

Blast Traumatic Brain Injury: The history, pathology and mechanisms of injury

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Statement of Originality

I declare that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Those who have co-authored are appropriately acknowledged.

Contribution

The Centre for Blast Injury Studies has previously published work on musculoskeletal injuries. However, this was the first time that the CT-post mortem brain images have been used as part of research.

Most of the work for this PhD was completed by me, including data collection, analysis and write-up. However, supervision was sought from subject matter experts and supervisors for some aspects.

Contributions are listed below:

Professor Anthony Bull - Formulation of ideas/hypotheses, analysis of data

Professor Mark Wilson - Formulation of ideas/hypotheses, analysis of data

Professor Peter Hutchinson - Formulation of ideas/hypotheses

Professor Iain Gibb - Formulation of ideas/hypotheses, Generation of data

Lt Col David Baxter - Generation of data

Dr Sarah Dixon Smith - Analysis of data

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Abbreviations

AIS – Abbreviated Injury Score

AnUBIS - AnÃ-vehicle Under-body Blast Injury Simulator

ASDH – Acute Subdural Haematoma

bTBI – Blast TraumaÃ Brain Injury

C0/C1 – Cervical Spine 0 to Cervical Spine 1

CNS – Central Nervous System

CRASH-CT - CorÃcoid RandomizaÃon aÃer SigniÃcant Head Injury Computerised Tomography Score

CSF – Cerebrospinal Ãuid

C-spine – Cervical Spine

CT – Computerised Tomography

CTPM – Computerised Tomography Post-Mortem

CWIED - Command Wire Improvised Explosive Devices

DAI -DiÃuse Axonal Injury

EFP - Explosively Formed Penetrator

EU – European Union

EU - TE-SAT - European Union Terrorism SituaÃon & Trends

FEM – Finite Element Modelling

GCS – Glasgow Coma Score

ICP – Intracranial Pressure

IED – Improvised Explosive Devices

IMPACT - InternaÃonal Mission for Prognosis and Analysis of Clinical Trials in TBI

IRA – Irish Republican Army

JTTR – Joint Trauma and Theatre Registry

MNSU – Mobile Neuro Surgical Unit

MRI – MagneÃc Resonance Imaging

PACS - PaÃent Archive and CommunicaÃon System (PACS).

PPE – Personal Protecti e Equipment

PTSD – Post Traumatic Stress Disorder

RCIED - Radio Controlled Improvised Explosive Devices

RPIED's - Rocket-Propelled Improvised Explosive Devices

SBNS – Society of British Neurosurgeons

SBNS BIC - Society of British Neurosurgeons Brain Injury Classification

SDH – Subdural Haematoma

SPSS – Statistical Analysis Software

TARN -Trauma Audit and Research Network

TBI – Traumatic Brain Injury

UBB – Underbody Blast

UCDP - Uppsala Conflict Data Program

UK – United Kingdom

UVIED - Under-Vehicle Improvised Explosive Devices

VBIED's - Vehicle Born Improvised Explosive Devices

VOIED's - Victim Operated Improvised Explosive Devices

WWII – World War 2

Abstract

Blast brain injury is known to have a high morbidity and mortality rate in the Iraq and Afghanistan commitments, equating to around 19% of all injuries and was prevalent in historic conflicts such as World War 2 (WW2).

The documentation and imaging from the St Hugh's College in Oxford archives gives an insight into the type of injuries suffered in WW2 pioneering treatments offered in contrast to the commitments of 2003-2012.

In addition to the WW2 archives, patients were identified from the Iraq and Afghanistan commitments between 2003-2012. These patients were collated from the Joint Trauma and Theatre Registry (JTTR) and the associated imaging identified, including computerised tomography post-mortems (CTPM), computerised tomography (CT) scans, magnetic resonance imaging and radiological reports.

In order to classify the CT scans, a CT-based scoring system was constructed and validated on a civilian cohort using inter-rater reliability and then used in the military cohort.

Chi's squared and Fisher's exact were used to identify constellations or mechanisms of injury. Distinct mechanisms of both mounted and dismounted blast were identified from Iraq and Afghanistan. In the mounted cohort, there were 3 distinct patterns of injury; an eggshell pattern of fractures, 3 or 4 point spinal fractures and perimesencephalic blood. In the dismounted cohort perimesencephalic blood was again visualised in conjunction with thoracic injury and there was a higher incidence of penetrating injury in comparison to the mounted cohort.

Brain injury pathology varied greatly between WW2 and the Iraq/Afghanistan campaigns, largely due to the development of improvised explosive devices. Although the imaging from WW2 was crude with only plain film x-rays, it demonstrates that penetrating injury was prevalent in both conflicts.

Many of the injuries identified are not amenable to clinical treatment and therefore efforts should be made to identify mitigation strategies from the hypothesised injury mechanisms.

Chapter 1. Introduction, Aims and Scope of Thesis

This chapter outlines in a narrative form the importance of blast injury, how this has changed over the years and focuses on head injuries in blast. There then follows a review of the main methods used in the literature to understand blast brain injury leading to the overall aims and scope of the thesis.

Parts of this chapter were published as: Ashworth ER, Baxter D, Gibb IE "Blast Traumatic Brain Injury" Ch 22 in "Blast Injury Science and Engineering: A Guide for Clinicians and Researchers" Bull AMJ, Clasper J, Mahoney PF, McGregor AH, Masouros SD, Ramasamy A (eds), 2022, Second Edition. Springer, ISBN:978-3-031-10354-4

(see Appendix A for appended chapter)

1.1. Blast physics and resulting injuries

Due to past and ongoing commitments such as Operation Telic in Iraq in 2003, Operation Herrick in Afghanistan and the current conflict in Ukraine, as well as terrorist bombing such as Manchester in 2017 and the Boston Bombing of 2013, bomb and blast injury is a major concern for both military and civilian populations.

Although the mechanisms and pathology of blast traumatic brain injury (TBI) is still to be understood (Bryden, Tilghman & Hinds, 2019), the physics behind blast itself is well documented (Ling et al., 2009). When an explosive device is detonated, a solid is converted to a hot gas via ignition, causing a “blast wave” to move at a high pressure and at fast speeds. This can be demonstrated using the Friedlander wave representation, where a rapid increase in pressure induces a period of “over-pressure” followed by reduction in pressure, including a period of negative (or below atmospheric) pressure (Tasissa et al., 2016; Figure 1-1).

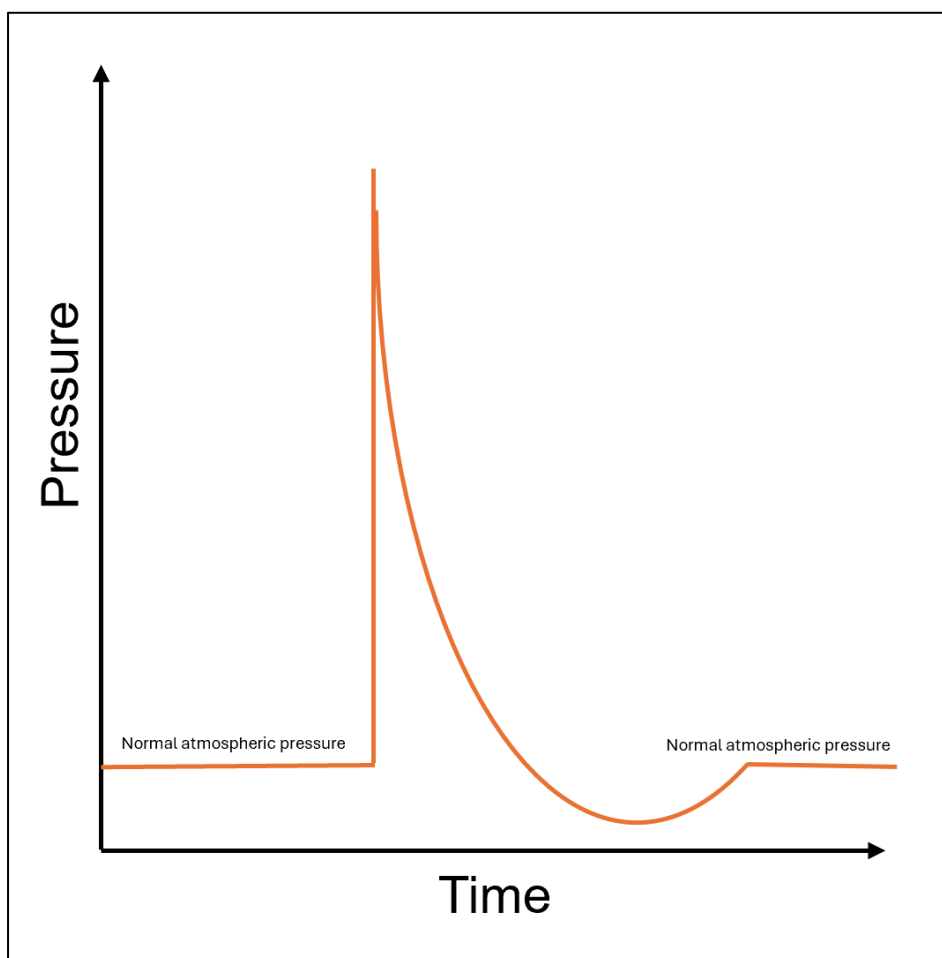


Figure 1-1 - An image to show a Friedlander waveform

This over-pressure of gas causes what is described as “blast wind”, which can travel at speeds of 2000km/hr. The movement of this blast wind and the shape of over-pressure curve varies between closed and open spaces. In closed spaces, such as vehicles, buildings, or built-up cities, the blast wave is reflected and dissipates far more slowly. It is much harder to predict or determine injuries as a result of a blast within this confined space as it is dependent on the distance of the person from the blast, their proximity to surrounding structures, and the ability of the surrounding structures to contain the blast pressure (Ling et al., 2009). Free field (open air) blast is very different in that the peak pressure drops quickly with increased distance from the seat of the explosion and even when very near the seat of the explosion the pressure reduces quickly.

Blast injuries can be categorised by which part of the blast they are caused by (Figure 1-2). Primary blast injuries are caused by the over-pressure coming into direct contact with the biological tissues. There is evidence that the primary wave causes tympanic membrane rupture, and the clinical consensus is that with such damage comes intracranial overpressure damage also, however with a lack of research and evidence in this area it is difficult to distinguish the effects of mild-TBI caused by overpressure and post-traumatic stress disorder (PTSD). In those patients close enough to suffer severe trauma from a primary blast wave there is a greater likelihood of also suffering from secondary and tertiary blast injuries, described below (Arnold et al., 2003; Owen-Smith, 1979; Champion et al., 2003). Primary blast wave has been extensively researched in traumatic brain injury, and it is thought to increase internal pressures, thereby increasing the risk of capillary breakdown. The primary blast wave is most likely to affect the bowel and lungs as air filled cavities and therefore patients who have experienced brain injury as a result of primary blast wave would also expect to have thoracic and abdominal injuries (Courtney & Courtney, n.d.).

Secondary blast is when material or debris energised as a result of the pressure produced from detonation makes an impact with the body. Such impact can cause penetrating injuries as seen with civilian head injuries – however, the forces and energy that propels these objects can often be much higher than any impact seen in a civilian trauma population (Centres for Disease Control and Prevention, 2006). It is likely that the dismantled cohort

will have evidence of penetrating brain injury due to secondary blast, whereas this will be less evident in the mounted cohort due to being protected by the vehicle.

Primary Blast is when the energy of the blast causes acceleration/deceleration of the person or large masses (such as vehicles or buildings) as a result of expulsion of kinetic energy and also incorporates blunt impact injuries. With head injuries, the injury can be caused by the shearing or rotational forces, or from the impact or collision of the head as a result of the movement. This could be seen as an impact or blunt injury in both cohorts due to bodily displacement. In vehicles this may be seen as an impact with the cabin roof of the vehicle compartment.

Quaternary Blast is less applicable to head injuries as it consists of all other injuries not encompassed by the other types such as burns or noxious gases (Centres for Disease Control and Prevention, 2006). If the cohorts were followed up as part of a long-term study then it may be seen that patients suffered infections as a result of quaternary blast in any cranial lacerations or open injuries.

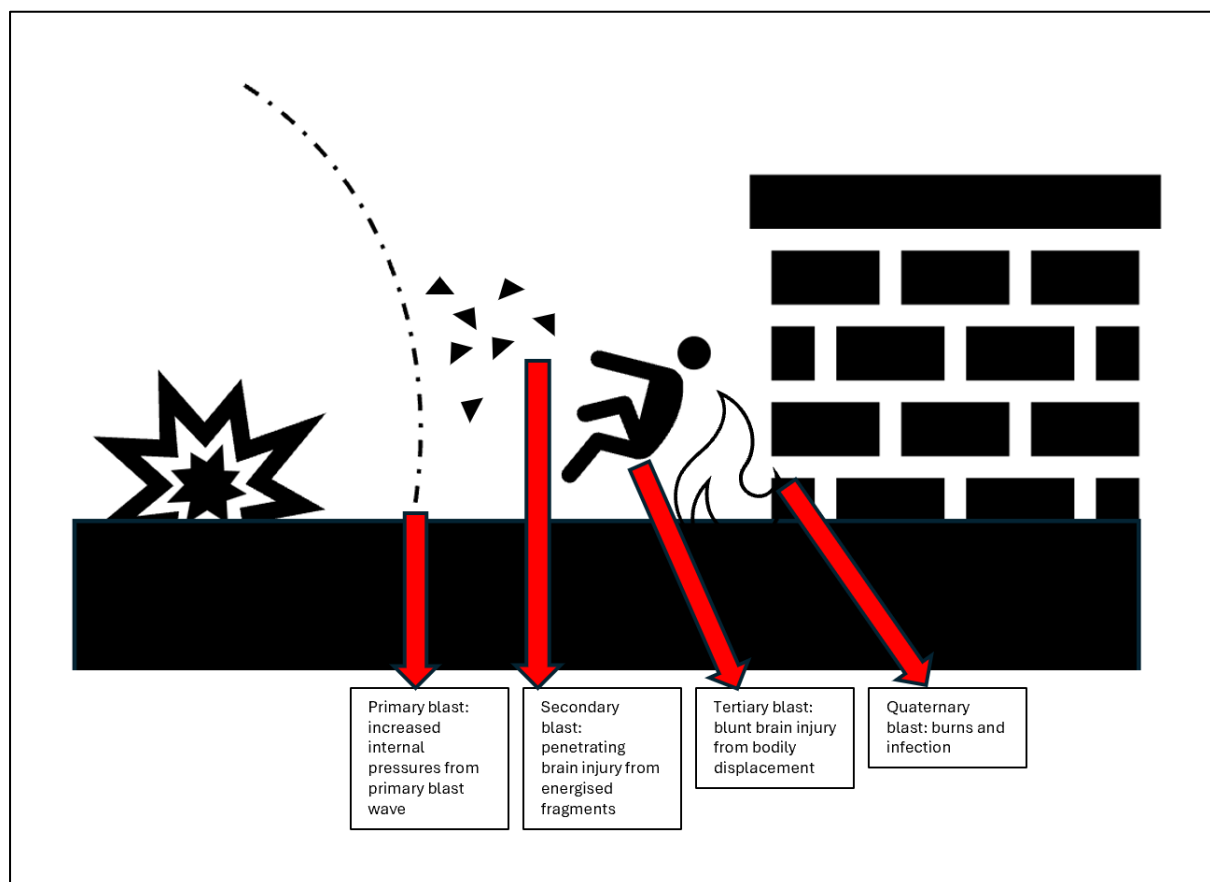


Figure 1-2 An image to show different types of blast injury and brain injuries expected

1.2. Change in blast tactics and attacks

With the focus of blast injury transitioning from larger warfare blasts to terrorism and extremist attacks, a greater understanding in the physics of blast and blast injuries is needed. Although the majority of these attacks occur in areas of conflict, over the past 10 years there has been an increase in attacks in the Western world and certainly an increase threat, with a greater emphasis put on improvised explosive devices (IED's) (Cernak & Noble-Haesslein, 2010).

Improvised Explosive Devices were the leading cause of death and disability of deployed troops during the era of the Iraq and Afghanistan operations (Belmont et al., 2012). With a broad definition, IED's can range from relatively simple home-manufactured devices to more refined and sophisticated products, spanning roadside devices, mines, explosively formed penetrators (EFP's) and suicide bombings (Ramasamy et al., 2008).

It is important to understand the differences between energy transfers of the different explosive types when looking at blast injury. Detonation of an anti-vehicle mines is a large exothermic reaction causing a large expulsion of energy as gasses expand. The large shockwave formed causes ejection of particles such as soil, gases and surrounding terrain which propels towards targets (Wilkinson & van Rij, 2017).

Improvised explosive device is the descriptor for an explosive that is used in any other way other than conventional military warfare. It consists of explosives attached to a detonating mechanism and have been typically used roadside since 2001 in the Iraq and Afghanistan wars. IED's encompass EFP's (explosively formed penetrators), RCIED's (radio controlled IED's), CWIED's (command wire improved IED's), UVIED's (under-vehicle IED's), RPIED's (rocket-propelled IED's), VBIED's (vehicle born IED's) and VOIED's (victim operated IED's). EFP's are projectiles that are formed from a high energy explosion or blast and are designed to penetrate through strong materials – specifically armoured vehicles. More recently, there have been concerns that there are risks of additional threats being added to IED's such as toxic noxious substances or chemical and biological weapons creating further life-threatening effects and complications to its detonation (Centres for Disease Control and Prevention, 2006).

1.3. Blast outside of conflict

Although much of the current blast injury data comes from military commitments in Iraq and Afghanistan, there have been many incidents of explosion causing mass casualties over the previous decades, adding data to the existing information on blast injury in personnel without specific personal protective equipment such as that in the military (Maitland et al., 2022).

Examples of these include previous IRA attacks throughout the 1970's, 80's and 90's. In November of 1974, two bombs detonated in pubs in central Birmingham, injuring 182 people and killing 21. Multiple IRA bombs were detonated in London including the Harrod's bomb in 1983, the Bishopsgate bombing in 1993 and the Dockland's bombing in 1996. Following this, in 1999 there was the Admiral Duncan bombing, a nail bomb explosion which killed three people and wounded approximately 70 (Maitland et al., 2022).

More recently, a bomb detonated from an improvised device comprising of a pressure cooker during the Boston Marathon in 2013, which killed 6 people and wounded 280 others. Because this was an open air explosion (compared to an enclosed, in vehicle one), the injuries were mainly of the lower extremities as opposed to thoracic and head injuries as these are further from seat of the explosion. The improvised nature of these explosive devices which use "shrapnel" such as ball bearings and nails, mean that casualties suffered secondary injuries. In the Boston bombing, only 14 of 189 fragments identified through radiological examination of casualties were identified within the head and neck region, with the majority (138) in lower extremities (Caterson et al., 2013). Similarly, in Manchester on the 22nd May 2017 a suicide bomber with an improvised explosive device using nuts and bolts as shrapnel killed 22 people and injured a further 250, the highest numbers of fatalities in the UK since the (7th July 2005) bombings in London (Caterson et al., 2013) (Craigie et al., 2020). Findings of the EU Terrorism Situation & Trend Report 2023 (TE-SAT) found that 16 terrorist attacks occurred in the EU in 2022, with 12 being prevented. There was still a trend in 2022 to use improvised explosive devices and manuals for creation such as still being circulated. There remains threat from both co-ordinated and lone actor incidents. IED's remain a risk in 2023 with ongoing and long-lasting conflicts (Europol, 2023). There are also industrial explosions that cause blast injuries, such as the Beirut port explosion of 2020 (El

Zahran et al., 2022). Again, there were few documented head injuries due to the free-field nature of the explosion.

1.4. Mechanisms

The mechanisms and causes behind blast induced head injury are still unknown and under-researched (Courtney & Courtney, 2015). However, it is known that an acceleration-deceleration motion on the brain can cause a mechanical internal impact of the brain upon bony prominences as with injuries within civilian trauma (Moss, King & Blackman, 2011) (Svetlov et al., 2012). It is hypothesised that over-pressurization caused by blast has a similar effect. In contrast to civilian TBI it is thought that there is a unique mechanism of cerebrospinal fluid cavitation, where microbubbles in CSF collapse as a result in the change of pressure (Yu et al., 2020). There is also a hypothesis that the blast wave increases thoracic pressure which has an impact directly on intracranial pressures therefore causing cranial injury (Bauman et al., 2009) (Courtney & Courtney, 2015).

At least four mechanisms by which the blast wave may result in brain injury have been proposed: a thoracic mechanism, head acceleration, direct cranial transmission and blunt/penetrating injury mechanism. The thoracic mechanism has previously been described as the blast wave pressure entering the thoracic cavity causing a travelling pressure up towards the brain causing injury (Bhattacharjee, 2008; Cernak & Noble-Haeusslein, 2010). Courtney and Courtney (2015) hypothesised that injury was caused by overpressure and acceleration of the head through the thorax when a ballistic or overpressure wave caused enough energy to do so (Courtney & Courtney, 2015). This was replicated in animal models when blast waves were applied directly to the thorax. The extent to which damage occurs is still unknown.

Head acceleration-deceleration is known to cause intracranial damage and traumatic brain injury, this is seen within civilian patients who have been involved in road traffic accidents (Zhang et al., 2022; Krave, Al-Olama & Hansson, 2011). Computer and numeric modelling have shown comparability of the acceleration injury in which the blast wave caused rapid head acceleration and associated damage or brain injury (Stuhmiller, 1994). The blast wave itself can cause a separate acceleration force within the secondary and tertiary head trauma mechanism (Finkel, 2006).

It has been hypothesised through animal models that primary blast waves are able to pass through the cranium causing direct blast wave injury on the brain (Chavko et al., 2007). This has been modelled through thinner skulls like those of rats, and larger thicker skulls of pigs. In thinner skulls the force of the blast wave remained unchanged, but even in thicker pig cranium, two-thirds of the force was able to pass through to brain tissue (Bauman et al., 2009). This mechanism is still under-researched and not fully understood and so it remains unclear as to the magnitude of damage that is caused, however finite element modelling has shown some evidence that when human skulls are exposed to blast waves the force is able to enter through the cranium causing damage to the intracranial structures (Stuhmiller, 1994; Taylor, Ludwigsen & Ford, 2014).

1.5. Experimental Research on Blast Trauma to Brain Injury

1.5.1. A Flask Full of Jelly: The First in Vitro Model of Concussive Head Injury—1830

One of the very first models of brain injury was the use of Isinglass, derived from the swim bladders of fish, within a glass container containing strands of wire and cork. Different measured forces were applied to the container and the communicated force was measured. Although a crude and basic model, this began to show the way in which repeated concussions and force applied to the skull affected the brain. The limitations in this experiment are vast and include having no illustrations or documentation of instrument set-up for reproducibility. There was a lack of measurements from the wires to analyse concussive force, in fact, there was very little documented on measurements of force at all (Feinsod, 2002).

