Assessment of Head Injuries: Blunt versus Penetrating

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Abstract. Current personal armour systems, such as helmets, are optimized for penetration protection to the vital areas of the body – most notably the head and torso. However, even if the helmet prevents penetrating injuries, impacts that produce behind-helmet blunt trauma (BHBT) can still occur. With current armour solutions, this presents a design trade-off – prevent penetrations which may result in high-rate blunt injuries, or limit blunt injuries while decreasing the penetration performance. As a first look at the mortality differences between blunt and penetrating head injuries, this study utilized a large civilian trauma hospital dataset (National Trauma Databank 2013-2015) to determine injury trends. While these civilian injuries are not specific to gunshot wounds or BHBT, the analyses did allow a direct comparison between head injuries categorized with either blunt or penetrating mechanism in a large dataset where mortality could be calculated. Examining patients with only head injuries (n=92,989 patients), 83,631 had blunt and 5,687 had penetrating mechanism injuries (3,671 patients had unspecified mechanisms). The mortality rate of those with blunt mechanism head injuries was 3% while those with penetrating mechanism head injuries was 54%, which was a statistically significant difference. Additionally there were differences in the types of head injuries between blunt and penetrating trauma (3% vs. 10% involved skull fracture without focal brain injury, 31% vs. 19% involved focal brain injury without skull fracture, and 16% vs. 52% had both skull fracture and brain injury, respectively). Cases of penetrating mechanism head injuries were more likely to involve co-occurring injuries to the skull and brain, i.e., increased injury severity. Thus, this analysis implies that preventing penetrating mechanism injuries with a helmet, even if blunt injuries occur, should increase survival for a person. However, with regards to BHBT, this assumes that the deformation shape and rate would only generate a blunt impact and injury to the head versus stopping the threat but still resulting in a penetrating impact and injury. Hence, BHBT metrics should consider shape and not just depth to evaluate significant injury risk. Additional research should be done investigating injury trends specific to gunshot wounds and blunt trauma to the head within a military dataset, likely through a case analysis comparison given the small number of cases available.

1. INTRODUCTION

Ballistically-rated personal protective equipment (PPE), such as a helmet, is designed to defeat fragments and bullets by absorbing and dissipating their kinetic energy without allowing the projectile to completely penetrate the armour. When a helmet is worn for protection, it is designed to prevent the penetrating threat, but in return may result in a blunt head injury following backface deformation of the helmet material. In such a case, the helmet has exchanged a penetrating head injury for the solider with a blunt head injury. There has been much debate over the injury implications for behind-armour blunt trauma, so it is relevant to look into the injury outcomes and patterns between penetrating and blunt trauma to the head. With current armour solutions and the goal to reduce the weight of body armour, this presents a design trade-off – prevent penetrations which may result in high-rate blunt injuries, or limit blunt injuries while decreasing the penetration performance [1].

There is currently a poor understanding of the implications for outcome between penetrating and blunt head injuries, which need to be understood to make future decisions about protection and allowable injury risk. As an example of the trade-off, maybe a simple linear skull fracture is an appropriate acceptable injury level if the helmet is protecting against a catastrophic penetrating skull and brain injury. Current laboratory testing can provide key outcome information for head impacts relating to helmets when investigating skull fracture. It is much more challenging to replicate brain injury within

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the laboratory setting, as it is typically an injury process which requires a living subject to propagate the bleeding and properly diagnose the patient based on neurological exams [2-4]. Alternatively, skull fracture can be generated in the laboratory, both with penetrating and blunt threats and specific fracture patterns are seen between the two mechanisms. The relationship between skull fracture patterns and brain injuries is currently poorly understood and documented.

Curently there is limited access to military medical records that contain enough detailed information to perform large sample size statistics on head injuries. Therefore, this study utilized the National Trauma Databank Research Dataset (NTDB RDS) to obtain injury and outcome information for civilian hospital patients with blunt or penetrating head injuries. The goal of this work was to eludicate injury and outcome pattern differences between penetrating and blunt head injuries, investigating the incidence of underlying brain injury associated with each. While this dataset contains a broader scope of head injuries than that just focused on behind-helmet blunt trauma (BHBT), it provided a large injury sample size to investigate the overall relationship between head injury mechanism (penetrating or blunt), associated injury patterns (skull fracture and brain injury), as well as outcome (mortality).

