DESIGN VALIDATION OF FUTURE BALLISTIC NECK PROTECTION THROUGH THE DEVELOPMENT OF NOVEL INJURY MODELS

by

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Abstract

The primary aim of this thesis was to develop more acceptable methods of ballistic neck protection that could replace the existing OSPREY ballistic neck collar. Clinical and post mortem injury analysis, computed tomography interpretation and ergonomics assessments were undertaken, resulting in the recommendation of two prototype designs to the Ministry of Defence. These two prototypes have subsequently been renamed the Enhanced Protection Under Body Armour Combat Shirt and the Patrol collar, and are now issued to all UK armed forces personnel deploying on operations overseas.

The secondary aim of this thesis was to develop methods to validate the potential medical effectiveness of future body armour designs. Two new novel injury models have been developed using an anthropometrically accurate three- dimensional representation of cervical anatomical structures. Penetration of representative fragment simulating projectiles through skin and muscle was determined experimentally using physical and animal simulants. The Coverage of Armour Tool is being used in the current Ministry of Defence VIRTUS procurement programme to rule out future body armour designs on medical grounds, thereby greatly reducing the number of prototypes requiring ergonomics assessment.

Dedication

I would like to thank my wife Cristina and my loving family for their continued support of me undertaking research such as this. Having only taken a year out of my twenty-one year clinical training programme for this PhD, I have had to undertake most of the experimental work in my spare time, using up valuable annual leave and weekends when I should have been with my family.

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List of Abbreviations

AIS	Abbreviated Injury Severity
ANOVA	Analysis of Variance
CA	Carotid Artery
CAD	Computer Aided Design
COAT	Coverage of Armour Tool
CT	Computed Tomography
DCC	Dismounted Close Combat
DE+S	Defence Equipment and Support
DICOM	Digital Imaging Communications in Medicine
DoP	Depth of Penetration
Dstl	Defence Science and Technology Laboratories
ECBA	Enhanced Combat Body Armour
EFP	Explosively Formed Projectile
EoS	Equation of State
EP-UBACS	Enhanced Protection Under Body Armour Combat Shirt
FSP	Fragment Simulating Projectile
HFN	Head Face Neck
IED	Improvised Explosive Device
IJV	Internal Jugular Vein
IMAP	Interactive Mapping Analysis Platform
IOTV	Improved Outer Tactical Vest
ITDU	Infantry Trials and Development Unit
JTTR	Joint Theatre Trauma Registry
KE	Kinetic Energy

MCC	Mounted Close Combat
MOD	Ministry of Defence Under Body Armour Combat Shirt
MOLLE	Modular Lightweight Load-carrying Equipment
MTP	Modified Terrain Pattern
MTV	Modified Tactical Vest
NATO	North Atlantic Treaty Organisation
PBO	Polybenzobisoxazole
pFCI	predicted Functional Capacity Index
PP	Polypropylene
RCDM	Royal Centre for Defence Medicine
PMHS	Post Mortem Human Subject
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PWC	Permanent Wound Cavity
PWT	Permanent Wound Tract
SC	Spinal Cord
STANAG	STANdardising AGreement
SUSAT	Sight Unit Small Arms Trilux
TNC	Trauma Nurse Coordinator
UBACS	Under Body Armour Combat Shirt
UHMWPE	Ultra High Molecular Weight Polyethylene
UK	United Kingdom (of Great Britain and Northern Ireland)
US	United States (of America)
VA	Vertebral Artery
WRT	Water Repellent Treated

Chapter 1: Introduction

1.1 Identifying the problem

This thesis describes the development of novel methods for protecting the neck from energised fragments and validating future tools capable of comparing the potential medical effectiveness of body armour designs. A database analysis was undertaken in 2009 prior to the start of the thesis, while the author was at medical school having served previously as a Dental Officer within the British Army. This analysis quantified the number and broad types of head, face and neck injuries sustained by UK soldiers deployed to Iraq and Afghanistan between 2004-2008. UK soldiers were found to have experienced three times as many penetrating neck wounds as their US counterparts despite almost identical incidences of head, face, extremity and thoraco- abdominal injuries. Informal conversations between soldiers from each nation had identified that this epidemiological difference in neck wound incidence most likely reflected attitudes in the uptake of ballistic neck protection.

Following approval by UK Joint Medical Command and competitive selection at the Higher Degree Board, this PhD was undertaken over a 5- year period (2010-2015), of which one year was full time and the remainder part time. The full time period consisted of detachments to Dstl Porton Down in 2010 and 2012, followed by an operational deployment to Afghanistan in 2012 to trial the prototypes. This meant that the majority of the thesis was undertaken in the author’s spare time, around clinical commitments training to be a consultant Maxillofacial surgeon. However the benefit of this extended period meant that there was a greater time to both plan and learn from the ergonomics and experimental trials described in the thesis. For example the experimental trial comparing methods of storage on projectile penetration took over two years to complete following initial ethical approval, with funding necessary from three very separate sources. In addition the requirement for such a trial only became apparent later on in this research and therefore its implementation would have been logistically highly difficult to achieve within the standard framework of a three-year degree.

1.2 Developing a framework

The development of body armour worn by UK forces has traditionally occurred through an iterative approach, reflecting the specific requirements of the operational theatre at that particular moment. The procurement of OSPREY as a complete body armour system in 2006 was the first major exception to this trend, reflecting an urgent operational requirement for a solution to protect against the threat in Iraq. The significant advantage of introducing such a system as a whole was that it had the potential for the individual components to integrate with one another in a more cohesive manner than those developed previously. OSPREY included ballistic neck collars, the first time protection specifically to the neck had been included. However no evidence could be found as to why these collars were designed to these specifications and no processes existed to define either the requirement or a framework to validate their design. A systems designed approach had been previously described for the design of explosive ordnance disposal suits (Couldrick, 2014); but due to its differing requirement most of its concepts could not be applied to the problem of neck wounds.

A major driving factor for this research became the Ministry of Defence VIRTUS procurement programme that will provide the replacement for the OSPREY personal body armour system currently worn by UK forces. OSPREY had been through four generations since its inception and it had been recognised that it had potentially become highly specific to the particular threat of the time (ie Afghanistan). There was a desire to develop an objective method of accurately comparing the predicted medical effects of different types of body armour that could potentially be incorporated into VIRTUS. This would ideally be computerised such that different armour designs could be compared without the requirement for expensive physical prototypes until later in the assessments.

1.3 Aims of this thesis

The aims of this thesis were two-fold and will be answered in the chapters described in brackets:

- To develop more acceptable methods of ballistic neck protection that could replace the existing OSPREY ballistic neck collar (Chapters 2- 9).
- The develop methods for validating the potential medical effectiveness of future body armour designs (Chapters 10- 15).

1.4 Concept of the thesis

The research described in this thesis in developing validated methods of neck protection is all encompassing, including clinical analyses, ergonomics assessments and modelling. For the purpose of this thesis, the text has been divided into two broad sections, such that each specific aim can be answered (Table 1); however in reality components of each of the two sections developed concurrently and the chapter order does not necessarily reflect the timeline in which they were actually undertaken. The first part of the thesis revolves around the design of the neck protection, using clinical, radiological and post mortem information to identify the structures within the neck that require protection (Chapters 2- 6). Representative projectiles from which to test armour materials are identified and a comprehensive literature review enables potential types and designs of neck protection to be tailored and developed (Chapters 3 and 5). These prototypes are evaluated in three successive ergonomics assessments, each improving on the previous assessments in terms of the designs used as well as the method in which they are evaluated (Chapters 7- 9).

Aims	Title	Chapter
	Introduction	1
To develop more acceptable methods of ballistic neck protection that could replace the existing OSPREY ballistic neck collar	Identification of the problem with combat neck wounds sustained by UK forces	2
	Systematic literature review to ascertain how the neck can be potentially protected from explosive fragmentation	3
	Analysis of hospital and post mortem records of survivors and those soldiers killed with neck wounds	4
	Analysis of Computed Tomography scans to characterise those fragments injuring the neck	5
	Analysis of Computed Tomography scans to scale external cervical anthropometric landmarks and internal anatomical structures	6
	Ergonomic assessments of ballistic neck collars from six different nations	7
	Ergonomic assessments of novel neck protection prototypes	8
	Ergonomic assessments of modified UBACS neck collar prototypes	9
To develop methods to validate the potential medical effectiveness of future body armour designs	Injury modeling: concepts and applications to the problem of neck wounds	10
	Experimental determination of an equation to describe the velocity required to perforate skin	11
	Experimental determination of equations to describe the velocity required to penetrate animal muscle and 20% gelatin	12
	Comparing the penetration of fragment simulating projectiles into fresh, refrigerated and frozen porcine tissue	13
	Use of Computerised Surface Wound Mapping to differentiate between three neck protection prototypes	14
	Use of the Coverage of Armour Tool to differentiate between three neck protection prototypes	15
	Future directions and the introduction of new neck protection designs for UK armed forces in Afghanistan	16
	Conclusions	17

Table 1: Aims of the thesis and how it is proposed that these will be achieved.

The second half of the thesis begins with a comprehensive review of the current challenges and potential solutions for modelling energised fragments perforating the neck (Chapter 10). Three successive experimental trials are described that were undertaken to identify relationships between the penetration of fragments into skin and muscle, including those stored post mortem in different manners (Chapters 11-13). Two computer models are utilised to compare the potential medical implications of different neck protection designs (Chapters 14 and 15). The thesis ends with a discussion on the concepts developed, implementation of the neck protection designs and proposed future developments (Chapter 16). A conclusion provides the reader with a brief synopsis of the lessons learned from this research and suggestions for future applications (Chapter 17).

Chapter 2: Identification of the problem with combat neck wounds sustained by UK forces

Chapter summary

Although US and UK forces have experienced similar increases in the incidences of face and head injuries in the 21st century compared to previous conflicts, UK soldiers experienced three times as many neck wounds as their US counterparts between 2004-2010. Three quarters of neck wounds sustained by soldiers from both countries were due to energised fragments, for which protection was potentially available by wearing a detachable neck collar. No evidence other than differences in the uptake of these collars could be found to explain the difference in neck injury incidence between nations incidence. Database searching could not provide evidence for the true uptake of neck collars on operations but a survey of a broad range of officers demonstrated that such collars were disliked and rarely worn due to discomfort and equipment integration issues. This chapter has demonstrated the need to potentially modify the neck protection worn by UK soldiers on current operations.

2.1 Aims of this chapter

- To describe the causes of neck wounds sustained on modern combat operations
- To provide evidence and possible reasons for the discrepancy between the incidence of neck wounds sustained by UK forces compared to US forces

2.2 Publications derived from this chapter

- Breeze J. Editorial: The problems of protecting the neck from combat wounds. Journal of the Royal Army Medical Corps 2010; 156 (3): 137–138 (Breeze, 2010).

- Breeze J, Gibbons AJ, Shieff C, Banfield, G, Bryant D, Midwinter MJ. Combat-Related Craniofacial and Cervical Injuries: A 5-Year Review From the British Military. Journal of Trauma and Acute Care Surgery 2011, 71 (1): 108–113 (Breeze et al., 2011a).

2.3 Introduction

The conflicts in Iraq and Afghanistan have resulted in well-publicised changes in the pattern of injuries sustained by UK soldiers on operations. Sixteen papers had described the incidence of combat injuries to the head, face and neck (HFN) regions in the 20th and 21st centuries prior to the start of this thesis in 2010 (Table 2). These papers demonstrated a clear overall increase in the incidence of HFN injuries over the time period studied. Reasons for this difference were ascribed to the use of body armour to protect the thoraco-abdominal regions, rapid aero-medical evacuation, innovations such as early use of blood products, the re-emergence of the tourniquet, and the development of novel haemostatic agents (Hodgetts et al., 2007; Wade et al., 2007; Owens et al., 2008). This had resulted in soldiers surviving to receive medical care in a field hospital who would have died in previous conflicts. Of all of these ascribed reasons, it was felt that the effectiveness of modern body armour to protect the head, thorax and abdomen had the largest effect on the relative incidence of HFN injuries (Wade et al., 2007; Powers, 2010).

Dates	Conflict	Nation	Incidence	Lead author (reference in brackets)
1914-1918	WW1	UK	31%	Dobson (Dobson et al., 1989)
1939 - 1945	WW2	UK	4%	Dobson (Dobson et al., 1989)
1950- 1953	Korea	US	16%	Tong (Tong et al., 2011)
1961- 1975	Vietnam	US	16%	Hardaway (Hardaway, 1978)
1982	Falklands	UK	29%	Jackson (Jackson et al., 1983)
1991	Iraq	US	22%	Carey (Carey, 1996)
1982	Lebanon	Israel	34%	Gofrit (Gofrit et al., 1996)
2001	Afghanistan	US	26%	Bilski (Bilski et al., 2003)
2001- 2005	Iraq + Afghanistan	US	29%	Owens (Owens et al., 2008)
2003	Iraq	US	25%	Montgomery (Montgomery et al., 2005)
2003- 2004	Iraq + Afghanistan	US	21%	Xydakis (Xydakis et al., 2005)
2004	Iraq	US	39%	Wade (Wade et al., 2007)
2006	Iraq	UK	32%	Ramasamy (Ramasamy et al., 2009a)
2006	Lebanon	Israel	29%	Levin (Levin et al., 2008)
2004- 2008	Iraq + Afghanistan	UK	29%	Breeze (Breeze et al., 2011a)

Table 2: Overall incidences of head, face and neck injuries from World War One to the start of this study.

Currently the modern UK soldier wears a number of items to protect against ballistic threats, including a combat helmet, ballistic eyewear, neck collars, pelvic protection and a body armour vest incorporating ceramic plates. It should be noted that with the exception of the ceramic plates that protect against high velocity projectiles, the remaining items are only designed to protect against energised explosive fragments (Lewis, 2006). The fragmentation vest and combat helmet provide excellent protection to the head and thoraco-abdominal regions, such that the extremities including the face and neck have a higher proportion of injuries (Wade et al., 2007) as they remain relatively unprotected (Figure 1).

Figure 1: A UK soldier wearing OSPREY Mark 4 body armour in conjunction with a Mark 7 helmet; downloaded from the Defence Images database.

2.3 Comparison of neck injury incidence sustained by UK soldiers to US soldiers

Research undertaken by the author prior to the start of this thesis demonstrated that the distribution of injuries within the HFN region itself differed between nations (Breeze et al., 2011a). For example although both the US and UK experienced similar incidences of face, eye and head injuries, the UK incidence of neck injury between 2004-2010 was 11% (Breeze et al., 2011a), compared to 3-4% experienced by that US (Owens et al., 2008; Wade et al., 2007; Gondusky and Reiter, 2005) (Figure 2). Informal conversations by the author between soldiers from both nations had identified that this could potentially be due to differences in the uptake of neck protection.

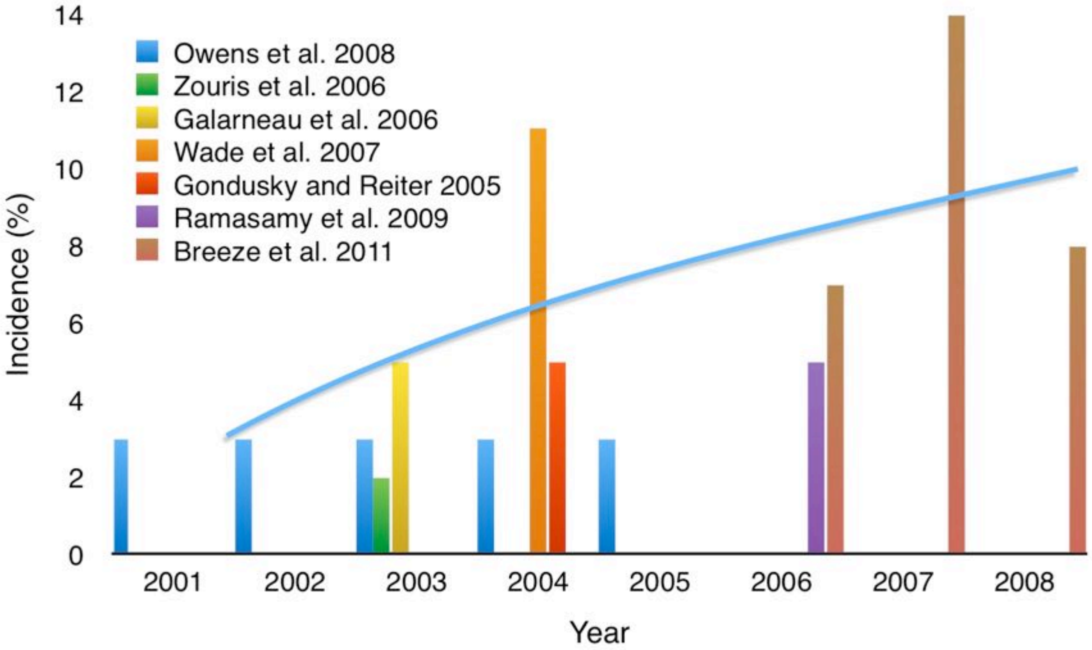


Figure 2: Incidences of combat neck injuries described in the literature in the 21st century, with a trendline demonstrating the mean incidence.

In previous conflicts differences in injury incidence could have been ascribed to the manner in which data is collected or in which it is classified into individual wounds. For example the term 'maxillofacial' is still used to describe anatomical areas very differently between institutions, with UK authors often including the neck and US authors the head. However the risk of such differences being due to data collection issues has reduced dramatically since the introduction of the Joint Theatre Trauma Registry (JTTR) (Russell et al., 2014). This database was first established by the UK in 2003, and utilises a format very similar to that used by the American and Canadian military, enabling valid comparisons to be made. It is based on the 2005 iteration of the original Abbreviated Injury Score (AIS) system (Gennarelli and Wodzin, 1971). This is an anatomical-based coding system created by the Association for the Advancement of Automotive Medicine to classify and describe the severity of specific individual injuries. The AIS system represents the threat to life associated with the injury rather than the comprehensive assessment of the severity of the injury. Each injury is represented by a seven-digit code that includes the body region, anatomical structure and severity of the injury. The body is divided into eight areas within AIS: Head, Face, Neck, Thorax, Abdomen, Spine, Upper extremity and Lower extremity. Severity is scored between 1 (minor) to 6 (maximum), with examples of injuries pertaining specifically to neck wounds demonstrated in Table 3.

AIS code	Severity	Example
1	Minor	Superficial skin laceration
2	Moderate	Laceration of external carotid artery)
3	Serious	Transection of external carotid artery)
4	Severe	Transection of internal carotid artery)
5	Critical	Transaction of internal carotid artery resulting in stroke
6	Maximum	Decapitation

Table 3: Examples of Abbreviated Injury Score (AIS) codes pertaining to the neck region.

Certified nurses perform the coding of injuries using AIS scores retrospectively once the patient has either been treated in the deployed field hospital (e.g. Camp Bastion) or when evacuated to the Royal Centre for Defence Medicine (RCDM), based at the Queen Elizabeth Hospital Birmingham. The strength of the AIS coding is that it is a public resource and used by the majority of healthcare providers. A disadvantage of the system is the limitation of descriptors and available codes, which must be inputted retrospectively by healthcare workers who may not be familiar with relevant terminology. The facility to select non-specified codes (AIS code 9) also potentially reduces the numerical significance. For example using the JTTR alone, 34% of penetrating neck injuries could not be further sub defined into individual damaged anatomic structures, reflecting a lack of detail in the data collected on these types of injury using such a method.

2.4 Causes of combat neck injury

Research undertaken by the author prior to the start of this thesis demonstrated that 79% of combat neck injuries were due to explosive events, with the remainder due to gunshot wounds (Breeze et al., 2011a). This reflects the proportion of injuries seen in most campaigns since World War One, with the exception of the Falklands war and the majority of the Northern Ireland conflict (Table 4). Injuries from explosions are best classified into four categories that enable more accurate comparisons to be made: primary, secondary, tertiary, and quarternary blast (Zuckerman, 1952). Primary blast injuries are caused by the sudden increase in pressure after an explosion and affect predominantly gas-containing organs such as the middle ear, lungs and gut. Secondary blast injuries are caused by energised fragments, such as bomb components or soil overlying buried explosive devices. Tertiary blast injury is caused when the casualty is thrown by the explosion and collides with nearby objects. Quaternary blast injury is related to the thermal effects of the explosion.

Conflict	Bullets	Fragmentation	Other
World War 1	39-65	35-61	-
World War 2	10-27	73-85	5
Korea	7-31	69-92	1
Vietnam	35-52	44-65	4
Borneo	90	9	1
Northern Ireland	55	22	20
Falklands	32	56	12
Iraq	19	81	-
Afghanistan	20	74	6

Table 4: Causes of combat injury broken down by wounding type; other causes include interpersonal assault and blunt trauma.

Figure 3: Range of sizes of energised fragments produced by a high explosive round fired from a 81mm mortar. Image kindly provided by Dr Debra Carr, Cranfield University.