1.5.2. Penetrating injury and gunshot wounds

Previous military commitments have shown evidence of gunshot wounds, for example in close combat war, such as World War 2 (Alvis-Miranda et al., 2015). Intracranial gunshot wounds are still prevalent in developing countries where there is national or state violence, however, this was less evident in Iraq and Afghanistan (Alvis-Miranda et al., 2016). The best prevention of gunshot wounds is appropriate personal and protective equipment and they are clinically managed through life-saving resuscitative care for haemorrhage. Long term

surgery, management of intracranial pressure and monitoring for infection should be considered. Due to the nature of ballistic, gunshot wounds cause cavities and higher velocity projectiles will also cause additional temporary cavity effects in their trail, which should be considered when assessing the nature of the injury (Alvis-Miranda et al., 2015).

1.5.3. Use of Shock Tubes

With the need for research on blast injury becoming apparent, experimental models that could be used to replicate the blast wave forces were needed so that studies could be controlled and repeated. Shock tubes have been used in the past to test blast loading under controlled conditions and are able to test a variety of materials. The blast wave formed by shock tubes can replicate the Friedlander wave form (Tasissa et al., 2016), but can also with some tuning replicate other forms of loading even those that are experienced in an enclosed environment. Shock and blast tubes vary across laboratories but can be air-driven or explosive driven, and tubes also vary in size and pressure.

Blast tubes have advantages in that they reproduce the biological systems of blast. It is also possible to take radiographic and electrophysiological measurements of large scale shock tubes therefore providing extra data and information on the pattern and mechanism of blast used (Säljö et al., 2010).

Blast tubes have been used to understand the effects of the blast wave components against brain matter and calvarium. Blast tubes in particular have provided evidence of vascular damage as a result of the primary blast wave (Tasissa et al., 2016).

1.5.4. Animal Studies

Animal models have been central to studying the biological effects of blast. These have varied in size, species and relevance. This heterogeneity amongst experiments has halted progression and translation (Sarah Watts et al., 2019). Animal models can be useful to understand pathophysiology, diagnosis, treatment and management however there are challenges with the translation and upscaling of these models, especially when looking at blast head injury due to the differences in skull structure and thickness. There has been discussion on standardizing animal models to aid progression, however it has also been argued that this could put a halt on novel research (Massoud et al., 1998).

Pig models have been used to investigate blast TBI pre-clinically. The calvarium of pig has features that make it comparatively suitable for exploring human injuries. In addition to structural similarities, pig models have also been found useful for biomarkers, imaging and testing potential therapeutics (Kinder, Baker & West, 2019).

1.5.5. Computerised models

Computer modelling for brain injury is still being developed to investigate the pathology and mechanism of brain injury, particularly in moderate to severe injury and in those injuries which cause fatalities. Finite Element Method (FEM) modelling has been used previously to research blast lung and eye injuries (Rossi et al., 2012). Panzer et al. (2012) described a method of FEM for researching blast loading on the brain. The FEM model showed that peak pressures in the brain were reliant on peak overpressures while the blast impulse has a direct effect on the blast strain rate. Other factors that affected the biomechanics but for which the mechanisms are unknown were cavitation within the brain (cerebrospinal fluid spaces) and skull deformations (Panzer et al., 2012). The model was shown to be useful, but again, with the heterogeneity of blast there is difficulty in translating the model to real world events.

1.5.6. Postmortem review

Post-mortem analyses of blast injuries are often undisclosed due to potential revealing of military vulnerabilities so the literature is limited. However, the published data that is available shows the value in post-mortem reviews, particularly for forensics. Post-mortem reviews allow retrospective analysis for future commitments or incidents using subject matter experts. This provides areas for both preventive actions and clinical areas to improve (Galante et al., 2021).

1.6. Areas for further research

The literature on traumatic brain injury in relation to blast is vast, however, there is little known about the brain injuries that occurred in recent commitments such as Afghanistan and Iraq. Brain injury, and in particular, mild brain injury, is hard to quantify and classify but knowledge is improving with new imaging techniques. During the Iraq and Afghanistan commitments, a database for every trauma call or patient treatment by Defence Medical Services was held, much like the civilian Trauma, Audit and Research Network (TARN) Database. This database, called the Joint Trauma and Theatre Registry (JTTR) included

comprehensive data about each patient injury, time to medical services, medical aid and treatment provided, and injury details. The limitation to this is that not all the details are accurate or recorded accurately on the database. This includes the body location and severity of injury, which was often overscored and not representative of the CT images or reports. In addition, the Abbreviated Injury Score (AIS) gives an idea of the severity of brain injury but not the underlying pathology, which in the case of blast brain injury can be heterogeneous. In order to fully understand the mechanisms of blast brain injury, the radiology records of all brain-injured patients should be reviewed using a robust radiological scoring tool. This can then be used to identify patterns (or constellations) of injury for future clinical care, or in the case of non-survivable injury, mitigation strategies. Injury mechanisms can be used to identify exactly how PPE or vehicles need to be modified to prevent future injuries thereby reducing the burden of injury or numbers of fatalities.

1.7. Thesis Aims and hypotheses

The aim of this thesis is to describe and understand the underlying pathology using radiology of blast brain injury. This will begin with a case study from World War 2 before validating a robust radiology tool for classifying computerised tomography images of brain injury. Once underlying pathology from the blast cohorts of Iraq and Afghanistan have been identified, these can be analysed for injury patterns and constellations to focus future mitigation strategies on to prevent injury in future conflicts.

The hypotheses for this thesis is that there will be evidence of primary, secondary and tertiary blast brain injury within the cohorts and that the injuries can be classified in terms of constellations of injuries. Primary blast injury may be exhibited through abdominal and thoracic injury with evidence of increased internal venous pressures causing brain haemorrhage. Secondary brain injury may be evident in the dismounted cohort, where there is direct exposure to energised fragments, thereby causing penetrating brain injury. Tertiary injury may be seen in both cohorts, particularly in the mounted cohort where there will be impact with the ceiling compartment of the cabin due to bodily displacement and an upwards force from the blast.

Chapter 2. Military Penetrating Brain Injury – a case study of early intervention on the battlefield

In 1940 the St Hugh's military hospital for head injury opened. Over the next ten years it treated more than 13,000 patients injured during the second World War. At the head of the hospital was Sir William Hugh Cairns who pioneered research, treatment and neurosurgery for military personnel. The hospital gave those patients specialist care that was not available at a general hospital.

The aim of this chapter is to discuss the history of the hospital and describe a case study of one of the admitted patients to understand the historical aspect of conflict trauma brain injury.

2.1. Introduction

“Cairns could not neglect detail in his projects, publications, or the treatment of patients. Consequently, his legacy has been lasting.” – Leslie John Williams CBE FRCP (1898–1982), British physician

Sir Hugh William Cairns was an Australian Neurosurgeon who joined the British Army after living much of his life in England (Stone, Patel & Bailes, 2016). He completed his Medical degree at the University of Oxford where he would, in time, set up the St Hugh's Military Hospital (figure 2.1).

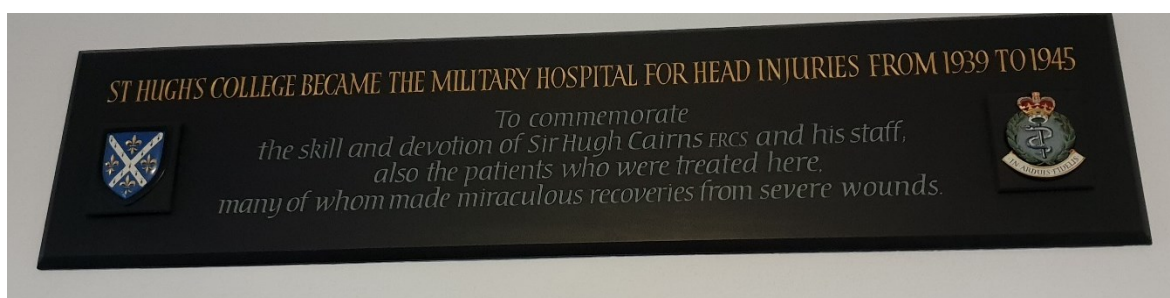


Figure 2-1 St Hugh's college plaque found at Oxford University detailing the history of the centre

Previous publications on Sir Hugh William Cairns highlight his involvement with the World War II treatment of head injuries and the improvement in neurosurgical care during this time. Most publications highlight Cairn's more pioneering work in the development of helmets to prevent motorcyclist brain injury as a result of a road traffic injury (Maartens, Wills & Adams, 2002; Stone, Patel & Bailes, 2016; Sundaravadhanan, 2017). Cairn's most famous (and most published) patient was Thomas Edward Lawrence, otherwise known as "Lawrence of Arabia" (Maartens, Wills & Adams, 2002). Lawrence suffered a fatal head injury after a motorcycle accident. Cairns drove over 100 miles to consult on Lawrence's injury and was permitted by the family to perform an autopsy. Although no autopsy report is available, it is published that Cairns predicted Lawrence would have been saved had he been wearing a helmet; helmets at the time were only used by those in motor races.

Cairns was trained under the well-known surgeon, Harvey Cushing, and as a result was guided to produce high quality documentation and records for future analysis and publication of his World War 2 clinical experiences and accelerated his career as an army surgeon. (Cairns, 1947) (Russell, 1951) (O. L. Zangwill, 1962; Symonds & Ritchie Russell, 1943)

In World War 1, Cushing demonstrated that early intervention of penetrating brain injury had an improved outcome for patients (Carey, 2011) and the mortality rate in those who did not receive early surgical intervention was 50% (Cushing, 1917). With this research in mind and the likelihood of World War 2, Cairns conceived the Mobile Neurosurgical Units and St Hugh's Hospital in Oxford to maintain Cushing's recommended 24-48 hour treatment period (Cushing, 1916).

St Hugh's in Oxford was primarily used for those military personnel suffering from head injury between 1940 and 1945. During the five years of being open, its caseload hit its peak during the Normandy commitments when it housed 430 injured patients. In total, 13,000 patients were referred and treated by St Hugh's hospital, in part, due to it being the only Neurology hospital of its time. After WW2, St Hugh's became a training facility for Neurologists and Neurosurgeons. Cairns used the centre for the training of neurosurgeons, nurses and research into military brain injury and trained the first female neurosurgeon, Diana Beck (Stone, Patel & Bailes, 2016). The Mobile Neurosurgical Units (MNSU's) comprised of a neurosurgeon, a triage neurologist, an anaesthetist, two general medical officers, two nurse sisters, four orderlies, and two drivers. Each unit had a generator, heater, water supply and two operating tables (figure 2.2). These units allowed for treatment as close to the time of injury as possible and repatriation to St Hugh's or a home hospital (Stone, Patel & Bailes, 2016).



Figure 2-2 A mobile Neurosurgical Unit from World War 2. The first MNSU parked outside of the Nuffield Institute of Medical Research, 1940. The vehicle housed all necessary equipment to perform emergency neurosurgical operations. From Cairns H: The organisation for treatment of head wounds in the British Army. Br Med Bull 3:9–14, 1945, by permission of Oxford University Press

2.2. Justification

Fifty percent of fatalities in the First World War had been injured in the head and neck, and fifteen percent of those treated by a Regimental Aid post had a head and neck injury. (Cope Z., 1953) In the First World War cohort, 90% of those with head injuries died, whereas in World War 2 there was a 50% survival rate (Newcombe, 1996), most likely due to the research of Cushing and the encouragement of early intervention within the first 24-28 hours of injury. Due to the number of MNSUs available, 13,000 patients received treatment through Cairns' neurosurgical treatment pathway. But the research and literature around penetrating brain injury in more recent conflicts is less well published. This paper aims to discuss the pathophysiology of World War 2 penetrating brain injury in contrast to the injuries seen in more recent conflicts such as in Iraq and Afghanistan.

2.3. Research Question

This is descriptive historical paper and therefore uses case studies as opposed to statistical analysis. The method used is that for a comparative case study, where multiple cases are compared to form a descriptive conclusion. The aim of this paper is to describe the World War 2 St Hugh's collection and broadly discuss the pathophysiology of brain injuries within the dataset.

2.4. Materials and methods

The historical World War 2 dataset sits in St Hugh's College Hospital and is available to the public with permission from the archivist. It is comprised of 3000 archived patient files from their inpatient stay between 1940-1945 and subsequent follow ups. There are 429 boxes which form the catalogue. For the purpose of this research, the first box containing 40 patient files was accessed; these were in alphabetical order and included patients with surnames beginning with A-C, this was due to the sheer volume of unarchived notes and to ensure complete notes were collected within the time frame that was significantly affected due to the COVID-19 pandemic; during the data collection period the COVID-19 pandemic started before further notes could be collected. The files were described as: "history of illness, lab reports, clinical charts, typescript notes, drawings and diagrams, photographs and/or correspondence, typescript sheets containing admission information, a case history and a record of treatment, as x-ray prints and negatives, observations on tests and checks, clinical charts or correspondence concerning housing, pensions and work placement". Records were visually inspected before being photographed by hand and filed under patient name electronically and securely stored under password protection. At the time of data collection, no records were electronically stored by the College's archive. Some of the records had faded or damaged with time, and some x-rays were unclear due to x-ray techniques and light damage. To avoid further damage to records, gloves were worn. All records were photographed, however, not all were amenable to analysis due to the damage. Although some records were damaged, there were enough records for all 40 notes to be examined.

As all files referenced in this study are a matter of public record concerning deceased individuals; ethics approval was not necessary.

In contrast to modern day imaging and the use of computerised tomography, during WW2, plain X-rays were used to visualise penetrating injury and foreign bodies (figure 2.3). Head x-rays show skull or bone defects, abnormalities, injuries and fractures. In addition, a skull x-ray will visualise any foreign bodies and penetrating fragments. Unfortunately, due to the two-dimensional format of an x-ray the depth and location of foreign bodies cannot be determined as accurately as modern imaging techniques such as computerised tomography scans (figure 2.4).

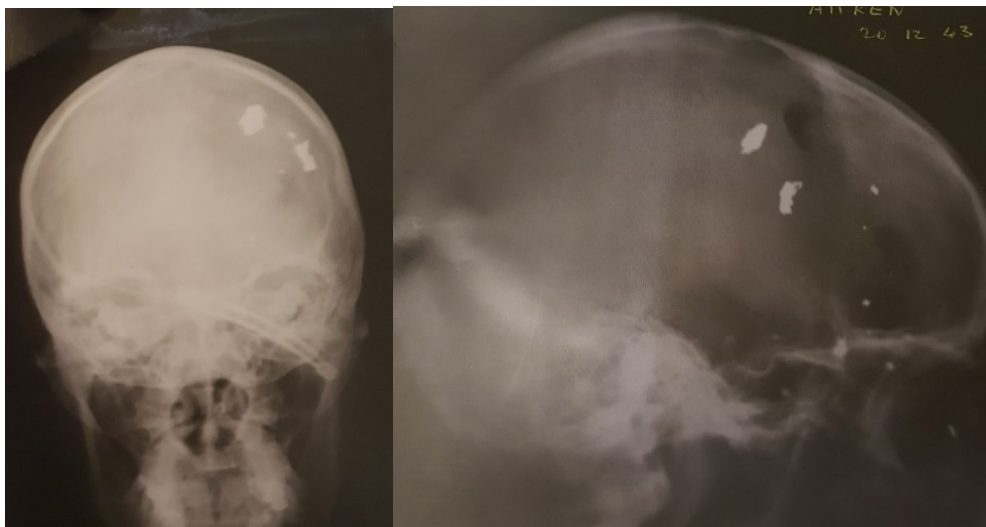


Figure 2-3 Two x-rays demonstrating penetrating brain injury. There are multiple penetrating fragments within the cranial tissue. (undated but approx. 1945, from St Hugh's College Archives)



Figure 2-4 Single slice of Computerised Tomography Post Mortem from Iraq commitments 2008-2012 showing perimesencephalic blood. The image is in sagittal view. reproduced with permission from defence medical services.

In addition to imaging and photography, medical documentation was used to map injuries and symptoms, and included in depth descriptions of medical history and the incident causing injury. Observations such as temperature, reflexes, sensation, and heart rate were also recorded. Some documentation was recorded by freehand (figure 2.5) with no pre-printed proforma whereas others were on standardised assessment sheets.

x-ray showed a foreign body in the right frontal sinus with involvement of the posterior wall (figure 2.6).

The patient went for surgery under regional block anaesthesia. There was comminution and depression of the frontal wall and sinus. All depressed bone was removed. The defect was initially 3 x 2cm, but for removal this was increased to leave a space of 3 x 4cm. The supra-orbital margin was loose and therefore removed. The posterior wall and floor of the frontal sinus, the roof of the ethmoidal sinus, and the orbital wall of the right eye were all found to be shattered. A metal foreign body was removed measuring 1 x 2 x 1 cm. Three tears to the dura were visualised, two of which were repaired. Under the third tear there was necrotic brain tissue along a 4cm track of the frontal lobe. The “mashed” tissue was removed, and the wound closed. The patient was for “usual nursing” and medication, in this case meaning usual rehabilitation care and assistance for the patient’s basic needs.

The next documentation is on the 25th of July 1944, four days following the initial assessment. The patient was alert and cooperative, with a healed surgical wound. There was pulsation under the skull defect where the depressed skull had been removed. Pupils were not equal but did react to light. Motor and sensation appeared normal.

On the 27th of August 1944, the patient had a lumbar encephalogram, which showed colourless cerebrospinal fluid. Imaging showed good filling of the ventricles and no midline shift (figure 2.7). The horn of the right lateral ventricle was marginally enlarged when compared with the left, otherwise the ventricles were equal. The patient had a good recovery with no motor or sensory issues. The plan was for a transfer back to a Polish hospital and return to duty after 3 weeks – approximately 2 months after the initial injury.

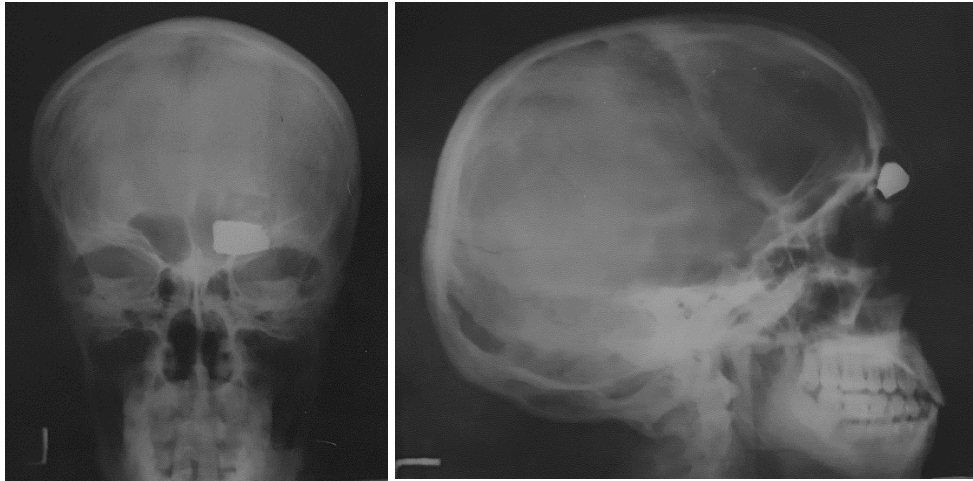


Figure 2-6 Plain film x-rays prior to surgery demonstrating a penetrating fragment to the frontal lobe in coronal (left) and sagittal (right) views,

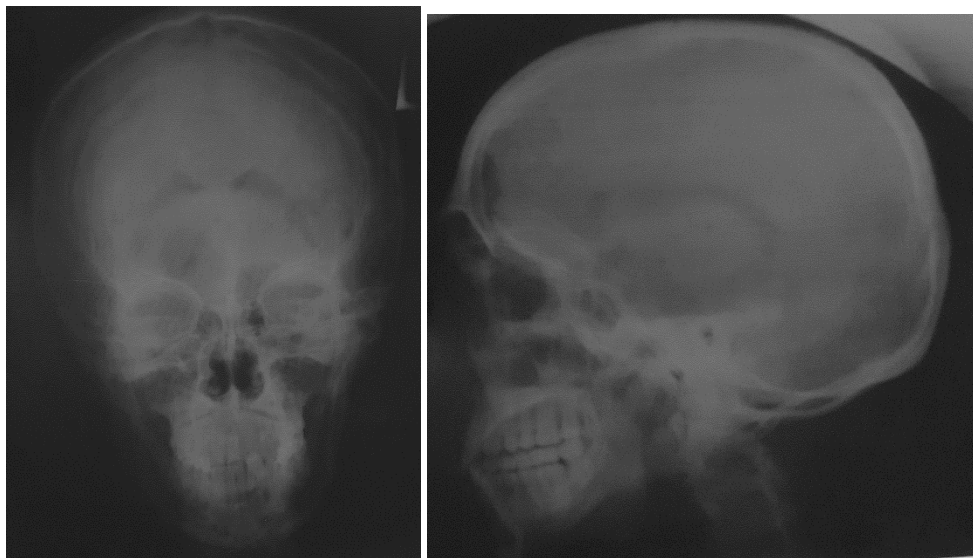


Figure 2-7 Plain film x-rays post-surgery demonstrating the removal of a penetrating fragment in coronal (left) and sagittal (right) views.

2.6. Discussion

The outcome from penetrating injury is dependent on several factors: intracranial path and location of injury, energy and speed of fragments, size and type of fragment, environment of injury and any other body injuries. Typically, in modern day warfare, penetrating injuries have a poor prognosis due to the extensive intracranial damage caused (van Rein et al., 2019), however, as demonstrated by the case study, some injuries seen in the World War II cohort had a good outcome. A theory behind this could be since the explosives used in WWII were less energised than in modern day conflict such as Iraq and Afghanistan and therefore

produced a less serious injury. St Hugh's saw approximately 13,000 patients during WWII and pioneered mobile neurosurgery units to provide high quality care as soon as possible after injury. The MNSU's saw and treated approximately 20,000 patients and pioneered "pre-hospital" neurosurgical care. Previous analysis showed that approximately 90% of patients (Stone, Patel & Bailes, 2016) who were treated with scalp lacerations and minor fractures were returned to their units and deployment, 70% of the brain injured were employable after injury. Post-war, St Hugh's went on to become a training ground for the next generation of nurses, neurologists, neurosurgeons, and anaesthetists.

As seen by the case study described, early treatment was not limited with the provision of an MNSU and meant that patients could return to duty after a period of convalescence. It was clear that this early intervention instigated by Cushings and Cairns benefited this patient and the mobilisation of neurosurgical expertise and skill had an effect on morbidity and mortality. These concepts are still applied to field hospitals in modern warfare. Instead of intervention in the first 24-48 hours, this time is reduced to one hour. The early intervention in trauma is now referred to as the "golden hour". This is the first hour since trauma where early intervention is key to survival, particularly in military settings. (Tallon, Lerner & Mosca, 2002).

The case study has also shown that x-rays and imaging are invaluable for diagnosing brain injury. In addition, they are a useful measurement of pathological disease progression. The x-rays images assist with directing surgical intervention, particularly when removing foreign bodies or performing craniectomies and craniotomies. As imaging techniques have improved, the use of x-rays in brain injury has been replaced by computerised tomography scans (Filler, 2009).