2. METHODS

Utilizing the NTDB RDS from 2013 through 2015 (American College of Surgeons), all patients with demographic information were initially selected. Data was imported into JMP®14 software (SAS, Cary, NC, USA) using a systematic approach where the International Classification of Diseases, ninth revision (ICD-9-CM) codes and other pertinent information provided by NTDB were joined in the order of 1) external cause of injury codes (RDS_ECODES), 2) diagnosis codes (RDS_DCODES), 3) demographic information (RDS_DEMO), 4) emergency department information (RDS_ED), and 5) hospital stay information (RDS_DISCHARGE) matching each specific patient when joining. A filtering process with exclusion criteria based on demographic information, external cause of injury codes, relevant military age, and Abbreviated Injury Scale (AIS) chapters matched to ICD-9-CM diagnosis was implemented (Figure 1). The total number of patients and their injury count was tabulated for each step, using the unique patient code. Initially there were 2,607,945 patients in the dataset from 2013-2015.

In this way, only patients with isolated head injuries were kept for analysis, as previous research has shown that a patient with injuries to multiple body regions has a higher likelihood of fatality [5] and the concomitant injuries may have influenced patient outcome. Once the head-injury only population was identified, the "external cause of injury codes" (RDS_ECODES) were used to distinguish between patients with penetrating and blunt mechanisms. Other injury mechanism types were excluded for this analysis. Additionally, analysis was performed to determine whether each patient had a skull fracture, brain injury, or both, to investigate the mortality rate for each group. For the purposes of this study, a head injury with a penetrating mechanism will be termed a penetrating injury, whether or not the injury involved penetration into the skull. Likewise, a head injury with a blunt mechanism will be termed a blunt injury for this paper, even if the skin and skull are broken. More details about each data filtering step are provided in the following paragraphs.

External Cause of Injury/Age Sorting

Patients with a lack of demographic information were excluded and then the remaining were filtered through the external cause of injury mechanisms. To evaluate injuries most relevant to the research question, only external cause codes associated with penetrating or blunt force trauma were included. These injury mechanisms were identified by using ICD-9-CM external cause of injury codes E2-20 and E800-999. Within that set, adverse outcome due to accidental poisoning (E850-869), surgical complications (E870-879), fire and flames (E890-E899), natural and environmental factors (E900-908, except 908.1-908.3, 908.8, 909.2, 909.3), suffocation or submersion (E910-913), other accidents (E924-928), adverse effects (E930-949), suicide by other than physical trauma (E950-952, E953-954,E958.1-959), and other inflicted injurious events (E961-962, 968, 968.3,972,977,979.3, 980-984, 988.1-988.4 ,988.7) were also excluded. Patients were then categorized by the injury type, either blunt, penetrating, or other/unspecified. Blunt events were mechanisms such as a fall, motor vehicle accident, or struck by/against an object. Penetrating mechanisms included firearms and cut or pierce events. Event mechanisms are characterized by the primary event and it is to be noted that there may be penetrating mechanisms in the blunt category and vice versa. For example, a person may be in a car

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accident, which would be characterized as a blunt mechanism, but then possibly have cut or pierce injuries from broken glass, which would not be characterized as penetrating in this database.
After external cause and mechanism sorting of population, the dataset was then filtered by a military relevant age, including only ages 17-55 in the dataset.