World War One was the first conflict to utilise less discriminate methods of ballistic injury that primarily relied on fragmentation (Figure 3). These ranged from smaller devices such as the hand grenade to weapons that could cause widespread fragmentation such as the aerial bombardment produced by shells. These types of fragmentation weaponry continued through World War Two and contrary to some reports in both Vietnam and the first Gulf War. Although used against UK forces in both Cyprus and Northern Ireland, the Improvised Explosive Device (IED) has become synonymous with the current conflicts in Iraq and Afghanistan, and has been the leading cause of death and injury amongst Coalition troops (Owens et al., 2008). It encompasses a wide spectrum of devices ranging from rudimentary homemade explosives to sophisticated weapon systems containing high-grade explosives (Ramasamy et al., 2009b). Within this generic definition, IEDs can be classified as roadside explosives and blast mines - usually formed from conventional military ordnance, Explosive Formed Projectiles

(EFP) devices and suicide bombings. These devices may be initiated in a number of different ways, but are generally either remotely or victim operated (Figure 4). Research undertaken by the author prior to the start of this research demonstrated that IEDs were responsible for 84% of all neck wounds due to explosive events (Breeze et al., 2011a).

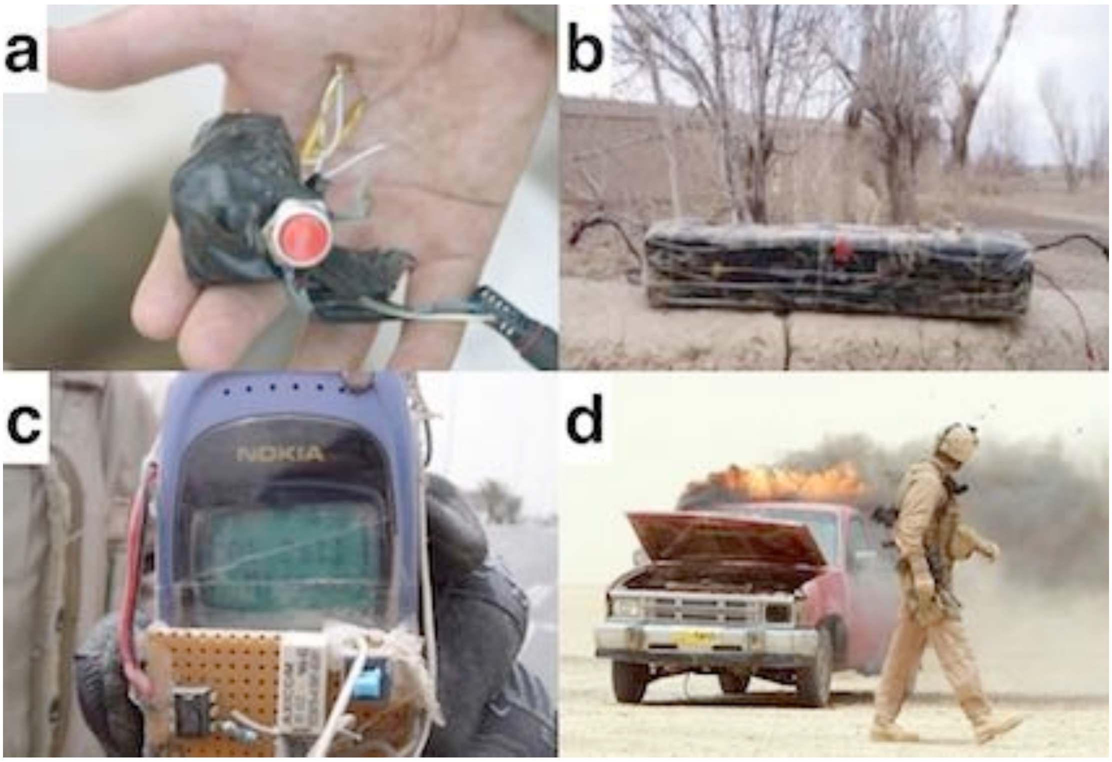


Figure 4: Examples of improvised explosive device in terms of methods of detonation; (a) remote via command wire, (b) victim operated pressure plate, (c) remote via mobile phone, (d) suicide bombing via car.

2.5 Methods of protecting the neck available to UK forces at the commencement of this research

Methods of protecting the neck have taken the form of flexible collars attached to the ballistic vest. These collars are designed to withstand energised fragmentation (i.e. secondary blast injury), which had been responsible for 79% of neck wounds. OSPREY had since its inception gone through four generations, incorporating various design modifications such as moving the ceramic plates from the outside to the inside of the vest (Brayley, 2011). The OSPREY body armour system had been procured in 2006 as part of an Urgent Operational Requirement (Lewis, 2006), and as such the collars themselves had not been individually designed nor previously assessed (Appendix A).

Figure 5: A close up of the full (left) and half (right) collars provided in the OSPREY body armour system.

At the start of the thesis UK soldiers were wearing OSPREY Mark 3 body armour, which had subsequently been replaced by Mark 4A by the end of the thesis. All four versions of the OSPREY body armour system (Marks 1-4) were issued with two sizes of detachable collar (half and full) to protect the neck (Figure 5). Both sizes of collar would fit onto all sizes of vest using metal press studs, with the larger collar designed to be worn in situations of increased threat due to its greater skin coverage. However no changes had been made to the neck collars in any of these generations except to alter the colour of the outer fabric (Figure 6).

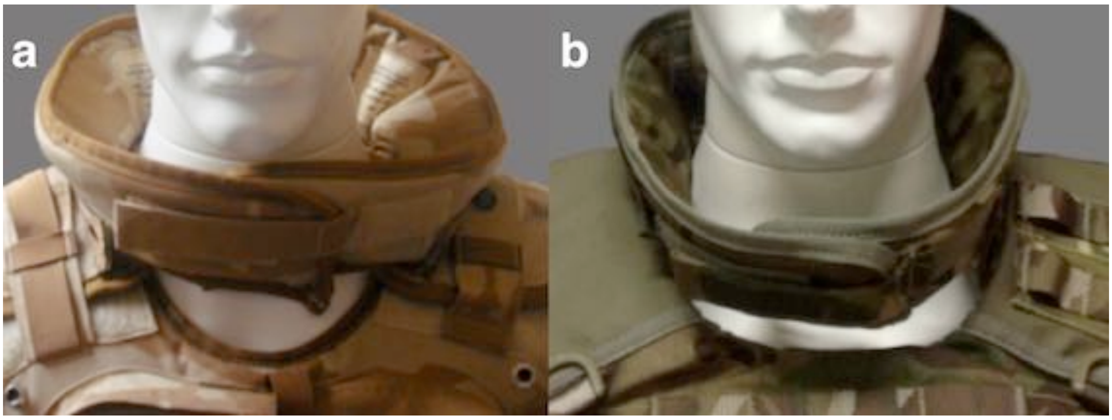


Figure 6: The half collars in Mark 1 (a) and Mark 4 (b) versions of OSPREY despite representing a time range of six years remained unchanged except for a colour change.

Prior to the introduction of OSPREY in 2005, no specific protection for the neck had ever been issued to UK soldiers (Lewis, 2006; Brayley, 2011; Dunstan, 1984; Stansfield et al., 2008; Woosnam-Savage et al., 2002). However, for a short two-year period (2006-2007), an additional body armour system was available with the code name KESTREL (Figure 7). This system was designed to be used only in a static position such as while providing top cover in the turret of a vehicle. The neck and arm components were non- detachable but provided similar anatomical coverage and levels of ballistic protection to the detachable neck collars and brassards used in OSPREY. The KESTREL system was never personal issue and was given to soldiers when they took command of a particular vehicle. It was discontinued after UK forces left Iraq due to the predominantly dismounted role that soldiers undertook in Afghanistan.

Figure 7: A comparison of the only two UK body armour systems to incorporate neck protection; OSPREY (left) and KESTREL (right).

2.6 Attitude survey undertaken with serving military officers on Intermediate Staff and Command course

The wearing of collars has traditionally not been mandatory and has been up to the commanders individual discretion based on a risk assessment of the threat at that particular moment. However prior to the start of this thesis no evidence existed to accurately ascertain the uptake of neck protection. 71 male officers undertaking the Intermediate Staff and Command course at the Defence Academy, based at Cranfield University, were surveyed by the author (Breeze et al., 2011c). This group was chosen not to represent the population at risk but reflected that it was these officers that would make the command decisions as to the wearing of body armour in the tactical situation. 58% had worn neck collars previously on exercise and 6% on operational tours. 31/71 (44%) of the servicemen had served in Iraq, of which 4/31 (13%) had worn neck collars on that deployment. None of the 49 servicemen who had served in Afghanistan had worn neck collars on that deployment. When asked why they had not worn the OSPREY neck collar, the most common reasons cited were that it was uncomfortable

(92%), it interfered with aiming a rifle (85%) and that it prevented them lying in a fully prone position (79%).

2.7 Conclusions and recommendations

A summary is provided in Table 5 and provides the rationale for the research undertaken in subsequent chapters.

Conclusion	**Recommendation**
79% of wounds to the neck during this period were from explosive events. Neck protection is designed to prevent perforation of energised fragments (secondary blast injury).	The use of neck protection has the potential to reduce the incidence of combat injuries if worn.
UK soldiers experienced three times as many neck wounds as their US counterparts between 2004-2010. No evidence other than differences in the uptake of these collars could be found to explain this difference.	Reasons for the difference in collar acceptability should be ascertained and potential solutions explored. Design feature differences between the collars should be identified.
An attitude survey demonstrated that none who had served in Afghanistan had worn their neck collars. Reasons cited were discomfort, interference with aiming a rifle and that the collar prevented them lying in a fully prone position.	Ergonomics assessments using these and other representative tasks should be undertaken using prototypes incorporating features from other designs of neck protection to identify more successful alternatives.

Table 5: Conclusions and recommendations based upon the findings from Chapter 2.

Chapter 3: Systematic literature review to ascertain how the neck can be potentially protected from energised fragments

Chapter summary

A systematic review of the scientific and commercial literature was undertaken to identify past and present types of neck protection and recommend combinations of neck protection designs that could be subsequently evaluated by ergonomics testing. Variations in collar designs were identified as well as additional methods of protection such as a nape collar and a ballistic scarf. No evidence was found to substantiate the theory that any type of neck protection reduced the incidence of neck injury. Neck collars utilised by UK and US forces use a para- aramid as the ballistic protective material but other potential materials such as ultra high molecular weight polyethylene and silk exist. These different designs and materials require ergonomic assessments to ascertain the most advantageous design features that can be incorporated into future prototypes. Even if a ballistic protective material stops a projectile, the residual kinetic energy may push the ballistic protective material with it into the body, necessitating the minimum distance from skin surface to critical anatomical structure to be ascertained.

3.1 Aims of this chapter

- To identify other designs of neck protection that have not been previously utilised by UK forces.
- To ascertain evidence that any particular design of neck protection reduced wound incidence or severity.
- To recommend combinations of neck protection designs that could be subsequently evaluated by ergonomics testing.

3.2 Publications derived from this chapter

- Breeze J, Helliker M, Carr DJ. An integrated approach towards future ballistic neck protection materials selection. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 2013; 227 (5): 581–587 (Breeze et al., 2013a).
- Breeze J, Horsfall I, Hepper A, Clasper J. Face, neck, and eye protection: adapting body armour to counter the changing patterns of injuries on the battlefield. British Journal of Oral and Maxillofacial Surgery 2011; 49 (8): 602–606 (Breeze et al., 2011b).
- Breeze J. Obtaining multinational consensus on future combat face and neck protection. Journal of the Royal Army Medical Corps 2012; 158 (2): 141–142 (Breeze, 2012).

3.3 Collaborations

This chapter details a literature review that identifies both body armour design features and ballistic protective materials that may be suitable for protecting the neck. The author worked with Professor Horsfall at Cranfield university using his collection of body armour from different countries to identify types of body armour and design features that could be utilised in future ergonomics assessments (Chapter 7). Dr Debra Carr provided invaluable advice regarding ballistic protective materials and potential means of testing them. Mr Alan Hepper and Dr Simon Holden at Dstl kindly provided the author with access to the US Improved Outer Tactical Vest and an introduction to the manufacturers of the nape pad and ballistic scarf.

3.4 Introduction

Prior to the start of this thesis it had been identified that wounds to the neck region were present in 11% of all UK soldiers sustaining battle injuries compared to 3-4% in their US counterparts. No other reason could be found to explain this difference apart from the low uptake of the detachable neck collars provided with the OSPREY body armour system. The survey of military officers described in Chapter 2 had attempted to ascertain reasons for the poor uptake, finding that the collar interfered with the aiming of a rifle and that it prevented them lying in a fully prone position. The first step in developing an improved design of neck protection was to identify other existing neck protection designs that could subsequently be evaluated through ergonomics and clinical assessments.

3.5 Systematic review of the literature

Utilising the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology (Moher et al., 2009), evidence was sought to provide answers for the following questions:

- What effect does the wearing of neck protection have on reducing injury incidence and severity?
- What types of neck protection are available to non-UK forces?
- Are there any other types of commercially available neck protection designs that have not been described in answers to the previous questions?
- What ballistic protective materials are available to be utilised within any identified designs of neck protection?

The following scientific databases were searched: PubMed, ProQuest, Web of Science and Google Scholar. Four limited-access sources were also interrogated: the Ministry of Defence online library, the Barrington digital library at Cranfield University, the Dstl Athena online library and the proceedings of the Personal Armour Systems Symposia (PASS) conferences. The following keywords were utilised: neck, cervical, prevention, military, protection, armour, wound, injury.

3.6 Effect of neck protection on reducing neck injury

No experimental studies such as a randomised control trial were identified in the literature. Fox et al. (Fox et al., 2006) published a case series describing the treatment of 63 US soldiers who had sustained penetrating neck wounds. They described a lower incidence of injuries sustained at the base of the neck in comparison to higher up. The authors felt that this reduced incidence of wounds was due to the protection provided by the collar portion of US Interceptor body armour. However without knowledge of whether the injured soldiers were wearing the collar at the time of injury the authors admitted that little substantive conclusions could be made from this observation.

3.7 Types of neck protection available to non-UK forces

The US military first introduced neck protection to their body armour with the Interceptor system in 1998 (Brayley, 2011). In contrast to OSPREY the neck collar of Interceptor was a three-piece design, with the two side portions being securely fastened to the vest (Figure 8). The front 'gorget' part was designed to be easily detachable in situations of decreased threat. The successor to interceptor was the Modified Tactical Vest (MTV) used by the Army and Air Force and introduced to US soldiers serving in Iraq during 2006. The collar design used in the MTV was almost identical to

Interceptor, although the fastenings had become more secure with the addition of Velcro and Modular Lightweight Load-carrying Equipment (MOLLE) loops (Figure 8).

Figure 8: The three-piece detachable neck collar utilised in Interceptor (left) was taken into the newer US Army Modular Tactical Vest (right).

At a similar time to the introduction of the MTV, the US Marine Corps introduced its own replacement to Interceptor, termed the Improved Outer Tactical Vest (IOTV). The IOTV system utilises a different style of neck collar than the MTV (Figure 9) and is only available in a single size. Although it is also composed of three overlapping segments, the collar is significantly shorter than that used in Interceptor and the subsequent MTV. However of greater significance is that the neck collar is part of a large sleeve, that is worn under the body armour vest itself, adding considerably to the weight and bulk of the garment.

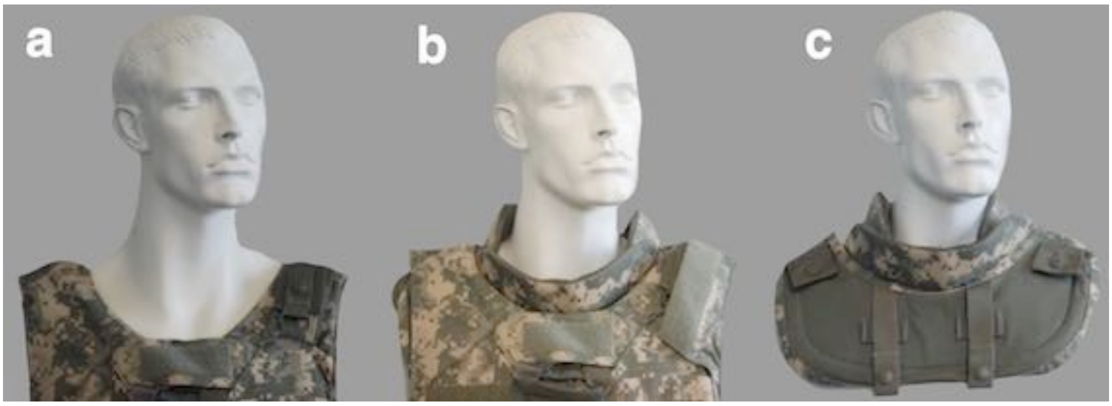


Figure 9: The Marine Corps IOTV has a lower cut at the neck than OSPREY (a); it utilises a close fitting three- piece collar (b) that is retained underneath the vest (c).

In 2007 the US Army in a direct response to the reported increase in the incidence of neck wounds introduced 430,000 helmet nape pads as an urgent operational requirement to troops on deployment in Afghanistan and Iraq (Brown et al., 2008). The nape pad attaches to the rear of the combat helmet and was secured with a single loupe of Velcro (Figure 10). Senior commanders had also contemplated light handheld or deployable shields to improve neck protection further but no additional information about these methods of protection was described.

Figure 10: Two nape protection designs, each of which attach to the rear of the helmet; nape pad used by US forces (left) and commercial nape pad with overlapping segments (right).

No information in the open literature was found describing the designs of neck protection systems utilised by non-US and UK forces. However at Cranfield University in the Impact and Armour group there are a number of body armour systems utilising neck protection systems and two additional design features were identified from these (Figure 11). The first was a two-piece collar utilised by Norwegian forces which overlaps at the front and was non detachable. The second was a non-detachable single piece collar with the anterior neck exposed. A number of these designs were utilised in the first ergonomics trial, which will be described in Chapter 7 of this thesis. In addition the author of this thesis helped to organise a multinational body armour conference in 2010 and surveyed the procurements managers of ten NATO and European countries regarding their current neck protection designs and what their anticipated future requirements would be (Table 5).

Nation	**Current protection**	**Future direction**
UK	Detachable semi- rigid collar of two different heights. No indication for nape protection	Currently evaluating different designs of detachable neck collar
US	Detachable short neck collar. Nape protectors also available	Likely to be similar design but less bulky under the vest
Germany	Detachable short flexible collar	Likely to be similar design but overlapping plates
Canada	Detachable semi- rigid collar	Likely to be similar design but shorter
Switzerland	Detachable short flexible collar	Likely to be similar design
Denmark	Non detachable short flexible neck collar	Changing to detachable collar with two different heights heights
Netherlands	Non detachable short flexible neck collar	Changing to detachable semi rigid collar. Will be trialing nape protectors
Belgium	Non detachable short flexible neck collar	Changing to detachable semi rigid collar. Will be trialing nape protectors
Sweden	Non detachable short flexible neck collar	Changing to detachable semi rigid collar
Austria	Detachable semi- rigid high collar	Likely to be similar design but shorter

Table 6: Current types of neck protection and anticipated future requirements.

Figure 11: Ballistic neck collar designs in the Dutch (a) and Norwegian (b) body armour systems. Images kindly provided by Professor Ian Horsfall at Cranfield University.

3.8 Other commercially available types of neck protection

No additional commercial designs of neck collar were identified. However a different design of nape pad was identified that used overlapping segments (Figure 10). In addition a ballistic scarf was identified that incorporated a square of ballistic protective material that could be wrapped around the neck (Figure 12). The author contacted the manufacturer of this scarf who kindly provided an example, which underwent subsequent ergonomics assessment.

Figure 12: A ballistic scarf in which the standard cotton shemagh is reinforced with a central square of a para- aramid ballistic fibre.

3.9 Ballistic materials choice

The scientific and commercial literature contain a large quantity of information about ballistic protective materials for use in military body armour systems. However not a single reference could be found regarding ballistic materials for neck protection. In terms of materials selection, neck protection is best thought of as being an extension of the soft component of military body armour. Its aim is to defeat energised fragments, or to significantly reduce their energy to minimise wounding potential (Carr et al., 2012). Soft body armour is composed of multiple components, of which the ballistic protective fabric is only a part. Multiple plies of ballistic fabric are assembled into a 'ballistic panel', which is then inserted into a UV-resistant and water-resistant cover, which is generally made of a coated nylon or polyester woven fabric. Finally this assembly is inserted into a replaceable outer carrier, which is printed with the appropriate camouflage pattern.

Class	Trade name	Manufacturer
Para-aramid	Kevlar ®	DuPont ®
	Twaron ®	Teijin Aramid ®
Nylon	Cordura ®	DuPont ®
Ultra high molecular weight polyethylene (UHMWPE)	Dyneema ®	DSM Dyneema ®
	Tensylon ®	DuPont ®
	Spectra ®	Honeywell ®
Polybenzobisoxazole (PBO)	Zylon ®	Toyobo Corporation ®
Polypropylene (PP)	Tegris ®	Milliken & Company ®
Silk	N/A	N/A

Table 7: Classification of potential soft armour ballistic material appropriate for neck protection.

