

cause injury. Heart injury (as well as lung injury) has also been generated within a primate model of axial loading [23] utilising a drop testing device. Injuries to the stomach, liver, gallbladder, and heart are described following rapid buttock first deceleration in black bears [24].

Table 3

Logistic regression showing effect of injuries upon mortality within mounted blast casualties. OR = Odds Ratio, SE = Standard error. Mediastinal injury includes cardiac, thoracic aorta, pulmonary vessels and SVC injury. Pelvic includes pelvic fracture. GI injury includes upper and lower GI injuries. Abdominal vascular includes abdominal aorta, IVC and other named vascular injury.

Injury Type	B	S.E.	Sig.	OR	95% CI for OR	
					Lower	Upper
Mediastinal	3.02	1.29	0.019	20.38	1.63	254.60
Lung Laceration	2.43	0.98	0.013	11.39	1.68	77.38
Head	1.96	0.33	0.000	7.07	3.73	13.42
Rib/Sternal fractures	1.06	0.33	0.002	2.89	1.50	5.56
Pelvic	1.04	0.43	0.016	2.83	1.21	6.60
GI	1.02	0.67	0.126	2.78	0.75	10.32
Abdominal vascular	0.95	1.05	0.365	2.58	0.33	20.05
Kidney	0.84	0.74	0.259	2.31	0.54	9.92
Liver	0.83	0.65	0.200	2.30	0.64	8.24
Lower limb	0.45	0.32	0.168	1.56	0.83	2.94
Blast Lung	0.46	0.62	0.456	1.58	0.47	5.29
Spleen	0.19	0.63	0.767	1.21	0.35	4.15
Lung Contusion	0.11	0.44	0.811	1.11	0.47	2.63

Hosmer-Lemeshow test 10.156, $p=0.118$, $df=6$, area under ROC = 0.854.

We propose that the severe torso injuries sustained during underbody blast events are at least partly attributable to pure axial loading. Whilst all of the injuries within the analysis are potential targets for further study, mediastinal injuries are the most lethal and perhaps a suitable marker of absolute unsurvivability.

There are limitations to this study. The data was prospectively maintained, but has been retrospectively interrogated. Although KIA and DOW groups have been combined for the purposes of this analysis, it is important to note that all deaths within the mediastinal group occurred prior to any medical treatment.

The incident data has also been reviewed to ascertain blast conditions. The data was interrogated to only include underbody IED blasts events but there may be a variable amount of estimated vehicle flight and roll over between vehicle classes along with variation in explosive device. It is likely that the initial IED strike and axial load would have been the most energetic insult, it is difficult to discount the involvement of other forces as the cause of injury.

There are also limitations to the statistical analysis of this data. Logistic regression allows an estimation of effect size from particular injuries but confidence intervals for the relevant odds ratios are wide. These wide intervals reflect the relatively low numbers of certain injuries. Additionally, precise coefficients and odds ratios generated by the regression differ slightly depending upon the included factors and there is no set limit or guidance regarding the optimal number of included groups.

Further work must investigate the relationship between high rate axial loading and visceral and vascular injury. The aorta is recognised as a target for biomechanical study but physical and experimental models of aortic injury [25–27], have all been developed with regards to frontal and lateral automotive impact. This previous work includes detailed computational models but these are validated only against experiments of chest compression and not against aortic stress. The contribution of inertial change to mediastinal injury within an axial loading environment (aircraft crash) has been modelled [21] although there is very poor understanding of the tissue response to this form of loading. A physical model is required in order to describe the precise mechanism by which axial load within the underbody blast environment may cause these injuries.

Understanding the loading characteristics associated with these particular injuries will allow correlation between loading and survivability and enhance our ability to predict and influence “future unexpected survivors” [7].

Conclusion

Torso injury is clinically important within the context of mounted/under body blast and this study has shown that mediastinal injury is the strongest predictor of mortality.

We hypothesise that visceral injuries in response to this loading is due to propagation of stress waves and inertial effects within tissues and tissue interfaces. Aortic injury in particular may be caused by the generation of longitudinal aortic tension due to relative displacement of the heart and aortic arch to more fixed areas of the vessel.

These injuries do not occur in isolation; they may be considered the pinnacle injury of the visceral response to blast. The “all or nothing” phenomenon of under body blast injury and severe polytrauma is difficult to quantify using conventional injury scoring systems which rely upon somewhat arbitrary injury descriptions and which are “maxed out” by a single fatal injury. Devastating injuries such as mediastinal and massive head trauma may be used as surrogate markers of survivability but no mechanical description of these injuries due to UBB yet exists.

Future mitigating strategies will rely upon the development of a quantitative relationship between loading characteristics and individual injuries within the complex underbody blast environment. Mechanistic links between injuries must also be investigated to ensure that relief of one does not adversely affect others. It is important to remark that non-survivable injuries are not necessarily non-preventable.

Conflicts of interest

The authors have no conflicts of interest to disclose.

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