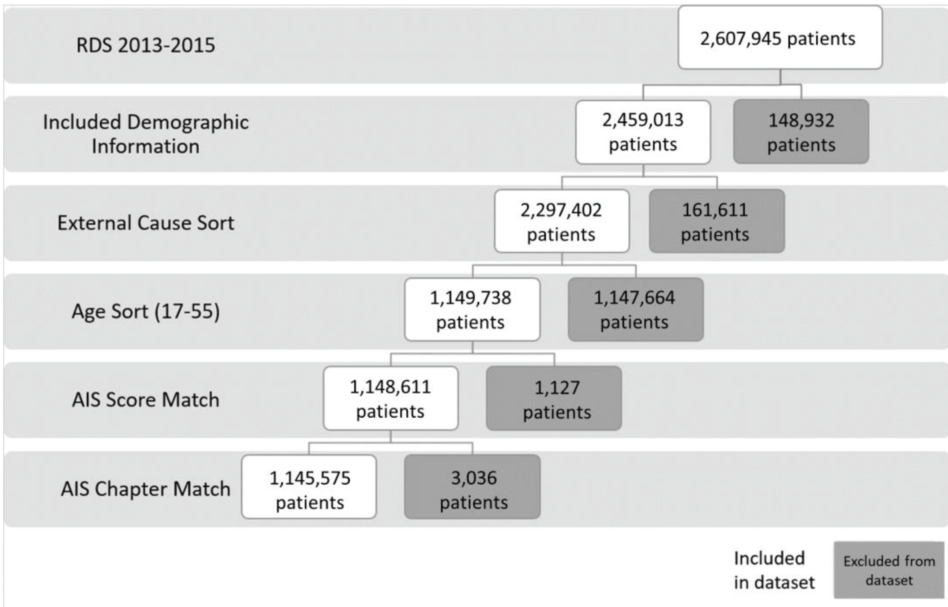

Figure 1: Filtering process from NTDB RDS 2013-2015 with patient quantities for each step in the filtering process. Totals presented in the gray boxes indicate the data that was excluded from the dataset through each step in the process, while the white boxes represent the included data.

Head Injury Population/AIS Sorting
NTDB uses ICD-9-CM as the main injury coding component within the database. ICD-9-CM groups the head, neck, and face together, making it difficult to separate out head injuries. Therefore, ICD-9-CM diagnosis codes (D codes) were mapped to AIS scores [6,7] using a protocol that was developed by certified coders of both ICD and AIS to isolate head injuries of interest. This allowed for separation of scalp, brain, and skull injuries from face and neck injuries through AIS chapter classification. Although the map is robust, there was no match in AIS for some ICD-9-CM D codes. For example, codes that included multiple body regions or multiple injuries within one code, such as fractures involving skull or face with other bones (804) had no equivalent AIS score. Therefore, incidents and injuries that did not match with any AIS codes or chapters were excluded from this analysis (Figure 1). After mapping the injuries to AIS chapters, it was possible to select only the injuries that were associated with the head (i.e., AIS Chapter 1). From this cohort a head-injury-only population was determined by totaling the injuries within each region and selecting patients with chapter 1 injuries only.

Level of Medical Care
Patients were either admitted to the emergency department, hospital, or both and both the emergency department cases and hospital admissions were included in the dataset. Patients that were either not applicable (BIU1) or not known/not recorded in the hospital disposition (HOSPDISP) were excluded from this analysis.

Specific head injury designations
The ICD-9-CM codes were used to classify the specific head injuries in the patients, in particular, skull fracture and focal brain injury. Using the diagnosis code (D-code) descriptions for presence of skull fracture, the patient was categorized as either having or not having a skull fracture. In addition to D-codes describing any type of skull fracture, skull fracture was also implied for any ICD code that had an open brain injury, even if skull fracture was not specifically described in the D-code (i.e., 851.1, 851.3, 851.5, 851.7, 851.9, 852.1, 852.3, 852.5, 853.1, and 854.1). Similarly, D-code descriptions were

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used to categorize patients with focal brain injuries. For the purposes of this study, the definition of focal brain injury included the brain and surrounding internal soft tissue structures. D-codes such as cerebral contusion, injury to cranial nerves, cerebellum/brain stem laceration, and subdural, subarachnoid or extradural haemorrhages were categorised as a focal brain injury. Any crush, unspecific blood vessel injury, superficial wound, skull fracture only, or unspecified brain injury were not included in the focal brain injury category for this study. Concussion was also excluded because of the inconsistencies with diagnosis and notations within NTDB. Because some of the head injury patients had both skull fracture and focal brain injury, each patient was then further separated by the groups described in Table 1 to elucidate possible trends within the head injury population and for a better understanding of coexisting injuries.