To meet the protection requirements for typical military threats, the ballistic panel to provide protection to the thorax generally consists of approximately 20-50 layers of ballistic material (Lee et al., 1994). The number of layers utilised in neck protection would likely need to have significantly less than this number to retain flexibility, but no evidence to the desired thickness or weight of material could be found. The current OSPREY and US IOTV neck collars consist of multiple layers of a water repellent treated (WRT) para-aramid woven fabric protected in a water and UV resistant cover, placed in an outer carrier made from Cordura® nylon. The literature review identified a number of ballistic protective materials in addition to that currently used in these collars (Table 7). The author assisted in the testing of a number of prototype ballistic protective materials that had been identified by commercial manufacturers as potentially being of use for neck protection (Figure 13). A common manner of comparing the ballistic protective capability of a material in comparison to its mass is to plot V_{50} velocity (the velocity at which 50% of a particular projectile are defeated by the material) against areal density (Sellier and Kneubuehl, 1994). Areal density is an alternative term for mass per unit area (kg/m^2) for a two-dimensional object (Iremonger and Went, 1996). Areal density is cumulative such that if a single layer of material is 0.5 kg/m^2, it would require three layers to achieve 1.5 kg/m^2. It should be noted that although areal density is cumulative, the V_{50} of materials increases non-linearly with increasing areal density. Using test results for those materials identified in Table 7 derived from the open literature (Chocron et al., 2008; Fournier, 2009), a plot of areal density versus V_{50} velocity was produced (Figure 14). The most promising results were provided by UHMWPE, such as Dyneema® felt. The properties of silk would potentially be advantageous, but no test results for its use could be found; it is however being utilised in the newly introduced Tier 1 pelvic protection with early reports from deployed surgeons suggesting a significant reduction in injury incidence (Lewis et al., 2013).

Figure 13: The author assisting in the testing of a number of ballistic protective materials to ascertain V_{50} velocities using a 1.10g FSP fired from a gas gun.

The role of a ballistic protective material is to dissipate the kinetic energy of an impacting FSP and prevent it perforating through it. This will be dependent on factors such as material type and weave, as well as the number of layer and orientation of the material. Any remaining kinetic energy of the projectile will either completely perforate the armour causing a penetrating injury or may push the ballistic protective material with it into the body (termed pencilling) if the projectile is stopped (Lewis, 2005). Pencilling is dependent on many factors, but is more common in lower areal density armour, where the fabric has a greater freedom of movement. It is therefore essential to know the minimal distance from the skin to an underlying critical structure. Pencilling is of more relevance in the neck than the thorax, due to the superficial position of the vasculature and its lack of bony protection. It should be recognised that the concept of penciling is primarily of relevance to FSPs and does not pertain to high impact velocity projectiles such as bullets.

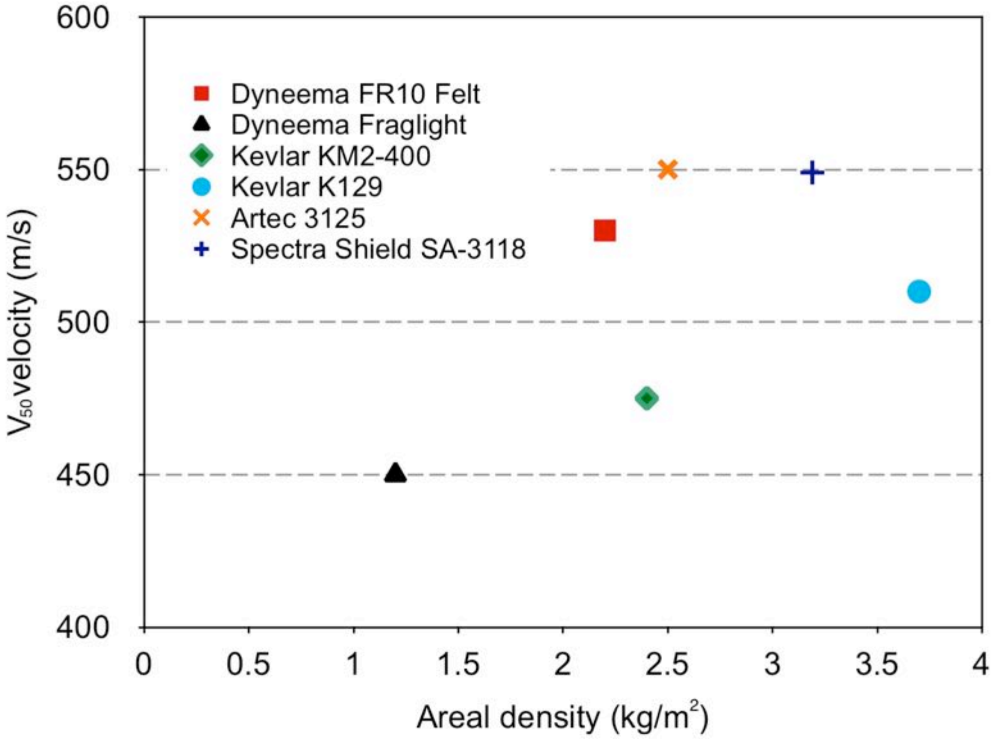


Figure 14: A comparison plot of areal density versus manufacturers published V_{50} velocity for a 1.10g Fragment Simulating Projectile; derived from the following references (Fournier, 2009; Chocron et al., 2008).

In terms of materials selection there are other variables of importance such as degradation and wear, water sensitivity and flexibility. These variables are out of the scope of this thesis but a full review on their importance to the concept of neck protection was published as a separate peer reviewed paper (Breeze et al., 2013a).

3.10 Conclusions and recommendations

A summary is provided in Table 8 and provides the rationale for the research undertaken in subsequent chapters.

Conclusion	Recommendation	Demonstrated in
No objective evidence to find the effectiveness of neck protection in reducing injury incidence or severity could be found.	A review of neck injuries from energised fragments and relating those to protection worn.	Chapter 4
Even if a ballistic protective material stops a projectile, the residual kinetic energy may push the ballistic protective material with it into the body (termed pencilling).	Once the anatomical structures necessitating protection have been identified, the minimum distance from the structure to the skin surface will determine the maximum depth of pencilling for that ballistic material	Chapter 6
Different designs of neck collar were identified than that utilised in OSPREY. Collars differed in height, numbers of segments and projection from the skin surface.	Ergonomics assessment should be undertaken with a representative selection of neck collars representing the different features identified.	Chapters 7 and 8
In addition to collars, other types of neck protection were identified such as ballistic scarves and nape pads.	These types of neck protection require ergonomic assessment and comparisons to neck collars.	Chapter 8
The ballistic protective material used in current UK and US neck collars is made of a para-aramid but other materials exist that the evidence would suggest may be equally suitable.	Ergonomics testing should be undertaken with prototypes composed of UHMWPE and silk in addition to a para- aramid; it is recognised that for the interim a replacement neck collar will be made of the existing material for contractual issues.	Chapters 7 - 9
The weight and bulk of any type of neck protection is the sum not only of the ballistic protective material but also the other components such as the cover and outer carrier.	Ergonomic assessments should ascertain the maximum mass, surface area and thickness that are acceptable. This could be used to calculate an areal density from which the ideal ballistic material should be chosen in terms of its V_{50} protective ability for a particular FSP.	Chapters 8 and 9

Table 8: Conclusions and recommendations based upon the findings from Chapter 3.

Chapter 4: Analysis of hospital and post mortem records of survivors and those soldiers killed with neck wounds

Chapter summary

Post mortem and clinical records of all neck injuries sustained by UK military personnel in Iraq and Afghanistan due to hostile action between 01 January 2006 and 31 December 2012 were analysed. Anatomical structures directly responsible for death and morbidity at one- year post injury were ascertained. Uptake of neck collars was determined where recorded and related to the location of the soldier at the time of injury. Of the 92 soldiers who died from a neck wound and which post mortem records were available, the neck was contributory to death in 59/92 (64%) cases. 7% of survivors sustaining a neck wound had an injury that caused functional, aesthetic or psychological consequences at one year (morbidity). Death from neck injury was primarily due to neurovascular damage with an additional contribution from airway compromise. Morbidity was primarily from brachial plexus damage and trauma to the larynx or its innervations.

4.1 Aims of this chapter

- To use the JTTR to identify all UK soldiers sustaining a neck wound during a seven- year period while serving in Iraq or Afghanistan.
- To use post mortem records to ascertain those anatomical structures within the neck that were directly responsible for death.
- To use clinical records of survivors to ascertain those anatomical structures within the neck that caused reported morbidity at 12 months post injury.
- To describe the location of injury in terms of surgical neck zone.

- To ascertain if the service person was wearing the issued neck collar at the time of injury.

4.2 Publications derived from this chapter

- Breeze J, Allanson-Bailey LS, Hunt NC, Delaney RS, Hepper AE, Clasper J. Mortality and morbidity from combat neck injury. Journal of Trauma 2012; 72 (4): 969–974 (Breeze et al., 2012a).
- Breeze J, Masterson L, Banfield G. Outcomes from penetrating ballistic cervical injury. Journal of the Royal Army Medical Corps 2012; 158 (2): 96–100 (Breeze et al., 2012c).

4.3 Collaborations

This chapter describes clinical and post mortem analysis of neck wounds. Two consultant pathologists (Dr Nick Hunt and Dr Russell Delaney) spent a considerable amount of time with the author re analysing the records of previous post mortems that they had undertaken. A consultant head and neck surgeon (Lieutenant Colonel Graham Banfield) kindly assisted the author in examining many clinical and post mortem records to identify those anatomical structures causing morbidity and death.

4.4 Introduction

The neck is a potentially vulnerable part of the body as demonstrated by wounds affecting this area being present in 11% of all UK soldiers sustaining battle injuries. Neurovascular structures are relatively superficial in the neck and even small fragments can cause significant trauma (Barker and Himdani, 1987), which can be difficult to manage surgically if at the base of the neck or base of the skull (Figure 15).

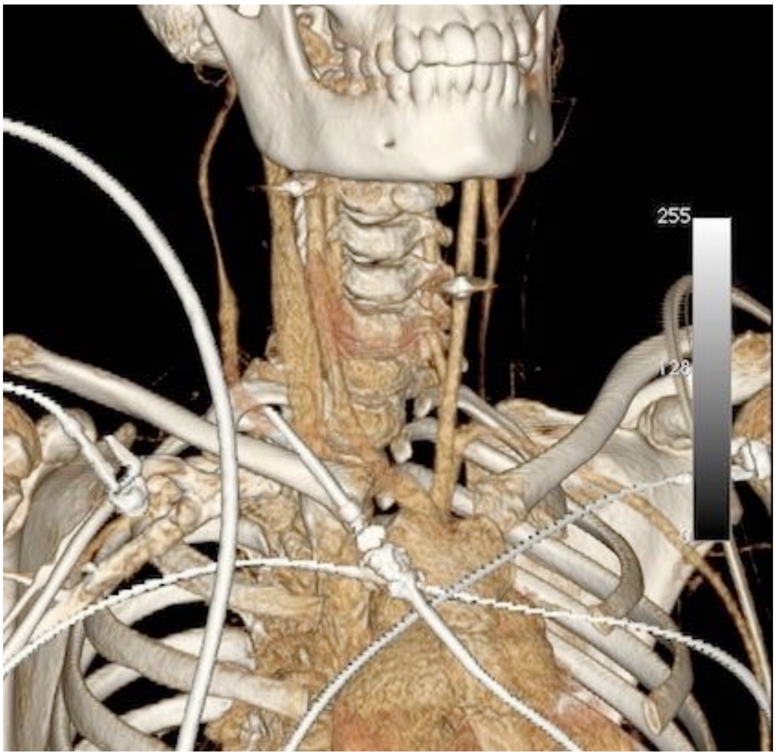


Figure 15: Three- dimensional reconstruction of a CT angiogram demonstrating energised fragments lying in close proximity to the common carotid and external carotid arteries.

After repatriation to the United Kingdom, UK armed forces personnel injured in conflicts in Iraq and Afghanistan are initially treated at RCDM. All servicemen killed in action or who died from wounds are investigated by H.M. Coroner and undergo a post-mortem examination. Data on both groups is collected within the JTTR, a restricted database introduced in 2003 that describes every admission generating a trauma call to a British Field hospital and/or requiring evacuation back to the United Kingdom. Patients recorded in JTTR have their injuries organised according to the AIS system, an anatomical scoring method that relates every injury sustained to a score that is well correlated to severity and outcome (Champion et al., 2003). Although the JTTR is a powerful epidemiological tool it suffers from the limitations of most large databases in that the clinical detail is in the form of a fixed dataset which can mean that the necessary detail to make some conclusions are not collected. This is not the fault of any particular link in the system, it just reflects that a large amount of information on many complexly injured soldiers must be gathered in a small amount of time by a limited number of individuals. The use of AIS scores enables valid comparisons between large groups with a dataset in a single database as well as between datasets in separate databases to be made (such as between the UK and US versions of the JTTR) and these are excellent for demonstrating injury trends. However the limited numbers of codes to describe injuries, as well as non-specific codes being used when insufficient details are recorded, means that on an individual soldier basis conclusions can be limited. Optimising designs of neck protection means accurate knowledge of where an individual anatomical structure is injured as well as where the entry wound is located. This information cannot realistically be gathered by JTTR database searching alone and requires analysis of clinical records for survivors and post mortem records for those soldiers that died to provide the necessary level of clinical detail.

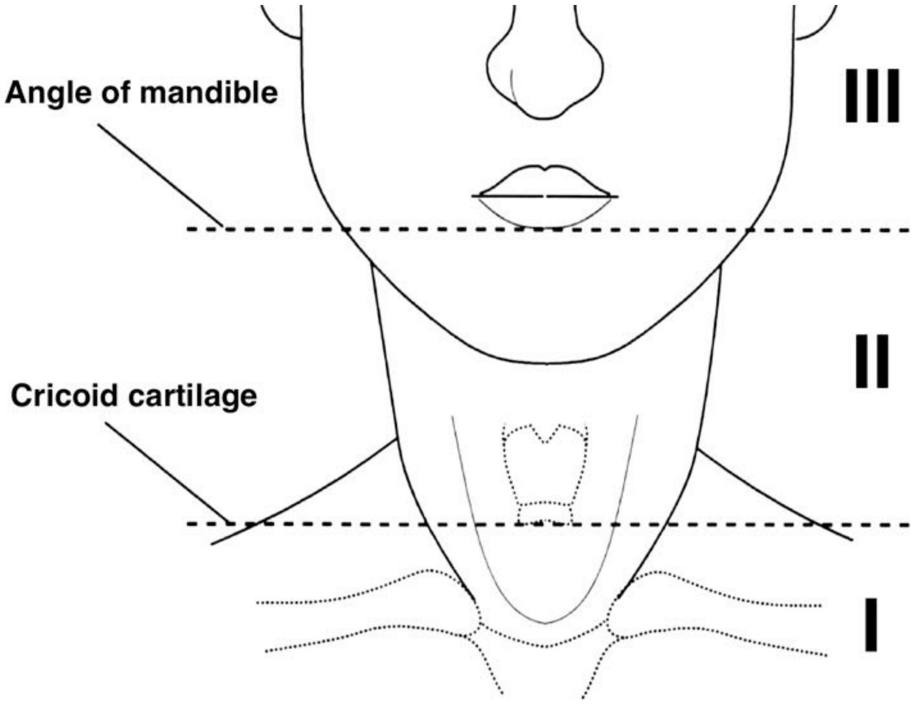


Figure 16: Pictorial representation of the surface markings depicting the three neck zones: Zone I being the area of neck between clavicles and cricoid cartilage, Zone II between cricoid cartilage and the angle of the mandible, and Zone III the remaining area above that.

At the time of the commencement of this research, no method to objectively compare the coverage provided by different designs of neck protection existed. One simple method for comparison would be to divide the neck into the internationally recognised surgical zones as originally described by Monson (Monson et al., 1969). Divisions are based on surface markings, with Zone I being the area of neck between clavicles and cricoid cartilage, Zone II between cricoid cartilage and the angle of the mandible, and Zone III the remaining area above that (Figure 16). Current US neck collars are detachable and cover Zone I (Table 9). In contrast UK collars are far larger and come in half and full sizes, covering Zones I+II, and Zones I-III respectively. Of note in both sizes of UK collar there was a small area at the base of Zone I anteriorly that remains uncovered.

Collar	Image	Coverage of Neck Zones
UK OSPREY Mark 4 with Half collar		All of Zone II plus superior part of Zone I
US Improved Outer Tactical Vest		All of Zone I

Table 9: A simple comparison of the coverage provided by different designs of neck collar in a horizontal shot- line using surgical neck zones.

4.5 Method

The JTTR was used to identify all neck injuries sustained by UK military personnel in Iraq and Afghanistan due to hostile action between 01 January 2006 and 31 December

2012. 2006 was used as the start date as a lot of extra data fields were included after this date in JTTR enabling greater fidelity in the information gathered, particularly in terms of the wearing of body armour at the time of injury. Using the unique identifiers available within the JTTR it was possible to identify the postmortem record numbers of those soldiers who had died and in whom a neck wound was present. Patients with neck wounds were identified as those with AIS 2005 (military) codes 300099.9 to 350200.2.

Following permission of Her Majesty's Coroners for Wiltshire and Swindon, and Oxfordshire with jurisdiction for investigating the deaths of service personnel these records were analysed in conjunction with the Home Office pathologists who originally undertook the post mortem. For each neck wound it was determined whether injury to that anatomical structure was directly contributory to death or whether the solder died from other causes. Injuries from explosions were divided into three groups; those in which there was no penetration of the skin into underlying muscle (blunt), those in which individual discrete areas of penetration of the skin were found (discrete fragments), and finally those in which there was generalised extensive neck injury not confined to an individual area (extensive). For those discrete fragments only, the entry point of the projectile was recorded in terms of which neck zone was affected.

For those soldiers who survived and in whom a neck wound was present, all electronic patient records from the Queen Elizabeth Hospital Birmingham, including operation notes and multidisciplinary review clinics, were reviewed. This is the only hospital in which these types of battle injuries are managed following a soldier's evacuation to the UK. The CT scans of every soldier evacuated to the UK with a neck wound were re-analysed to look for injuries to underlying cervical anatomical structures that had not been coded into JTTR. Any soldiers who were returned to their unit following initial injury, did not require surgery and were not evacuated to the UK were assumed to have only superficial injuries and were excluded from further analysis. Long-term morbidity was determined by hospital notes analysis as those injuries to cervical anatomical structures from which the patient complained of functional, aesthetic or psychological consequences at one year post injury.

For both survivors and those who died, clinical photographs assisted the clinical notes in dividing the impact location of perforating fragments into one or more surgical neck zones. The location of the soldier at the time of injury was determined as well as whether they were believed to have been wearing neck protection. Potentially preventable injuries were defined as the following:

Those neck injuries that could be confidently ascribed to the passage of one or more penetrating energised fragments and could therefore have been potentially prevented by wearing neck protection under the assumption that such protection would stop all fragments regardless of their mass, shape or velocity.

4.6 Results

During this seven-year period (01 January 2006 to 31 December 2012), neck wounds were present in 234 (11%) of the 2093 UK soldiers injured during combat in Iraq and Afghanistan. Of the 234 neck wounds, 175 (75%) were sustained by soldiers involved in an explosive event (Figure 17). The remaining 59 (25%) were soldiers injured by a gunshot wound and were excluded from further analysis. No UK soldier during this period sustained a combat neck wound by another mechanism of injury. Of the 175 neck injuries from explosive events, 81/175 (46%) were found in survivors and 94/175 (54%) were sustained in those who died. In the 81 survivors, 62 (77%) were believed to have been injured by fragmentation; in the remaining 19 (23%) survivors there was insufficient information from clinical records or military situation reports to judge what the primary cause of injury was. Of the 175 neck injuries it was recorded whether they were wearing issued neck collars at the time of injury in only 54 (31%). Of these 4/54 (7%) were wearing OSPREY collars, with the remaining 50/54 (93%) choosing not to wear their neck collar.