2.7. Limitations

Ideally, for a full analysis of WWII brain injuries, all records would need to be analysed and categorised by injury, survival etc. such as in the modern day Joint Trauma Theatre Registry or Trauma and Audit Research Network database (Gennarelli & Wodzin, 2008). This would be very time consuming given the handwritten aspect of the notes and variability between records. Files were not alphabetically stored, nor organised by date. They were placed disorganised within a WW2 trunk in paper folders and had previously never been used or

analysed. This made the analysis of cases very difficult and time consuming. More recently, this work has been archived alphabetically by patients and would lend itself to an interesting historical piece, both with the radiology records and the handwritten diaries and medical records.

As previously noted, there is variable quality of the records; some records have kept well and are intact, whereas others have decayed over time. Some records have been damaged at the time of writing, i.e. blood stains, rips or dust. The x-rays have also decayed with light exposure making some clearer than others. It is important to understand that the threshold for sending personnel back to the frontline was much lower in WWII than it would be in current day warfare (Stone, Patel & Bailes, 2016; Cairns, 1947) and therefore this is not a truly comparable outcome – however the functional improvements in cognition and mobility are (Cullen & Weisz, 2011).

2.8. Summary

This chapter has discussed the historical aspects of conflict injury through a neurotrauma case study. It has set the scene for the importance of delivering good clinical care at the point of injury and the clinical need to understand the underlying pathology for conflict brain injury. Historically, there was no way to classify these injuries, yet the utility of imaging has been highlighted, and so the next chapter of this thesis uses inter-rater reliability to validate a novel radiological brain injury classification system.

With current conflicts in the Middle East and Eastern Europe, there is an increased use in close-arm combat with limited resources as seen in WWII. Using information from historical conflicts such as WWII can inform future care both from images and medical records, show shortfalls in PPE and how to deploy care to the frontline such as the use of the Mobile Neurosurgery Units.

Chapter 3. The SBNS Traumatic Brain Injury Classification – an overview and inter-rater reliability validation

In the previous chapter, an example of conflict brain trauma from historical archives was described, with findings related to penetrating injury. The importance of radiology was identified as key to the analysis of these injuries and so in this chapter a novel CT based classification system is identified, described and validated prior to its use in subsequent chapter.

This chapter was published in part as: Wilson MH, Ashworth A, Hutchinson PJ, British Neurotrauma Group. A proposed novel traumatic brain injury classification system - an overview and inter-rater reliability validation on behalf of the Society of British Neurological Surgeons British Journal of Neurosurgery. 2022 36:633-638.

(see Appendix A for appended paper)

3.1. Introduction

Injuries from World War 2 were predominantly penetrating, as conflict used more close-quarter weapons in contrast to recent conflicts where improvised explosive devices were used. In addition, mounted blast was much less due to an increased number of “foot soldiers”. Historically, there was no way to classify these injuries until imaging advanced and became more diagnostic of injury. Classically, traumatic brain injury (TBI) has been described as mild, moderate and severe based on the first recorded Glasgow Coma Score (GCS – 13-15; 9-12 and < 8 respectively) (Teasdale & Jennett, 1974; Jennett, 1972), however this was not invented until after World War 2.

This has served well over the last 40 years (Teasdale et al., 2014) especially in remote regions of the world where Computer Tomography (CT) scanning is not possible. However, on an individual patient level, it does not take into account the actual pathology when predicting outcome (Carter et al., 2016). A postictal patient can be GCS 3 with no brain injury and a patient who dies of an extradural might initially have had an initial GCS of 15. The dramatic increase in CT scan availability since the 1970’s offers more pathology and patient specific grading of injury severity. Computerised tomography scans provide much greater indication as to the actual parenchymal nature of TBI rather than the functional (neurological) result (Nayebaghayee & Afsharian, 2016). It could be considered that extra-axial haematoma on their own, whilst they reflect head injury, are not in themselves brain injuries. As they expand however, they may cause brain injury through underlying ischaemia or shift (e.g. Duret’s haemorrhages or coning) if not acted upon.

Lack of imaging may be the cause of a generic “traumatic brain injury” diagnosis being pervasive throughout the patient pathway – from pre-hospital and critical care (where most services have a generic TBI protocol) through to death where a common cause of death is “traumatic brain injury” (Wilson et al., 2016). As pre-hospital imaging becomes potentially possible (Schwindling et al., 2016), earlier diagnosis will enable more pathology specific protocols to be developed. In addition, being able to quantify injury and track disease progression will be beneficial both for civilian and military cohort where time to treatment is critical and based upon the underlying pathology or mechanism.

Applying treatments, be they pharmacological (such as neuroprotectants), physiological (such as targeted cerebral perfusion pressure) or surgical (such as decompression) generically across the TBI spectrum is illogical. When potential treatments are studied, it may be that a potentially revolutionary treatment for one subtype of injury is discounted because its effects are diluted when multiple types of brain injury are included.

3.1.1. Current radiological classification systems

A distinction needs to be made between “classification” and “prognostication” tools. Although commonly referred to as classification tools, the Marshall (Marshall *et al.*, 1991) and Rotterdam (Maas *et al.* 2005) systems are principally used for scoring (which can then be used to classify “severity”) but they do not classify the type of brain injury according to the type and volume of intracranial blood. Brain injury is often heterogeneous, and an individual patient may have several different brain injuries (e.g right subdural and left frontal contusion). A comprehensive system needs to account for these different injuries, not just report “the worst one” as occurs in the abbreviated injury scoring (AIS) system (Gennarelli and Wodzin 2006). The AIS system (as used by the Trauma Audit Research Network in the UK) is a form of radiological classification in that it reports the highest scoring brain injury, but it takes the severity of a location and size of injury and converts it to a number (score). Not all of those numbers are comparable. For example, a cerebellar extradural (score = 3) is not the same as a cerebral laceration (score also = 3). A system that classifies and scores by pathologies may improve specificity.

Current radiological and prognostic tools assessing TBI severity have improved outcome prediction on populations of patients, but beyond predicting survival at 24 hours, they lack precision at an individual patient level (Steyerberg *et al.*, 2008; Stevens & Suiter, 2013). Accurately predicting outcome could support the setting of limits of further interventions, however there is no tool that can provide this accurately and hence this is often done on experience and multi-disciplinary consensus.

Saatman *et al* (2008) demonstrated the heterogeneity of brain injury resulting in GCS < 8 across a range of conditions - extradural (epidural), subdural, contusions, subarachnoid haemorrhage, diffuse axonal injury and general swelling (reflecting hypoxic injury)(Saatman *et al.* 2008). They propose the development of a multidimensional classification model.

However, the beauty and universality of GCS has largely been achieved because of its simplicity and a radiological classification system, to achieve universal adoption, should similarly be usable by clinicians and non-clinicians alike.

The history of development of the Marshall and Rotterdam systems may explain why they are not pathology based. The Marshall CT classification (table 3.1) was introduced in 1991 principally to categorise severity of diffuse injury but it was accepted for its descriptive and predictive value (Marshall *et al.* 1991). The IMPACT (International Mission for Prognosis and Analysis of Clinical Trials in TBI) utilises the Marshall CT score for 6-month outcome prediction in moderate to severe TBI. However, the Marshall CT classification system was not designed for outcome prediction hence in 2005 Maas *et al.* redesigned it for 6-month mortality prediction resulting in the Rotterdam score (Maas *et al.* 2005) (table 3.2). Traumatic subarachnoid blood was added as it had been shown to be a strong independent predictor of outcome (Kakarieka, Braakman & Schakel, 1994).

<i>Category</i>	<i>Definition</i>
Diffuse injury I (no visible pathology)	No visible intracranial pathology seen on CT scan
Diffuse injury II	Cisterns are present with midline shift 0-5mm and /or lesion densities present; no high or mixed density lesion > 25cc may include bone fragments and foreign bodies
Diffuse injury III (swelling)	Cisterns compressed or absent with midline shift 0-5mm; no high or mixed density lesion > 25mm
Diffuse injury IV (shift)	Midline shift > 5mm; no high or mixed density lesion > 25cc
Evacuated mass lesion	Any lesion surgically evacuated
Nonevacuated mass lesion	High or mixed density lesion > 25cc; not surgically evacuated

Table 3-1 The Marshall Computed Tomography (CT) Classification system (Marshall et al. 1991)

<i>Predictor Value</i>	<i>Score</i>
Basal cisterns	
Normal	0
Compressed	1
Absent	2
Midline shift	
No shift or shift $\leq 5\text{mm}$	0
Shift $> 5\text{mm}$	1
Epidural mass lesion	
Present	0
Absent	1
Intraventricular blood or subarachnoid haemorrhage	
Absent	0
Present	1
Sum score	+1

Table 3-2 The Rotterdam Computed Tomography Classification - one point is added as a sum score to make the Rotterdam grade numerically total 6 points, consistent with the motor score of the Glasgow Coma Scale and with the Marshall classification. Reproduced from (Maas et al. 2005)

The Helsinki CT score (table 3.3) takes the Rotterdam scoring system one stage further and proposes a “score” specifically for the type of injury (mass lesion) and its size (Raj et al., 2014). The authors report that this provides a more accurate 6-month outcome prediction.

<i>Variable</i>	<i>Score</i>
Mass lesion type(s)	
Subdural haematoma	2
Intracerebral haematoma	2
Epidural haematoma	-3
Mass lesion size $> 25\text{cm}^3$	2
Intraventricular haemorrhage	3
Suprasellar cisterns	
Normal	0
Compressed	1
Obliterated	5
Sum score	-3 to 14

The probability of 6-month outcome is defined as $1/(1+e^{LP})$, where $LP_{\text{Mortality}} = -2.666 + 0.287 \times \text{Helsinki Computerized tomography score}$ and $LP_{\text{unfavourable outcome}} = -1.636 + 0.319 \times \text{Helsinki computerized tomography score}$. The Helsinki computerized Tomography score ranges from a minimum of -3 to a maximum of 14 points

Table 3-3 The Helsinki CT score (Raj et al. 2014)

A comparative study of the Rotterdam and Marshall scoring systems found that both were good at predicting early death in TBI in Nepal, though the authors suggested that other factors (subarachnoid blood, midline shift and the status of the peri-mesencephalic cisterns) were also predictive (Munakomi, 2016). In conclusion, they suggested these individual

characteristics gave better prognostication than the scoring systems themselves. Chun *et al* demonstrated that both Rotterdam and Marshall classification systems had good interobserver reliability when assessed by neuroradiologists and neurosurgeons (Chun *et al*. 2010).

All the above are scoring, not classification systems. They do not allow comparison between patients as the same score can be achieved through different types of brain injury or volume of haemorrhage. None of the current systems consider the location, size and type of the injury. It is clearly appreciated that areas of the brain have different function and eloquence and hence comparable injuries in one area can potentially have considerable difference to injuries in another.

It should also be noted that systems requiring calculation of intracerebral blood volume, are advised to use the ABC/2 system as a good formula of volume measurement (Newman, 2007).

It could be argued that a magnetic resonance imaging classification system would be more predictive, however, CT scanning is still the workhorse of acute brain injury and is more ubiquitous around the world. For this reason, an injury specific classification based on CT is highly desirable.

Given the complexity of current systems described above and their lack of utility in a clinical setting and use for classifying the volume and type of haemorrhage from imaging, a new classification tool is needed that can be used quickly and give a clear classification of the injury and be used by all members of the multidisciplinary team rather than just those who are used to complex imaging techniques.

3.1.2. The SBNS TBI CT Classification System

The ubiquity and speed of image acquisition with CT scans make them the ideal tool on which to base a uniform classification system. The need for a simple classification was discussed with the British Neurotrauma Group and developed by Mark Wilson and Peter Hutchinson (co-authors). The proposal was then presented to the SBNS council and approved for publication. The proposed system should not require a radiologist to report

and does not require additional measures such as biomarkers. The variables that can be used to describe an injury are its type, severity and location.

There are only a limited number of traumatic brain injury types, although they can occur in combination and in areas of brain of different eloquence. Traumatic Brain Injury types visible on CT are: Extradural, acute subdural, intracerebral haematoma / contusion, traumatic subarachnoid haemorrhage, diffuse axonal injury and hypoxic injury.

The proposed SBNS Brain Injury Classification System (figure 3.1) grades individual brain pathology severities. All brain injuries are scored between zero and three. Additionally, a score can be assigned to “mild TBI/concussion” with a history of TBI but no evidence on CT. There is also a score for raising the signs of raised intracranial pressure or “tightness” (sulcal, ventricular and basal cistern effacement). Hence possible scores are: mild TBI (m+ve/-ve), extradural (E 0-3), subdural (SD 0-3), subarachnoid (SA 0-3), contusion (C 0-3), diffuse axonal injury (DA 0-3), hypoxia (H 0-3), + “Tightness” (0-3). The location of each injury can also be recorded (Frontal, Parietal, Occipital, Temporal, Cerebellum, Brainstem).

Where blood volumes are noted (e.g. extradural haematoma), this can be estimated or calculated using $ABC/2$ (Kothari et al., 1996). For subarachnoid haemorrhage, the key thickness of > 1mm of blood can be anywhere within the subarachnoid space. Small contusions are < 2cm in diameter with medium being 2-5cm diameter. Large are > 5cm diameter.

The intention is not to sum the scores as there is no suggested linear relationship, however it can enable comparisons between patients (e.g. a group of patients with an acute subdural haematoma with no more than a 1 in any other category).

The classification itself is quick and easy to use, and can be used across the multidisciplinary teams. For a member of the clinical team who is able to read scans, the classification takes a matter of minutes to complete, it can therefore be utilised by nurses, medics and radiologist for cross-team communication.

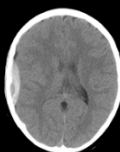
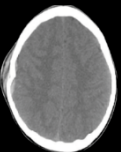
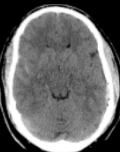
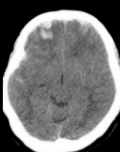
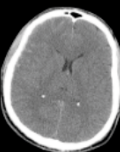
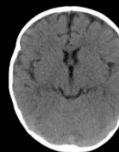
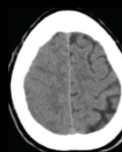
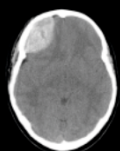
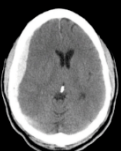
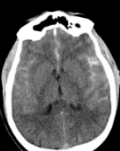
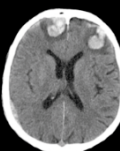
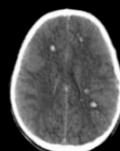
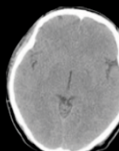
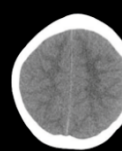
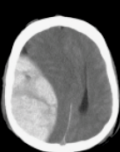
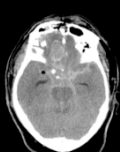
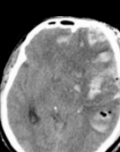
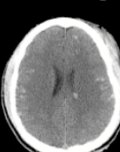
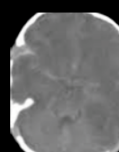
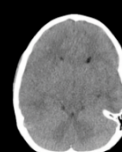
Severity	Extradural	Subdural	Subarachnoid	Contusion / Haematoma	Diffuse Axonal Injury*	Hypoxia*	Signs of *ICP Tightness	Location of Injuries
0	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Left/Right
1	 <10mls	 <10mls	 <1mm thick	 1 small contusion	 1-2 micro- haemorrhages	 Slight loss of grey/white	 Mild sulcal effacement	Frontal Parietal Occipital Temporal Cerebellum Brainstem
2	 10-20mls	 10-20mls	 >1mm thick or localised clots	 1 Medium or 2 contusions	 2-5 micro- haemorrhages	 Some sulcal effacement	 Severe sulcal effacement	
3	 20mls+ (or with midline shift)	 20mls+ (or with midline shift)	 Intra-cerebral/ ventricular / diffuse blood	 Large or multiple (3+) contusions	 >5 micro- haemorrhages/ involves brain stem	 Complete loss of grey/white	 Effacement of sulci and basal cisterns	
*Hypoxia and DAI are easier to visualise on MRI								
Chronic SDH can be reported using same as Acute SDH. Skull fractures can be simple (1), depressed (2) or compound (3)								

Figure 3-1 The SBNS TBI CT Classification. All brain injuries are scored between zero and three. Additionally, a score can be assigned to “mild TBI / concussion” with a history of TBI but no evidence on CT. There is also a score for “tightness” representing the resulting raised ICP (sulcal, ventricular and basal cistern effacement). Hence possible scores are: mild TBI (m+ve/-ve), extradural (E 0-3), subdural (SD 0-3), subarachnoid (SA 0-3), contusion (C 0-3), diffuse axonal injury (DA 0-3), hypoxia (H 0-3), + “Tightness” (0-3).

The aim of this study is to conduct an inter-rater reliability evaluation of the SBNS TBI CT Classification system in order to then use this system to analyse brain pathology from the blast injured cohorts of Iraq and Afghanistan (Chapters 4 and 5) and show its utility for future clinical care across the wider multidisciplinary team.

3.2. Methods

Data from the “Trauma to Injury to Brain Across London” (TriBAL) dataset was used (<http://www.imperialneurotrauma.co.uk/tribal.pdf>). This dataset comprised an audit across London’s Major Trauma Centres capturing data of all TBI patients in London (with a positive CT for acute blood or skull fracture) over a 4-month period. CT scan details and injury scoring using the SBNS brain injury classification (BIC) system were captured for the first 50

consecutive datasets. This included size, location and type of haemorrhagic injury, presence of consciousness and presence of skull fracture and pneumocephalus. This was collected for the first CT scan upon presentation to hospital.

The CT head scans were reviewed by 5 raters of different levels and types of experience, as has been done for other CT classification systems previously (Khan *et al.* n.d., Chun *et al.* 2010). The raters comprised a nurse, senior house officer (resident physician), neurosurgical registrar (chief resident), neurosurgical consultant (attending physician) and a consultant neuroradiologist. Raters were blinded to each other and to the patient demographics. Access was given to the initial CT head scan (soft tissue and bone windows) for each patient on admission and raters were asked to classify this according to the SBNS BIC.

Data were analysed using SPSS 24.0 (IBM, Armonk, NY: IBM Corp). Inter-rater reliability and overall agreement were calculated through the Cronbach's alpha including confidence intervals for intra-class coefficients. Cronbach's alpha was also calculated with each individual rater's score removed to check the weighting of each rater on agreement. Cronbach's alpha measures internal consistency and reliability, a score above 0.7 shows acceptable consistency, above 0.8 shows good consistency and above 0.9 shows excellent consistency. The approach has been used to be consistent with other studies. Cohen's Kappa was calculated to assess agreement between individual raters. Landis and Koch guidelines were used to interpret agreement where 0 is poor, 0-0.2 is slight, 0.2-0.4 is fair, 0.4-0.6 is moderate, 0.6-0.8 is substantial and 0.8-1.0 is almost perfect (Landis & Koch, 1977). The agreement of the reviewer's interpretation was determined by comparison to the consensus opinion once all reviewers had scored the CT scans as defined in the methods of a previous study (Chun *et al.* 2010). Average inter-item correlation was calculated to analyse internal consistency and reliability. It is a measure of consistency of individual classification types (for example, each injury type). To show that the values of Cronbach's alpha were not heavily weighted on one particular rater, values were calculated with each rater removed. This was calculated for the removal of each rater, in turn.

3.3. Results

The study patients had a median age of 54.5 years with an interquartile range (IQR) of 35.3 – 72.1 years and were predominantly (84%) male. The median pre-hospital GCS was 12 (IQR 8-

15)), and in-hospital GCS was 11 (IQR 6-15). The most common mechanism of injury was falls of less than 2m (32%) followed by falls greater than 2m (30%) (Table 3.4). As a mean number of diagnoses from raters, 24 of the 50 patients had acute subdurals (20.7%), 7 had extradural haematomas (6.1%), 21 had subarachnoid haemorrhage (18.1%), 5 had chronic subdural haematomas (3.9%), 16 had evidence of Tightness (13.9%), 23 had skull fractures (19.3%), 2 (1.4%) patients had evidence of diffuse axonal injury, and nil with overt hypoxia (hypoxia and DAI are normally seen on magnetic resonance imaging; Table 3.5).

<i>Mechanism</i>	<i>No. (%)</i>
Assault (blunt)	5 (10)
Fall >2m	15 (30)
Fall <2m	16 (32)
RTC Vehicle	2 (4)
RTC Pedestrian	6 (12)
RTC Cyclist	2 (4)
Unknown	4 (8)

Table 3-4 Patient demographics

<i>Injury</i>	<i>Mean No. of injuries (% range from all raters)</i>
ASDH	24 (20.7, 14-31)
EDH	7 (6.1, 4-13)
Contusion	20 (16.9, 15-23)
SAH	21 (18.1, 16-32)
CSDH	5 (3.9, 3-7)
DAI	2 (1.4, 0-5)
Tightness	16 (13.9, 7-21)
Skull Fracture	23 (19.3, 19-26)
Hypoxia	0 (0, 0)

Table 3-5 Injury pathology as identified by all raters

3.3.1. Inter-rater reliability

Agreement by percentage was measured for same injury and the same score for each individual pathology. Results above 70% were shown for all injuries indicating good

agreement. However, some injuries were low in prevalence (such as DAI and chronic subdurals) and therefore these results should be analysed with caution (Table 3.6). Scores for agreement of absence or presence of injury (by consensus) were above 80 % agreement. All injuries showed good or excellent consistency other than DAI (which is usually diagnosed on MRI imaging) and Tightness (Table 3.6). Inter-item correlations were lower for DAI and for Tightness (Table 3.6).

Removing individual raters when calculating the Cronbach's alpha did not impact the score significantly using a non-parametric test for significance ($p > 0.05$) and therefore it can be assumed the Cronbach's alpha is accurate (Table 3.7).

Kappa coefficients were calculated between individual raters and as a whole group of raters. The grouped values were compared to a previous study which also used 50 CT scans of traumatic brain injury and interobserver variability when assessing for injury (Chun *et al.* 2010). Previous inter-observer and inter-rater reliability studies for CT scoring tools, not just those for head CTs, used percent numbers between 41 and 50 for inter-rater reliability and 5 separate raters (Chun *et al.*, 2010; Khan *et al.*, 2011). The Kappa coefficient for the SBNS classifications are lower than those of the other rating tools (Marshall, Rotterdam and individual assessment), however, as highlighted this is dependent of prevalence of injuries (Table 3.8). The Median Kappa coefficients for injuries between raters was also calculated (Table 3.9).

<i>Injury</i>	<i>Agreement of same injury same score (%)</i>	<i>Agreement for absence or presence of injury (%)</i>	<i>Cronbach's alpha</i>	<i>Average Inter-Item Correlation between individual raters</i>
ASDH	76	83.6	0.93	0.73
Contusion	78.8	91.2	0.92	0.72
CSDH	93.6	95.6	0.93	0.70
DAI	96.8	96.8	0.70	0.48
EDH	92	93.2	0.90	0.69
SAH	74.4	84.8	0.87	0.59
Tightness	79.2	84.4	0.77	0.42
Skull #	90	N/A	0.93	0.72

Table 3-6 A table to show the percentage agreement of raters for same injury and same score, and for absence or presence of injury my majority vote. Additionally, Cronbach's alpha for individual injuries, where scores above 0.7 show acceptable consistency, above 0.8 good consistency and above 0.9 excellent consistency. Finally the last column displays the median inter-item correlation matrix values between raters.