Table 1: Head Injury Group Definitions

Group	**Head injury category**
None	No skull fracture and no focal brain injury
SF	Skull fracture, no focal brain injury
FB	Focal brain injury, no skull fracture
Both	Skull fracture and focal brain injury

Mortality was used as a means to investigate the differences in patient outcomes between blunt and penetrating mechanism populations using the hospital disposition code (expired). To calculate mortality, the number of patients within an injury grouping that died was divided by the total number of patients within that injury grouping. Prevalence of patients with each injury type was calculated by dividing the population by primary mechanism (blunt/penetrating). Further comparative numbers and percentages were calculated by dividing the number of interest by the total number in the group. In this way, a cross-tabulation table was created for both blunt and penetrating trauma providing the number of patients within each head injury category shown in Table 1. To determine if there was statistical significance between the mortality rates between blunt and penetrating mechanisms of injuries , a two-tailed z-score was calculated and evaluated at 0.05 for significance.

3. RESULTS

Using 2013-2015 NTDB RDS after applying all the exclusion criteria there were 83,631 patients with blunt mechanism head injuries and 5,687 patients with penetrating mechanism head injuries. Each of these groups were further broken down to investigate trends between skull fracture and focal brain injury.

Blunt mechanism head injuries

Table 2 shows the results of the blunt mechanism head injury analysis, where the majority of patients didn't have skull fracture or brain injury due to the blunt mechanism (49%, 41,264/83,631) and overall mortality was 3% (2,304/83,631). Comparing mortality rates between those with only a skull fracture (3%, 76/2,723), those with only a focal brain injury (4%, 1,064/26,313), and those with both a skull fracture and brain injury (6%, 833/13,331), there is a slight increase in mortality for the combined head injury group. While those with a blunt mechanism only sustained a skull fracture in 19% of patients, the percentage with a brain injury was closer to even at 47%. Blunt mechanism injury patients with a skull fracture had a higher incidence of associated brain injury at 83% (13,331/16,054), compared to those without skull fracture with a brain injury incidence of 39% (26,313/67,597).

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Table 2. 2013-2015 NTDB RDS patients with isolated blunt mechanism head injuries, where a) number of patients that died in each injury category (red) and the total in that category and b) the percent of patients in that injury category that died (red) and the percent of patients from the blunt mechanism injury population that fell into that injury category.

2013-2015 NTBD RDS Blunt Mechanism Head Injuries and Deaths

	No Skull Fx	**Skull Fx**	Total
No Focal Brain Inj	**331** **4,1264**	**76** **2,723**	407 43,987
Focal Brain Inj	**1,064** **26,313**	**833** **13,331**	1,897 39,644
Total	1,395 67,597	909 16,054	2,304 83,631

	No Skull Fx	**Skull Fx**	Total
No Focal Brain Inj	**1%** **49%**	**3%** **3%**	1% 53%
Focal Brain Inj	**4%** **31%**	**6%** **16%**	5% 47%
Total	2% 81%	6% 19%	3% 100%

Penetrating mechanism head injuries

For the 5,687 patients with penetrating mechanism head injury, the overall mortality was 54% (3,066/5,687), as shown in Table 3. The majority of patients had both skull fracture and brain injury, 52% (2,979/5,687), with the smallest percentage of the group only having a skull fracture (10%, 573/5,687). Comparing mortality rates between those with only a skull fracture (57%, 325/573), those with only a focal brain injury (59%, 618/1,054), and those with both a skull fracture and brain injury (67%, 1984/2979), the combined head injury group had the highest mortality. Patients with a skull fracture had a higher mortality rate (66%, 2,339/3,552) than those without a skull fracture (35%, 757/2,135). Penetrating mechanism injury patients with a focal brain injury also had a higher mortality rate (65%, 2,602/4,033) than those without (30%, 494/1,654).