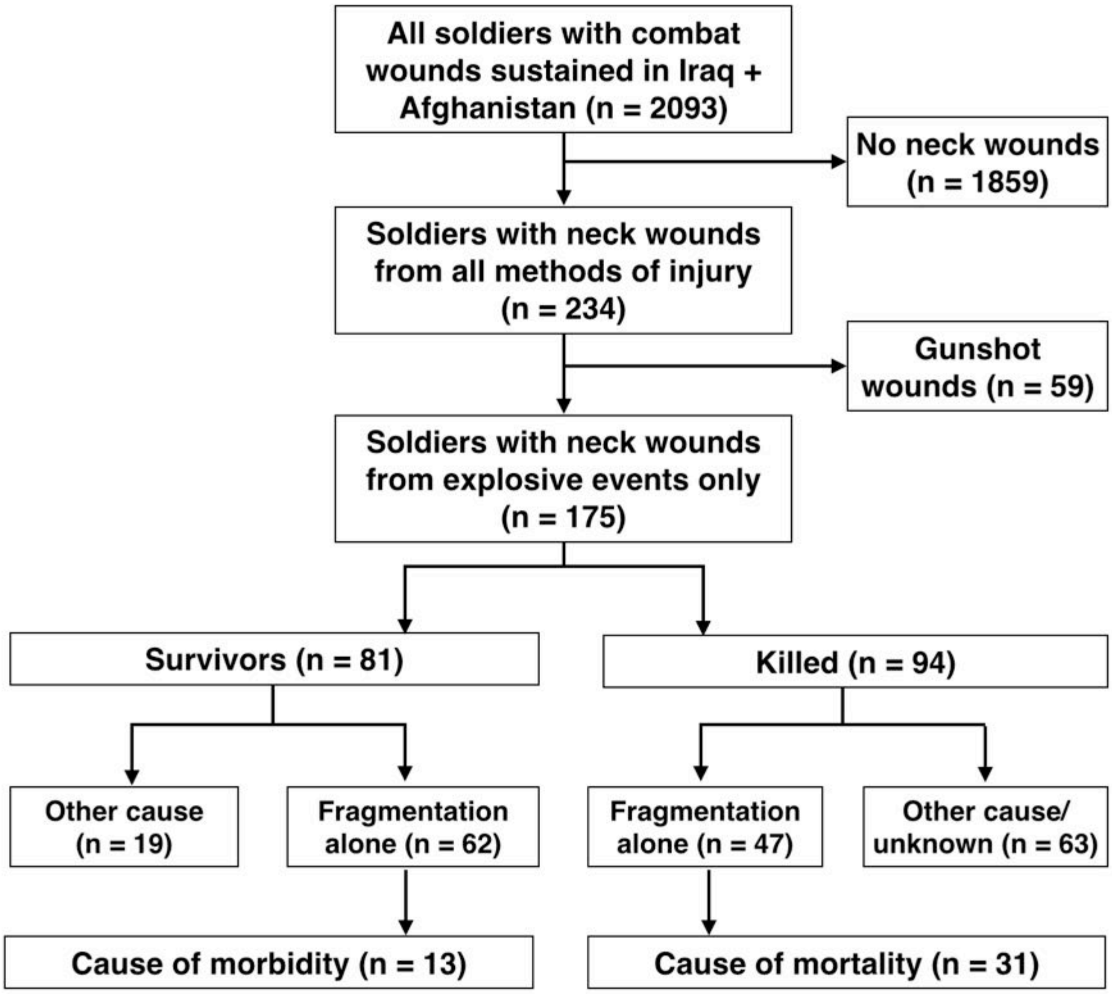


Figure 17: Identification of those survivors with morbidity at one year and those who died of neck wounds due to penetrating fragmentation.

Description	**Explosion (blast or blunt)**	**Explosion (extensive)**	**Explosion (fragmentation)**	**Total**
Death from neck wound alone	1	4	14	19
Death from neck wound and other body area	4	19	17	40
Neck wound no contribution to death	17	0	16	33
Total	22	23	47	92

Table 10: Pathological analysis of injury highlighting groups in which the neck wound was due to fragmentation and either caused death or was contributory to it.

In 2/94 soldiers who were killed with a neck wound, post mortem records could not be retrieved for security reasons. Using the post mortem records of the remaining 92 soldiers who died and records were available, the pathologists were able to make an opinion as to whether the neck wound was the sole cause of death, contributory to death or unrelated to death (Table 10). The cohort of interest was those killed by individual explosive fragments for which the neck was either the cause of death or contributory to death (highlighted in yellow) as it is these injuries that neck protection is designed to mitigate against. None of these 31 soldiers were believed to have been wearing neck protection at the time of injury. The anatomical structures causing these deaths are demonstrated in Table 11. In 8 deaths more than one structure was believed to have been responsible for death, bringing the total number of structures to 39. The clinical records of all 81 survivors with a neck wound from an explosive event were analysed. 36/81 (44%) demonstrated evidence of energised fragments that had penetrated the neck skin. 20/36 (56%) resulted in damage to a cervical anatomical structure other than muscle or skin, of which 13/20 (65%) were experiencing morbidity at least one year after injury. In 4 deaths more than one structure was believed to have been responsible for morbidity, bringing the total number of structures to 17 (in 13 soldiers). No mortality or morbidity was found to projectiles damaging skin alone, the phrenic nerve, thyroid gland, external carotid artery, internal jugular or external jugular veins.

Structure	**Structure responsible for mortality (post mortem records)**	**Structure responsible for morbidity (hospital records)**
Common Carotid Artery	Yes (11)	Yes (1)
Internal Carotid Artery	Yes (6)	Yes (1)
Vagus nerve (incl. laryngeal nerves)	No (0)	Yes (2)
Vertebral Artery	Yes (1)	Yes (1)
Larynx	Yes (4)	Yes (3)
Oesophagus	No (0)	Yes (1)
Pharynx	No (0)	Yes (1)
Spinal Cord	Yes (10)	Yes (1)
Brachial plexus	No (0)	Yes (4)
Trachea	Yes (7)	No (0)
Vocal cord	No (0)	Yes (2)
Total	**39 structures (31 soldiers)**	**17 structures (13 soldiers)**

Table 11: Cervical anatomical structures believed to have caused mortality and morbidity from explosive fragments (incidence of soldiers with that particular injury in brackets).

It was possible to determine the entry point on the neck of soldiers injured by discrete explosive fragments in 30/62 survivors and 42/47 those who died, reflecting the detailed photographs and drawings provided with the post mortem records. Often there was more than one neck zone with an entry wound such that 42 neck zones were affected in the 30 charted survivors, and 65 neck zones were affected in those soldiers that died (Table 12). Zone II was the most commonly affected area by discrete fragments followed by Zone III. The anterior part of the neck was injured much more commonly than the posterior part of the neck. Only 19/107 (18%) of penetrating explosive fragments hit the neck posteriorly.

Neck zone	**Survivor**	**Died from wound other than neck**	**Died from neck wound itself**	**Total**
III alone	3	2	2	7
III and II	12	1	2	15
II alone	20	7	7	34
II and I	2	4	15	21
I alone	4	2	5	11
All zones	1	5	13	19
Total	42	21	44	107

Table 12: Surface Wound entry location in terms of neck zone for individual energised fragments.

Table 13 demonstrates the location of the soldier at the time of neck injury. Armoured vehicles included the Challenger II tank, Bulldog, Viking, Vector, Warrior and Mastiff. Light vehicles included the Land-Rover, Pinzgauer and Panther. The Jackal was the only open vehicle in this series. It was not possible to determine the exact mechanism of all of the neck injuries in those that survived and therefore whether they were potentially preventable or not (unknown category). 51/77 (66%) of the potentially preventable neck wounds occurred while the individual was dismounted.

Location	**Died from neck wound itself**		**Did not die from the neck wound**		
	Not preventable	**Potentially preventable**	**Not preventable**	**Potentially preventable**	**Unknown**
Armoured vehicle	2	2	13	3	1
Light vehicle	4	8	9	3	2
Open vehicle/ top cover	9	7	6	3	0
Dismounted	30	30	4	21	16
Total	45	47	32	30	19

Table 13: Location of soldier at time of sustaining neck injury from a fragmenting munition or explosive event.

4.7 Conclusions and recommendations

A summary is provided in Table 14 and provides the rationale for the research undertaken in subsequent chapters.

Conclusion	Recommendation	Demonstrated in
In 64% of soldiers killed with a penetrating neck wound, the neck was contributory to death.	The following structures responsible for mortality require protection: carotid and vertebral arteries, spinal cord, brachial plexus, trachea and pharynx	Chapters 5- 15
16% of survivors sustaining a neck wound had an injury that caused functional, aesthetic or psychological consequences at one- year post injury.	The following additional structures responsible for morbidity require protection: brachial plexus and laryngeal nerves.	Chapter 5-15
18% of penetrating explosive fragments hit the neck posteriorly.	Although nape protection would be of limited benefit in comparison to circumferential collars, this method of protection still requires ergonomic assessment.	Chapter 8
7% of soldiers were wearing their neck OSPREY neck collars at the time of injury.	Reasons for the lack of uptake of existing neck protection should be sought during ergonomics assessment.	Chapters 7 - 9
51/77 (66%) of the potentially preventable neck wounds occurred while the service person was dismounted	Ergonomics assessments should focus on dismounted close combat tasks.	Chapters 7 - 9

Table 14: Conclusions and recommendations based upon the findings from Chapter 4.

Chapter 5: Analysis of Computed Tomography scans to characterise those fragments injuring the neck

Chapter summary

An accurate knowledge of the shapes and masses of energised fragments injuring the neck is essential in testing potential ballistic protective materials as well as the penetration of Fragment Simulating Projectiles (FSPs) into tissues and simulants. Energised fragments dissected out in post mortem examinations of wounded soldiers are measured to help select representative FSPs but insufficient numbers have been excised from the neck for recommendations to be made. Therefore the 1.10g cylindrical FSP remains the industry standard despite limited evidence for its suitability. Computed tomograms (CTs) of 110 consecutive UK soldiers whose necks were wounded by explosive fragments were analysed. Retained fragments were classified according to shape, and their dimensions used to estimate volume and mass. These calculations were then compared with the actual measurements of the excised fragments. The use of CT to estimate the masses of retained fragments that were not excised increased this group from 18 to 199 fragments. A 0.49g cylinder and a 0.51g sphere are recommended to be added to the existing 1.10g FSP for testing of ballistic neck protection materials.

5.1 Aims of this chapter

- To determine if CT can be used to accurately estimate the masses of fragments excised from the necks of injured UK service personnel.
- To classify those retained fragments on CT in terms of size and shape to recommend representative FSPs.

5.2 Publications derived from this chapter

- Breeze J, Leason J, Gibb I, Allanson-Bailey L, Hunt N, Hepper A, Spencer P, Clasper J. Characterisation of explosive fragments injuring the neck. British Journal of Oral & Maxillofacial Surgery 2013; 51 (8): e263–6 (Breeze et al., 2013d).
- Breeze J, Leason J, Gibb I, Hunt NC, Hepper A, Clasper J. Computed Tomography Can Improve the Selection of Fragment Simulating Projectiles From Which to Test Future Body Armor Materials. Military Medicine 2013, 178 (6): 690–695 (Breeze et al., 2013e).

5.3 Collaborations

This chapter describes the novel use of CT scans to identify representative FSPs that can assist in future testing. The author identified the concept and worked with a consultant pathologist (Dr Nick Hunt) to characterise those fragments physically removed from the neck post mortem. A consultant radiologist (Lieutenant Colonel Iain Gibb) went through every CT scan of those killed with a neck wound to identify any retained fragments. He showed the author how to measure and characterise these fragments, which the author subsequently performed alone with the CT scans of the survivors.

5.4 Introduction

The previous chapter has demonstrated that energised fragments were the most common cause of combat injuries to the neck in UK service personnel deployed to Afghanistan between 2006-2010, with reported mortality of 42%. This high mortality is primarily due to the superficial positions of the vascular structures running within it, in combination with no inherent anatomical protection provided from the cervical vertebrae to anterior impacts (Figure 18). The aetiology of these fragments when encountered clinically can be diverse, ranging from bits of metal and plastic, to ejected soil debris and human body parts in suicide detonations (Figure 19). If identifiable, such fragments are best categorised as primary fragments, which originate from the explosive device or projectile itself and secondary fragments, which are derived from objects close to the explosion (Ryan et al., 1991; Cummins and Goodpaster, 2014a; 2014b).

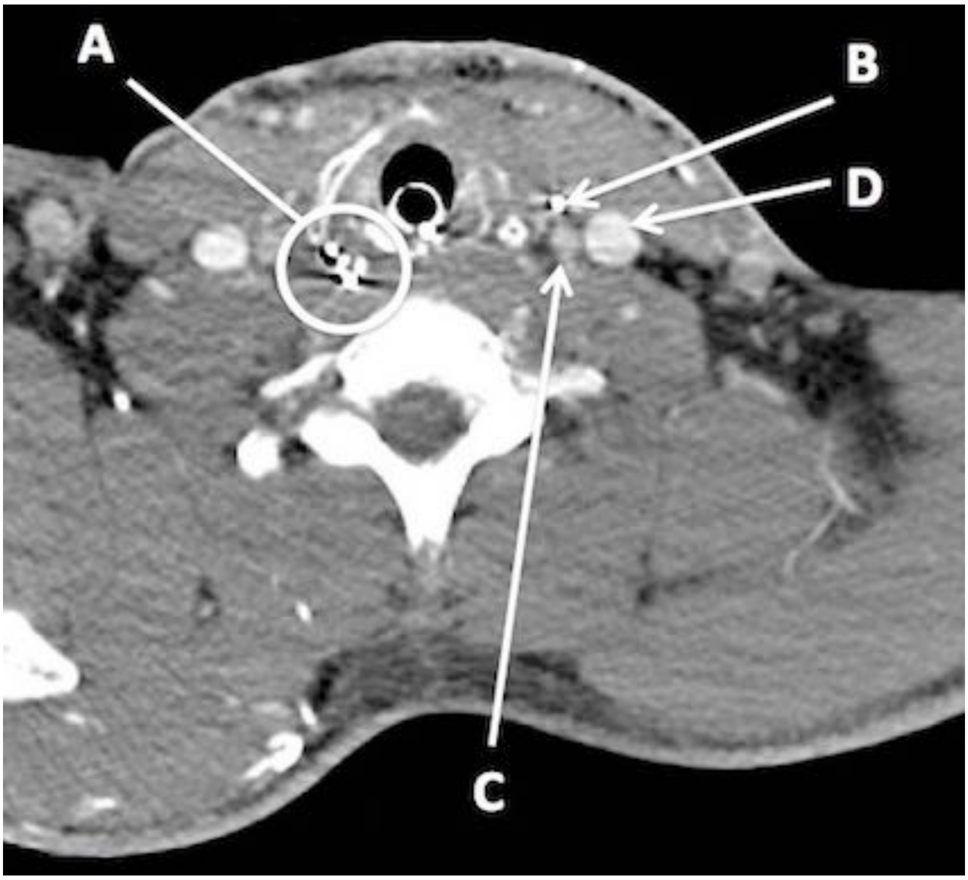


Figure 18: Axial CT angiogram at the level of C4 from a UK serviceman injured by an improvised explosive device. Multiple small fragments are seen on the right side of the neck (A). A fragment (B) lies adjacent to the carotid artery (C) and internal jugular vein (D).

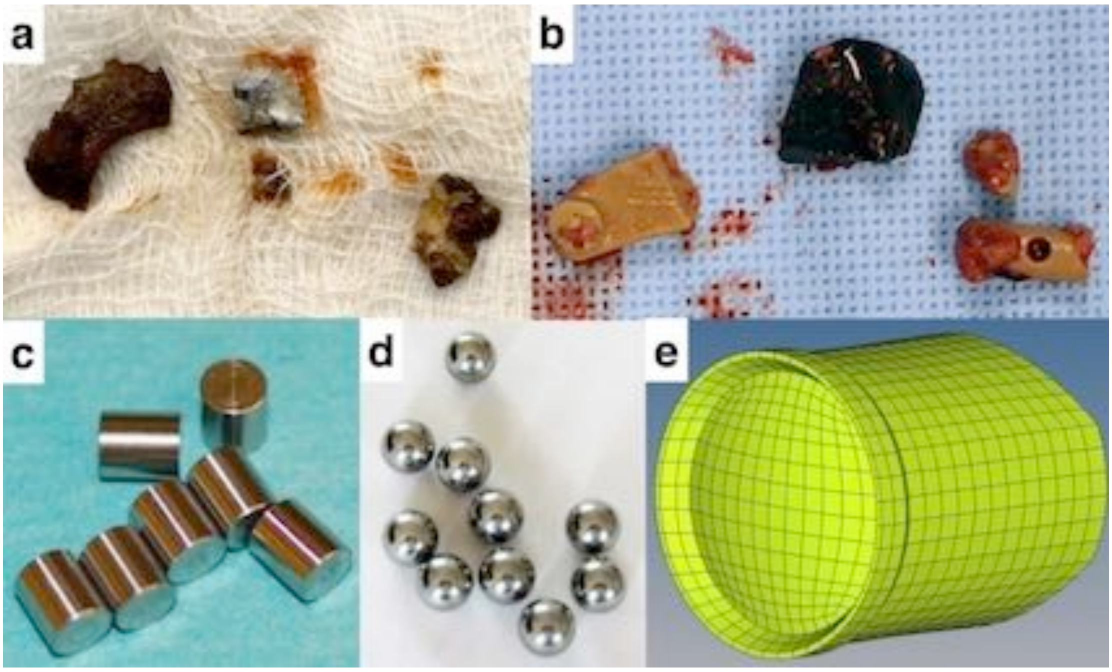


Figure 19: Fragments excised from the necks of injured soldiers (a+b) are used to identify appropriate fragment simulating projectiles (c+d), which can be utilised in computer injury models (e).

Fragments can be either random in nature (so called 'natural' fragments) or preformed (Cummins and Goodpaster, 2014a). Natural fragments are generally produced by larger artillery shells and tend to produce heterogenous range in terms of size and shape (Gurney, 1943). Initial velocities may be very high (>1500m/s) but because of their irregular shape velocities decline rapidly (Ryan et al., 1991; Bowyer, 1996; 1997; Hill et al., 2001). Pre-formed fragments are either incorporated into the explosive device itself, or are produced by notching of metal plates or the inside of the grenade casing (Figure 20), which break off into predefined shapes (Hill et al., 2001). Such pre-formed fragments tend to be relatively light (often 0.1- 0.4g) but numerous, increasing the probability of a hit in lightly armoured soldiers (Bowyer, 1997).

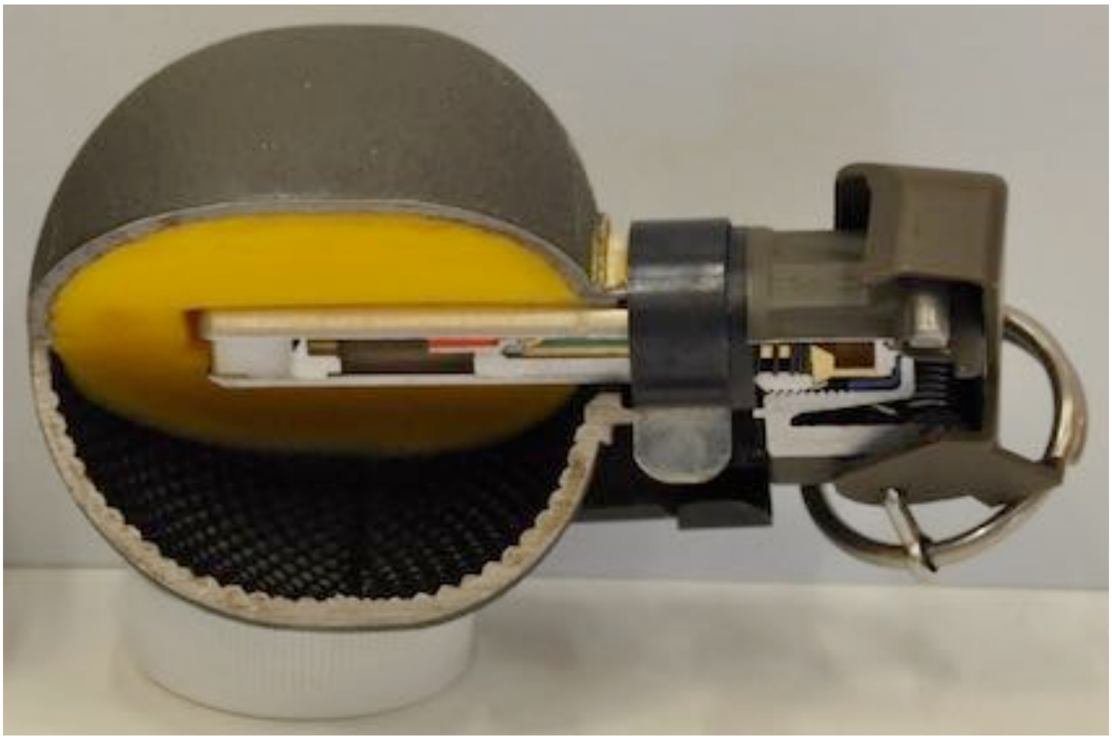


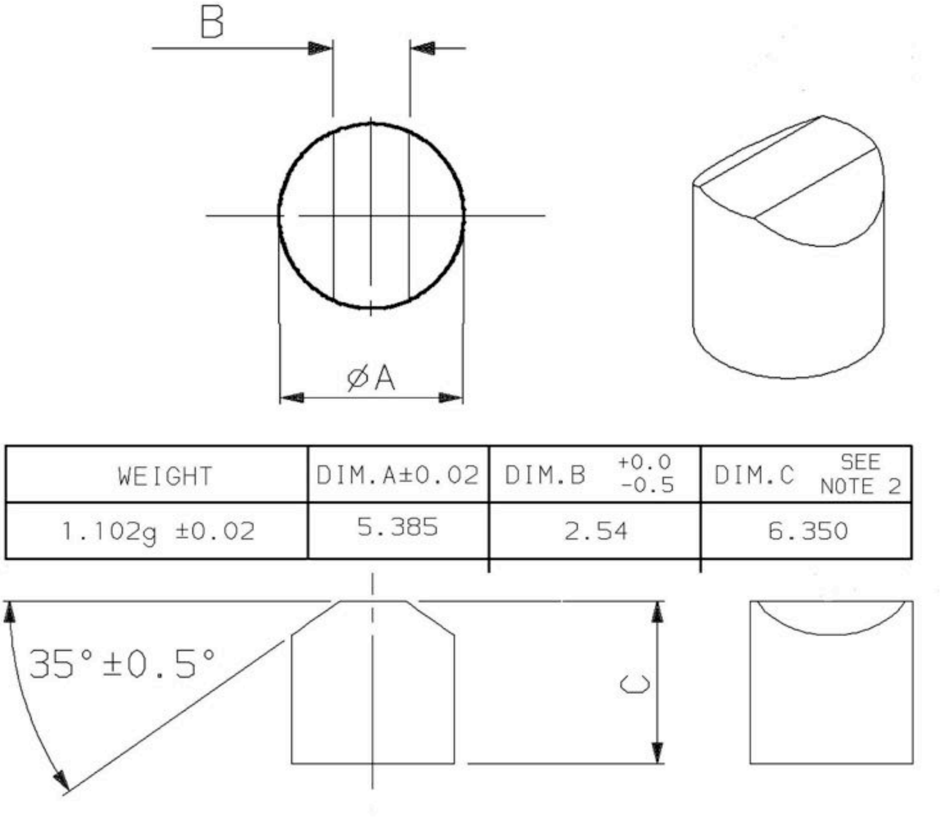
Figure 20: Cross section of the current L109 A1 fragmentation grenade used by UK forces in which the core (yellow) contains an explosive which is ignited by the fuse and propels up to 1800 fragments weighing approximately 0.20g, each formed by dimples in the inner surface of the steel casing.