	<i>Cronbach's alpha</i>	<i>RATER 1 removed</i>	<i>RATER 2 removed</i>	<i>RATER 3 removed</i>	<i>RATER 4 removed</i>	<i>RATER 5 removed</i>
ASDH	0.93	0.91	0.92	0.92	0.96	0.91
Discrepancy		0.02	0.01	0.01	-0.03	0.02
CSDH	0.92	0.90	0.92	0.89	0.96	0.92
Discrepancy		0.03	0.01	0.03	-0.04	0.01
Contusion	0.93	0.96	0.91	0.92	0.90	0.91
Discrepancy		-0.03	0.02	0.02	0.04	0.02
DAI	0.74	0.63	0.71	0.58	0.71	0.58
Discrepancy		0.11	0.03	0.16	0.03	0.16
EDH	0.90	0.84	0.92	0.85	0.88	0.90
Discrepancy		0.06	-0.02	0.05	0.02	0.00
SAH	0.87	0.85	0.85	0.84	0.85	0.83
Discrepancy		0.02	0.04	0.06	0.05	0.07
Skull #	0.93	0.92	0.95	0.90	0.90	0.89
Discrepancy		0.01	-0.02	0.03	0.03	0.03
Tightness	0.79	0.71	0.79	0.69	0.79	0.72
Discrepancy		0.07	-0.01	0.09	0.00	0.07

Table 3-7 Cronbach's alpha for each injury type showing the change in Cronbach's alpha with removal of each rater. Negative change in score means that the reliability of the ratings would improve if that rater was removed.

<i>Injury</i>	<i>Kappa co-efficient between raters: SBNS BIC</i>	<i>Kappa co-efficient between raters using other diagnostic tools (Chun et al., 2010)</i>
ASDH	0.4484	0.531
EDH	0.4252	0.615
CONTUSION	0.4517	0.332
CSDH	0.5232	NO COMPARISON
DAI	0.3889	0.332
TIGHTNESS	0.2792	NO COMPARISON
MIDLINE SHIFT >5	NO COMPARISON	0.652
EFFFACED/ABSENT BASAL CISTERNS	NO COMPARISON	0.691
SKULL FRACTURE	0.7132	0.59
SAH	0.319	0.669
ANY ABNORMALITY	0.4436	0.568

Table 3-8 Comparison of average Kappa coefficients for individual injuries with the literature.

	<i>Kappa Coefficient</i>	<i>with DAI removed</i>
Rater 1 v Rater 2	0.45	0.47
Rater 1 v Rater 3	0.50	0.53
Rater 1 v Rater 4	0.43	0.45
Rater 1 v Rater 5	0.46	0.46
Rater 2 v Rater 3	0.35	0.4
Rater 2 v Rater 4	0.43	0.35
Rater 2 v Rater 5	0.38	0.34
Rater 3 v Rater 4	0.39	0.46
Rater 3 v Rater 5	0.47	0.5
Rater 4 v Rater 5	0.58	0.57

Table 3-9 Median Kappa coefficients for injuries between raters. Diffuse Axonal Injury was excluded because of low numbers.

3.4. Discussion

We have described a novel and simple classification system that enables comparisons based on discrete CT pathology and assessed its inter-rater reliability amongst healthcare professionals with varying experience of analysing CT scans. The results demonstrate strong

agreement between raters for all injuries except for DAI, which shows fair agreement justified by its lower prevalence compared to other injuries. Other scoring systems in the literature have found comparable results, in particular, in response to low prevalence of injuries (Chun *et al.* 2010). When compared with the results from Chun *et al.* (2010) (table 3.6), the SBNS score showed comparable levels of agreement using Kappa coefficients for ASDH and DAI. Agreement was stronger using the SBNS score for contusions and skull fractures. There was weaker agreement using the SBNS score than other classifications for extradural haematoma and subarachnoid haemorrhage. There was no comparison for consciousness, midline shift, effacement of basal cisterns and chronic subdural haematoma. These results therefore show that the SBNS BIC, when compared to other scores is comparable, if not better at diagnostically categorising some injuries. The benefit of the SBNS BIC however is the simplicity and the reporting of actual brain injury pathology enabling patient and treatment comparisons. The inclusion of a score for signs of raised ICP ("consciousness") should additionally support additional comparisons between patients especially where ICP monitoring is not routine (Chesnut *et al.*, 2012). Chun *et al.* (2010) also found that contusions and DAI had the lowest sensitivity for detection by CT imaging, whereas EDH, intraventricular haemorrhage and parenchymal hematomas had the highest. It was also found that there was poor agreement between raters for SDH and contusion, in particular in relation to measuring volumes of blood using the classification and scoring tools. One reason for this may be due to the accuracy of volumes needed for the tools which has been mitigated by the SBNS classification using broader scoring categories for volumes of blood (Chun *et al.* 2010). Chun *et al.* (2010) only used experienced neurosurgeons and neuroradiologists whilst in this current study agreement was demonstrated across a breadth of experiences.

This study has some limitations. The sample size was comparable to those of similar studies, however, due to the number of injuries within the scoring system, this resulted in a small prevalence of some injuries, meaning that the statistics may have been skewed. Despite this limitation, it is accepted that Kappa scores as low as 0.41 may be acceptable in healthcare applications (McHugh, 2012). Intra-rater reliability was not used, to be consistent with other studies validating tools and due to the heterogeneity of brain injury and therefore validate

this tool in the same way. Other tools were not used as comparators as there is nothing that uses solely CT images for categorisation that could be comparable.

To improve the study further and investigate inter-rater reliability more scans of varying pathology would be useful along with more raters. Inter-operator reliability – i.e. asking the same clinician to rate the same scans more than once would also show the reproducibility of results and further strengthen the utility of the tool.

3.5. Future work

This study focuses on blunt TBI. It could be possible to extend the classification system into penetrating injuries by adding in Penetrating (low velocity = 1, high velocity = 2) and the location affected. Penetrating TBI from gun/knife crime, terrorism, conflict and work related injury can contribute a large burden of TBI care (Sears et al., 2013; Chang, Guerriero & Colantonio, 2015). This can also be complex pathologically with low and high velocity components, the effects of blast and the ensuing risks of infection (Magnuson, Leonessa & Ling, 2012). Therefore, the utility of this scoring system for such additional injuries has not been assessed and it is expected that it will be modified as future work in this field progresses. As the World War 2 caseload demonstrated, there is a high burden of penetrating injury in conflict medicine historically and using such a tool to classify injuries could provide an insight in the development of conflict TBI.

3.3.2. Converting this classification system into a prediction tool:

Once used in a larger population it will be possible to provide a weighting to the classification of different injury types to provide a clinical prognosis or outcome. For example, the outcome of patients who suffer from DAI varies significantly to those who have an extradural haematoma. Scores for injuries can be weighted to reflect these differences in prognosis to predict outcome, in the way that current systems such as the Marshall CT score do. Similarly, assessment in changes of scores over time may be a prognostic indicator and identify the need for intervention.

Radiological severity of brain injury is just one factor in outcome prognosis. The constitutional factors of the patient (age/comorbidities), extent of other injuries and

neurological and physiological factors can also be influential, hence these should be factored in.

It is envisaged that utilising large data and outcome registries we will be able to populate an equation and develop the factors a,b,c,d,e,f,g to weight individual pathological elements and more accurately predict not just of mortality but also functional outcome:

$$\text{e.g. } a(mTBI (+ve/-ve)) + b(E(0-3)) + c(SD(0-3)) + d(DA(0-3)) + e(H(0-3)) + f(T(0-3)) + g(\text{"Tightness"}(0-3))$$

(where E = Extradural score, SD = Subdural score, DA = Diffuse Axonal score, H = Hypoxia score and T = Tightness score).

Additionally physiological parameters could subsequently be included:

$$\text{e.g. } h(\text{Frailty Index}) + i(\text{Other injuries} - \text{ISS}) + j(\text{Neurology} - \text{GCS}) + k(\text{Physiology, BP, Glucose, Lactate etc}).$$

Over time these components will be refined. For example, a biomarker level may give a further indication of amount of neuronal damage, which when put into the above will enable even greater prognostication. This does, however, require very large datasets and an understanding of covariant factors. Patient data and characteristics would be collected along with outcome to determine the weighting.

3.6. Conclusion

Current CT classification of TBI systems are not injury pathology specific and are difficult to remember and apply. Here a simple (mild, moderate and severe) system for different types of brain injury is presented that allows for concomitant brain injuries. The system has good inter-rater reliability across a broad range of experienced users. Utilising such a classification has the potential to assist in clinical management, and enable more specific investigation of potential neuroprotectant, physiological and surgical treatments and more accurate prognostication for individual patients.

Future application of the tool would be for communication across teams of the patient injury, and a record of patient progression due to its simplicity and ease of scoring. It is also a useful scoring tool to be used as part of patient databases and big data capture.

This tool was used for classifying the CT scans in this study due to its application in both living and post-mortem scans. It can also be used by the PhD student with no medical training and it is the only tool that quantifies the volume and type of brain injury in order to assess and correlate injury patterns.

The following two chapters utilise this tool to classify and understand the underlying pathology of fatalities in both dismounted and mounted blast injury from the Iraq and Afghanistan conflicts.

Chapter 4. Injuries in fatalities of underbody blast: identification of five distinct mechanisms of head injury.

The previous chapter validated a radiology classification tool within a civilian population, for the use of understanding the underlying pathology of brain injury from CT scans. This chapter uses the tool to classify the CT brain scans of military personnel who were fatally injured during Iraq and Afghanistan commitments in underbody blast only. As such, this is directly addressing the main thesis aim which is to understand the radiology and pathology of blast brain injury.

This chapter was published in part as: Ashworth, E., Baxter, D., Gibb, I., Wilson, M. & Bull, A.M.J. (2022) Injuries in Underbody Blast Fatalities: Identification of Five Distinct Mechanisms of Head Injury. Journal of Neurotrauma. doi:10.1089/neu.2021.0400.

(see Appendix A for appended paper)

4.1. Introduction

As shown in Chapter 1, Traumatic Brain Injury (TBI) is a common injury in conflict due to blast. During the last century's conflicts, for example in Northern Ireland, the Falklands and Vietnam, between 16 and 21% of personnel suffered a TBI (Champion et al., 2003). More recently, blast was identified as the primary mechanism of TBI in Iraq and Afghanistan (Bhattacharjee, 2008), responsible for up to 81% of injuries (Wade et al., 2006; Belmont et al., 2012; Eskridge et al., 2012; Snell & Halter, 2010; Stewart, Pearce & Clasper, 2019; Regasa, Agimi & Stout, 2019). Of the 2440 personnel injured and listed in the Joint trauma and theatre registry, TBI was present in 424 (Hawley et al., 2014). Blast injuries can be described as primary, secondary, tertiary and quaternary. Primary blast brain injuries are caused by a wave of over-pressurised air from the detonation of an explosive device, yet the details of how this produces brain injury is not well understood (Bryden, Tilghman & Hinds, 2019). Secondary blast is when material or debris, as a result of the forces produced from detonation, makes an impact with the body and can be akin to ballistic trauma. Tertiary blast is when the expulsion of kinetic energy from the blast causes acceleration/deceleration and can result in very severe blunt trauma. Quaternary blast is less applicable to head injuries as this consists of all other injuries not encompassed by the other types such as burns or noxious gases (Centres for Disease Control and Prevention, 2006). In this paper primary, secondary and tertiary blast traumatic brain injuries are classified as blast traumatic brain injury (bTBI) as it is not possible to identify different components of blast to the causal effect in clinical scenarios as opposed to modelled events.

Underbody Blast (UBB), or mounted blast, has been a common mechanism of injury in recent UK commitments (Ramasamy et al., 2008; Carey, 1987). This mechanism has been extensively studied in terms of injury patterns on regions of the body, however, the evidence on head and neck injury patterns is limited. UBB most commonly arises due to the use of Improvised Explosive Devices (IEDs) against vehicles and IEDs remain a threat worldwide (Eastridge et al., 2012). When an IED is detonated under a vehicle, the force and energy created causes soil and the vehicle to be expelled upwards, deforming the vehicle floor (Ramasamy et al., 2011). Any participants inside the vehicle are also exposed to rapid acceleration leading to injuries of the lower limbs, pelvis, spine, thorax, neck and head.

There are two main injury profiles identified: lower limb injury due to floor deformation and pelvis, spine and head injury due to the acceleration of the seat and vehicle (figure 4.2). The acceleration of the seat forces the pelvis up, increasing the load upon the spine, thorax, neck and head, however, the precise mechanism which causes head injury remains unknown (Ramasamy et al., 2008). As rapid acceleration causes injury to the entire body, collecting additional data including injuries to the abdomen and thorax will help show correlation between specific brain injuries and mechanism.

The United Kingdom Joint Trauma and Theatre Registry (JTTR) is a prospective database of trauma casualties from UK military commitments, including all fatalities. Injuries are classified using the Abbreviated Injury Scale (AIS) 2005-Military2 (Gennarelli & Wodzin, 2006) and the worst injuries from the AIS are described as “Top Injury 1” and “Top Injury 2”. Previous analysis from the JTTR showed that of all UBB fatalities, 75% of fatalities had injuries to the Central Nervous System (CNS) encompassing the head, neck and spine (Stewart, Pearce & Clasper, 2019). Three injury mechanisms were proposed: direct trauma to the cranium as a result of the head striking the vehicle roof or other object producing skull fractures and cervical spine injuries (55%); through force transmission from below and from the cervical spine to the base of the skull (32%); and compression/bending of the neck producing brainstem injuries and high cervical spine injuries (12.5%) (Stewart, Pearce & Clasper, 2019). This research was based upon classification of AIS scores only, which showed that head injuries in this group of fatalities is significant to warrant further exploration into injuries and mechanism (Stewart, Pearce & Clasper, 2019). Computed Tomography Post Mortems (CTPMs) undertaken as part of forensic examination on repatriation have also been used to identify mechanisms of injury of underbody blast in various studies including spinal and pelvic injuries to (Spurrier et al., 2015) enabling comparisons between studies.

There are various scoring methods for brain injury currently used across neurosurgery and neurotrauma; all vary by method and prognosis. The Marshall CT, CRASH-CT and IMPACT models being some of the most commonly used. The Marshall CT Classification uses CT variables for prognosis only, but does not classify the TBI on CT according to radiology status (such as actual brain pathology and injury location) and options for radiology variables are limited (Marshall et al., 1992). The Rotterdam score addressed some of the limitations of

the Marshall score, adding additional injury variables such as subarachnoid haemorrhage and extradural haemorrhage (Deepika et al., 2015). The IMPACT and CRASH-CT models for classification are useful for triage as they rely on the pathological and physiological features of the patient's presentation – therefore not impacting or directing immediate care but providing a retrospective score. Both scores give binary outcomes (either favourable or unfavourable) and are therefore poor prognostically (Menon & Zahed, 2009).

A recently-presented tool, the Society of British Neurosurgeons Brain Injury Classification (SBNS BIC) (Wilson, Ashworth & Hutchinson, 2022), uses CT scans and classifies injuries by quantity (severity) using acute subdural haematoma, chronic subdural haematoma, extradural haematoma, contusions, subarachnoid haemorrhage, diffuse axonal injury, hypoxia, consciousness and evidence of skull fracture. These are given a number to represent the severity of injury and can be identified by location. For clarity and comparison purposes the SBNS BIC was chosen for this study (Wilson, Ashworth & Hutchinson, 2022).

Given that the prevalence of brain injury in mounted blast is high and that trauma to the head has been found to be one of the most life threatening injuries (Eastridge et al., 2012), there is a need to identify the mechanisms that cause specific head injuries in order to develop mitigation or treatment strategies.

The aim of this study is to combine JTTR injury scoring with radiological findings to identify the patterns of head injury of fatalities in under body blast to elucidate the mechanisms causing such injuries and whether mortality could be mitigated.

4.2. Methods

Following permission from the Surgeon General (United Kingdom), Defence Medical Services Caldicott Guardian, a search of JTTR was performed to identify fatalities who had suffered head injury and relevant CTPM images were reviewed on the MoD Patient Archive and Communication System (PACS). The search criteria were an Abbreviated Injury Scale (AIS) of 2 or above in the head region, as a result of UBB. The inclusion dates were 2007-2013 to encompass commitments from Iraq and Afghanistan. All fatalities had a CTPM. The CTPMs were performed as soon after fatality as possible. In those patients who survived to be treated in a UK hospital, but subsequently died of wounds, the initial scan (the first scan on arrival to a medical facility) was used for classification purposes. Demographics from the

JTTR were collected along with details from the radiology records. In addition, the top injury regions 1 and 2 were collected, these were the two body regions with the most severe injuries.

Head injuries were scored radiologically using the SBNS BIC. The SBNS BIC creates a score for different types of head trauma giving each injury a score from 0-3 depending on severity. Specifically, data on extradural haematoma, acute subdural haematoma, chronic subdural haematoma, subarachnoid haemorrhage, contusions, diffuse axonal injury, hypoxia, brain oedema (raised intracranial pressure) and presence of skull fracture are included. This was collected along with the AIS (Baker *et al.*, 1974) which is used in the JTTR. The AIS version used is the AIS military version (AIS 2005-Military2). The radiological features were classified by a Consultant Radiologist, Neurosurgical Consultant and a Trauma Nurse.

Extra parameters collected included any other head injury not encompassed by the SBNS BIC to identify mechanism and patterns of injury that may not be typically associated with trauma but would be useful to explore mechanism of injury (Appendix 1). These were: ventricular blood, location of injury, pattern of injury, skull fractures, spinal injury location and extra-cranial injury listed by the JTTR. Additionally, spinal injuries by vertebral region (C0-C1, any other C-spine fracture, thoracic, lumbar and sacral fractures) and the extra-cranial injury AIS scores of three or higher (Baker *et al.*, 1974) of the thorax and abdomen were also recorded as a way of exploring injury mechanism.

Basic demographics, injuries and correlation analyses were conducted to identify injury patterns and potential mechanisms.

Pearson's chi squared was used to reject independence between injuries using a p-value of 0.05 for significance. In those injuries with lesser prevalence, a Fisher's exact test was used with a p-value of 0.05 to reject independence. Multiple independence tests were calculated on the data, increasing the risk of false positives (Type I error). However, the risk of Type I error was deemed to have a lower impact than the risk of a Type II error in order to identify potential patterns of injury as this is the first time the data has been manipulated in this way and used for injury correlation purposes. For these reasons a Bonferroni correction was not applied to the data (Armstrong, 2014).

The injuries that showed correlation were divided up into injury constellations, of which there were four, and it was determined what percentage of patients fell under each category.

Statistical analysis was performed using Microsoft Excel 2007 (version 12.0, Redmond, WA, USA) and IBM SPSS (version 26, Armonk, NY, USA).

4.3. Results

Complete CTPMs were available for forty-six UK military fatalities of UBB who also were listed as having a brain injury, out of a total 212 fatalities for the same time period (2007-2013).

The SBNS Brain Injury Classification Tool showed that subarachnoid haemorrhage was the most frequent injury, occurring in 37 (80.4%) fatalities. Skull fracture was present in 29 (63.0%) fatalities, of which 5 (10.9%) had an eggshell pattern of fractures. Contusions were seen in 13 (28.3%) fatalities; however, extradural, acute subdural, diffuse axonal injury and tightness were seen in much lower numbers of 2 (4.4%), 3 (6.5%), 1 (2.2%), and 7 (15.2%) respectively. Chronic subdural haematomas and hypoxic changes were not seen (table 4.1).

	<i>Subarachnoid</i>	<i>Skull Fracture</i>	<i>Contusion</i>	<i>Tightness</i>	<i>Acute Subdural</i>	<i>Extradural</i>	<i>DAI</i>	<i>Hypoxia</i>	<i>Chronic Subdural</i>
Injury prevalence # (%)	37 (80.4)	29 (63)	13 (28.3)	7 (15.2)	3 (6.5)	2 (4.4)	1 (2.2)	0 (0)	0 (0)
Risk Ratio	1.84	0.76	1.54	1.8	0.93	3.09	N/A	N/A	N/A
Fishers Exact	0.0001	0.02	0.26	0.37	1	0.56	0.39	N/A	N/A

Table 4-1 Head injury prevalence as categorised by the SBNS brain injury classification, displaying Risk Ratio and Fisher's Exact Test (n=46).

Additional radiological examination showed that the most common additional injury found was blood within the ventricles, more specifically the lateral ventricles and 4th ventricle in 29 (63%) and 16 (34.8%) respectively. Blood in the foramen magnum was present in 9 (19.6%) fatalities, brain stem in 4 (8.7%) and pneumocephalus unrelated to tissue degradation in 3 (6.5%) fatalities (table 4.2). The Fisher's exact test shows that only the risk

ratio of 2.03 of 4th ventricle blood is statistically significant. Without further data available, the risk ratios are still clinically significant in determining injury mechanisms.

	<i>4th Ventricle</i>	<i>Lateral Ventricles</i>	<i>Foramen Magnum</i>	<i>Brain Stem</i>	<i>Pneumocephalus</i>	<i>Perimesencephalic blood</i>
Prevalence of Injury. # (%)	29 (63)	16 (34.8)	9 (19.6)	4 (8.7)	3 (6.5)	20 (43)
Risk Ratio	2.03	1.07	2.78	3.09	4.63	6.17
Fisher's exact	0.0011	0.84	0.77	0.21	0.3	0.00001

Table 4-2 Prevalence of additional locations of head injury not categorised by the SBNS, displaying Risk Ratio and Fisher's Exact Test.

Spinal fractures of the lumbar (24; 52.2%), sacral (23; 50.0%), thoracic (22; 47.8%) and other cervical-spine region (21; 45.7%) were similar in frequency. In addition, atlanto-occipital fracture (fractures to the C0-C1 region) were seen in 14 fatalities (30.4%).

Based on AIS scores, thorax injury was described as the secondary injury in 26 (56.5%) cases, abdomen in 5 (10.9%), spine in 4 (8.7%) and limbs in 3 (6.5%). Nine (19.6%) had evidence of perimesencephalic blood.

The Chi-squared and Fisher's exact tests showed independence could be rejected between contusions and fractures at C0/C1, abdomen injury, and abdomen and thoracic injury together. Independence could also be rejected for fourth ventricle blood and blood in the lateral ventricles, foramen magnum and perimesencephalic blood. The Chi-squared and Fisher's Exact also showed a rejection of independence for skull fractures and injury to the brainstem, and three or more spinal fractures. Additionally, independence could be rejected for patients with multiple spinal fractures and injuries to the thorax, abdomen and both injuries co-existing. For those injuries where it was found that independence could be rejected, an injury constellation was hypothesised. Four of these groups were identified. These were perimesencephalic blood or blood in the ventricles and injury to the abdomen or thoraces, multiple spinal injuries with abdomen and thoracic injury, contusions and a fracture at C0-C1 with abdomen and thoracic injury and multiple spinal injuries. In addition to the constellations, an eggshell pattern of fractures was identified which can occur in all four constellations. All fatalities were assessed to see whether they fell into one of these four injury constellations or none at all (table 4.3).