Table 3. 2013-2015 NTDB RDS patients with isolated penetrating mechanism head injuries, where a) number of patients that died in each injury category (red) and the total in that category and b) the percent of patients in that injury category that died (red) and the percent of patients from the penetrating mechanism injury population that fell into that injury category.

2013-2015 NTDB RDS Penetrating Mechanism Head Injuries and Deaths

	No Skull Fx	**Skull Fx**	Total
No Focal Brain Inj	**139** **1,081**	**325** **573**	494 1,654
Focal Brain Inj	**618** **1,054**	**1,984** **2,979**	2,602 4,033
Total	757 2,135	2,339 3,552	3,096 5,687

	No Skull Fx	**Skull Fx**	Total
No Focal Brain Inj	**13%** **19%**	**57%** **10%**	30% 29%
Focal Brain Inj	**59%** **19%**	**67%** **52%**	65% 71%
Total	35% 38%	66% 62%	54% 100%

Blunt and Penetrating Mortality Comparison

A z-score for a proportion comparison between the overall mortality rate of blunt or penetrating mechanism injuries was calculated. The value of z is -157.0404 which equates to a resultantant p value < .00001. Significance was calculated at $p<0.05$. Therefore, the mortality rate of those with penetrating head injuries was significantly different than the mortality associated with blunt head injuries.

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4. DISCUSSION

While this research would ideally be performed using a military dataset to more closely match blunt and penetrating mechanisms that are pertinent to the US military, that was not possible given the limited data accessability and the small numbers in military injury data versus the large civilian hospital dataset that is available through NTDB. Within each injury mechanism category, regardless of whether the source of data is military or civilian based, there can be a wide range of injury mechanisms that may demonstrate their own unique injury patterns and outcomes. For example, the penetrating injury category includes mechanisms of gunshot wounds and stab wounds. Similiarly, blunt mechanisms vary between falls, motor vehicle crashes, and sports injuries. However, at this early state of understanding the pathophysiologic differences between blunt and penetrating mechanism head injuries, describing the general outcomes across the wide spectrum of insults within the blunt and penetrating injury mechanisms acts an an initial survey of the unique injury patterns and outcomes present within each mechanism to help inform future research directions for more specific mechanisms. Consequently, considering the shear number of incidents and many types of injury mechanisms included in this civilian dataset, analysis of the NTDB data was suitable for this inital inquiry, especially after applying the proper exclusions to investigate specific head injury diagnoses [8]. Future work will be completed with more specific military datasets to ensure the data trends are similar and to investigate more into specific injury patterns and cases related to gunshot wounds and behind-helmet-blunt-trauma. The results presented in this paper agree with previous smaller comparisons in mortality between penetrating and blunt mechanisms of injuries to the head, and further analysis into specifics within mechanisms is suggested [9].

Given that skeletal injury can more easily be created and measured in the laboratory versus brain injury, which requires living tissue, it was important to investigate the relationship between skull fracture and brain injury. While more work can be done to investigate specific linked injuries, this study provides the first documentation of the relationship between skull fracture and brain injury for both blunt and penetrating threats. Results showed that combined head injuries (those including both skull fracture and brain injury) were more frequent with penetrating threats, encompassing 52% of the penetrating dataset but only 16% of the blunt dataset. For the blunt mechanism, there were more patients with only skull fracture (2,723) compared to the penetrating mechanism dataset (573), but the percentage of blunt mechanism skull fracture only patients (3%) was still less than the penetrating mechanism skull fracture only patients (10%). Former research has shown that occult brain injuries can go undocumented in Emergency Department (ED) records when the patient dies before being admitted to the hospital, so additional investigation into the patients with skull fractures but no brain injuries was undertaken considering how high the mortality rate was for this group in the penetrating injury mechanism. After examining that count, 261 of the patients that died from penetrating mechanism injuries that were reported as only sustaining skull fracture (out of the 325 listed) were deaths reported in the ED instead of the hospital. This is likely due to under-reporting of the focal brain injuries for this group since the patient often expires before more definitive studies to identify brain injury can be performed [10]. Given this information, if proper injury documentation were available, one would expect the skull-fracture-only mortality rate to drop, with a corresponding increase in mortality rate and count for the skull fracture and focal brain injury group of patients.