To enable the testing of new body armour materials, the properties of the fragments injuring soldiers (mass, shape, density, and velocity) must be understood so that realistic but repeatable substitutes can be used. In addition any types of model that attempt to simulate penetration of fragments into the neck require accurate knowledge because fragment characteristics in terms of mass and shape alter the characteristics of the resultant wound tract. A number of standardised fragment simulating projectiles (FSPs) have been developed over the years, which enable reproducible comparisons between experiments. These FSPs are grouped by shape (eg cylinder) and mass (eg 1.10 g), with the most comprehensive description of these types being found within the 2nd edition of the NATO STANdardising AGreement (STANAG) 2920 (NATO Standardisation Agreement, 2003). A summary of the most common shapes and masses of FSP is demonstrated in Table 15. It is recommended that all FSPs are made of cold rolled, annealed steel, and should be fully quenched and tempered to a Rockwell hardness value of 30 +/- 1.

Shape	Masses available (g)
Cylinder	0.16, 0.24, 0.33, 0.49, 1.10, 2.83, 4.15
Sphere	0.18, 0.26, 0.37, 0.51, 1.13, 2.99, 4.11
Cube	0.16, 0.24, 0.33, 0.49, 1.10, 2.83, 4.15
Parallelopoid	0.20, 1.10, 2.85

Table 15: Commonly utilised standardised Fragment Simulating Projectiles as described in NATO STANAG 2920.

The 1.10 g steel FSP has traditionally been used as the international standard for the ballistic testing of all body armour (Iremonger and Went, 1996; Sellier and Kneubuehl, 1994; Kneubuehl et al., 2011) (Figure 21). This FSP is believed to have been derived from fragment masses produced by a World War One 155 mm artillery shell (Figure 19), although interestingly the original report from 1943 which first showed the dimensions of a chisel nosed cylindrical FSP stated that the mass (minus sabot) was 1.59g (Sullivan, 1943).



WEIGHT	DIM.A±0.02	DIM.B +0.0 -0.5	DIM.C SEE NOTE 2
1.102g ±0.02	5.385	2.54	6.350

Figure 21: A pictorial representation of a 1.10 g chisel-nosed FSP, derived from measurements described in NATO standardising agreement.

Fragments removed from wounded servicemen can be characterised in terms of material, shape, and mass. Few published descriptions of the shape and composition of retained fragments in wounded soldiers exist, and the most informative papers concern the shapes of those retained in the eye (Skeoch, 1945; Woodcock et al., 2006). However, the advent of rapid, high resolution computed tomography (CT) has resulted in most wounded NATO soldiers having CT scans on arrival at the field hospital, and it is now also done routinely on US, UK, and Israeli military personnel as part of the post-mortem examination. CT could therefore potentially accurately locate retained ballistic projectiles, and therefore could potentially be used to measure their dimensions.

5.5 Methods

The CT scans of 110 consecutive UK soldiers whose necks were wounded by energised fragments between 01 January 2008 and 31 December 2011 were analysed. Injuries were divided into those caused by improvised explosive devices (IEDs), mines or rocket-propelled grenades (RPGs). Visible fragments were initially identified using soft tissue algorithms (Figure 22), and subsequent measurements were calculated using bone algorithms to reduce scatter and thereby improve accuracy. In addition to the recognised shapes of fragments based on NATO standardised FSPs (cylindrical, square, spherical and triangular), stellate shapes were added, which were identified as being common after preliminary testing (NATO Standardisation Agreement, 2003).

Figure 22: Retained fragments in the neck viewed using soft tissue (a) and bone (b) equations, methods of manipulating the image post processing of the scan.

The volume of each fragment was calculated using defined measurements (Figure 23). The volume of a stellate fragment was calculated as that of a stellated dodecahedron.

Mass was calculated by multiplying the estimated volume by the density of plain carbon C22 (AISI 1020) steel (7.82 g/cm^3). This method was used to estimate the mass of all retained fragments visible on CT. The estimated mass of each one was grouped according to that of the closest NATO standardised FSP, and a combined total was calculated. Finally, preoperative CT scans of all UK service personnel who had had explosive fragments excised from their necks during this period were identified. The known masses of the excised fragments were compared with those estimated from CT using a general linear model. Pearson's correlation coefficient was used to show correlation.

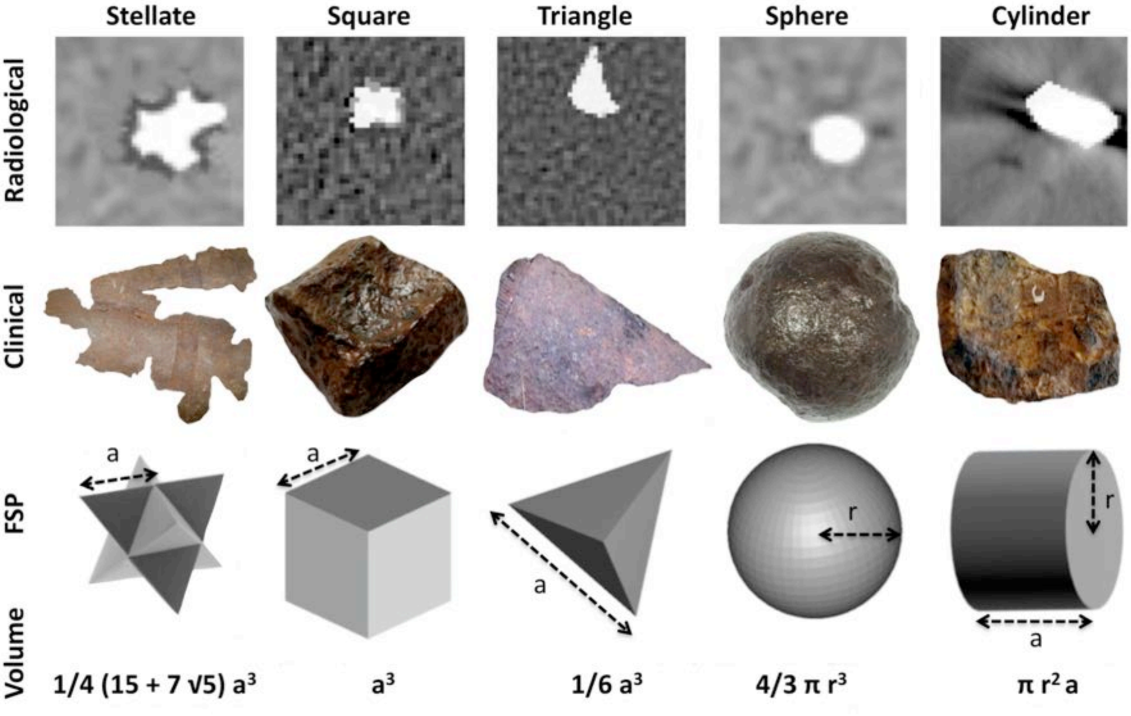


Figure 23: Clinical, radiographic, and mathematical appearances of FSPs including volume calculations.

Wound tract lengths were measured when one of two criteria were present: the first was a clearly visible wound tract between skin surface wound and fragment; the second was when occurrence of a single retained fragment and a single skin surface wound. Depth of Penetration (DoP) was measured from skin surface to the front of the fragment.

5.6 Results

94/110 (85%) soldiers had been injured by IEDs (85%), 11/110 (10%) by RPGs and 5/110 (5%) by mines. Of the 33 who died, fragments were visible on CT in 24/33 (73%), and 74 individual fragments could be measured (mean 3.1/neck). Of the 77 who survived, 48 (62%) had fragments that were visible on CT, and 125 fragments could be measured (mean 2.6/neck). Cylinders (57%) and spheres (20%) were the most commonly found shapes in soldiers wounded by IED (Table 16). Spheres (70%) were found more commonly than cylinders (17%) in soldiers wounded by RPGs or mines.

Shape	IED	RPG	Mine	Total n (%)
Cylinder	96	4	1	101 (51)
Sphere	33	16	5	54 (27)
Stellate	17	2	0	19 (10)
Square	14	1	1	16 (8)
Triangle	9	0	0	9 (5)
Total	169	23	7	199 (100)

Table 16: Shapes of energised fragments retained in the neck identified from computed tomography.

A total of 14 fragments were retrieved at post-mortem, and 4 were retrieved from survivors. Of these 18 fragments, 16 could confidently be matched to their pre-excision position on CT (Table 17). The mass of the excised fragments was normally distributed using an Anderson–Darling test. Statistical analysis could not be done on the single stellate fragment. The known and estimated masses of the fragments correlated highly (Pearson's coefficient = 0.987). The 95% confidence interval demonstrated that known and estimated masses of spherical and cylindrical fragments did not differ significantly ($p = 0.64$).

Shape	**Mean estimated volume (cm^3) from CT**	**Mean estimated mass (g) from CT**	**Mean known mass (g) following excision**	**% difference**
Sphere (n=7)	0.06	0.44	0.41	7
Cylinder (n=8)	0.10	0.78	0.71	10
Stellate (n=1)	0.05	0.37	0.29	28
Total (n=16)	0.07	0.53	0.47	13

Table 17: Mass of excised energised fragments retained in the neck compared with that estimated from volume measurements derived from computed tomography.

The estimated masses of all fragments visualised on CT were grouped according to FSP size and compared to the masses of the 18 fragments recovered from the neck and 642 fragments recovered from the remainder of the body. Close correlation was found between the estimated fragment masses from CT scans of those who died compared to the known excised masses post mortem. Fragments in survivors were generally lighter than those found post mortem (Table 18). Adding estimated fragment masses derived from CT to known excised fragment masses, increased the percentage of retained neck fragments under 1.10 g from 14/18 (78%) to 201/217 (93%) and 0.49 g from 14/18 (78%) to 184/217 (85%).

Mass	**Whole body, n (%)**	**Neck only, n (%)**				
	Excised post mortem	Excised from survivors	Excised post mortem	Estimated from CT scans of survivors	Estimated from CT scans post mortem	Cumulative (Excised + Estimated)
=<0.16	200 (31)	1 (25)	9 (64)	92 (74)	41 (55)	143 (66)
=<0.49	326 (51)	4 (100)	10 (71)	110 (88)	60 (81)	184 (85)
=<1.1	457 (71)	4 (100)	10 (71)	124 (99)	63 (85)	201 (93)
=<2.84	549 (86)	4 (100)	12 (86)	125 (100)	67 (91)	208 (96)
Total	642 (100)	4 (100)	14 (100)	125 (100)	74 (100)	217 (100)

Table 18: Known and estimated masses of retained neck fragments compared to those recovered in the remainder of the body.

It was possible to measure DoP for 98/125 (78%) retained fragments in survivors and 48/74 (65%) of retained fragments in those who died (Table 19).

FSP Mass (g)	Retained neck fragment mass range (g)	Retained fragments with visible tracts	Mean DoP (in mm), standard deviation in brackets
0.16	0.04 - 0.32	62/91	28 (7)
0.49	0.33 - 0.79	43/62	64 (21)
1.10	0.80 - 1.96	30/39	78 (22)
2.84	1.97 - 3.22	11/11	94 (32)

Table 19: Estimated depth of penetration of fragments retained in the neck.

5.7 Conclusions and recommendations

The following summary is provided in Table 20 and provides the rationale for the research undertaken in subsequent chapters.

Conclusion	Recommendation
The number of fragments actually excised from the neck during this period was small and therefore could be construed as being potentially unrepresentative. The use of CT to estimate the masses of retained fragments that were not excised increased the number of fragments from 18 to 199.	This approach could be used to increase the number of representative fragments for selecting FSPs to test armour to protect other parts of the body.
Cylinders were the most common shape identified in soldiers injured by improvised explosive devices. The 0.49 g cylinder represented greater than 85% of the fragments masses calculated.	Although the 1.10 g FSP is likely to remain the standard projectile testing due to the weight of existing experimental data using it, a 0.49 g cylinder could potentially supplement it for testing neck protection.
Spheres were the most common shape identified in soldiers wounded by rocket-propelled grenades or mines. The 0.51 g sphere represented greater than 85% of the fragments masses calculated.	A 0.51 g sphere would be a useful additional FSP for future testing of neck protection and has the additional advantage in ballistic experimentation that their regularity reduces the inherent variation in results that are found when tests are done with shapes such as cylinders.
In 7% of wounds a wound track completely traversing the neck was visible, and it is likely that these represent the passage of fragments greater than 2.84 g. All were from post mortem CTs of soldiers known to have died from the neck wound itself, demonstrating that such a wound track in the neck is likely to be associated with high mortality.	Measurement of the diameter of the wound tract could potentially be used to quantify the tissue damage produced by a projectile. This should be tested experimentally by firing projectiles of known mass and velocity into animal surrogates and measuring the diameter of the permanent wound tract using a CT scanner.

Table 20: Conclusions and recommendations based upon the findings from Chapter 5.

Chapter 6: Analysis of Computed Tomography scans to scale external cervical anthropometric landmarks and internal anatomical structures

Chapter summary

Military specific anthropometric measurements are required to define the external skin coverage provided by neck protection prototypes in terms of surgical neck zones. In addition scaling of any future numerical representations of cervical anatomical structures is required in terms of vessel diameter and depths of structures from the skin surface. Contrast-enhanced computed tomography (CT) angiograms of 50 UK servicemen were analysed. Mean diameters and distances from the skin surface were determined for the carotid artery, internal jugular vein, vertebral artery and spinal cord at the three surgical neck zones. Future external cervical anthropometric assessments should use the vertical angle of mandible to mid-claviclular distance in combination with the horizontal neck circumference. Cervical neurovascular structures are least vulnerable posterosuperiorly and therefore adding a nape protector would appear to be less justified. Cervical vessels are most vulnerable in Zone 1 and a circumferential collar of ballistic material at least 75 mm high would cover this area in 95% of this population, which should be assessed through ergonomic trials.

6.1 Aims of this chapter

- To determine military specific external anthropometric measurements for neck protection prototypes.
- To measure the sizes and depths of cervical anatomical structures at reproducible spinal levels in military personnel and use that to scale the structures within the numerical model.

- To determine the minimal critical distance from skin surface to the most superficial vascular structure at risk which will determine the limit the depth to which any pencilling of a body armour material can occur.

6.2 Publications derived from this chapter

- Breeze J, West A, Clasper, J. Anthropometric assessment of cervical neurovascular structures using CTA to determine zone-specific vulnerability to penetrating fragmentation injuries. Clinical Radiology 2013; 68 (1): 34–38 (Breeze et al., 2013g).

6.3 Concept

This chapter describes how CT scans were used to define external neck skin anthropometric distances and measure the diameters of cervical neurovascular structures. All measurements were made by the author working with a consultant radiologist (Lieutenant Colonel Andrew West) using a cohort of CT scans at the Queen Elizabeth Hospital Birmingham.

6.4 Introduction

At the time of the commencement of this research, no method to objectively compare the coverage provided by different designs of neck protection existed. As described in Chapter 4, one simple method for comparison would be to use surgical neck zones. This involves dividing the neck into three vertical anatomical zones based upon the surgical accessibility to the underlying soft tissue structures. Such an approach could act as an interim measure for comparisons to be made until the surface wound mapping (SWM) programme was instigated. As a reminder to the reader, Zone I is the area between the inferior margin of the clavicle and the cricoid cartilage, Zone II between cricoid cartilage and angle of the mandible, and Zone III the between angle of mandible and base of skull (Figure 24). Mortality and morbidity analysis (Chapter 4) had demonstrated that injuries to Zone I had the highest mortality and anterior neck injuries were more common than posterior ones.

Although the surface markings of these three neck zones have been described, how these relate to the internal anatomy has not. This is essential because damage to internal structures is often defined by the equivalent vertical position along the spinal cord, the so- called 'spinal level'. Neither the UK Defence Standardisation agreement (Defence Standard 00-250, 2008) or NATO standardising agreement 4512 (NATO Standardisation Agreement, 2004), which both provide standardised anthropometric agreements measurements for military specific populations, currently include cervical measurements. These studies use neck circumference as the horizontal measurement as it is easily measured clinically in person. The only civilian study to describe the vertical cervical height measured from the angle of the mandible to the sterno- clavicular joint (Harty et al., 2004), which is not a true representation of the vertical height of Zones I + II.

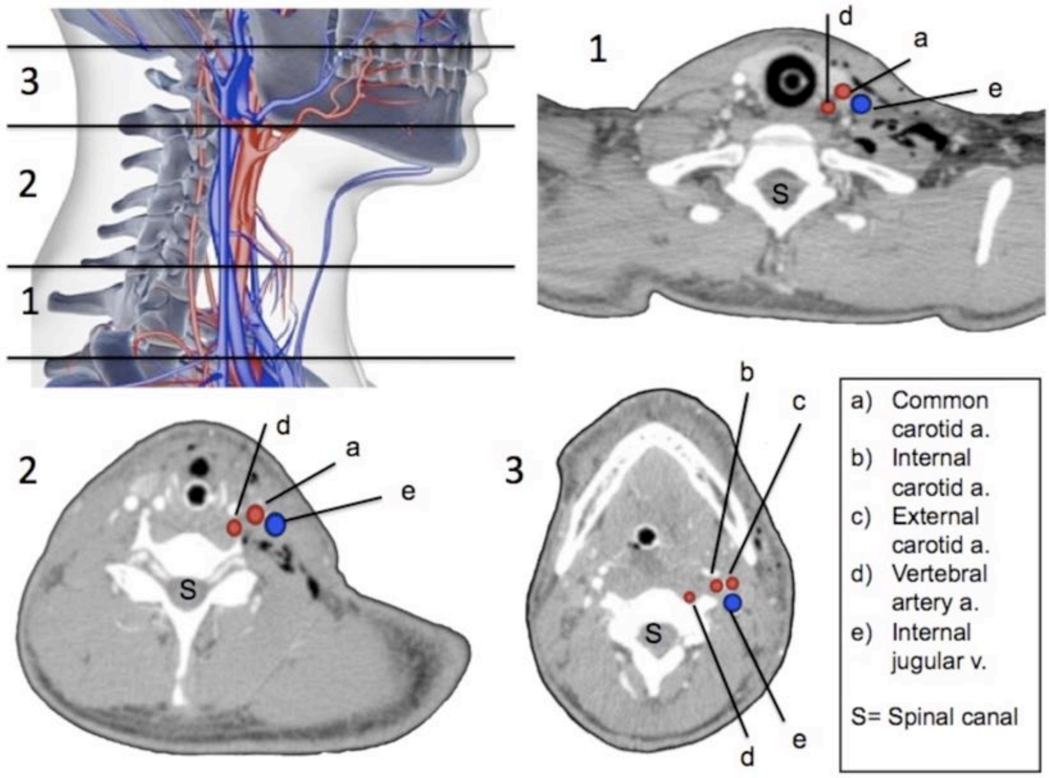


Figure 24: Pictorial demonstration of the three zones of the neck using axial CT scans at the vertical midpoint of each zone (for clarity the spinal cord is not shown on the saggital view).

The longer- term validation of the neck collar programme will revolve around the development of an accurate three- dimensional representation of internal cervical anatomical structures. However no information could be found in the literature describing the sizes of cervical neurovascular structures or their depths from the skin surface. The only three papers describing the position of either the internal jugular vein (Lim et al., 2006; Ishizuka et al., 2010; Lee et al., 2006) or the carotid arteries (Lo et al., 2006) did so in relation to the skin surface at the level of the sixth cervical vertebral body only. Finally an accurate knowledge of the depth of vascular structures from the skin surface was shown in the literature review (Chapter 3) to be of relevance in 'pencilling', the distance to which a body armour material can deform when hit by a projectile. Any ballistic protective garment would need to be constructed from a number of layers of material that would result in pencilling of a depth less than the distance from skin surface to the most superficial neurovascular structure.