Perimesencephalic blood, blood in the ventricles and injury to the abdomen or thoraces was present in 44.4% of patients. Multiple spinal injuries with abdomen and thoracic injury were prevalent in 37.7% of patients. Contusions and a fracture at C0-C1 was present in 15.6%, and spinal fractures with brainstem injury in 13.3%. There were 31.1% of patients who did not fall into any of these categories, mainly due to the fact they had devastating head injury beyond assessment. There was minimal overlap between categories, other than between patients with multiple spinal fractures and perimesencephalic blood both with abdomen and thoracic injury, where 7 patients had both injury constellations.

		Injury Constellation					
		Multiple spinal and abdo/thoracic injury, n(%)	Perimesencephalic and ventricular blood with abdo/thoracic injury, n(%)	Spinal and brainstem injury, n(%)	Contusions and injury at C0C1 with abdo/thoracic injury, n(%)	Eggshell pattern skull fracture, n(%)	None or decapitation,
Number of patients (%)		17 (37.7)	20 (44.4)	6 (13.3)	7 (15.6)	5 (10.9%)	14 (31.1)
Injury Constellation	Multiple spinal and abdo/thoracic injury, n(%)		7 (15.2)	2 (4.3)	3 (6.5)	2 (4.3)	
	Perimesencephalic and ventricular blood with abdo/thoracic injury, n(%)			3 (6.5)	2 (4.3)	1 (2.1)	
	Spinal and brainstem injury, n(%)				1 (2.1)	2 (4.3)	
	Contusions and injury at C0C1 with abdo/thoracic injury, n(%)					1 (2.1)	

Table 4-3 Injury Constellations and their associations with other injuries by number of patients

4.4. Discussion

This study is the first study to identify injury constellations of fatalities with associated head and neck injuries due to UBB by combining data from the JTTR with the available scans and images of post-mortems from Operation Herrick in Afghanistan and Telic in Iraq. Five injury constellations were found that may highlight potential mechanisms of injury. These are described below.

4.4.1. Multiple spinal injuries in addition to skull fractures and brain stem injury.

The data showed a link using tests of independence between fractures at the C0-C1 junction and three or more fractures of different regions of the vertebrae (cervical, thoracic, lumbar, sacral) and skull fractures (figure 4.1). The likely mechanism for this would be an axial force

causing compression of the spine by an upwards force of the blast (figure 4.2 thereby being a tertiary blast injury. Three or more fractures were present in 46% of the cohort, indicating a substantial injury prevalence. This severe type of injury would not be amenable to treatment, therefore focus should be aligned to mitigation, for example through seat design, restraints or vehicle floor and compartment design, for example increasing crumple zones withing vehicles.

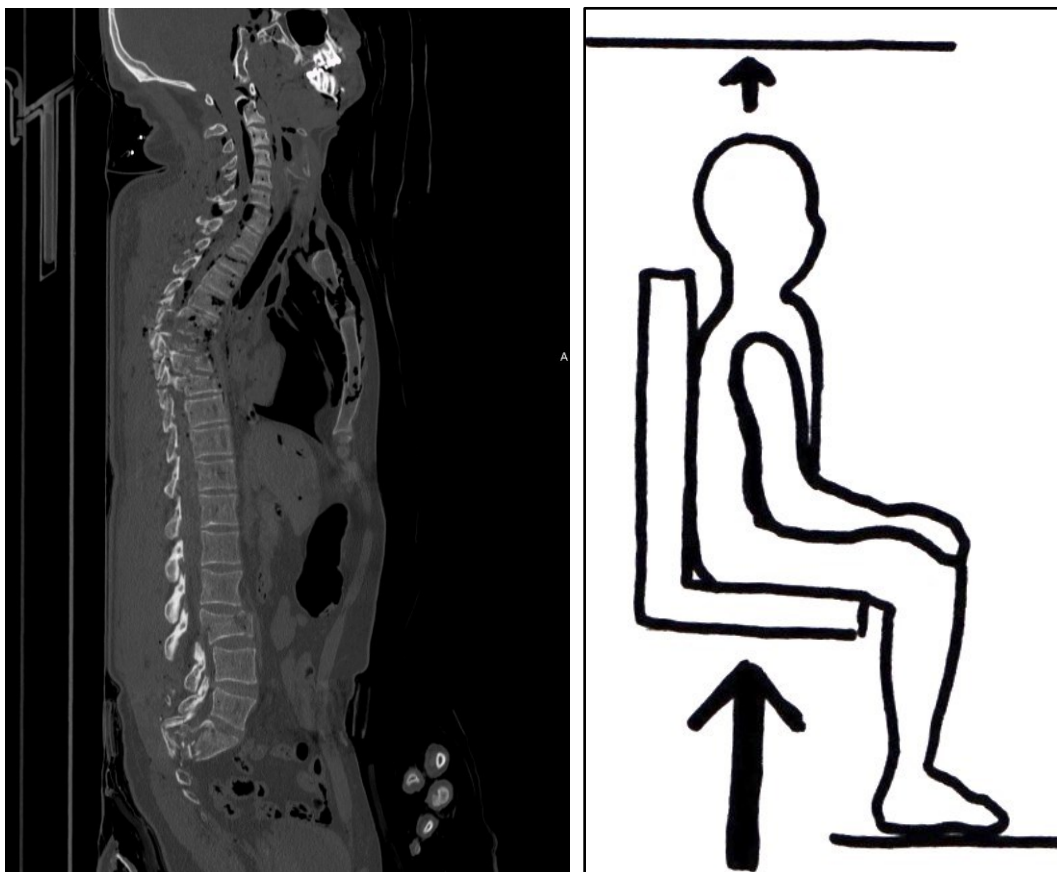


Figure 4-1 Computerised Tomography Post-Mortem image of the spinal column displaying multiple spinal fractures.

Figure 4-2 A diagram demonstrating the axial loading force from underbody blast causing spinal fractures and head impact with the cabin roof.

4.4.2. Increased compartment pressures causing intracranial bleeds.

The prevalence of perimesencephalic blood (posterior fossa, fourth and lateral ventricle blood) is an unusual injury constellation (figure 4.3). The number of fatalities with perimesencephalic blood was much higher in this cohort than typically seen in a civilian population (Şahin, Delen & Korfali, 2016). A venous mechanism of injury is

suggested/hypothesised. Additionally, the Fisher's exact test of blood in the lateral ventricles with thorax injury, and lateral ventricles with both thorax and abdominal injury co-existence was found to be less than 0.05, rejecting independence. The mechanism of injury could be due to an extension of the Monroe-Kellie doctrine that the sum of volumes of brain, cerebrospinal fluid (CSF) and intracerebral blood is constant (Mokri, 2001) (figure 4.4). Therefore an increase in abdomen pressure increases thoracic pressure and therefore intracerebral pressure transmitted via the venous system, thus producing the perimesencephalic blood (Wilson, 2016). A similar mechanism is seen in civilians undergoing physical exertion and straining, increasing jugular pressure and causing veins and capillaries to swell causing a perimesencephalic non-aneurysmal bleed (Matsuyama et al., 2006). The exact cause of the increased pressures could be due to the blast wave and therefore being classified as a primary blast injury, although this is not likely in UBB with advances in under vehicle armour re-design. The more likely mechanism is the forcing of the body upwards by the floor of the vehicle and therefore a tertiary blast injury due to bodily displacement, combined with restraint around the abdomen and subsequent inertia of the upper part of the body – thereby causing an increase in pressures. In the equivalent civilian injury, no treatment is required and the patients recover with no long-term follow-up (Matsuyama et al., 2006; Şahin, Delen & Korfali, 2016). Therefore, mitigation of this injury mechanism is not a priority, however the clinical significance of haemorrhage as a marker of raised torso pressure but not long-term morbidity should be considered for potential triage and direction of clinical care. In addition, the weight of helmets or night vision goggles may contribute to injury severity.

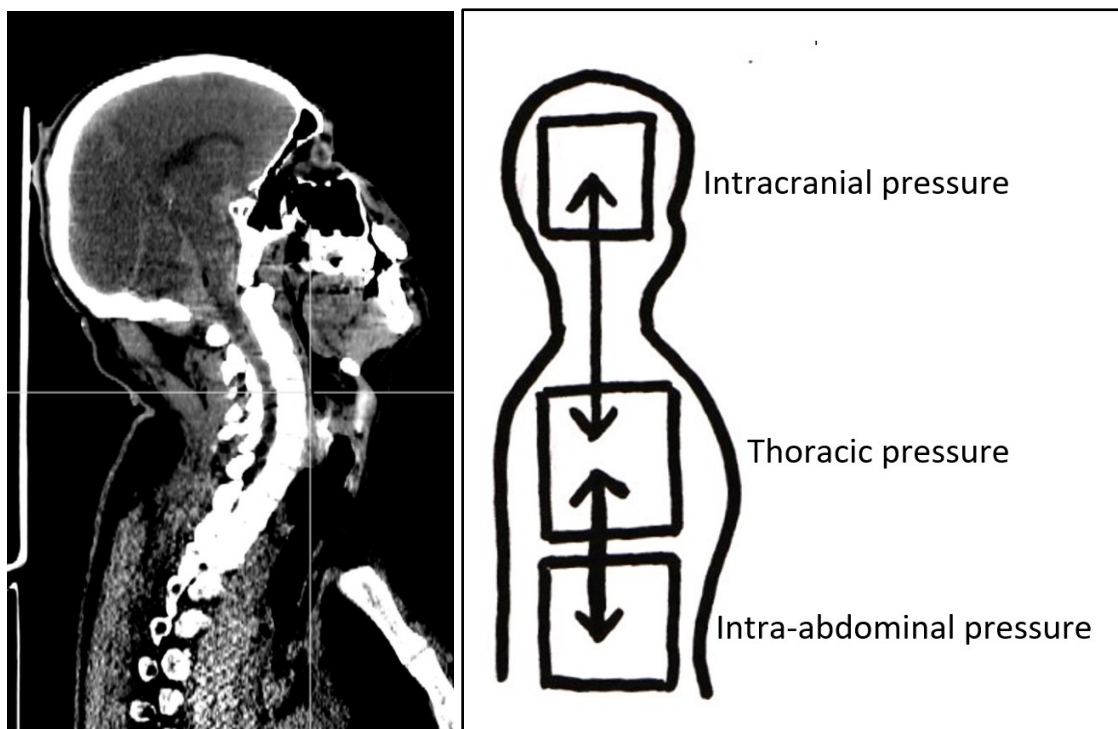


Figure 4-3 Computerised Tomography Post-Mortem image displaying blood around the brainstem. (Reproduction of figure 2.4 in chapter 2)

Figure 4-4 Figure demonstrating an extension of the Monroe Kellie 2.0 hypothesis

4.4.3. Spinal and Brainstem injury

The data shows a greater incidence in posterior fossa subarachnoid haemorrhage than seen in non-blast injury patients, a theory for this being compression at the C0-C1 junction. In addition, the presence of subarachnoid blood in the 4th ventricle may suggest a brainstem injury. The presence of C1 and condylar fractures show that energy is transmitted through the entire spine and into the skull (figure 4.3). This pattern of injuries supports the theory that the skull, neck and spine is susceptible to tertiary blast injury forces causing shearing, flexion/ extension and rotational injuries. This is further supported by previous research that demonstrated C1 burst fractures in the spine are indicative of loading to the spine (Spurrier et al., 2016).

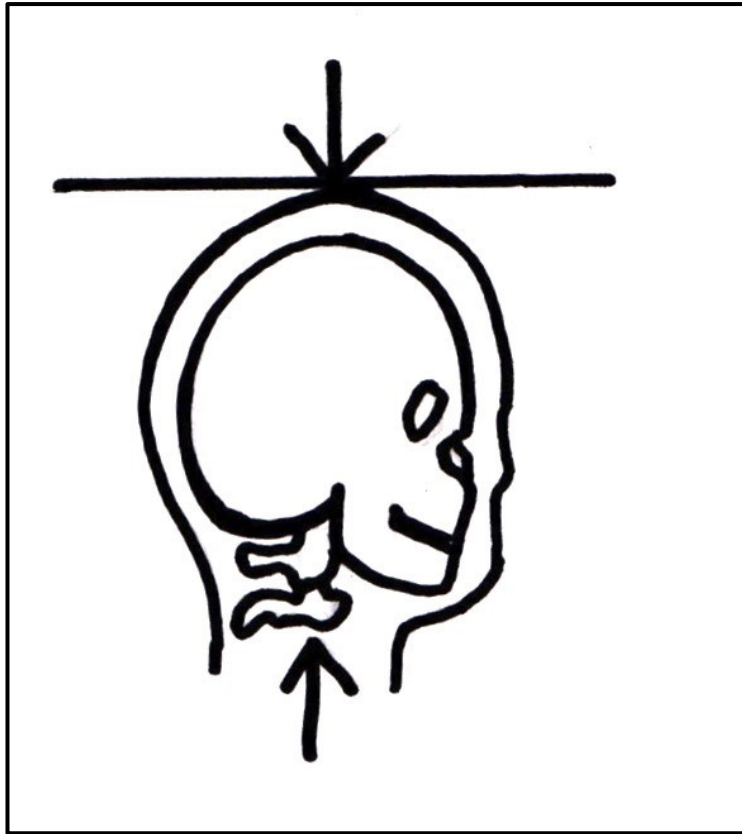


Figure 4-5 A diagram to show the upwards and impact force on the cranium of the roof cabin in underbody blast causing compression and the C0-C1 junction.

4.4.4. Contusions with injury to C0-C1

The fourth injury constellation was injury at C0-C1 combined with abdominal or thoracic injury. Although there is no likely specific mechanism that causes this injury, it is likely to be similar to that which causes a brainstem and skull fracture injury (figure 4.3) and therefore a tertiary blast injury. Contusions and injury to the c-spine indicate the head and neck have undergone significant force and it is likely the angle of the neck and head on impact of the blast will determine which injury this manifests as. In addition, shaking of the head can cause shearing or coup-contrecoup type injuries which may be presented as contusions in the post-mortem images.

These mechanisms are likely to coexist in any given blast, but this description of distinguishable injuries will allow development of mitigation strategies or clinical treatments.

4.4.5. Direct impact to skull.

Skull fractures were prevalent in 63% of the cohort. An “eggshell” pattern of fractures was seen in a small group of fatalities (11%), indicating a high energy direct impact and tertiary blast injury, most likely with the ceiling of the cabin (figure 4.5 and 4.6). Despite this being a small number, it is not an insignificant injury as this pattern is associated with massive underlying brain injury and large amounts of subarachnoid haemorrhage. This type of injury is not survivable despite the best clinical care; however, it may be possible to mitigate against such injuries with in-vehicle restraints, vehicle design changes or personal protective equipment. Injuries of this kind are only seen in civilian cohorts if a subject has received a significant direct impact force, for example a fall from great height or a high speed road traffic collision (Hamel et al., 2013).

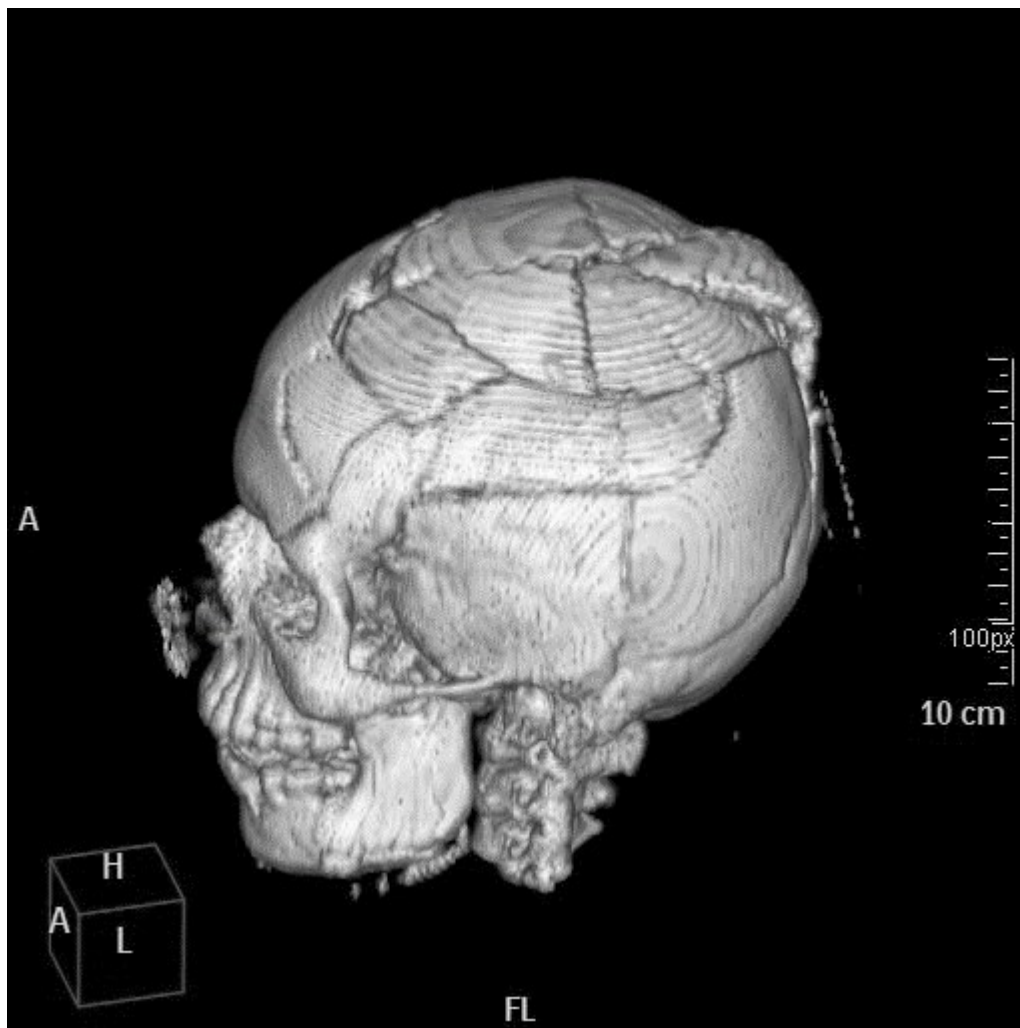


Figure 4-6 Reconstructed Computerised Tomography Post-mortem displaying an eggshell pattern of skull fractures.

4.5. Limitations

The study has some limitations in that data is limited to injury images alone and more information on personal protective equipment, location in vehicle and type of vehicle would prove useful in the context of understanding injury mechanisms. However, such data is sensitive as it could expose vulnerabilities and therefore it is not readily available for analysis. Also, the dataset is not complete for all fatalities, with images missing for some fatalities who suffered injury in locations distant from field hospitals.

CTPMs in themselves can be inaccurate for diagnostic purposes due to degradation and decomposition which are further affected by the different length of time between death and imaging for individual fatalities. Artefacts from resuscitation attempts may also cause ambiguity in imaging diagnostics. However, in 21 cases, there was no evidence of resuscitation.

The injury constellations identified here enable injury mechanisms to be postulated and so mitigation to be designed. This was only possible by the inclusion of CTPM data and combining that with the injuries listed within the JTTR.

4.6. Summary

This chapter has shown that there are distinct mechanisms of injury as a result of mounted blast that could have potential mitigation strategies. Multiple spinal injuries in addition to skull fractures and brain stem injury and direct impact fractures to the skull could be mitigated through vehicle design and the use of restraints. Vehicles with a “V-shaped” floor acting as a crumple zone, along with education of military personnel on the importance of PPE adherence could prevent these injuries. Spinal and brainstem injuries due to bodily displacement could again be mitigated through vehicle design, but also restraints that absorb more energy, thereby reducing some of the inertia experienced by the patient, this, in turn may prevent some of the coup-contre-coup or non-specific intracranial haemorrhages.

This chapter has reported on the radiological pathology of mounted (in vehicle) blast brain injury in fatalities from the Iraq and Afghanistan commitments. The next chapter will use the same radiological classification to understand the radiological pathology of dismounted

blast brain injury from Iraq and Afghanistan in order to draw similarities or differences in injury.

Chapter 5. Injuries in fatalities of dismounted blast: identification of three mechanisms of head injury

The previous chapter analysed the radiological pathology of mounted blast brain injury in fatalities of Iraq and Afghanistan commitments, to hypothesise injury constellations. This chapter uses the same methodology to understand the pathology of dismounted fatalities.

This chapter was published in part as: Ashworth E, Baxter D, Gibb CI, Wilson M, Bull AMJ. Injuries in Fatalities of Dismounted Blast: Identification of Four Mechanisms of Head and Spine Injury. J Neurotrauma. 2024 Jul;41(13-14):e1678-e1684. doi: 10.1089/neu.2023.0289.

(see Appendix A for appended paper)

5.1. Introduction

Blast is the most common injury mechanism in conflicts of this century (Champion et al., 2003; Bhattacharjee, 2008; Wade et al., 2006; Belmont et al., 2012) due to the widespread use of explosives and improvised explosive devices (IEDs) and this has continued up to this day in Ukraine (Zhang et al., 2022). Blast has multimodal effects: primary, secondary, tertiary and quaternary. Primary injury is the result of the blast wave, which affects the interfaces between materials of different densities such as gas or fluid-filled cavities like the lung and bowel. Secondary blast injury is trauma (anatomical disruption) caused by highly energised fragments from the blast, which is thought to be higher in dismounted blast than mounted (in-vehicle) blast due to the lack of protection from the vehicle exterior (Bryden, Tilghman & Hinds, 2019). Tertiary blast is where the force of the blast physically moves the body or large materials causing extreme blunt force trauma (Clasper J & Edward D., 2022). Quaternary blast is injury that is not encompassed by the other three types and includes those produced by chemicals, blood born viruses or heat injury (Centres for Disease Control and Prevention, 2006). It is important to understand the categories of blast as an exposed victim will experience primary blast differently to a mounted victim. Mounted victims are affected more by tertiary blast due to the impact of energy through the vehicle. Traumatic Brain Injury (TBI) is commonly suffered in conflict (Champion et al., 2003), and historically brain injuries seen in soldiers were predominantly a result of penetrating, high energised fragments, including shells or ammunition (Kocsis & Tessler, 2009), causing injuries such as occipital penetrating injuries (Lanska, 2009). In dismounted personnel there are fewer impact skull fractures and more penetrating injuries (Singleton et al., 2013), and severe head injury is uncommon (5%) (Oh et al., 2016). Injuries from recent conflicts have included haemorrhagic injury and skull fractures (Eastridge et al., 2012; Wade et al., 2006; Regasa, Agimi & Stout, 2019). As much of the current research is based on categorical data from spreadsheets and databases (including the Joint Trauma and Theatre Registry - JTTR; Smith et al., 2007), the lack of imaging precluded the identification of haemorrhagic and fracture patterns. The overall injuries are different between mounted and dismounted cohorts with a higher prevalence of dismounted fatalities (Singleton et al., 2013).

As the pattern of injuries in the mounted cohort from this dataset has been previously published (Ashworth et al., 2022), this paper will analyse dismounted injuries only in order

to hypothesise the mechanisms that produced these in order to enable future mitigation and protection to be investigated. The aim of this study is to combine JTTR injury scoring with radiological findings to identify the patterns of head injury of fatalities in dismounted blast in order to elucidate the mechanisms causing such injuries.