This particular study excluded concussion-type injuries because they are not “focal” brain injuries. These injuries are typically associated with blast or blunt trauma to the head, but due to complications in diagnosing this injury, especially in patients that don’t survive, it was excluded from analysis for this first investigation into head injuries [3]. This exclusion made up the majority of patients that did not have skull fracture or focal brain injury. Future research with this data will investigate the breakdown of injury types within the focal brain injury and skull fracture categories to further elucidate injury patterns, especially linking skull fracture with the most frequently occuring focal brain injuries, as this is pertinent to injury risk predictions being developed in the laboratory.

For patients with a skull fracture, those resulting from a blunt mechanism accounted for only 19% of the dataset, while those resulting from a penetrating mechanism accounted for 62% of that dataset. As one would expect from penetrating trauma, skull fracture was a more prominent injury result. Overall between both datasets, skull fracture without brain injury was infrequent compared to the alternate injury counts. Future analysis will be undertaken to better understand if there is skull fracture pattern

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deliniation between these groups, with the hypothesis that simple linear skull fractures are less likely to be associated with significant underlying brain injury compared to complex skull fractures.

In every injury category between blunt and penetrating mechanisms, the penetrating trauma resulted in higher mortality for the patients. This was most pronounced for patients with both a skull fracture and a brain injury, where the blunt mechanism had a mortality of 6% and the penetrating mechanism had a mortality of 67%. Additionally, the blunt mechanism cases had more patients without skull fracture (81% versus 19%) and more patients without focal brain injury (53% versus 47%), whereas the penetrating mechanism cases had much higher percentages of patients with skull fracture (62% versus 38%) and focal brain injury (71% versus 29%). This signifies that for the civilian dataset overall, blunt trauma results in fewer skull fractures and brain injuries compared to penetrating trauma and when they do occur with blunt trauma, the patients are more likely to survive. Although this dataset did not contain BHBT events, the analysis suggests that if a helmet protects the wearer from a penetrating insult, it could improve the wearers chance of survival and reduce the risk of serious injury, even if it still resulted in a blunt injury. This assumes that if the helmet stopped the threat from entering the head, the speed and shape of the back face deformation would not result in a penetrating injury. Therefore, when considering helmet backface measures and their relationship with injury, the velocity, size, and shape of the deformation should be taken into consideration, not just deformation depth or whether or not the threat perforated the helmet. Future work will investigate the mortality risk of non-penetrating BHBT impacts, specifically to investigate the comparative risk between high-rate, focal blunt injuries and penetrating trauma to verify the analysis of the civilian data for military populations.

5. CONCLUSION

Body armour research currently involves a trade-off between preventing penetrations but possibly inducing blunt injury due to back face deformations. This study investigated the differences in head injuries and mortality between blunt and penetrating mechanisms within a civilian trauma hospital dataset (NTDB RDS 2013-2015). The mortality rate of those with blunt impact head injuries was 3% while those with penetrating impact head injuries was 54%, which was a stastistically significant difference. Additionally there were differences in the types of head injuries between blunt and penetrating mechanisms (3% vs. 10% involved skull fracture without focal brain injury, 31% vs. 19% involved focal brain injury without skull fracture, and 16% vs. 52% had both skull fracture and brain injury, respectively). Cases of penetrating mechanism head injuries were more likely to involve co-occurring injuries to the skull and brain, i.e., increased injury severity. Thus, this analysis implies that helmets designed to prevent penetrating mechanisms should increase survival of the wearer, even if there is a risk of resulting blunt injury. However, with regards to BHBT, this assumes that the deformation shape and rate would only generate a blunt injury to the head versus stopping the threat but still resulting in penetrating injury. Hence, BHBT metrics should consider shape and not just depth to evaluate significant injury risk. Additional research should be done to link these civilian injury trends to more specific injury patterns specifically associated with penetrating gunshot wounds and high-rate blunt head impacts.

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