6.5 Method

Both sides of the neck of 50 consecutively evacuated UK servicemen without neck wounds were retrospectively analysed using contrast enhanced CT angiograms. All measurements were made using a workstation that allowed multiplanar reformats to be performed. These scans had all been undertaken as part of a trauma series in the initial management of servicemen with either limb or thoracoabdominal vascular trauma. All scans were performed on a GE 64-slice CT scanner (General Electric Medical Systems, Milwaukee, US) in a mixed arterial/venous phase of enhancement. 1.25mm axial slices in soft tissue and bony reformats were reconstructed in 3 planes for review. All measurements were made with the subject on their back and their arms by their sides. CT angiograms were chosen as they remain superior to MR when analysing cervical vascular trauma (Cox et al., 2007; Fox et al., 2005; 2006), and suffer from less technical variability than ultrasound in terms of variations in the angulation of the probe and the necessity of compressing structures to obtain an image (Lim et al., 2006). The superior and inferior spinal levels as well as the vertical midpoint for each of the three surface neck zones was determined.

Neck Zone	**Cervical vertebral level**		
	Superior border	**Inferior border**	**Vertical midpoint**
Zone I	Body of C6	Body of T1	Body of C7
Zone II	Upper border of C3	Body of C6	Body of C4
Zone III	Base of skull	Upper border of C3	Body of C2

Table 21: Corresponding cervical spinal levels of superficial surgical neck zones.

To recommend future cervical external anthropomorphic measurements, the neck circumference and the vertical heights of each neck zone was ascertained.

Measurements were made between landmarks that could be identified with ease both clinically and on CT (Table 21). Neck circumference was measured at the level of the inferior margin of the cricoid cartilage. The inferior border of Zone I (as demarcated clinically by the clavicle) was taken as the spinal level corresponding to the acromioclavicular joint (ACJ) posteriorly and sternoclavicular joint (SCJ) anteriorly. In order to compare the neck skin coverage by different designs of protection, the curved surface area of the mean neck was calculated. Zones I + II was calculated as circumference multiplied by the neck height from clavicle (corresponding to body of T1) to angle of the mandible (ie). Zone III was calculated as half of the circumference multipled by the neck height between angle of mandible and base of skull. The total area was Zones I + II + III and was described in metres squared.

In order to scale the dimensions of internal neurovascular structures in the neck to calibrate future injury models, a number of additional measurements were made. Mean diameters and distances (to the closest 0.5mm) of the most lateral aspect of the vessel to the closest skin surface were determined for the carotid artery (CA), internal jugular vein (IJV), vertebral artery (VA) and spinal cord (SC) at the vertical midpoints of these three surgical neck zones (Table 21). Diameters were measured as the largest cross sectional distance from one outer surface to the opposite outer surface. In the upper zone of the neck, the depth of CA to skin was to the most superficial visualised branch on the CT scan, be that internal or external CA.

6.6 Results

The demographics of the patients studied were as follows (mean values, with standard deviation in brackets): age 29.7 years (4.4), mass 82.6 kilograms (6.3) and height

177mm (7.5). The mean thickness of cervical skin (epidermis and dermis) was 2.0mm (0.5mm) anteriorly and 3.0mm (0.5mm) posteriorly. The depth of skin remained constant from the most superior to the most inferior part of the neck. The radiological vertical and horizontal cervical anthropometric measurements can be seen in Table 22. The surface area of Zones I + II was calculated as 0.41m x 0.104m = 0.04264m^2. The surface area of Zone III was calculated as 0.5 x 0.41 x 0.050 = 0.01025 m^2. The total surface area of the neck was therefore calculated as 0.5314m^2.

Measurement (mm)	**Horizontal measurement**	**Vertical measurements**		
	Neck circumference	**Zone I**	**Zones I + II**	**Zones I + II + III**
Description	Cricoid cartilage	Cricoid cartilage to SCJ	Mandible angle to midpoint clavicle	Base of skull to ACJ
Mean	410	51	104	154
Standard deviation	26	12	15	38
95% CI	358- 478	27- 75	74- 134	78- 230

Table 22: Potential horizontal and vertical cervical anthropometric measurements (all measurements in mm); CI= confidence interval.

The widths and depths from the skin surface of the neurovascular structures at the vertical midpoints of each neck zone are shown in Table 23. There was no difference in the widths and depths from skin surface of vessels from the left side of the neck in comparison to the right and therefore the results were combined. The diameter of all three vascular structures measured was greater and the vessels were more superficial as the anatomical plane moved caudally. The width and depth from the skin surface to the SC remained almost constant between spinal levels. The VA remains narrow and further from the skin surface than the other vessels throughout its course. Both the SC and VA were protected by between 4- 6mm of bone throughout their course except for the VA in Zone I.

Structure	Measurement	Zone III	Zone II	Zone I
Carotid artery	Diameter of structure	4.5 (1.0)	6.5 (1.0)	7.0 (0.5)
	Depth of structure to skin	37.0 (5.0)	29.0 (5.5)	21.0 (3.5)
Internal jugular vein	Diameter of structure	8.0 (1.5)	12.0 (2.0)	14.0 (3.5)
	Depth of structure to skin	25.0 (4.0)	18.0 (4.5)	15.0 (3.0)
Vertebral artery	Diameter of structure	3.5 (0.5)	3.5 (0.5)	4.0 (0.5)
	Depth of structure to skin	40.5 (8.0) of which 6.3 was bone	41.5 (8.0) of which 5.9 was bone	37.0 (6.0)
Spinal cord	Diameter of structure	12.5 (1.5)	12.5 (0.5)	12.0 (1.0)
	Depth of structure to skin	59.0 (5.5) of which 4.5 was bone	57.0 (8.5) of which 5.0 was bone	60.5 (5.5) of which 5.0 was bone

Table 23: Mean diameters and distances (standard deviation in brackets) of cervical neurovascular structures at vertical midpoints of each surgical zone- in mm.

6.7 Conclusions and recommendations

A summary is provided in Table 24 and provides the rationale for the research undertaken in subsequent chapters.

Conclusion	Recommendation	Demonstrated in
Chapter 4 demonstrated that mortality and morbidity is highest in Zone I. This is likely due to cervical vessels being widest and most superficial inferiorly in Zone I.	Consideration should be made towards ergonomics assessment of prototypes with greater coverage of Zone I.	Chapters 7 - 9
The spinal cord and vertebral arteries are better protected than the IJV and CA due to their greater depth and bony coverage, except for the VA in Zone 1 before it enters the foramen transversarium at C6	Consideration should be made towards ergonomics assessment of prototypes with greater coverage of the anterior part of the neck than the posterior part	Chapter 7
Neck skin thickness was found to be 2-3mm.	Skin should be modelled as a separate 2-3 mm layer.	Chapter 11
The vertical distance between ACJ and foramen magnum (Zones I- III) showed greatest variability, although this may have reflected patient positioning in the scanner. The distance between angle of mandible to midpoint of the clavicle (reflecting Zones I + II) showed low variation and is easily measured clinically in person	It is therefore recommended that this vertical distance in conjunction with the neck circumference at the level of the cricoid cartilage for both future civilian and military vertical and horizontal anthropomorphic neck measurements	Chapter 7
Assuming that our sample was representative and neck height is normally distributed, the distance between SCJ and cricoid cartilage is between 27- 75mm in 95% of the population.	It can be assumed that a circumferential ballistic collar at least 75mm high would cover Zone 1 of the neck in 95% of the population	Chapter 8

Table 24: Conclusions and recommendations based upon the findings from Chapter 6.

Chapter 7: Ergonomic assessments of ballistic neck collars from six different nations

Chapter summary

At the start of this thesis in 2010, the OSPREY neck collar was disliked by soldiers and rarely worn due to perceived discomfort. A literature review had identified design features in neck collars used by other nations that may potentially inform a more acceptable solution. The aim of this trial was to compare the fit, form and function of neck collars of six designs of neck collar to identify optimal design features, which could be incorporated into prototypes for future testing. 71 participants assessed two allocated neck collars while performing representative military tasks. Shorter and thinner collars were rated the most comfortable, despite lying close to the neck. It was easier to aim a rifle wearing collars with overlapping segments, especially when in the prone position. Although higher and more rigid collars were perceived as being the least comfortable, this could potentially be offset by the higher levels of ballistic protection they provide. Other methods of protecting the neck require assessment such as nape protectors and ballistic scarves in combination with the use of backpacks and biometric data collection.

7.1 Aims of this chapter

- To compare the fit, form and function of six designs of neck collar while performing common military tasks.
- To compare the coverage of neck skin provided by each collar on an anatomical mannequin using recognised surgical zones.
- To identify optimal design features within these collars, which could be incorporated into prototypes for future evaluation.

7.2 Publications derived from this chapter

- Breeze J, Watson CH, Horsfall I, Clasper JC. Comparing the comfort and potential military performance restriction of neck collars from the body armor of six different countries. Military Medicine 2011; 176 (11): 1274–1277 (Breeze et al., 2011c).

7.3 Collaboration

This chapter describes an ergonomics assessment that was undertaken with the assistance of Professor Ian Horsfall and Dr Celia Watson of the Impact and Armour Group based at the Defence Academy at Cranfield University. Assessments were carried out on UK Army and Royal Marines officers who were attending the biannual Intermediate Command and Staff Course.

7.4 Introduction

Protection against energised fragmentation injuries to the neck issued to UK soldiers are currently in the form of collars attached to the ballistic vest. Post-mortem analysis of 5 years of combat neck injuries sustained by UK soldiers described in Chapter 4 demonstrated that these collars could potentially have mitigated many injuries from energised fragments if worn. The uptake of OSPREY neck collars by UK forces was not recorded on JTTR until recommended by the author. However surveying recently deployed military officers suggested uptake to be very low, with collars generally only worn in static locations such as top cover.

The term ergonomics in a military environment is generally taken to mean a group of processes by which equipment is assessed as to its practicality, efficiency and safety. As such ergonomics is key to the potential effectiveness of a design of personal protective equipment as it will likely ascertain its acceptability to soldiers. Prior to the start of this research very little published research existed as to ergonomic assessments of military body armour systems in general (Ivins et al., 2007), and no formal assessment could be identified for any previous ergonomic assessment of neck protection.

7.5 Method

Neck collars from the armed forces of six countries were assessed and standardised photographs on an anatomical mannequin taken (Figures 25-30). Each participant assessed two randomly allocated collars to rate one collar against the other. As four of the six collars were integral to the vest itself, it was not possible to attach different collars to the same tactical vest. The collars reflected the possible permutations in neck collar design as identified from the literature review (Chapter 3). Healthy volunteers were used and therefore ethical approval was not required.

Figure 25: UK OSPREY Mark 2 body armour with fully detachable half neck collar.

Figure 26: US Interceptor armour- the front portion of the neck protector is detachable but the sides and rear portions of the neck protector are non- detachable.

Figure 27: Norwegian armour with non- detachable neck protectors.

Figure 28: French armour with non- detachable neck protectors.

Figure 29: Danish armour with non- detachable neck protectors.

Figure 30: Dutch armour with non- detachable neck protectors.

Methods of objectively comparing between designs using representative military tasks were required. Two papers were identified in the literature review that described ergonomic assessments of military body armour (Ivins et al., 2007; Horsfall et al., 2005), but neither paper described methods to evaluate neck protection. A military judgement panel was convened to identify a set of representative physical military tasks that would reflect those tasks that a soldier would be expected to perform whilst on an operational tour. These were performed wearing standard British Combat 95 uniform, Mark 6A helmet and SA-80 rifle with the Sight Unit Small Arms Trilux (SUSAT) telescopic sight attached. The ambient temperature was 16 degrees Celsius. Descriptions of each neck collar in terms of rigidity and design as well as anatomical coverage of the neck in terms of neck zone (Chapter 5) can be found in Table 25.

Armour description	Collar attachment	Collar rigidity	Stand off from skin	Overlapping segments	Neck coverage
UK OSPREY Mark 2 vest with half neck collar (Figure 23)	Detachable	Semi-rigid	Yes	No	Zones I + II
US Interceptor Outer Tactical Vest (Figure 24)	Detachable	Semi-rigid	No	Yes	Zones I + II
Norwegian Fragmentation Vest (Figure 25)	Integral	Semi-rigid	Yes	Yes	Zone I + half Zone II
French tactical vest 05F81201 manufactured by Sioen Armour (Figure 26)	Integral	Semi-rigid	Yes	Yes	Zone I + half Zone II
Danish 'Fragmentationvest' produced by Danish Materiel Command (Figure 27)	Integral	Flexible	No	Yes	Zone I
Dutch DUTA-11-04 manufactured by American Body Armour (Figure 28)	Integral	Flexible	No	No	Zone I

Table 25: Ballistic collars used and a description of their shape and structure as well as anatomical area of coverage.

7.5.1 Ability to aim a weapon

This was assessed by asking each participant to fire the rifle in the standing, kneeling and prone positions (Figure 31). In addition participants stood in the turret of an armoured fighting vehicle and simulated taking a shot (so called 'top cover').

Figure 31: Participants assessing ability to aim a weapon in the kneeling (top) and 'top cover' positions (bottom).

7.5.2 Overall comfort

This was assessed by asking each participant to perform a 20 meters leopard crawl to simulate movement when under fire, and a 20 meters fireman's lift carrying a simulated casualty weighing approximately 70kg.

7.6 Results

71 male service personnel undertook the assessment over the period of a single day. The ambient temperature and humidity ranged between 19-21^{o}C and 28-30% respectively.

7.6.1 Ability to aim a weapon

For all armour systems it was easier to fire while prone and hardest to fire while standing (Table 26).

Nation	Total using this collar	Number rating it 1st
Norway	21	16/21 (76%)
Denmark	24	18/24 (75%)
Holland	23	12/23 (52%)
France	22	11/22 (50%)
US	25	9/25 (36%)
UK	27	9/27 (33%)

Table 26: Participants who rated their neck collars their top choice regarding ease of firing a rifle.

7.6.2 Overall comfort

The results for overall comfort are demonstrated in Table 27, with the Danish design being the most comfortable to wear.

Nation	Total using collar	Number rating it 1st
Denmark	24	18/24 (75%)
Holland	23	16/23 (70%)
US	25	16/25 (64%)
Norway	21	12/21 (57%)
France	22	10/22 (45%)
UK	27	10/27 (37%)

Table 27: Participants who rated their neck collars their top choice regarding overall comfort.

7.7 Conclusions and recommendations

A summary is provided in Table 28 and provides the rationale for the research undertaken in subsequent chapters.

Conclusion	**Recommendation**	**Demonstrated in**
Shorter and thinner collars were rated the most comfortable, despite lying close to the neck. It was easier to fire a rifle using collars made of overlapping segments, most likely because these segments allow the collar to slide under the helmet, especially in the prone position.	The following design features should be specifically incorporated into new prototypes which require subsequent assessment: overlapping segments, stand-off from neck skin, coverage of Zone I of the neck with as much of Zone II as military task acceptability and equipment integration allows.	Chapters 8 + 9
Standardised reproducible photographs allowed accurate comparisons in both surface area coverage and distances from skin to collar.	These types of photographs should be taken of all prototypes in any future human factors assessment of neck collars to accurately compare coverage.	Chapters 8 + 9
The comfort of wearing a neck collar did not appear to be related to how close the neck collar was to the neck. The OSPREY collar for example was rated the least comfortable despite lying furthest from the neck.	Prototypes should not be discounted just because they lie in close association to the neck skin. An objective assessment of comparing designs with different approximation to the skin surface is required to ascertain its importance.	Chapter 9
Variations in stand off from neck skin demonstrated in the collars mean that the size of the collar alone does not necessarily relate to anatomical coverage of the neck from threats of differing shot lines.	An objective assessment of the coverage provided by each prototype neck collar prototype from different shot lines is required.	Chapter 10
Although the higher collars were rated by participants as the least comfortable, this may be offset by the greater levels of ballistic protection they provide.	A method of objectively comparing the clinical consequences of differences in coverage is required.	Chapter 11
Although a range of representative tasks were undertaken with standardised equipment, a large component of the assessment involved subjective comparisons by participants of acceptability	Methods of comparing between prototypes with greater objectivity should be attempted, such as the use of physiological assessments.	Chapters 8 + 9
This assessment was undertaken in the UK, with environmental conditions unrepresentative of that experienced by soldiers currently on operational deployment in Afghanistan.	An assessment of prototypes should ideally be undertaken with environmental conditions, personal equipment and weapons systems representative of a current operational environment.	Chapter 9

Table 28: Conclusions and recommendations based upon the findings from Chapter 7.

Chapter 8: Ergonomic assessments of novel neck protection prototypes

Chapter summary

The systematic review of the commercial and scientific literature identified two other potential methods of providing neck protection in addition to collars. A novel concept was also identified, based upon incorporating ballistic protective material into the collar of the existing Under Body Armour Combat Shirt (UBACS). These three prototypes and two neck collars designed using the optimised design features ascertained from the previous assessment were compared. Ten participants wearing standard military equipment compared these five prototypes during a treadmill test using physiological measurements including neck skin temperature, heart rate and in ear temperature. Prototypes were subjectively compared regarding their effect on soldier performance using representative military tasks. Both neck collars and the modified UBACS prototype demonstrated 90% acceptability in terms of military task performance. Neck collars remain the most successful design in terms of military performance and comfort but the modified UBACS prototype should also be developed further.

8.1 Aims

- To compare new methods for protecting the neck including those designs other than a collar using a revised set of military representative tasks.
- To utilise physiological measurements to objectively compare between prototypes.

8.2 Publications derived from this chapter

- Breeze J, Clasper JC. Ergonomic assessment of future methods of ballistic neck protection. Military Medicine 2013; 178 (8): 899–903 (Breeze and Clasper, 2013b).

8.3 Concept

This chapter describes an ergonomics assessment undertaken using three novel prototypes and two commercially available methods of neck protection. The three prototypes were designed by the author using concepts identified from the previous ergonomic assessment, in conjunction with the literature review. The armour designs were manufactured by Dstl, with the grateful assistance of Dr Simon Holden.

8.4 Introduction

The first ergonomics assessment compared six representative neck collars from different nations (Chapter 7). This identified a number of design features incorporated within these collars that the participants found to improve comfort and equipment integration. Notably the OSPREY collars were consistently the least acceptable design due to interference with the helmet, preventing the user from adopting the prone position. It was identified that flexible collars with overlapping segments caused the least restriction in performance and two prototype designs of collar were developed incorporating a mixture of these features. A number of limitations in this trial were noted and recommendations made, including the desire for more objective methods for comparison between prototypes. Evidence describing the physiological burden of wearing body armour exists but none could be found specifically for neck protection. In addition the author was able to work in partnership with the procurement teams at DE&S and ITDU who were able to recommend more representative military tasks for which to assess future prototypes.

Figure 32: The original Under Body Armour Combat Shirt issued to UK service personnel deploying to Afghanistan in 2010.

The systematic review of the commercial and scientific literature identified two other potential methods of providing neck protection in addition to collars (Chapter 3). The first was a nape pad attached to the rear of a combat helmet, and the second a 'shemagh' style scarf, which contained an additional central panel of ballistic protective material. In addition a novel concept was identified by the author of this thesis, which involved incorporating ballistic protective material into the collar of the UBACS garment worn by UK servicemen under the OSPREY body armour vest (Figure 32).

8.5 Method

The trial was performed in February 2012 using ten infantry soldiers with recent operational experience in Afghanistan. Ranks ranged from private soldier to sergeant. Ambient temperature and humidity were measured at two-hourly intervals and ranged between 30-33^{o}C with a relative humidity of 29-36%. Trial participants all wore standardised equipment issued to UK soldiers serving in Afghanistan, including an OSPREY Mark 4 ballistic vest, Mark 7 combat helmet and a 35- litre rucksack weighing 15 kg. A weight of 15 kg is representative of that used in the Army's pre-deployment Advanced Combat Fitness Test. Heights of participants ranged between 174-191 cm (mean 185 cm) and weight between 76-89 kg (mean 82 kg). Healthy volunteers were used and therefore ethical approval was not required. Standardised photographs were again taken using an anatomical mannequin (Figure 33).

Figure 33: The five prototypes assessed in this trial compared on the same anatomical mannequin; a) Three-piece neck collar, b) Two-piece neck collar, c) Nape pad, d) Ballistic Shemagh, e) UBACS incorporating modified neck collar.

The five neck protection prototypes were assessed and the results compared to one another and to a control wearing no neck protection. Subjective assessments were followed directly by objective assessments for each participant. Prototypes 1 and 2 were detachable neck collars comprised of three or two overlapping segments respectively (Figures 31a and 31b). Prototype 3 was a detachable nape pad that was attached to the posterior aspect of the Mark 7 helmet harness using two straps (Figure 31c). Prototype 4 was a current UK military issue scarf (shemagh) incorporating a 4mm thick rectangle of ballistic protective material in its centre, which was wrapped around the neck of participants (Figure 31d). Prototype 5 was a modified UBACS, with two layers of

UHMWPE felt incorporated into the collar (Figure 31e), with total areal density of 1.3 kg/m^2. A detailed comparison of the physical properties of each prototype is demonstrated in Table 28.

The percentage of the neck covered a prototype was related to the total neck surface area of 0.05314m^2 calculated from CT measurements in Chapter 6. The mass of each prototype was measured and included both the ballistic protective material as well as cover material (Table 29). The ballistic protective materials utilised were representative of those commonly used in modern armour systems.

Prototype	**Mass (g)**	**Height (mm)**	**Area of coverage (m^2)**	**% coverage of 50th percentile neck**
Three-piece neck collar	197	61	0.026	49%
Two-piece neck collar	208	63	0.026	49%
Nape pad	76	84	0.018	34%
Ballistic scarf	412	158	0.082	100%
Modified UBACS	51	57	0.021	39%

Table 29: Comparisons of physical characteristics of neck protection prototypes.