Methods to obtain relevant information on conflict injuries is facilitated for UK military personnel by the JTTR (Smith et al., 2007). The UK JTTR is a database comprising all injuries sustained for both survivors and fatalities from Operation Telic (Iraq) and Herrick (Afghanistan). Parameters collected and used here include Glasgow Coma Scale score and anatomical injuries scored using the Abbreviated Injury Scale (AIS version 2005 Military; Gennarelli & Wodzin, 2006). Additionally, radiological images are available for many of the injuries. This is the first analysis of head injuries in dismounted fatalities.

5.2. Methods

With permission from the Surgeon General (United Kingdom), Defence Medical Services Caldicott Guardian, a JTTR search was conducted for all patients who had suffered a brain injury. The search criteria were fatalities with a head injury with AIS of 2 or more due to dismounted blast. AIS of 1 under head region was not included as these are superficial lacerations or injuries. The inclusion dates were 2007-2013 to include fatalities from Iraq and Afghanistan. CT post mortems (CTPMs) were collected as soon as possible following confirmation of fatality (Gibb et al., 2022). In some cases, patients survived until transfer to a UK medical facility before subsequently dying of wounds in hospital (n=3); in these cases, the initial CT upon arrival to the theatre of operation was used.

Data collected were: basic demographics, radiological features, and the two body regions with the most severe injuries. In detail, head injury severity and type was scored radiologically using the SBNS BIC (Wilson, Ashworth & Hutchinson, 2022) which assigns a score of 0-3 for each injury; inclusive of extradural haematoma, acute subdural haematoma, chronic subdural haematoma, subarachnoid haemorrhage, contusions, diffuse axonal injury, hypoxia, brain death (raised intracranial pressure), presence of skull fracture and whether the injury was penetrating (secondary blast) or blunt force (primary blast) trauma. Facial injury was described as any injury to the face that had fractured facial bones. The radiology records were investigated and classified by a Consultant Radiologist, Neurosurgical

Consultant and a Trauma Nurse. Additional radiological parameters were collected to ensure complete analysis, these were: ventricular blood and its location, pattern of injury, skull fractures, spinal injury and location, and extra-cranial injury of AIS 3 or more in the abdomen or thorax.

To test the hypothesis that there exists a discrete set of constellations or patterns of injury, a correlation analysis of injuries was conducted, where a Pearson's chi squared or Fisher's exact test was used to test the independence of each individual variable against each other. Fisher's exact was used when there were fewer than 5 counts of a variable, Chi-squared was used in those variables with five or more counts. An alpha of 0.08 or less was used as the threshold to reject independence, higher than normally used as the objective is to hypothesise injury mechanisms and the numbers available were low considering the heterogeneity of injury constellations. As multiple independence tests were calculated on the data, the risk of false positives (Type I error) was increased. However, the risk of Type I error was deemed to have a lower impact than the risk of a Type II error and so Bonferroni correction was not applied to the data (Armstrong, 2014). An odds ratio was performed where possible to determine whether the correlation was positive or negative.

Statistical analysis was performed using Microsoft Excel 2007 (version 12.0, Redmond, WA, USA) and IBM SPSS (version 26, Armonk, NY, USA).

5.3. Results

Complete CTPMs were available for seventy-one UK military fatalities of dismounted blast (2007-2013); eleven fatalities had no images or CTPM available. Radiological brain injury parameters are shown in Table 5.1; skull fracture was the most prevalent injury (in 59 of the fatalities, 83.1%) followed by subarachnoid haemorrhage (31, 43.7%). Contusion (18, 13.1%), laceration (6, 8.5%), acute subdural haematoma (5, 7.0%) and extradural haematoma (1, 1.4%) were seen in much smaller numbers (Table 5.2.). Chronic subdural haemorrhage, diffuse axonal injury and hypoxia were not seen on imaging.

	Acute Subdural	Subarachnoid	Extradural	4th Ventricle	Lateral Ventricles	Foramen Magnum	Perimesencephalic	Brain Stem	Penetrating injury	Thoracic injury	Facial	Skull Fracture	Other C-Spine	C0-C1	T-Spine	L-Spine	S-Spine	Abdomen injury	Tightness
Contusion	0.05																		
Acute Subdural		0.05																	
Subarachnoid			0.05																
Extradural				0.05															
4th Ventricle					0.05														
Lateral Ventricles						0.05													
Foramen Magnum							0.05												
Perimesencephalic								0.05											
Brain Stem									0.05										
Penetrating injury										0.05									
Thoracic injury											0.05								
Facial												0.05	0.05	0.05	0.05	0.05	0.05		
Skull Fracture													0.05						
Other C-Spine														0.05					
C0-C1															0.05				
T-Spine																0.05			
L-Spine																	0.05		
S-Spine																		0.05	
Abdomen injury																			0.05
Tightness																			

Table 5-1 Chi-squared and Fisher's exact analysis of independent variables. Those variables where independence could be rejected are highlighted in colour by injury constellation ($p < 0.08$). The cells marked black are negative correlations. Blue – extra-axial and parenchymal haemorrhage, Peach – deep haemorrhage, Purple – facial injury, Green – spinal injury.

	Extradural	Acute Subdural	Chronic Subdural	Subarachnoid	Contusion	Diffuse Axonal Injury	Hypoxia	Tightness	Skull Fracture (Y/N)
Number of fatalities (n=71)	1	5	0	31	13	0	0	6	59
Percentage of total	1.4	7.0	0.0	43.7	18.3	0.0	0.0	8.5	83.1

Table 5-2 Pathophysiology of dismantled blast brain injury as categorised by the SBNS Brain Injury Classification (n=71)

The most common additional injury was blood located in the ventricles (Table 5.3.), equally in the lateral ventricles (23, 32.4%) and fourth ventricle (22, 31.0%). Blood was also seen in the foramen magnum in 5 patients (7.0%), brainstem in 2 (2.8%) and pneumocephalus in 1 patient (1.4%).

	<i>4th Ventricle</i>	<i>Lateral Ventricles</i>	<i>Foramen Magnum</i>	<i>Brain Stem</i>	<i>Pneumocephalus</i>
<i>Number of fatalities (n=71)</i>	22	23	5	2	1
<i>Percentage of total</i>	31.0	32.4	7.0	2.8	1.4

Table 5-3 Location of blood identified radiologically in dismantled blast fatalities with head injury (n=71)

Spinal fractures were seen in all regions of the spine (Table 5.4.) but were most prevalent in the sacral region (19, 26.8%) and in C0-C1 (10, 14.1%) and thoracic spine (10, 14.1%) regions. Other C-spine fractures occurred in 8 (11.3%) fatalities and lumbar fractures in 7 (9.9%).

	<i>C0-C1</i>	<i>Other C- spine</i>	<i>T</i>	<i>L</i>	<i>S</i>
<i>Number of fatalities (n=71)</i>	10	8	10	7	19
<i>Percentage of total</i>	14.1	11.3	14.1	9.9	26.8

Table 5-4 Spinal fractures in dismantled blast fatalities with head injury (n=71)

Penetrating injuries due to secondary blast were prevalent in 21 (29.6%) of fatalities.

Based on AIS scores, thorax injury was described as the secondary injury in 41 (57.8%) fatalities, abdominal in 32 (45.1%). When analysing skull fractures (Table 5.5.), facial only fractures were seen in 25 (35.2%) of fatalities. Of those with facial fractures only, 16 had no further underlying brain injury (blood in the ventricles excluded). Four (5.6%) fatalities had facial fractures with an additional base of skull fracture, three of whom had no demonstrable underlying brain injury on imaging, which was confirmed through the accompanying radiology reports.

	<i>Facial fractures only with brain injury</i>	<i>Facial fractures only with no brain injury</i>	<i>Skull fractures only with brain injury</i>	<i>Both facial and skull fractures</i>	<i>Facial fractures with base of skull fracture only</i>	<i>Decapitation or little brain tissue/skull left</i>	<i>No fractures with brain injury</i>
<i>Number of fatalities (n=71)</i>	25	16	7	18	4	9	8
<i>Percentage of total</i>	35.2	22.5	9.9	25.4	5.6	12.7	11.3

Table 5-5 Facial and skull injuries in dismounted blast fatalities who had head injury (n=71)

There were no correlations between pneumocephalus and any other injuries. This is excluded from the results table (Table 5.1). Odds ratios less than 1.0 showed a negative correlation between thoracic injury and 4th ventricle blood, abdominal and penetrating injury, and skull fracture with lethality, resulting in the identification of four mostly distinct injury clusters. The first is non-overlapping with other constellations and contains acute subdural, subarachnoid and extradural injuries (which we term *extra-axial and parenchymal haemorrhage*). There were 32/71 fatalities with this injury constellation. The second injury constellation, which we term *deep haemorrhage*, is a proximal set of injuries with blood in the ventricles, around the brainstem and perimesencephalic blood (total: 37/71 fatalities). The third injury constellation partially overlaps with the second with both exhibiting L- and S-spine injuries, the *spinal injury* constellation, comprising C-, T-, L-, and S-spine injuries combined with abdomen and thorax injury (total: 45/71 fatalities). The fourth injury constellation, *facial*, includes facial injuries, skull fracture and other C-spine injuries (total: 61/71 fatalities) (Table 5.6).

<i>Injury constellations</i>	<i>Number of Fatalities (%)</i>
Spinal injury and facial injury	17 (23.9)
Deep haemorrhage, extra-axial and parenchymal haemorrhage & facial injury	10 (14.1)
Deep haemorrhage, spinal injury and facial injury	9 (12.7)
All four constellations	8 (11.3)
Deep haemorrhage & facial	5 (7.0)
Facial injury alone	5 (7.0)
Extra-axial and parenchymal haemorrhage, spinal injury and facial injury	4 (5.6)
Deep haemorrhage, extra-axial and parenchymal haemorrhage & spinal injury	3 (4.2)
Extra-axial and parenchymal haemorrhage & facial injury	3 (4.2)
Extra-axial and parenchymal haemorrhage & spinal injury	2 (2.8)
Spinal injury alone	2 (2.8)
Deep haemorrhage and Extra-axial and parenchymal haemorrhage	1 (1.4)
Deep haemorrhage alone	1 (1.4)
Extra-axial and parenchymal haemorrhage alone	1 (1.4)
Deep haemorrhage injury and spinal injury	0 (0)

Table 5-6 Coexistence of the four identified injury constellations.

Twenty-seven (38%) had a CT scan displaying no brain tissue injury (excluding intra-ventricular blood).

5.4. Discussion

This study is the first to identify injury constellations of fatalities with associated head and neck injuries in the dismantled cohort using data from the JTTR with the available scans and

images of post-mortems from Operation Herrick in Afghanistan and Telic in Iraq. Four injury constellations have been identified (Table 5.6):

5.4.1. Extra-axial and parenchymal haemorrhage

The cluster of correlations between acute subdural, subarachnoid haemorrhage, contusions and extradural haemorrhage show there was prevalence of intracranial haemorrhage even in early fatalities. This demonstrates that brain injury can be visualised on a CTPM even with early termination of a circulation volume. Although these injuries are non-specific to any direct mechanism, they identify that the PPE used did not prevent intracranial injury. It is likely that this is a mixture of coup-contre coup injury and tertiary blast injury of body displacement causing an impact.

5.4.2. Deep haemorrhage

Similarly to the mounted cohort (Ashworth et al., 2022) perimesencephalic injury was seen and is unusual. The number of fatalities with perimesencephalic blood was much higher in this cohort than typically seen in a civilian population (Şahin, Delen & Korfali, 2016). In civilians, perimesencephalic blood is usually seen as a result of straining or physical exertion, mimicking the Valsalva manoeuvre, causing veins and capillaries to swell and a non-aneurysmal bleed to occur. In civilians, this pathology is not fatal and patients recover quickly (Matsuyama et al., 2006). A hypothesised mechanism, based on the direct connection between the intrathoracic and intracerebral vascular system (the modified Monroe-Kellie principle; (Wilson, 2016) is that primary blast wave induced rise in intrathoracic pressure is transmitted directly through the vascular system resulting in perimesencephalic vascular rupture in much the same way as seen in spontaneous perimesencephalic bleeds that occur when straining (e.g. Valsalva manoeuvres) (Monro, 1783). This is therefore a primary blast injury as a direct result of the over pressure and subsequent underpressure causing the primary blast wave. It is hypothesised that intraventricular blood is correlated with this mechanism which is termed *deep haemorrhage*. Further mechanistic research or using larger datasets will enable this to be explored further.

5.4.3. Spinal injury

The cluster of spinal injuries and injury to the thorax and abdomen suggests evidence of massive through-body injury as a result of blast. This type of injury, although unlikely to be amenable to pre-hospital treatment due to its severity, could be mitigated through modification of personal protective equipment. We hypothesise that the presence of abdominal or thorax injury may be indicative of an underlying spinal injury in the survivors cohort, and so this should be investigated. Spinal injuries were due to a blunt force as opposed to penetrating injury. This injury falls under tertiary blast injury due to bodily displacement and potentially primary blast injury as the primary blast wave affected the abdominal and thoracic cavities.

5.4.4. Facial injury

Fifty-eight percent of fatalities had a facial injury alone with no additional skull fractures. (n=25 with brain injury, n=16 with no brain injury. Of these, 25.6% had no underlying brain injury other than blood in the ventricles. However, there were 4 (5.6%) fatalities who had a facial injury with a base of skull fracture only, most of whom had no underlying brain injury other than blood in the ventricles (table 5.5). The additional correlation between facial injuries and skull fractures and facial injuries with C0-C1 injury shows a likely mechanism to be impact force to the face and neck. This may be due to the primary blast wave if patients were in close proximity to the blast or due to tertiary blast and displacement causing a direct impact.

5.4.5. Summary

As the fatalities were close to the blast, these fractures suggest that the facial bones could be acting as a “crumple” zone thereby preventing underlying brain injury. This has been hypothesised by previous research in civilian trauma which found that there was a link between frontal sinus volume, cranial facial insult and underlying intracranial trauma supporting a “crumple zone” hypothesis (Cai et al., 2017). In addition, there are some parallels between this blast injury constellation and temporal-mandible joint fractures in motorcyclists with incomplete helmet protection who have suffered a collision (Cavalcante et al., 2012).

There has been previous research exploring the link between facial fractures and underlying brain injury, suggesting that facial injury is a predictor of central nervous system trauma (Pappachan & Alexander, 2006), and that concussion was the highest incident injury. As the images in this study were from CTPMs, it is not possible to identify if patients had suffered a concussion. We would hypothesise that this would have been present in survivors. In addition, due to the instant impact of death, microhaemorrhages or diffuse axonal injury (DAI) would not necessarily be visualised. The absence of DAI on imaging, in itself, is not evidence of absence of injury due to the complexity of DAI diagnosis. Further research in this area could be possible in a survivor cohort, however, this is entirely dependent on whether the facial injuries were survivable and did not compromise the airway. DAI can cause respiratory arrest and therefore distinguishing the cause of death (airway compromise vs respiratory arrest) would be paramount.

Some injuries had a negative correlation meaning they did not occur together, such as lacerations and skull fractures. This is likely due to the fact the skull fracture prevented pressure from building up. The negative correlation between abdomen injury and penetrating injury is not understood and highlights the complex environment as does the negative correlation between thoracic injury and fourth ventricle blood.

The four injury patterns are largely, but not completely, independent with many injuries co-existing. The most common co-existing injuries being spinal with facial injury where 53.5% of fatalities had both injury constellations (including in combination with others). There were just 8 (11.3%) casualties who had overlap of all 4 injury constellations suggesting that all 4 injuries co-existing was unlikely. (Table 5.5 and Table 5.6.).

The theory behind the mechanisms for these injury constellations can only be hypothesised at this point. Those fatalities with the spinal injury constellation will have been located very close to the blast causing catastrophic whole-body injury. Those fatalities with facial injury would have most likely been further away and facing the blast therefore causing frontal and facial fractures.

Deep haemorrhage appears to occur in around one third of fatalities, but the variability of this cannot at this point be explained. However, it is important to note that an isolated

intracranial pressure (perimesencephalic injury) is not usually associated with fatality in civilians.

Some of these injuries may be mitigated against, for example, facial injuries could be prevented through helmet design. A helmet with a conical shape over the face would provide a crumple zone with the potential to reduce risk or severity of facial fractures. Protection from primary blast wave is much more complicated, and it is known that the primary blast wave predominantly affects air or fluid filled cavities the most. Therefore PPE that aims to protect those regions of the body against primary blast should be prioritised.

There is currently limited research on the underlying radiology and pathophysiology of the dismantled cohort beyond the injuries listed on the JTTR, particularly in the survivor population. Previously, in survivors, research has focused on minor TBI and the cross-over with post-traumatic stress disorder, whereas for the basis of this research, the moderate to severe TBI cohort would be comparable. Moderate to severe blast TBI in survivors is yet to be explored.

This study is limited by the use of imaging and the JTTR dataset alone. Information on vehicle data, proximity to blast and personal protective equipment would provide further information on the injuries seen. However, this data is sensitive and can expose military vulnerabilities. It is also important to note that there are some instances where the dataset is incomplete.

There may be biases in the data where some data was missing initially, in particular in those cases where patients were not taken initially to a UK facility where imaging could be recorded. In these specific regions there could be a difference in the IED's used and therefore a different injury seen. The "died of wounds" cohort is underrepresented and therefore it is hard to extrapolate conclusions based on those patients who had a longer survival than those who had instant fatality as a result of blast.

Computerised tomography postmortems in themselves can be limiting. There is some evidence of body degradation in some images due to the length of time between death and imaging. In addition, the act of resuscitation can cause some disruption to the body and leave artefacts.

Injuries due to blast are unique in pathophysiology and although some can be compared to non-blast trauma, the mechanisms behind such injuries are hypothetical until further research is undertaken. The injury constellations presented here can be used to identify management strategies and clinical care for future patients.

Chapter 6 - Survivors of mounted and dismounted blast

The previous chapter analysed the radiological pathology of dismounted fatalities from Iraq and Afghanistan in order to hypothesise injury mechanisms. This chapter will describe the data available from the survivor cohort.

6.1. Introduction

Current conflicts and terrorism mean that the burden of blast injury is increasing for both military and civilian personnel, worldwide. Survivors of blast injuries represent a unique group of trauma patients, often experiencing a combination of complex physical and psychological challenges (Singleton et al., 2013). Blast injuries result from explosions, which can occur from military combat, industrial accidents, terrorist attacks, and natural disasters. These injuries are often characterized by their heterogeneity and complex injuries, as blasts generate high-energy shock waves capable of causing severe damage to internal organs, soft tissues, bones, and the central nervous system (Centres for Disease Control and Prevention, 2006). Survivors may endure a combination of primary blast effects (caused by the shock wave itself), secondary injuries (from debris), and tertiary injuries (from being thrown by the blast) or quaternary injuries as a result of infection or burns (Arnold et al., 2003). An important part of understanding blast is looking at why patients survived over others, to mitigate against fatalities.

The United Kingdom military holds a prospective database of trauma casualties from UK military commitments. United Kingdom Joint Trauma and Theatre Registry (JTTR) includes all survivors and fatalities of trauma. Injuries are classified using the Abbreviated Injury Scale (AIS) 2005-Military2 (Gennarelli & Wodzin, 2008) (Gennarelli & Wodzin, 2006) and the worst injuries from the AIS are described as “Top Injury 1” and “Top Injury 2”.

Survival data for this study was collected but has not yet been analysed in depth for correlations as with the fatality data. This analysis was not used as part of the PhD project due to time constraints and the vast quantity of work involved in correlation analysis, this will however, be completed as part of a post-doctoral project.

This chapter will provide an overview of the available survival data.

6.2. Methods

With permission from the Surgeon General (United Kingdom), Defence Medical Services Caldicott Guardian, the JTTR was interrogated to find survivors of blast injury who had sustained a brain injury. This produced anonymised casenote numbers which had to be crossmatched to computerised tomography (CT scans) from both field hospitals and the

Queen Elizabeth Hospital in Birmingham. In some cases the dates of the scans did not match up to dates of injury. In these cases, incident reports had to be checked to find out where patients were transferred and the possible dates of scans. Anonymised scans were then read to check they matched the date and injury descriptors from incident reports.

Initially the patient dataset included a head AIS of 1, however, after matching case notes to brain CT scans from the role 1 and role 2 military hospital facilities, it was found that an AIS 2 had evidence of brain injury whereas AIS 1 was superficial injuries such as facial lacerations or subgaleal haematomas, therefore AIS 1 was not included.

The CT scans were read and classified by a Consultant Neurosurgeon, Consultant Radiologist and a Specialist Nurse. Injuries that were classified included: acute subdural haematoma, chronic subdural haemorrhage, subarachnoid haemorrhage, contusions, diffuse axonal injury, hypoxia, asphyxia, skull fracture, fourth ventricular blood, lateral ventricle blood, foramen magnum blood, brain stem blood, pneumocephalus, location of injury, pattern of injury, C0-C1 fracture, other C-spine fracture, thoracic spine fracture, lumbar spine fracture, sacral spine fracture, open or closed injury, non-displaced or displaced fracture, facial fractures, mandible fractures, base of skull fracture, comminuted fracture <3cm or 3-6cm or >6cm, penetrating fragments <3 fragments or >3 fragments, number of lobes involved in injury, superficial haemorrhage, deep haemorrhage, highest AIS, extracranial injury body region.

6.3. Results

The JTTR data showed that there were 62 survivors of blast who suffered a brain injury with an AIS of 2 or more in the head region and who had scans amenable to analysis.

There were 23 mounted (in-vehicle) patients including one patient on a boat. There were 38 dismounted (on foot) patients.

The most common form of haemorrhage to the brain was contusions with 43.6% of patients suffering one of these. Thirty-seven percent of patients suffered a subarachnoid haemorrhage and 21% of patients suffered an acute subdural haemorrhage. Unlike in the mounted cohort, there was a much smaller population of patients with blood in the

ventricles or around the foramen magnum and brainstem, and no patients had perimesencephalic haemorrhage (table 6.1 and 6.2).

Twenty-two percent of patients had facial fractures, and this was evident in both the mounted and dismount cohort (table 6.2).

	Extradural	Acute Subdural	Chronic Subdural	Subarachnoid	Contusion	Diffuse Axonal Injury	Hypoxia	Tightness	Skull Fracture (Y/N)
Mounted	1	5	0	10	10	0	0	0	13
Dismounted	1	8	0	13	17	0	0	1	29
Total	2	13	0	23	27	0	0	1	42
Percentage of total	3.23	20.97	0.00	37.10	43.55	0.00	0.00	1.61	67.74

Table 6-0-1 A table displaying the number and percentages of patients with injuries as recorded by the SBNS Brain Injury Classification

	4th Ventricle	Lateral Ventricles	Foramen Magnum	Brain Stem	Pneumocephalus	Facial	Coup-contre coup
Mounted	0	2	0	0	5	6	3
Dismounted	1	3	0	0	12	8	2
Total	1	5	0	0	17	14	5
Percentage of total	1.61	8.06	0.00	0.00	27.42	22.58	8.06

Table 6-0-2 A table displaying the number and percentages of patients with intracranial injury patterns

Twenty-seven percent of patients had pneumocephalus, likely due to penetrating fragments, which were evident in 30.7% of patients (table 6.2 and 6.3).