8.6.1 Subjective assessment (representative military tasks)

Trial participants performed tasks and then subjectively assessed each configuration as to whether they could perform firing prone, fire standing, leopard crawl and casualty drag to an acceptable standard of military performance. Overall acceptability was determined as the mean of the four percentages. A cut- off value of 90% was determined by a military judgement panel prior to the assessment as a minimum acceptable level for overall performance of military representative tasks as no published standard existed.

8.6.2 Objective assessment (physiological measurements)

Only limited published evidence documenting the physiological burden and other ergonomic consequences of wearing body armor exists (Ricciardi et al., 2008; Caldwell et al., 2011). Physiological measurements were determined for each prototype design using three non- invasive parameters: in ear temperature, heart rate and neck skin temperature. These measurements were again chosen by a military judgement panel due to a lack of previous evidence to suggest which parameters should be measured. Each participant was asked to walk using a treadmill for 15 minutes, (4 km/h for nine minutes, 7 km/h for six minutes), and three physiological measurements were taken at three-minute intervals.

In-ear temperature was chosen to represent core body temperature and was measured with a tympanic thermometer (Braun$^{©}$ ThermoScan 5 IRT4520). Infrared tympanic measurements of this type have been demonstrated to be highly representative of core body temperature (Jefferies et al., 2011). Participants were asked to stand still on the sides of the treadmill for 10-15 seconds when temperature measurements were taken. Such an approach attempted to prevent concerns regarding potential inaccuracies that might occur with subject movement, and has been successfully used in previous military heat stress trials (Bricknell, 1997). Heart rate was measured with a wireless pulse oximeter (Nonin$^{©}$ Onyx 9500) placed on the digital finger. Neck skin temperature was measured with an infrared thermometer (Tecnimed$^{©}$ Thermofocus 0800), the type of which has previously demonstrated to have good accuracy and repeatability as a means of non-invasive temperature measuring (Kistemaker et al., 2006). The skin thermometer was held at a distance of 3cm from the skin to one side of the cricoid cartilage following a single wipe of the skin with antiseptic cloth.

The aggregated mean of the individual measures, for each physiological parameter, for each neck protection configuration, was plotted against time. The values for each physiological measurement were also compared to the values for the control configuration at 3, 9 and 15 minutes. A Chi Squared test was utilised with a null hypothesis that there was no statistical difference between each prototype and the control at each of the above time points ($p < 0.05$ denoting statistical significance due to rejection of null hypothesis). Statistical analysis was undertaken using the SPSS IBM statistical package (version 21, Microsoft Corporation, Redmond, Washington, US).

8.7 Results

8.7.1 Subjective assessment

Both designs of neck collar (two-piece and three-piece prototypes) and the modified UBACS prototype were acceptable for all military tasks (Table 30). It was possible to fire standing with all prototype designs but marked differences were found in tasks that required the participant to adopt a prone position. The nape pad prevented neck extension (required for prone firing and leopard crawl) and lateral neck movements (required for casualty drag). The ballistic scarf became dislodged during neck movements and was perceived as being very hot. Participants felt that the scarf would be unacceptable at most times of the year in the current operational environment of Afghanistan, but could potentially be useful in colder conditions or static sentry duty. All participants stated that the modified UBACS prototype caused rubbing on the skin and irritated the inferior surface of the mandible when zipped up.

Prototype	**Military task**				**Overall military task acceptability**	**Overall Comfort**
	Fire Prone	**Fire Standing**	**Leopard Crawl**	**Casualty Drag**		
No neck protection	100%	100%	90%	100%	97.5%	90%
Three-piece collar	90%	100%	90%	90%	92.5%	90%
Two-piece collar	80%	100%	90%	90%	90%	90%
Nape pad	40%	100%	30%	60%	57.5%	90%
Ballistic scarf	30%	90%	20%	10%	37.5%	30%
Modified UBACS	90%	100%	80%	90%	90%	90%

Table 30: Acceptability of neck protection configuration in terms of ability to perform military tasks and overall comfort.

8.7.2 Objective assessment

No statistical difference was found between any of the five prototypes, for either mean tympanic temperature or mean heart rate (Figure 34). Participants wearing the ballistic scarf and the modified UBACS prototype were found to have a statistically significantly higher (p= 0.029 and p= 0.044 respectively) neck skin temperature compared to the control configuration at 9 minutes and 15 minutes.

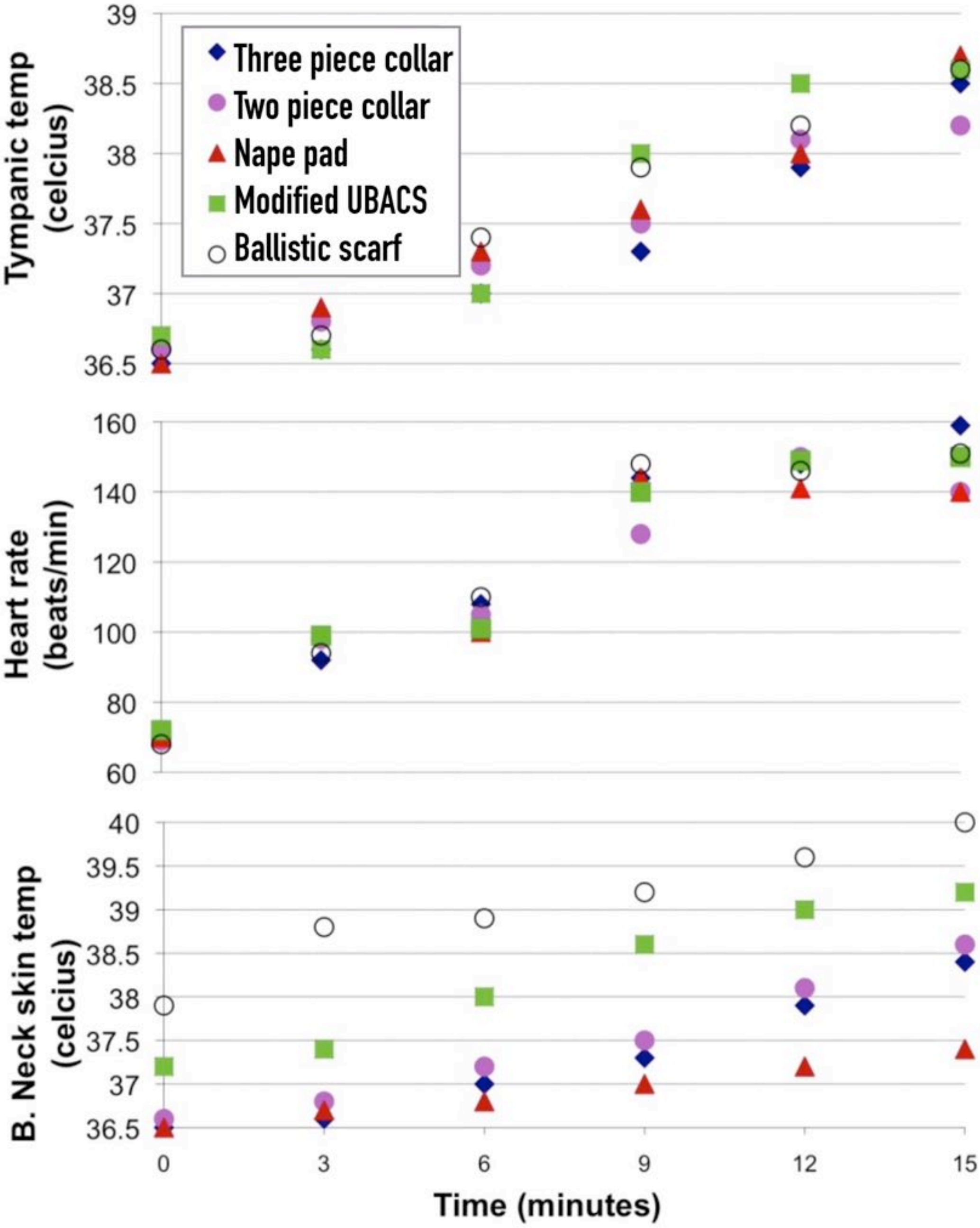


Figure 34: Graphs comparing physiological changes over time in a) tympanic temperature, b) heart rate and c) neck skin temperature across the five neck protection prototypes.

8.8 Conclusions and recommendations

A summary is provided in Table 31 and provides the rationale for the research undertaken in subsequent chapters.

Conclusion	**Recommendation**
The three-piece and two- piece collar prototypes were identical to one another in terms of military performance and comfort. The use of standardised photographs alone could not compare the coverage provided by each design from different angulations.	A method of objectively ascertaining the potential medical consequences of the differing coverage provided by different prototypes and from different angulations is required.
No statistical difference was found in either tympanic temperature or heart rate between any of the five prototypes and the control configuration.	Consideration could be made to changing either task duration or intensity in attempt to differentiate between designs in the future.
Statistically significant differences in neck skin temperature were found and May have reflected the closeness of the ballistic protective material to the skin surface. These higher skin temperatures were not related to perceived comfort or the ability to complete the military tasks assessed.	The use of thermistors incorporated in clothing would potentially be a better method for the continuous monitoring of physiological data.
The nape pad only covered 34% of the neck surface area but had significant effects on the ability to perform tasks; it prevented neck extension (required for prone firing and leopard crawl) and lateral neck movements (required for casualty drag).	Ergonomic assessments would suggest that there is no evidence to support the use of nape pads but further medical assessments are required to support this recommendation.
The ballistic scarf became dislodged during neck movements and was perceived as being very hot in the ambient conditions experienced in this study.	The scarf could potentially be useful in colder conditions or static sentry duty and further assessment is recommended. Consideration should be made to making the whole scarf out of a ballistic protective material such as silk.
Subjectively both designs of neck collar and the modified UBACS prototype were acceptable for all military tasks. Participants particularly liked the modified UBACS prototype as they were familiar with the design. When the collar was fully zipped up, trial participants stated that the increased collar thickness caused rubbing on the skin under the mandible.	A modified UBACS is a viable method for potentially protecting the neck and requires further assessment. The collar design should either be modified such that it does not rub on the skin or consideration made to using less layers of ballistic protective material in the collar.

Table 31: Conclusions and recommendations based upon the findings from Chapter 8.

Chapter 9: Ergonomic assessments of modified UBACS neck collar prototypes

Chapter summary

Reinforcing the collar of the existing UBACS is a novel method for potentially providing ballistic protection to the neck. Three differing designs of modified UBACS were developed using one of three ballistic protective materials: two layers of para-aramid felt, one layer of UHMWPE felt or two layers of a silk fabric. These nine prototypes and a standard UBACS were trialled against one another in an ergonomics assessment run by the author in Afghanistan using representative military tasks. Subjective assessment of these nine configurations in terms of comfort, heat dissipation and overall acceptability were compared. All military tasks could be performed with all nine configurations of prototypes. Although silk was the most comfortable material, it was not functionally practical in any of the three designs. A modified UBACS has the potential to provide neck protection without reducing performance when collars incorporating one layer of UHMWPE or two layers of the para-aramid felts are used. Should a requirement for a zip be maintained, it should be moved to one side of the midline to reduce rubbing on the chin and be covered with ballistic protective material.

9.1 Aims of this chapter

- To compare three designs of reinforced neck collar within the existing under body armour combat shirt.
- To compare three combinations of ballistic protective material within each design to ascertain their impact upon each design.
- To undertake an ergonomics assessment in an operationally relevant environment using representative personal equipment.

9.2 Publications derived from this chapter

- Breeze J, Granger CJ, Pearkes, TD, Clasper JC. Ergonomic assessment of enhanced protection under body armour combat shirt neck collars. Journal of the Royal Army Medical Corps 2014; 160 (1): 32–37 (Breeze et al., 2014b).

9.3 Collaborations

This chapter describes an ergonomics assessment undertaken in Afghanistan using three novel prototypes of reinforced UBACS neck collar. The author identified identified all of the concepts. Design 1 was manufactured by DE&S with the grateful assistance of Adrian Randall at Defence Clothing. Design 3 was manufactured by Dstl with the grateful assistance of Robert Robinson Collins. Design 2 was manufactured in Afghanistan by altering Design 2 using materials recycled from older prototypes. The assessments were undertaken in conjunction with two deployed Royal Army Medical Corps officers, Major Tim Pearkes and Major Chris Granger. Approval for this trial to take place in Afghanistan was granted by Permanent Joint Headquaters.

9.4 Introduction

A novel method of providing protection to the neck was identified in the previous ergonomics assessment (Chapter 7), based upon incorporating ballistic protective material into the collar of the UBACS. This concept could potentially act as an irreducible minimum amount of protection (Tier 1 level protection) with the option to wear an OSPREY neck collar in addition (Tier 2 level protection) during situations of increased threat; such a tiering system is currently being used successfully for pelvic protection in the deployed UK military (Lewis et al., 2013). The modified UBACS trialled in Chapter 7 used 2 layers of UHMWPE with total areal density of 1.3 kg/m^2. Although it was liked in principle, the ballistic protective material used was perceived as being too thick when the collar was zipped up. It did however demonstrate its potential for protection of the neck and further ergonomic assessment was recommended.

Figure 35: Modified UBACS neck collar prototypes 1-3 fitted on an anatomical mannequin.

Three modified UBACS were developed (termed prototypes 1-3) and incorporated in differing degrees the following features developed from the previous ergonomic assessments (Chapters 6 and 7); stand off from the neck skin, overlapping collar segments, skin coverage of Zone 1 of the neck. Prototype 1 was identical to the existing UBACS, with the only modification being the incorporation of ballistic protective material into the collar, and was analogous in design to that tested in the trial described in Chapter 7 (Figure 35). Prototype 2 was identical to Prototype 1, but with an additional semicircle of ballistic protective material at the front and rear to cover those areas of the upper thorax not currently covered by the OSPREY vest (Figure 36). Design 3 was a standard UBACS shirt with the collar modified to cross over at the front and enabled the collar to stand up without the requirement of a zip.

Figure 36: (a) A standard UBACS with ballistic material in the neck collar (Prototype 1) worn with the OSPREY vest, (b) gap in protection between collar and OSPREY vest highlighted in yellow, (c) Addition of semicircle of ballistic material under collar (Prototype 2).

9.5 Method

An ergonomics assessment was undertaken by the author in Afghanistan on Operation HERRICK 17A over two weeks in October 2012. The ambient temperature and humidity ranged between 35-41^{o}C and 19-31% respectively. Twenty deployed UK servicemen (10 infantry soldiers, five Royal Logistic Corps personnel and five combat medical technicians) ranging in rank from private soldier to sergeant assessed each prototype. This was a healthy volunteer study and therefore no ethical approval was required. Participants were chosen to represent the broad range of UK service personnel who would be expected to wear these garments on a daily basis. Prototypes 1-3 were assessed, each with one of three different constituent ballistic protective materials (Figure 35). Each of these nine configurations were compared to one another and to a standard unmodified UBACS using representative Dismounted Close Combat (DCC) and Mounted Close Combat (MCC) tasks that had been recommended by Defence Equipment and Support (Table 32).

Serial	Type	Task
A	N/A	Put on body armour with OSPREY neck collars attached
B	DCC	Fire weapon prone
C	DCC	Fire weapon kneeling
D	DCC	Fire weapon standing
E	DCC	Leopard crawl
F	DCC	Route clearance with VALLON and buried explosive device confirmation drill
G	DCC	Put on and take off standard issue G10 respirator
H	MCC	Ingress through rear door of Mastiff, sit down and fasten seat-belt
I	MCC	Ingress through turret of Mastiff into 'Top Cover' position
J	MCC	Fire General Purpose Machine Gun from top cover position in Mastiff
K	N/A	Take off body armour with OSPREY neck collars attached

Table 32: List of representative Dismounted Close Combat (DCC) and Mounted Close Combat (MCC) tasks undertaken in this assessment.

Three ballistic protective materials were used (Figure 36), with only one material type per collar. These were either two layers of a para-aramid felt (areal density 0.25 kg/m^2 per layer), one layer of UHMWPE) felt (areal density 0.6 kg/m^2) or two layers of a silk fabric (areal density 0.15 kg/m^2 per layer). The two layers of silk were identical to that used in current Tier 1 pelvic protection (Lewis et al., 2013). The single layer of UHMWPE was approximately half the areal density of that assessed in the previous trial (Chapter 8). The ballistic protective materials were enclosed by a lightweight knitted fabric front and rear cover material that was identical in all configurations. Although ideally the three materials used would be ideally matched in terms of areal density and material properties, pragmatically this was not possible with the resources available.

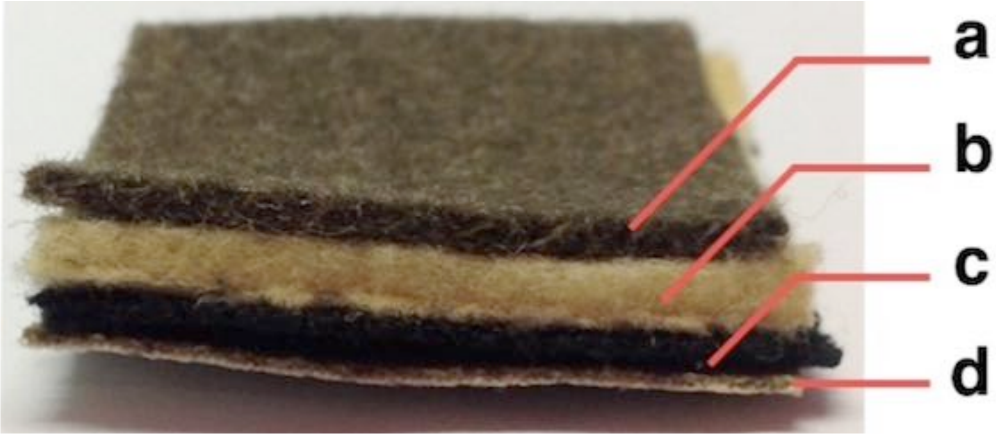


Figure 37: Types of ballistic protective and cover materials used; a) Para-aramid felt (1 layer); b) Ultra High Molecular Weight Polyethylene felt (1 layer); c) Silk fabric (2 layers); d) Cover material. Only one type of ballistic protective material was used in each collar.

Each participant assessed the standard UBCACS first, followed by the nine modified UBACS prototype configurations in a random order. Participants performed each task once and tasks took between 2-4 minutes each to perform. Participants were unaware of which ballistic protective material was in each collar. It was also possible to anonymise between the prototype 1 and 2 designs by adding a single semicircle of thin non-ballistic protective material at the front and rear of each prototype to mimic the appearance of prototype 2.

9.6.1 Objective assessments

A range of static and dynamic representative military tasks (Figure 38, Table 30) were chosen which had evolved from those used in the previous two assessments (Chapters 7 and 8), in conjunction with advice from DE&S and evolving evidence in the literature (Harman et al., 2008; Ricciardi et al., 2008; Caldwell et al., 2011). All tasks were undertaken using standardised clothing and equipment, including the issued 35- litre rucksack, a Mark 7 helmet and the current short OSPREY Mark 4 neck collars attached to the ballistic vest. Each rucksack was filled with bags of saline to give an additional mass of 10 kg. All participants were asked after each task whether they could complete the task without constraints, complete the task but with certain constraints, or whether they were unable to complete the task. Examples of constraints included having more difficulty to sight an aimed shot or more effort required to extend the neck in the prone position. For a configuration to pass the task it required 90% or more of the participants to be able to complete it without constraints (Table 2). This cut-off was agreed with DE&S and had been utilised in the previous ergonomics assessment (Chapter 7).

Figure 38: Examples of representative military tasks: a) VALLON route clearance, b) Use of G10 respirator, c) Firing standing, d) Firing prone.

9.6.2 Subjective assessment

The effect of each configuration on perceived comfort, equipment integration, heat dissipation and overall acceptability was recorded using a five- point Likert scale contained within a paper questionnaire (Appendix B). This assessment method has previously been used successfully in determining the impact of body armour on lower body movement (Park et al., 2014). The overall acceptability scores from the Likert scales were converted into binomial data by combining all the agree and disagree responses into two categories of "acceptable" and "unacceptable", enabling a chi-squared test to be performed. The null hypothesis was that there was no difference in acceptability between that configuration and the standard UBACS. Statistical analysis was undertaken using the IBM SPSS statistical package (Version 21, Microsoft Corporation, Redmond, Washington, US), with statistical significance defined as a p value < 0.05.

9.7 Results

The height and weight of participants ranged between 175-193 cm (mean 186 cm) and 71-88 kg (mean 78 kg). All tasks could be performed with all configurations using the threshold of 90% (Table 33). The most difficult tasks to complete were prone firing and the leopard crawl, with the participants stating in the questionnaire that the collar in prototypes 1 and 2 caused unacceptable rubbing underneath the chin when trying to make an aimed shot.

Configuration	**Task**										
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**
Standard UBACS											
UBACS Prototype 1 (2 layers silk)		▨									
UBACS Prototype 1 (2 layers para-aramid)		▨			▨						▨
UBACS Prototype 1 (1 layer UHMWPE)											
UBACS Prototype 2 (2 layers silk)		▨									
UBACS Prototype 2 (2 layers para-aramid)		▨									
UBACS Prototype 2 (1 layer UHMWPE)					▨						▨
UBACS Protype 3 (2 layers silk)											
UBACS Prototype 3 (2 layers para-aramid)											
UBACS Prototype 3 (1 layer UHMWPE)		▨			▨						▨

Table 33: Objective assessments of prototypes using representative military tasks outlined in Table 31; White box = task completed, Grey box = task completed but with constraints. No participant was unable to complete a task.