	<3 penetrating fragments	>3 penetrating fragments	Total
Mounted	1	2	3
Dismounted	6	10	16
Total	7	12	19
Percentage of total	11.29	19.35	30.65

Table 6-0-3 A table displaying the number and percentages of patients with intracranial penetrating fragments (foreign bodies)

Only 7 of the 62 patients suffered spinal fractures (11%) and these were limited to high C-spine (C0-C1) and Lumbar fractures (table 6.4).

	C0-C1	Other C-spine	Thoracic	Lumbar	Sacral
Mounted	2	0	0	2	0
Dismounted	2	0	0	1	0
Total	4	0	0	3	0

Table 6-0-4 A table displaying the number and percentages of patients with injuries across spinal regions

Extra-cranial injury was also collected, 22 (35.5%) patients suffered a lower limb injury, 27 (43.6%) suffered an upper limb injury, 19 (30.7%) patients suffered a thorax injury. 15 (24.2%) had an abdominal injury. Extra-cranial injury was collected as an AIS of 2 or more (table 6.5).

	Upper Limb	Lower Limb	Thorax	Abdomen
Mounted	11	10	8	6
Dismounted	16	12	11	9
Total	27	22	19	15
Percentage of total	43.55	35.48	30.65	24.19

Table 6-0-5 A table displaying the number and percentages of patients with extracranial injuries

6.4. Discussion

The results of the survivor's dataset, although not yet analysed for correlations, mirror some of those seen in fatality group. Facial fractures were evident in a 22% of survivors and the percentage across mounted and dismounted was similar. In the dismounted fatality cohort, 25.4% of patients had facial fractures, and in the mounted fatality cohort 25% had facial fractures (Chapters 4 and 5).

There was a high proportion of patients with extracranial injuries, the most common being upper limb injuries, however using AIS alone does not identify what these injuries were or how severe.

Survival correlations for both mounted and dismounted patients should be analysed in the same way as the fatalities in order to compare any potential similarities or differences and identify if any mechanisms could be mitigated against, either through personal protective equipment, changes in vehicle design or clinical care interventions.

6.4.1. Limitations

As with all work, this phase of the research has its limitations. The initial dataset was much larger as it included all patients scoring an AIS of 1 in the head region. After going through all scans with a head injury, AIS of 1 was excluded as these were superficial injuries such as subgaleal haematomas (not injury of the brain itself) or lacerations to the head. The data that is not available for this cohort is the type of vehicle or personal protective equipment that the patients were using, due to this being classified information that may expose weaknesses as a force. In addition, the data does not include patient proximity to the blast, however, this should be considered as the risk of injury is less when further away from the point of detonation.

6.4.2. Future Work

To fully understand the implications of this dataset on the victims of blast, it needs to be analysed for mechanisms of injury in the same way that the fatality dataset has been and compared to the results of the fatalities. This will strengthen the mechanistic hypotheses and give more information for future modelling and development of mitigation strategies to prevent fatality. This was outside the timeframe of the thesis due to the labour intensive nature of collecting data and analysing scans.

In addition, there may be some injury mechanisms from this dataset that could be mitigated against therefore preventing

This chapter has provided a brief overview of the survival data that was collected, the next chapter will conclude the thesis and discuss future work.

Chapter 7 - Discussion, Conclusions and Future Work

The previous chapter analysed the radiological pathology of survivors from Iraq and Afghanistan for future analysis. This final chapter will bring the findings of the thesis together to propose future work

7.1. Introduction

This thesis has investigated radiological components of blast trauma brain injury in order to understand the underlying mechanisms and pathology. This included a historical chapter, looking back at a blast injury case study from the second world war, summarising the differences in medical documentation, imaging, and mechanism. The importance of imaging was highlighted, leading to the work in the following chapter.

To further understand blast brain injury from more recent conflicts and following a radiological approach highlighted in the historical chapter, a radiological classification was validated using inter-rater reliability. This tool was proved to be useful in understanding and quantifying the pathology of brain injury using computerised tomography scans.

The classification tool was then used in mounted fatalities from the Iraq and Afghanistan commitments from which injury constellations were identified and potential mechanisms that produced the injury constellations were hypothesised. The same methodology was used in the dismounted fatalities cohort.

These two substantive chapters showed that there were different mechanisms for both mounted and dismounted brain blast injury. In mounted blast, there were mechanisms related to the upwards force of the blast in the vehicle compartment and direct impact to the skull, having an effect on both the cranium and the spine. There was a pattern of three or four point spinal fractures showing injury as a result of axial load, similarly causing compression at the C0-C1 junction, base of skull fractures and contusions.

Dismounted blast was more heterogeneous, with a higher rate of penetrating injury from energised fragments. There was a high rate of facial fractures with no underlying skull fractures, indicating that personnel were further away from the blast but still susceptible to injury as a result. The interpretation of this is that the primary blast wave was less injurious,

but the secondary blast injuries due to fragments had a greater relevance. However, if no secondary injuries were evident, then this would suggest that in these cases the facial region could have acted as a crumple zone to absorb some of the energy as a result of the primary blast or shock wind.

In both cohorts, there was prevalence of perimesencephalic blood indicating an increased venous cranial pressure; this pattern of injury was found to be present with thoracic or abdominal injury, potentially demonstrating an extension of the Monroe-Kellie principle.

These important findings may have implications for future research; this is described below.

7.2. Implications for civilian brain injury due to blast

Although currently there are few UK military commitments where blast is of concern, there are multiple conflicts worldwide where civilians are at risk of blast or conflict injury. In addition, there have been multiple civilian blasts in the past decades as a result of either industrial explosions or terrorism attacks. The Uppsala Conflict Database Program (UCDP) has shown that since 2012 there has been a sharp increase in state-based violence, non-state violence and one-sided violence globally, increasing the risk of injury to civilians (Uppsala Conflict Data Program, 2023). It is estimated that in recent conflicts (between 1960 and 2019), civilian fatalities account for between 13-85% of the total mortalities, showing a significant increase in recent years (Khorram-Manesh et al., 2021). One of the reasons for this is the use of large-scale artillery in densely populated cities in contrast to the conflict in World War 2. Therefore, understanding potential injuries will help with directing clinical care, improving outcomes and long-term care for these patients (Khorram-Manesh et al., 2021).

Since the start of this PhD, the Ukraine and Gaza/Israel conflicts have commenced and therefore this data gives an insight into some of the injuries that may be seen by both injured civilians and military personnel.

In addition to civilian blast injury, there is an increased focus on facial injuries in motorcycle incidents and therefore the development of helmets to prevent facial injuries in the form of a crumple zone could be used in parallel to improve PPE for both patient groups. There is a trade-off in helmet design between weight and protective effect. A protective helmet may

be heavy and cumbersome and in turn this can also increase axial loading and cause further injury (as well as decrease military performance), however, a helmet that is too lightweight will not offer enough protection – this is a major factor to consider with helmet design.

7.3. Implications for military brain injury

With global tensions mounting and the potential for UK military commitments alongside current conflicts, this data will be useful in both preventing and treating potential military injuries for UK personnel. UK medical commitments are not only the provision of healthcare to UK military service personnel but also work on the reconstruction and support of other healthcare systems. The results from this research will be useful in treating the military in other conflicts where conflict or blast injury had not been researched previously. Passing on this knowledge will assist these regions with their clinical treatment, diagnosis, and potential for preventing injuries in the future.

The dataset has shown that some of the patients who previously were thought to have fatal brain injury instead had a potentially survivable brain injury as a result of whole-body trauma. These results show that if the mechanism of mounted blast can be mitigated then there may be a chance of survival in this patient cohort thereby reducing fatalities in future conflicts (Singleton et al., 2013).

It is hoped that this data will contribute to future development of military personal protective equipment and vehicles as it has highlighted some mechanisms which have potential to be mitigated or investigated further for mitigation strategies. For example, full face helmets with large crumple zones and rigid interiors to prevent impact which could be tested using crash dummies within in-vehicle simulated blast. This could be engineered in a cone shape, allowing for a larger area to absorb some of the energy and protecting the facial bones and sinuses. This would also prevent airway loss and death due to hypoxia.

In addition, adding a much greater crumple zone to the floor or seat of the vehicle compartment to absorb some of the upwards force causing axial load injuries which could be tested using a blast simulator. V-shaped vehicle floors, or honey-combed flooring would absorb or deflect more energy than existing vehicle floor designs, thereby reducing the effect of the upwards force on the patient and reducing the tertiary blast injury experienced in a vehicle. Impact seats are currently used in helicopters and could therefore be adapted

for IED blasts in military vehicles, they have an energy absorbing design and reduce movement caused by impact, again, reducing the chance of tertiary blast injury. Body armour that might sustain at high loading rates (such as through the use of shear thickening materials) would allow for an extra layer of protection against increased compartmental pressures but also manoeuvrability for personnel and could be tested using blast simulators or in smaller scale, a blast gas gun to see if it has a protective effect against the primary blast wave in abdominal and thoracic cavities.

7.4. Implications for radiology

Traumatic brain injury (TBI) can be classified or scored in different ways. Traditionally terms such as mild, moderate and severe based on the Glasgow Coma Score (GCS) have been used, where mild has a GCS of 13-15, moderate 9-12, and severe 3-8 (Teasdale & Jennett, 1974). These scores are based on the patient's presentation which is affected by many variables including the time of presentation. Therefore, although they relate to the patient's physiology and pathology, they are not a diagnosis for the underlying injury and can be skewed by medication or other medical diagnoses.

Classification and scoring tools can be useful for measuring disease progression and injury patterns. The most common classification systems currently used are: the Marshall (Saatman et al., 2008) the Crash CT system (MRC Crash Trial & Collaborators et al., 2008) and the Rotterdam score (Fujimoto et al., 2016). Although these use some radiological variables, they attempt to combine factors to make a score and thus are not meaningful when looking directly at radiological pathology (Zafonte, 2017).

Traumatic brain injury, in general, is heterogeneous and complicated. Therefore, the SBNS classification system validated through this thesis will be valuable in understanding the radiological aspect of brain injury and the mechanism that caused it. It has proven useful for military and civilian purposes, and as discussed in Chapter 2, can be used by multiple members of the multi-disciplinary team. The implications of this are that it will improve communication of the severity of injury between teams, particularly with remote referrals.

However, the utility of the scoring system is limited when there is penetrating injury which is prevalent in both civilians and military personnel. If using the scoring system alone, there is no indication of the location of intracranial injury which has relevance for the patient's

functional outcome as different lobes have different functions. The scoring system is currently used for classification only and offers no prognostic scoring unlike other current brain injury scoring systems.

7.5. Future work

7.5.1. World War 2 further analysis

There is a vast amount of data within the World War 2 archives at St Hugh's college. Future work would include a more detailed analysis of the brain injuries suffered and an attempt to quantify these and relate them to mechanism. These injuries would vary to those seen in current urban conflicts but would provide an insight into the evolution of conflict. In World War 2, military personnel were subjected to blast from rocket propelled grenades, missiles and iron bombs. The conflict in Iraq and Afghanistan occurred in larger open spaces and blast injury was largely due to improvised explosive devices. Current conflicts are occurring in densely populated and built-up cities, using large-scale artillery such as missiles, which have potential to cause much greater damage and the result of the blast can be amplified due to buildings (when both inside and outside the building). Due to the upscale of artillery and greater energy explosives, the severity of injuries being seen may be much greater than those of World War 2. As the tactics of war have changed, the pathology and mechanisms of injury may have changed with it, however, with the current conflict in Eastern Europe, penetrating brain injury is still occurring reflecting some similarities in TBI presentation. There has been a staggering increase in man on man warfare, including gunshot wounds not dissimilar to those seen in WWII. In addition, there are limited resources in some of these regions and therefore there are similarities to the provision of care in the WWII that could be useful for current conflicts.

There are also post-mortem records within this dataset which would prove useful when comparing to the Iraq and Afghanistan cohorts. These records include brain imaging, photographs and x-rays detailing the potential cause of death. Post-mortems from both conflicts could be used to compare the cause of death and hypothesise mechanisms. Some of these patients would have been exposed to blast and therefore may have some of the same radiological characteristics that could be used to explore the evolution of blast injury

and clinical care. Further research on this dataset would be possible with the digitisation and sanitisation of records to ensure they are correctly archived and more accessible.

There is a distinct difference in the documentation of the World War 2 patients compared to current National Health Service documentation. From a nursing aspect, this would make a useful opinion piece to describe the changes in nursing documentation in the digital world and to demonstrate how the nursing role has changed over time. The nursing documentation is more subjective; however, it does provide detail about the patients and may show that the utilisation of digital notes has changed the information now recorded about patients and where it may fall short in comparison to historical nursing records.

7.5.2. Quantifying the radiological classification

The SBNS classification system would have an increased benefit if it could be predictive of functional outcome and mortality. This could be achieved by adding a weighting to the scoring, e.g. $a(\text{mTBI (+ve/-ve)}) + b(E(0-3)) + c(SD(0-3)) + d(DA(0-3)) + e(H(0-3)) + f(T(0-3)) + g(\text{"Tightness"}(0-3))$ (where E = Extradural score, SD = Subdural score, DA = Diffuse Axonal Score, H = hypoxia score and T = Consciousness score). This would make the tool comparable in utility to the existing classification tools, but harnessing the increased benefits provided by the new tool. (Chapter 2). These weightings would involve in-depth work looking at the prognosis of each individual injury depending on injury severity and then validating the prognosis weighting prospectively with a patient cohort and another prognostic imaging tool to ensure accuracy and correlation. To do this, the classification system would need to be used as part of a large study data set and would be very labour intensive, however, prognosis in patients is an important part of research and care delivery.

7.5.3. Exploring the Monroe-Kellie 2.0 principal in blast

The hypothesis that perimesencephalic blood in the blast cohort is an extension of the Monroe-Kellie 2.0 principal (Wilson, 2016) needs a larger dataset to support it. A dataset of more blast injury victims, including their other injuries such as abdominal and thoracic injuries as well as CT scans would show the prevalence of perimesencephalic blood in both mounted and dismounted cohorts.

The presence of perimesencephalic blood is indicative that these patients did not die due to their brain injury but instead other significant injuries to the torso or abdomen increasing compartmental pressures and therefore is a primary blast wave injury. This could be used to develop further PPE, such as body armour that would absorb some of the energy and therefore reduce risk of injury. It could also be used to direct clinical care of blast injury patients to the diagnosis and treatment of thoracic and abdominal injuries of blast victims. This will form part of the post doctoral work proposed below.

7.5.4. Personal protective equipment and vehicle design

This thesis has highlighted likely mechanisms of injury that have potential for mitigation.

In the mounted cohort the mechanisms are related to axial load and therefore the upwards force of the compartment, forcing the body upwards and subsequently impacting the ceiling of the cabin. More specifically, the three- and four-point fractures could be mitigated through better energy absorption through the floor or seat of the vehicle, or both. For example, a much larger crumple zone may be able to provide this. In addition, better restraints would prevent movement of the spine and patient, although they might further restrict upward movement and so increase compression. Having this crumple zone and mitigating axial load would also prevent the C0-C1 junctional compression injuries, and subsequent contusions associated with this mechanism. This previously unsurvivable mechanism could potentially turn into a treatable and survival injury and improve patient outcome.

The eggshell pattern of fractures is an unsurvivable injury and unlikely to be mitigated without preventing the upwards force and subsequent impact with the ceiling compartment,

therefore, a crumple zone absorbing some of the impact from the blast could prevent this bodily movement. A helmet that has much greater energy absorption and tougher inner layer could potentially lessen the impact to the cranium.

In the dismounted cohort, there was a distinct increase in facial fractures, where the facial zone was acting as a crumple zone. This could be mitigated by full face protection that could absorb some of the energy of the blast and early use of airway adjuncts as part of the clinical care. As with the mounted cohort there was evidence of perimesencephalic blood that was hypothesised to be linked to abdominal and thoracic injury increasing intercompartmental pressures. Better full body protection against blast with more rigidity and energy absorption could help lessen these injuries.

Further work would be to design and model these potential equipment changes and determine if they would mitigate the injuries described. Previously, drop rigs, blast tubes and an-vehicle underbelly blast injury simulators (AnUBIS) have been used to simulate blast and develop mitigation equipment and strategies against blast injury (Nguyen et al., 2019). In this case, energy absorption and strength of PPE such as body armour and helmets could initially be tested using the drop rigs and AnUBIS, but to fully understand the mechanism and efficacy of PPE, using crash test dummies and a simulated under vehicle blast with in vehicle filming would provide useful evidence for the efficacy of any new PPE.

7.5.5. Telic and Herrick Survivor Analysis

This thesis only describes the fatalities of the Telic and Herrick data in detail, with some description of the survivor data for which an analysis of the potential injury clusters and mechanisms would be useful.

A similar analysis of the survivor dataset would contribute to a further understanding of the mechanisms causing mortality and morbidity. These mechanisms could again be used to develop new clinical treatments on the frontline or mitigation strategies such as personal protective equipment. Being able to prevent injury in survivors would improve long term outcomes and functional independence in veterans. It is well documented that minor traumatic brain injury has long term effects on patients and therefore having a greater understanding of how to prevent it would be beneficial to the armed forces community.

Understanding the pathology and injury prevalence in survivors would also strengthen the hypotheses of the underlying mechanisms causing mortality.

7.5.6. Conclusion

This is the first time that the post-mortem CT scans from the Iraq and Afghanistan commitments have been analysed in full, using a classification system outside of the Joint Trauma and Theatre Registry. In addition, this is the first analysis of the historical neurosurgical files held at St Hugh's College.

Both sets of data show the implications of military blast injury and the potential for future work for both clinical and engineering mitigation strategies. With the increase in conflict globally over the past few years, blast brain injury remains a research priority and further work needs to be undertaken in this area for the benefit of both civilian and military blast victims.

Post-doctoral work now following on from this thesis is conducting a mechanistic correlation analysis of the survivor cohort, using the same techniques as the fatalities. This will highlight if there are any specific mechanisms that caused fatality or whether it is due to a greater injury burden.

In addition to the survivor cohort, with support from the Academic Department of Military Surgery and Trauma, more research will be undertaken to explore the thoracic/abdominal mechanism with brain injury. Other research into abdominal and thoracic blast injury by research fellows within the military has highlighted there is a strong link between injury to the torso and abdomen with brain injury and it is acknowledged that this needs to be investigated further. The full abdominal and thoracic injury JTTR data will be collected, and all patient data will be interrogated to gather which of those patients suffered intracranial haemorrhage. This will be cross matched to the SBNS classification data where the exact type of abdominal or thoracic injury will be classified and correlation analysis will be undertaken. This may strengthen the understanding of the Monroe-Kellie 2.0 theory and provide further input into protecting patients against primary blast wave to the abdomen and thorax.

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Appendix A: Publications arising from the thesis

Ashworth ER, Baxter D, Gibb IE “Blast Traumatic Brain Injury” Ch 22 in “Blast Injury Science and Engineering: A Guide for Clinicians and Researchers” Bull AMJ, Clasper J, Mahoney PF, McGregor AH, Masouros SD, Ramasamy A (eds), 2022, Second Edition. Springer, ISBN:978-3-031-10354-4

Wilson MH, Ashworth A, Hutchinson PJ, British Neurotrauma Group. A proposed novel traumatic brain injury classification system - an overview and inter-rater reliability validation on behalf of the Society of British Neurological Surgeons British Journal of Neurosurgery. 2022 36:633-638.

Ashworth E, Baxter D, Gibb I, Wilson M, Bull AMJ. Injuries in fatalities of underbody blast: identification of five distinct mechanisms of head injury. J. Neurotrauma 40, (2023) 141-147

Ashworth E, Baxter D, Gibb I, Wilson M, Bull AMJ. Injuries in fatalities of dismounted blast: identification of four mechanisms of head and spine injury. J. Neurotrauma 41, (2024) e1680–e1686

RESEARCH ARTICLE



A proposed novel traumatic brain injury classification system – an overview and inter-rater reliability validation on behalf of the Society of British Neurological Surgeons

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ABSTRACT

Introduction: The measurement of traumatic brain injury (TBI) 'severity' has traditionally been based on the earliest Glasgow Coma Score (GCS) recorded, however, the underlying parenchymal pathology is highly heterogeneous. This heterogeneity renders prediction of outcome on an individual patient level inaccurate and makes comparison between patients both in clinical practice and research difficult. The complexity of this heterogeneity has resulted in generic all encompassing 'traumatic brain injury protocols'. Early management and studies of neuro-protectants are often done irrespective of TBI type, yet it may well be that a specific treatment may be beneficial in a subset of TBI pathologies.

Methods: A simple CT-based classification system rating the recognised types of blunt TBI (extradural, subdural, subarachnoid haemorrhage, contusions/intracerebral haematoma and diffuse axonal injury) as mild (1), moderate (2) or severe (3) is proposed. Hypoxic brain injury, a common secondary injury following TBI, is also included. Scores can be combined to reflect concomitant types of TBI and predominant location of injury is also recorded. To assess interrater reliability, 50 patient CT images were assessed by 5 independent clinicians of varying experience. Interrater reliability was calculated using overall agreement through Cronbach's alpha including confidence intervals for intra-class coefficients.

Results: Interrater reliability scores showed strong agreement for same score and same injury for TBIs with blood on CT and Cronbach's alpha co-efficient (range 0.87–0.93) demonstrated excellent correlation between raters. Cronbach's alpha was not affected when individual raters were removed.

Conclusions: The proposed simple CT classification system has good inter-rater reliability and hence potentially could enable better individual prognostication and targeted treatments to be compared while also accounting for multiple intracranial injury types. Further studies are proposed and underway.

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Introduction

Classically, traumatic brain injury (TBI) has been described as mild, moderate and severe based on the first recorded Glasgow Coma Score (GCS – 13–15; 9–12 and <8 respectively).^{1–3} This has served well over the last 40 years⁴ especially in remote regions of the world where computer tomography (CT) scanning is not possible. However, on an individual patient level, it does not take into account the actual pathology when predicting outcome.⁵ A postictal patient can be GCS 3 with no brain injury and a patient who dies of an extradural might initially have had a GCS of 15. The dramatic increase in CT scan availability since the 1970s offers more pathology and patient specific grading of injury severity. CT scans provide much greater indication as to the actual parenchymal nature of TBI rather than the functional (neurological) result.⁶ It could be considered that extra-axial haematoma on their own, whilst they reflect head injury, are not in themselves brain injuries. As they expand, however, they may cause brain injury through underlying ischaemia or shift (e.g. Duret's haemorrhages or conning) if not acted upon.

Lack of imaging may be the cause of a generic 'traumatic brain injury' diagnosis being pervasive throughout the patient pathway – from pre-hospital and critical care (where most services have a generic TBI protocol) through to death where a common cause of death is 'traumatic brain injury'.⁷ As pre-hospital imaging becomes potentially possible,⁸ earlier diagnosis will enable more pathology specific protocols to be developed.

Applying treatments, be they pharmacological (such as neuro-protectants), physiological (such as targeted cerebral perfusion pressure) or surgical (such as decompression) generically across the TBI spectrum is illogical. When we study potential treatments, it may be that a potentially revolutionary treatment for one subtype of injury is discounted because its effects are diluted when multiple types of brain injury are included.

Current radiological classification systems

A distinction needs to be made between 'classification' and 'prognostication' tools. Although commonly referred to as

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Table 1. the Marshall computer tomography (CT) classification.

Category	Definition
Diffuse injury I (no visible pathology)	No visible intracranial pathology seen on CT scan
Diffuse injury II	Cisterns are present with midline shift 0–5 mm and /or lesion densities present; no high or mixed density lesion > 25 cc may include bone fragments and foreign bodies
Diffuse injury III (swelling)	Cisterns compressed or absent with midline shift 0–5 mm; no high or mixed density lesion > 25 mm
Diffuse injury IV (shift)	Midline shift > 5 mm; no high or mixed density lesion > 25 cc
Evacuated mass lesion	Any lesion surgically evacuated
Nonevacuated mass lesion	High or mixed density lesion > 25 cc; not surgically evacuated

classification tools, the Marshall⁹ and Rotterdam¹⁰ systems are principally used for scoring (which can then be used to classify 'severity') but they do not classify the type of brain injury. Brain injury is often heterogeneous, and an individual patient may have several different brain injuries (e.g. right subdural and left frontal contusion). A comprehensive system needs to account for these different injuries, not just report 'the worst one' as occurs in the abbreviated injury scoring (AIS) system.¹¹ The AIS system (as used by the Trauma Audit Research Network in the UK) is a form of radiological classification in that it reports the highest scoring brain injury, but it takes the fidelity of a location and size of injury and converts it to a number (/score). Not all of those numbers are comparable. For example, a cerebellar extradural (score = 3) is not the same as a cerebral laceration (score also = 3). A system that classifies and scores by pathologies may improve specificity.

Current radiological and prognostic tools assessing TBI severity have improved outcome prediction on populations of patients, but beyond predicting survival at 24 h, they lack precision at an individual patient level.^{12,13} Accurately predicting outcome could support the setting of limits of further interventions, however, there is no tool that can provide this accurately and hence this is often done on experience and multi-disciplinary consensus.

Saatman *et al.* demonstrated the heterogeneity of brain injury resulting in GCS < 8 across a range of conditions – extradural (epidural), subdural, contusions, subarachnoid haemorrhage, diffuse axonal injury and general swelling (reflecting hypoxic injury).¹⁴ They propose the development of a multidimensional classification model. However, the beauty and universality of GCS has largely been achieved because of its simplicity and a radiological classification system, to achieve universal adoption, should similarly be usable by clinicians and non-clinicians alike.

The history of development of the Marshall and Rotterdam systems may explain why they are not pathology based. The Marshall CT classification (Table 1) was introduced in 1991 principally to categorise severity of diffuse injury but it was accepted for its descriptive and predictive value.⁹ The IMPACT (International Mission for Prognosis and Analysis of Clinical Trials in TBI) utilises the Marshall CT score for 6-month outcome prediction in moderate to severe TBI. However, the Marshall CT classification system was not designed for outcome prediction hence in 2005 Maas *et al.* redesigned it for 6-month mortality prediction resulting in the Rotterdam score¹⁰ (Table 2). Traumatic subarachnoid blood was added as it had been shown to be a strong independent predictor of outcome.¹⁵

The Helsinki CT score (Table 3) takes the Rotterdam scoring system one stage further and proportions a 'score' specifically for the type of injury (mass lesion) and its size.¹⁶ The authors report that this provides a more accurate 6-month outcome prediction.

A comparative study of the Rotterdam and Marshall scoring systems found that both were good at predicting early death in TBI in Nepal, though the authors suggested that other factors

Table 2. The Rotterdam computer tomography classification.

Predictor value	Score
Basal cisterns	
Normal	0
Compressed	1
Absent	2
Midline shift	
No shift or shift ≤ 5 mm	0
Shift > 5 mm	1
Epidural mass lesion	
Present	0
Absent	1
Intraventricular blood or subarachnoid haemorrhage	
Absent	0
Present	1
Sum score	+1

(subarachnoid blood, midline shift and the status of the perimesencephalic cisterns) were also predictive.¹⁷ In conclusion, they suggested these individual characteristics gave better prognostication than the scoring systems themselves. Chun *et al.* demonstrated that both Rotterdam and Marshall classification systems had good interobserver reliability when assessed by neuroradiologists and neurosurgeons.¹⁸ Whilst these systems do not necessarily grade the underlying pathology, they do grade resulting potential indicators of severity such as midline shift.

All the above are scoring not classification systems. They do not allow comparison between patients as the same score can be achieved through different types of brain injury. None of the current systems consider the location of the injury. It is clearly appreciated that areas of the brain have different function and eloquence and hence comparable injuries in one area can potentially have considerable different effects to injuries in another. It should also be noted that systems requiring calculation of intracerebral blood volume, are advised to use the ABC/2 system as a good formula of volume measurement.¹⁹

It could be argued that an MRI classification system would be more predictive, however, CT scanning is still the workhorse of acute brain injury and is more ubiquitous around the world. For this reason, an injury specific classification based on CT is highly desirable.

The two core principles of the proposed classification system are that it should be simple to use and grade specific pathologies. This would make it suitable for research purposes (to enable comparisons between patients) globally and may in the future with evidence, guide clinical management personalised to the severity of those specific pathologies.

The proposed SBNS TBI CT classification system

The ubiquity and speed of image acquisition with CT scans make them the ideal tool on which to base a uniform classification system. The need for a simple classification was discussed within the British Neurotrauma Group (BNTG) of the Society of

Table 3. The Helsinki computerized tomography score chart.

Variable	Score
Mass lesion type(s)	
Subdural haematoma	2
Intracerebral haematoma	2
Epidural haematoma	-3
Mass lesion size > 25 cm ³	2
Intraventricular haemorrhage	3
Suprasellar cisterns	
Normal	0
Compressed	1
Obliterated	5
Sum score	-3 to 14

The probability of 6-month outcome is defined as $1/(1 + e^{LP})$, where $LP_{Mortality} = -2.666 + 0.287 \times \text{Helsinki Computerized tomography score}$ and $LP_{unfavourable outcome} = -1.636 + 0.319 \times \text{Helsinki computerized tomography score}$. The Helsinki computerized tomography score ranges from a minimum of $\times 3$ to a maximum of 14 points.

British Neurological Surgeons (SBNS) and then developed by MW and PH. Key factors in the proposed system were agreed in that the new system should not require a radiologist to report it and it should not require additional measures such as biomarkers. The variables that can be used to describe an injury are its type, severity and location. The cut off boundaries of the 'mild', 'moderate' and 'severe' categories for the different pathologies were agreed by members of the BNTG. The proposal was then reviewed with the key stakeholders and presented to the SBNS council who endorsed its publication.

There are only a limited number of traumatic brain injury types, although they can occur in combination and in areas of brain of different eloquence. Traumatic brain injury types visible on CT are: extradural, acute subdural, intracerebral haematoma/contusion, traumatic subarachnoid haemorrhage, diffuse axonal injury and hypoxic injury.

The proposed SBNS Brain Injury Classification System (Figure 1) grades individual brain pathology severities. All brain injuries are scored between zero and three. Additionally, a score can be assigned to 'mild TBI/concussion' with a history of TBI but no evidence on CT. There is also a score for rating the signs of raised intracranial pressure or 'tightness' (sulcal, ventricular and basal cistern effacement). Hence possible scores are: mild TBI (m + ve/-ve), extradural (E 0-3), subdural (SD 0-3), subarachnoid (SA 0-3), contusion (C 0-3), diffuse axonal injury (DA 0-3), hypoxia (H 0-3), + 'Tightness' (0-3). The location of each injury can also be recorded (Frontal, Parietal, Occipital, Temporal, Cerebellum, Brainstem). Although not part of brain injury classification specifically, skull fractures can also be scored (1 - simple, 2 - depressed, 3 - compound).

Where blood volumes are noted (e.g. extradural haematoma), this can be estimated or calculated using ABC/2.²⁰ For subarachnoid haemorrhage, the key thickness of >1mm of blood can be anywhere within the subarachnoid space. Small contusions are <2 cm in diameter with medium being 2-5 cm diameter. Large are >5 cm diameter.

The intention is not to sum the scores as there is no suggested linear relationship, however it can enable comparisons between patients (e.g. a group of patients with an acute subdural haematoma with no more than a 1 in any other category).

Inter-rater reliability

Methods

Data from the 'Traumatic Injury to Brain Across London' (TriBAL) dataset was used (<http://www.imperialneurotrauma.co.uk/tribal.pdf>).²¹

This dataset comprised an audit across London's Major Trauma Centres capturing data of all TBI patients in London (with a positive CT for acute blood or skull fracture) over a 4-month period. CT scan details and injury scoring using the SBNS brain injury classification (BIC) system were captured for the first 50 consecutive datasets.

The CT head scans were reviewed by five raters of different levels and types of experience, as has been done for other CT classification systems previously.^{18,22} The raters comprised a nurse, senior house officer (resident physician), neurosurgical registrar (chief resident), neurosurgical consultant (attending physician) and a consultant neuroradiologist. Raters were blinded to each other and to the patient demographics. Access was given to the initial CT head scan (soft tissue and bone windows) for each patient on admission and raters were asked to classify this according to the SBNS BIC.

Data were analysed using SPSS 24.0 (IBM, Armonk, NY: IBM Corp). Inter-rater reliability and overall agreement of injury type and severity were calculated through the Cronbach's alpha including confidence intervals for intra-class coefficients. Cronbach's alpha was also calculated with each individual rater's score removed to check the weighting of each rater on agreement. Cronbach's alpha measures internal consistency and reliability, a score above 0.7 shows acceptable consistency, above 0.8 shows good consistency and above 0.9 shows excellent consistency. The approach has been used to be consistent with other studies. Cohen's Kappa was calculated to assess agreement between individual raters. Landis and Koch guidelines were used to interpret agreement where 0 is poor, 0-0.2 is slight, 0.2-0.4 is fair, 0.4-0.6 is moderate, 0.6-0.8 is substantial and 0.8-1.0 is almost perfect.²³ The agreement of the reviewer's interpretation was determined by comparison to the consensus opinion once all reviewers had scored the CT scans as defined in the methods of a previous study.¹⁸ Consensus was defined as when 80% or more of the blinded scores agreed for the presence or absence of injury. Average inter-item correlation was calculated to analyse internal consistency and reliability. It is a measure of consistency of individual classification types (e.g. each injury type). To show that the values of Cronbach's alpha were not heavily weighted on one particular rater, values were calculated with each rater removed. This was calculated for the removal of each rater, in turn. Skull fractures were not considered part of the brain injury classification and for the purposes of inter-rater reliability were considered present or absent.

Results

The 50 patients had a median age of 54.5 years with an inter-quartile range (IQR) of 35.3-72.1 years and were predominantly (84%) male. The median pre-hospital GCS was 12 (IQR 8-15), and in-hospital GCS was 11 (IQR 6-15). The most common mechanism of injury was falls of less than 2 m (32%) followed by falls greater than 2 m (30%) (Table 4). As a mean number of diagnoses from raters, 24 of the 50 patients had acute subdurals (20.7%), 7 had extradural haematomas (6.1%), 21 had subarachnoid haemorrhage (18.1%), 5 had chronic subdural haematomas (3.9%), 16 had evidence of tightness (13.9%), 23 had skull fractures (19.3%), 2 (1.4%) patients had evidence of diffuse axonal injury, and nil with overt hypoxia (hypoxia and DAI are normally seen on magnetic resonance imaging; Table 5).

Agreement by percentage was measured for the same injury and the same score for each individual pathology. Results above 70% were shown for all injuries indicating good agreement.

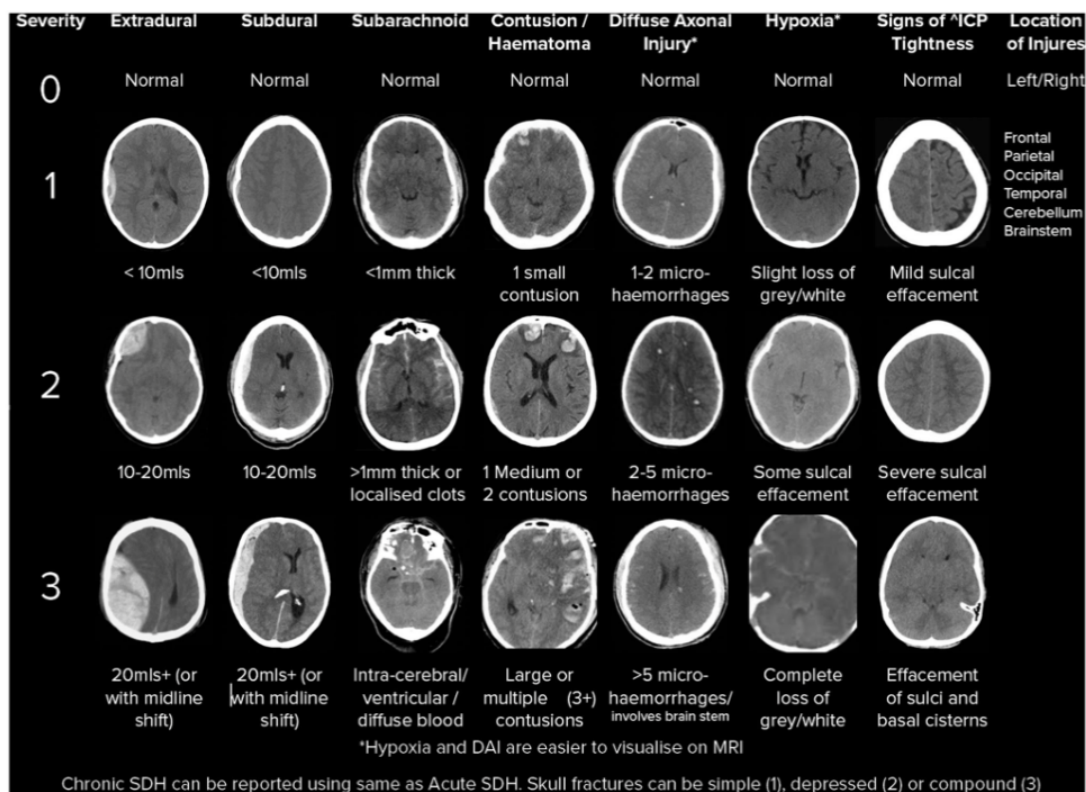


Figure 1. The SBNS TBI CT Classification. All brain injuries are scored between zero and three. Additionally, a score can be assigned to 'mild TBI/concussion' with a history of TBI but no evidence on CT. There is also a score for 'tightness' representing the resulting raised ICP (sulcal, ventricular and basal cistern effacement). Hence, possible scores are: mild TBI (m + ve/-ve), extradural (E 0-3), subdural (SD 0-3), subarachnoid (SA 0-3), contusion (C 0-3), diffuse axonal injury (DA 0-3), hypoxia (H 0-3), + 'Tightness' (0-3).

Table 4. Patient demographics.

Mechanism	No. (%)
Assault (blunt)	5 (10)
Fall >2 m	15 (30)
Fall <2 m	16 (32)
RTC vehicle	2 (4)
RTC pedestrian	6 (12)
RTC cyclist	2 (4)
Unknown	4 (8)

Table 5. Injury pathology as identified by all raters inter-rater reliability.

	Mean No. of injuries (% range from all raters)
ASDH	24 (20.7, 14-31)
EDH	7 (6.1, 4-13)
Contusion	20 (16.9, 15-23)
SAH	21 (18.1, 16-32)
CSDH	5 (3.9, 3-7)
DAI	2 (1.4, 0-5)
Tightness	16 (13.9, 7-21)
Skull fracture	23 (19.3, 19-26)
Hypoxia	0 (0, 0)

However, some injuries were low in prevalence (such as DAI and chronic subdurals) and therefore these results should be analysed with caution (Table 6). Scores for agreement of absence or presence of injury (by consensus) were above 80% agreement. All injuries showed good or excellent consistency other than DAI

(which is usually diagnosed on MRI imaging) and tightness (Table 6). Inter-item correlation was lower for DAI and for tightness (Table 6).

Removing individual raters when calculating the Cronbach's alpha did not impact the score significantly using a non-parametric test for significance ($p > 0.05$) and therefore it can be assumed the Cronbach's alpha is accurate (Supplementary Table 1).

Kappa coefficients were calculated between individual raters and as a whole group of raters. The grouped values were compared to a previous study which also used 50 CT scans of traumatic brain injury and interobserver variability when assessing for injury.^{18,22} Previous inter-observer and inter-rater reliability studies for CT scoring tools, not just those for head CTs, used patient numbers between 41 and 50 for inter-rater reliability and 5 separate raters.^{18,22} The Kappa co-efficient for the SBNS classification are lower than those of the other rating tools (Marshall, Rotterdam and individual assessment), however, as highlighted this is dependent of prevalence of injuries (Table 7). The Median Kappa coefficients for injuries between raters was also calculated (Supplement Table 2).

Discussion

We have described a novel and simple classification system that enables comparisons based on discreet CT pathology and

Table 6. A table to show the percentage agreement of raters for same injury and same score, and for absence or presence of injury my majority vote.

	Agreement of same injury same score (%)	Agreement for absence or presence of injury (%)	Cronbach's alpha	Average inter-item correlation between individual raters
ASDH	76	83.6	0.93	0.73
Contusion	78.8	91.2	0.92	0.72
CSDH	93.6	95.6	0.93	0.70
DAI	96.8	96.8	0.70	0.48
EDH	92	93.2	0.90	0.69
SAH	74.4	84.8	0.87	0.59
Tightness	79.2	84.4	0.77	0.42
Skull fracture	90	N/A ^a	0.93	0.72

Additionally, Cronbach's alpha for individual injuries, where scores above 0.7 show acceptable consistency, above 0.8 good consistency and above 0.9 excellent consistency. Finally the last column displays the median inter-item correlation matrix values between raters.

^aSkull fractures were measured as binary (present or absent) in this inter-rater reliability assessment.

Table 7. Comparison of average Kappa coefficients for individual injuries with the literature¹⁸.

Kappa co-efficient between raters	The proposed new classification	Previous studies ¹⁸
ASDH	0.4484	0.531
EDH	0.4252	0.615
Contusion	0.4517	0.332
CSDH	0.5232	No comparison
DAI	0.3889	0.332
Tightness	0.2792	No comparison
Midline shift >5	No comparison	0.652
Effaced/absent basal cisterns	No comparison	0.691
Skull fracture	0.7132	0.59
SAH	0.319	0.669
Any abnormality	0.4436	0.568

assessed its inter-rater reliability amongst healthcare professionals with varying experience of analysing CT scans. The results demonstrate strong agreement between raters for all injuries except for DAI, which shows fair agreement justified by its lower prevalence compared to other injuries. MRI may be more useful in quantifying DAI and hypoxia. Other scoring systems in the literature have found comparative results, in particular in response to low prevalence of injuries.¹⁸ When compared with the results from Chun *et al.* (Table 6), the new proposed classification showed comparable levels of agreement using Kappa coefficients for ASDH and DAI. We have attempted to mirror their inter-rater work to provide comparison. Agreement was stronger using the proposed classification for contusions and skull fractures. There was weaker agreement using the new system than other classifications for EDH and SAH. This may relate to the differences in the sampling of the study populations which were random CT positive head injuries in this study and <GCS 12 for Chun *et al.* There was no comparison for tightness, midline shift, effacement of basal cisterns and CSDH. These results therefore show that the proposed classification, when compared to other scores is comparable, if not better at diagnostically categorising some injuries. The benefit of the new classification, however, is the simplicity and the reporting of actual brain injury pathology enabling patient and treatment comparisons. The inclusion of a score for signs of raised ICP ('Tightness') should additionally support additional comparisons between patients especially where ICP monitoring is not routine.²⁴ Chun *et al.* also found that contusions and DAI had the lowest sensitivity for detection by CT imaging, whereas EDH, intraventricular haemorrhage and parenchymal hematomas had the highest. It was also found that there was poor agreement between raters for SDH and contusion in particular in relation to measuring volumes of blood using the classification and scoring tools. One reason for this may be due to the accuracy of volumes needed for the tools which has been mitigated by the proposed new classification using broader scoring categories for volumes of blood.¹⁸ Chun *et al.* only used experienced neurosurgeons and neuroradiologists whilst in this

current study we wanted to demonstrate agreement across a breadth of experiences.

This study has some limitations. The sample size was comparable to those of similar studies, however, due to the number of injuries within the scoring system, this resulted in a small prevalence of some injuries, meaning that the statistics may have been skewed. Despite this limitation, it is accepted that Kappa scores as low of 0.41 may be acceptable in healthcare applications.²⁵

Future work

This is a proposed classification system that is now being used in several studies. As increasing data is accumulated, it is fully expected that the system will be modified. Additionally, this study has focused on blunt TBI. It could be possible to extend the classification system into penetrating injuries by adding in penetrating (low velocity = 1, high velocity = 2) and the location affected. Penetrating TBI from gun/knife crime, terrorism, conflict and work-related injury can contribute a large burden of TBI care.^{26,27} This can also be complex pathologically with low and high velocity components, the effects of blast and the ensuing risks of infection.²⁸ Therefore, the utility of this scoring system for such additional injuries has not been assessed and it is expected that it will be modified as future work in this field progresses.

Converting this classification system into a prediction tool

When applied in a larger population, it is expected it will be possible to provide a weighting to the classification of different injury types to provide a clinical prognosis or outcome. For example, the outcome of patients who suffer from DAI varies significantly to those who have an extradural haematoma. Scores for injuries can be weighted to reflect these differences in prognosis to predict outcome, in the way that current systems such as the Marshall CT score do. Similarly, assessment in changes of

scores over time may be a prognostic indicator and identify the need for intervention.

Radiological severity of brain injury is just one factor in outcome prognostication. The constitutional factors of the patient (age/comorbidities), extent of other injuries and neurological and physiological factors can also be influential, hence these should be factored in:

It is envisaged that utilising large data and outcome registries we will be able to populate an equation and develop the factors a,b,c,d,e,f,g to weight individual pathological elements and more accurately predict not just of mortality but also functional outcome.

E.g.

$$a(mTBI (+ve/-ve)) + b(E(0-3)) + c(SD(0-3)) + d(DA(0-3)) + e(H(0-3)) + f(T(0-3)) + g(\text{"Tightness"}(0-3))$$

where E is the Extradural score, SD is the Subdural score, DA is the Diffuse Axonal Score, H is the hypoxia score and T is the tightness score.

Additionally physiological parameters could subsequently be included:

E.g.

$$h(\text{Frailty Index}) + i(\text{other injuries} - \text{ISS}) + j(\text{Neurology} - \text{GCS}) + k(\text{physiology, BP, Glucose, Lactate etc}).$$

Overtime these components will be refined. For example, a biomarker level may give a further indication of amount of neuronal damage, which when put into the above will enable even greater prognostication.

Conclusion

Current CT classification of TBI systems is not injury pathology specific and is difficult to remember and apply. Here we present a simple (mild, moderate and severe) system for different types of brain injury that allows for concomitant brain injuries. The system has good inter-rater reliability across a broad range of experienced users. Utilising such a classification has the potential to assist in clinical management and enables more specific investigation of potential neuroprotectant, physiological and surgical treatments and more accurate prognostication for individual patients.

Disclosure statement

No potential conflict of interest was reported by the authors.

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