Figure 39: (a) Silk in the collar of prototype design 3 causing it to drop down; (b) Modifications to the standard UBACS collar to produce standoff from the skin and moving the zip to one side of the midline.

The subjective participant assessment for each configuration is demonstrated in Table 34. Prototype 3 configurations that used either the UHMWPE or para-aramid felt were the only configurations to demonstrate no significant difference in user acceptability compared to a standard UBACS (p = 0.57 and 0.89 respectively). Perceptions in poor heat dissipation was described subjectively as the main reason for a configuration being unacceptable and was primarily found in the prototype 1 and 2 designs. Reinforcing collars with silk provided no statistical difference in perceived heat dissipation for the prototype 1, 2 and 3 designs compared to a standard UBACS (p values of 0.094, 0.062 and 0.13 respectively). All 20 participants found that silk was the most comfortable material when lying directly next to the skin. However silk in the collar lacked the rigidity required to maintain skin coverage in the Prototype 3 design (Figure 39). Prototype 3 demonstrated no significant difference in subjective user acceptability from a standard UBACS when worn by itself. However when worn in conjunction with the OSPREY neck collar it prevented participants from assuming the prone position.

Configuration	Comfort	Equipment integration	Heat dissipation	Overall acceptability
Standard UBACS	1	1	2	2
UBACS Prototype 1 (2 layers silk)	1	1	2	3
UBACS Prototype 1 (2 layers para-aramid)	2	1	5	3
UBACS Prototype 1 (1 layer UHMWPE)	5	1	5	4
UBACS Prototype 2 (2 layers silk)	2	1	2	3
UBACS Prototype 2 (2 layers para-aramid)	3	1	5	3
UBACS Prototype 2 (1 layer UHMWPE)	5	1	5	5
UBACS Protype 3 (2 layers silk)	2	1	1	4
UBACS Prototype 3 (2 layers para-aramid)	1	3	2	2
UBACS Prototype 3 (1 layer UHMWPE)	2	2	1	1

Table 34: Subjective assessments of prototypes ranked using five- point Likert scale; 1= strongly agree, 2= agree, 3= neutral, 4= disagree, 5= strongly disagree.

The final question in the subjective questionnaire asked whether the participant believed that wearing the collar would mean that they were less likely to get injured. However there was some ambiguity about what this question actually meant, mainly whether the potential extra weight and therefore reduced speed would offset any advantages of the collar. At the start of the trial the assessments were being undertaken in different locations, by two separate assessors. Therefore it was not possible to communicate the problems that were being encountered early enough for them to be resolved. It was therefore decided on balance not to include this question in the Likert scale ratings. However in the free text for this question the overwhelming opinion was that the collar would potentially reduce injuries as they recognised that the neck was very exposed, especially in summer when the shirt was zipped open.

9.8 Conclusions and recommendations

A summary is provided in Table 35 and provides the rationale for the research undertaken in subsequent chapters.

Conclusion	Recommendation
Two layers of para-aramid felt, or one layer of UHMWPE felt, maintained flexibility but was still rigid enough to maintained collar shape.	These combinations are suitable for a modified UBACS neck collar as this maintained rigidity and therefore neck skin coverage.
Silk in the collar of all prototypes caused the collar to fall down after repeated use, even with the collar zipped up in prototypes 1 or 2.	The use of silk in the collar portion of any modified UBACS design is not recommended, as this material alone is not sufficiently rigid.
Participants experienced unacceptable rubbing on the undersurface of the chin when zipped up with Prototypes 1 and 2.	Should a zip be a requirement in future iterations of the UBACS, it should be moved to one side of the midline.
Additional semicircles of silk in prototype 2 made no subjective difference to soldier acceptability compared to an unmodified UBACS when made of silk	Consideration should be made for incorporating these modifications should the future OSPREY neck collar have a gap in ballistic protection between it and the vest.
Prototype 3 demonstrated no significant difference in subjective user acceptability from a standard UBACS when worn by itself. However when worn in conjunction with the OSPREY neck collar it prevented participants from assuming the prone position.	The design utilised in prototype 3 is not recommended if an OSPREY ballistic neck collar remains a requirement.

Table 35: Conclusions and recommendations based upon the findings from Chapter 9.

9.9 A note for those reading this thesis

This section marks the end of the first of the two parts of this thesis. A number of acceptable prototypes have been developed and those cervical anatomical structures believed to be at risk have been identified. In the second part of the thesis that directly follows this, the concepts of injury modeling and how it may be applied to the problem of representing energised fragments penetrating the neck will be explained.

Chapter 10: Injury modelling: concepts and applications to the problem of neck wounds

Chapter summary

This chapter provides a brief summary of three published papers by the author describing the pertinent concepts regarding terminal ballistics and injury modelling in relation to protection against neck wounds. The ideal objective of an injury model is to demonstrate how the permanent wound tract and temporary cavity interacts with each anatomical structure in the neck as it is these two mechanisms that result in mortality and morbidity. Finite element numerical injury models are likely to represent the future of modelling as they can accurately represent both projectile and tissue variables using a scaled anthropometric mesh of cervical neurovascular structures. However the equations required to populate the material properties utilised within the model still require the testing of physical simulants and the model itself requires validation, using models that can simulate actual human anatomy such post mortem human subjects.

10.1 Aims

- To describe the pertinent concepts regarding terminal ballistics and injury modelling in relation to protection against neck wounds
- To describe current injury models and their uses and limitations
- To describe the Zygote model which will be used as the basis of the two injury models used to validate the designs developed in this thesis.

10.2 Publications derived from this chapter

- Breeze J, Newbery T, Pope DJ, Midwinter MJ. The challenges in developing a finite element injury model of the neck to predict the penetration of explosively propelled projectiles. Journal of the Royal Army Medical Corps 2014; 160 (3): 220–225 (Breeze et al., 2014c).
- Breeze J, Sedman AJ, James GR, Hepper AE. Determining the wounding effects of ballistic projectiles to inform future injury models: a systematic review. Journal of the Royal Army Medical Corps 2014; 160 (4): 273–278 (Breeze et al., 2014d).

10.3 Collaborations

This chapter describes the pertinent concepts regarding terminal ballistics and injury modelling in relation to protection against neck wounds. One of the primary outputs that will be described utilises the Zygote, a three- dimensional representation of human anatomical structures that was commercially procured by Dstl. The author worked with Dr Dan Pope and Dr Rob Fryer at Dstl to identify those structures within the Zygote that required inclusion within the model and to ensure that the geometries of each structure were appropriate and adequately scaled.

10.4 Introduction

Neck injury due to energised fragments experienced by UK service personnel deployed on current operations has been responsible for significant mortality and long-term morbidity. These injuries reflected the fact that the neck has little inherent anatomical protection to penetrating energised fragments, compounded by the fact that ballistic neck collars to protect against such injuries were rarely worn. The development of a more acceptable neck collar necessitated the manufacture of multiple designs of prototypes, each of which required ergonomics assessments to determine its acceptability for performing representative military tasks. However such trials are costly both financially and in terms of time. The ability to rule out a particular design of personal protective equipment on medical grounds prior to ergonomics assessment would reduce the number of prototypes that have to be tested, with resultant time and financial savings. An injury model should aim to provide an objective quantification of injury to a particular question, which in terms of ballistic simulation is a specified threat. As such a number of variables require definition including the anatomical area at risk, the nature of the threat and any protective mechanisms to potentially mitigate against that threat (Table 36).

Variable requiring modelling	**Knowledge determined from Chapters 2-9**
Projectile mass and shape	Analysis of retained fragments post mortem in conjunction with masses estimated from CT suggest testing with the following fragment simulating projectiles: 1.10g and 0.49g cylinders, 0.51g sphere.
Range of impact velocities	95% of predicted impact velocities of perforating energised fragments were below 348 m/s and this should be the upper limit of testing (as will be demonstrated in Chapter 11).
Cervical anatomical structures at risk	Clinical and post mortem analysis has identified the following anatomical structures requiring coverage: carotid arteries, vertebral arteries, spinal cord and brachial plexus.
Armour mechanisms	Two ballistic collars attached to the vest and three designs of EP-UBACS collars were acceptable in terms of ergonomics and require evaluation of their potential medical effectiveness.

Table 36: Variables requiring modelling to enable neck protection prototypes to be potentially differentiated on medical grounds derived from previous chapters in thesis.

10.5 Types of injury models pertinent to potentially modelling penetrating neck wounds

Injury models can be broadly categorised into physical and numerical, with numerous sub-types in each category (Table 37). These subtypes can be used in combination, for example a body armour material laid over a gelatin block, or firings into gelatin being used to generate equations for a numerical simulation.

Model type	Example
Physical	Manafactured tissue simulants eg gelatin, soap
	Animal models
	Post mortem human subjects
Numerical	Outcome related surface wound mapping
	Analytical boundary representation models
	Finite element models

Table 37: A broad classification of injury model types and examples pertinent to potentially modelling penetrating neck wounds.

An ideal model for simulating all aspects of penetrating neck injury should be able to simulate a complex range of interacting variables (Table 38), recognising that such a model does not currently exist.

Variable	Description	Potential solutions
Amour and projectile design	Shape, design features, size and thickness	Materials testing +/- tissue simulant Finite element model
Projectile armour interaction	Armour and projectile material properties including mass and projectile shape	Materials testing +/- tissue simulant Finite element model
Vulnerable anatomical structures	Three dimensional representation of structures in correct anatomical relationships to one another	Post mortem human subjects Numerical models based upon geometric anatomical meshes
Projectile tissue interaction	Interaction of the predicted permanent wound tract with individual anatomical structures and additional damage from the temporary cavity	Tissue simulants to derive values for equations to underpin a finite element model
Objective injury calculation	Simple scoring system able to predict death, incapacitation and long term morbidity	Outcome based surface wound mapping Analytical boundary models Finite element models

Table 38: Interacting variables necessary to generate an injury prediction to enable accurate comparisons between neck protection prototypes.

10.6 Armour and projectile design

Energised fragments should be represented within injury models using FSPs, enabling standasation of experimental methods and reducing variability. It is an accepted limitation of current models to utilise FSPs fired from a straight- barreled rifle, recognizing that in reality energised fragments travel at all angles with yaw and spin. Models potentially provide the ability to compare multiple designs of armour and projectiles without the expense and time constraints of making prototypes for physical all testing is desired. Numerical solutions enable prototypes to be laser- scanned into Computer Aided Design (CAD) files, which can subsequently be manipulated to reflect different design features (Figure 40).

Figure 40: Meshed images of a chisel-nosed cylindrical fragment simulating projectile and the Mark 4a OSPREY half neck collar.

10.7 Projectile armour interaction

A method based on the perforation of body armour material alone potentially represents the most simplistic injury model. For example the testing of composite helmets is based upon the concept that if a 1.10g FSP perforates the ballistic protective material at a certain velocity, the test is a fail irrespective of the interaction between the projectile and any tissue beneath it (Iremonger and Went, 1996). Alternatively the test could be modified to include a block of gelatin beneath it and the distance from skin surface to the closest anatomical structure causing death or morbidity included (Figure 41). Another approach utilised minimum distances within the thorax from the skin based on ultrasound measurements for stab resistant vests (Bleetman and Dyer, 2000; Bleetman, 2003). Based on the measurements derived from Chapter 5, the minimum mean distance from skin to carotid artery as it travels up the neck was 21mm (+/- 3.5mm).

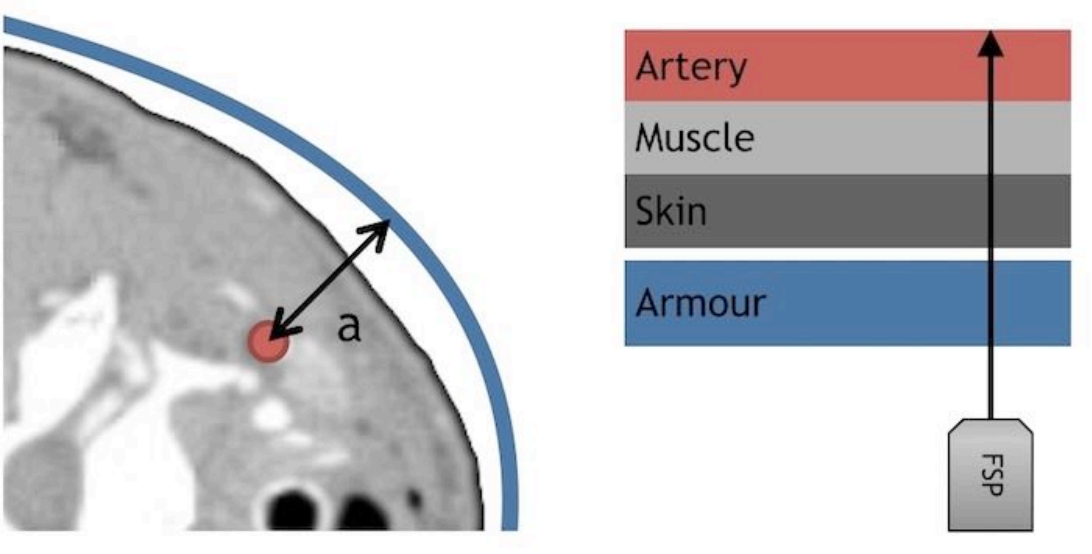


Figure 41: Critical distance to damage (label a) for FSP perforating the ballistic protective material demonstrated on an axial CT slice.

10.8 Vulnerable anatomical structures representation

Analysis of the injuries sustained in survivors and those who died as undertaken in Chapter 3 can provide an accurate knowledge of which anatomical structures require coverage. In the future this may become role specific to provide measures of predicted incapacitation. These structures require accurate three- dimensional representation in both their structure and their relationships to one another. No animal with the exception of primates can accurately represent human cervical anatomy (Figure 42), although this may potentially be overcome with the use of Post Mortem Human Subjects (PMHS) (Figure 43).

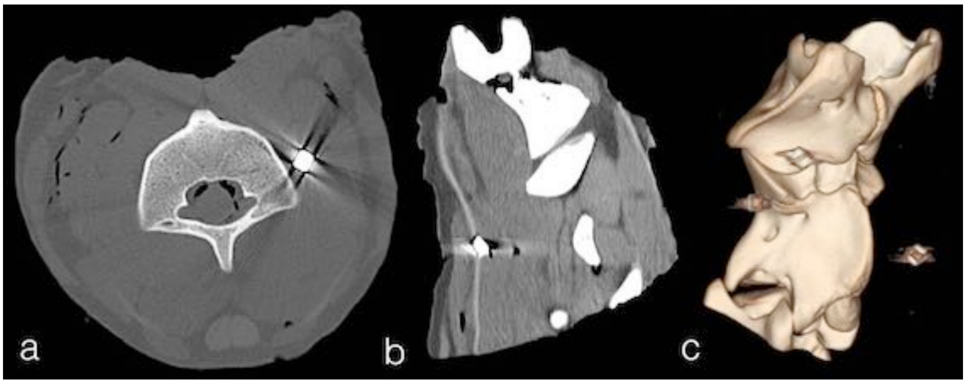


Figure 42: Computed Tomography scans taken after testing of cylindrical FSPs into a goat neck. The bony anatomy is potentially representative of a human but the vasculature is not.

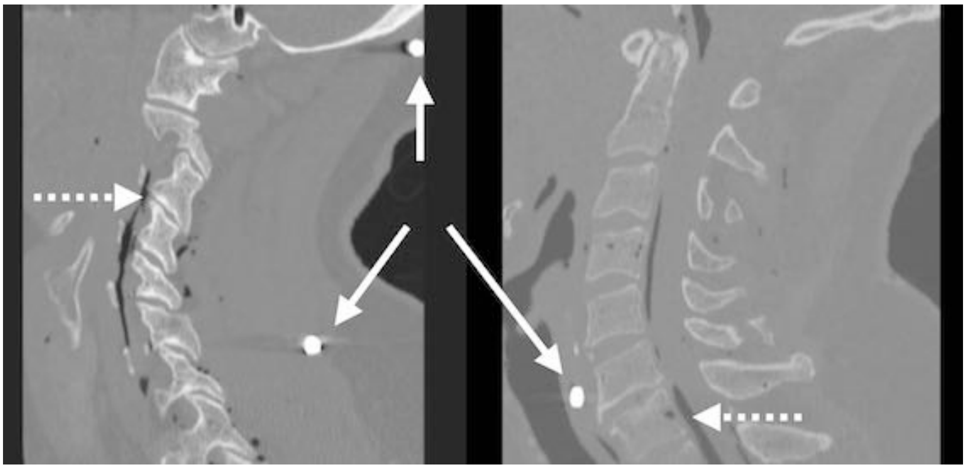


Figure 43: Computed Tomography scans after testing of cylindrical FSPs (solid arrows) into the neck of a post mortem human subject normal human anatomical relationships. Note inclusion of air (dashed arrows) post mortem that could mistakenly be assumed to be due to the passage of the projectile.

10.9 Projectile tissue interaction

Historical numerical simulations of injury have generally utilised an infinitely thin shot line to determine the path of wounding (Figure 44), with any anatomical structure along this line assumed to have been damaged. Another method is to utilise a cylindrical tract of destruction with a width the same as that of the projectile (Figure 44). In reality projectiles potentially injure anatomical structures through the production of a permanent wound tract (PWT) and additional damage from the temporary cavity (Amato et al., 1971; Korać et al., 2006). The PWT is the clinical result of the crushing and cutting effect of the projectile, in conjunction with the rapid radial displacement of the temporary cavity (Puckett and Grundfest, 1946; Newton Harvey and McMillen, 1947; Black et al., 1941) (Figure 82). It comprises a central permanent cavity, together with a zone of irreversible tissue damage lateral to the cavity that heals by scarring (Wang et al., 1988; Hopkinson and Watts, 1963) (Figure 45). Such effects are dependent upon the nature of the projectile (eg yaw, deformation, fragmentation) in combination with the density and architecture of the tissues it penetrates. A comprehensive literature review demonstrating objective evidence for potential wounding mechanisms was published by the author (Breeze et al., 2014d), but is largely beyond the scope of this thesis.

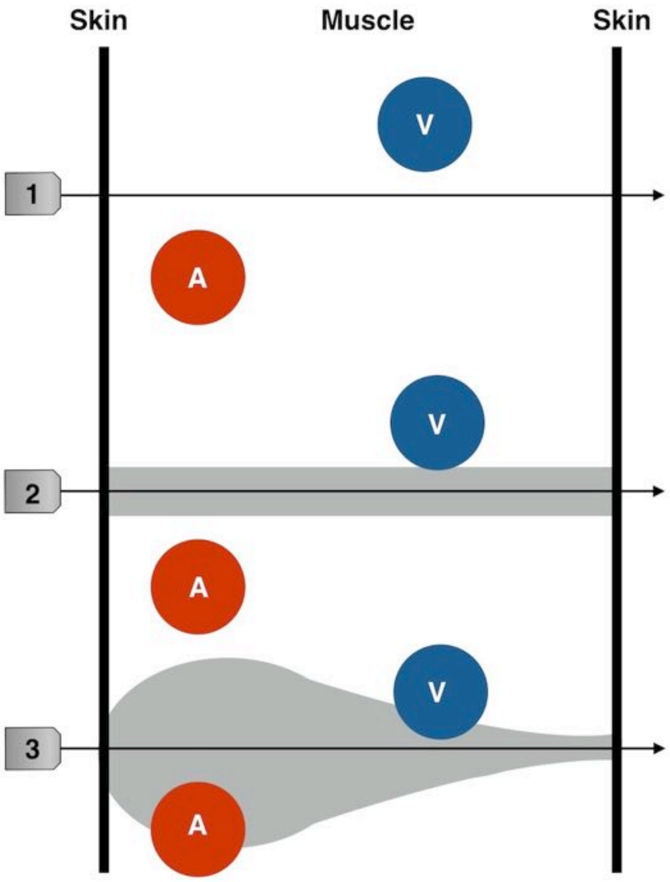


Figure 44: A projectiles passing through tissue using an infinitely thin shot line (1) would miss the artery (A) and vein (V). Damage occurs when the projectile width (2) or permanent wound tract (3) is utilised.

Accurately determining the dimensions of the PWT in tissue for a variety of projectile shapes and impact velocities is challenging. The aforementioned 'biological variation' inherent to such testing means that large numbers of animal experiments must be undertaken just to provide a small amount of statistically valid information on just a single projectile. The most promising approach identified in the systematic review was based on research undertaken in the 1970's and utilised the mass of tissue that required debridement by a surgeon following wounding (Jussila et al., 2005a). Such a method would inherently account for both projectile factors and tissue factors; however the experimental results produced equations describing the line of best fit with such poor correlation that this approach cannot be utilised with the existing limited data set alone, which would necessitate further testing. Therefore current models utilises PWT dimensions based on the permanent cavity produced in gelatin recognising that this approach will inevitably underestimate damage as gelatin has a greater tendency towards collapse than tissue and this method does not include the surrounding area of irreversible tissue damage.

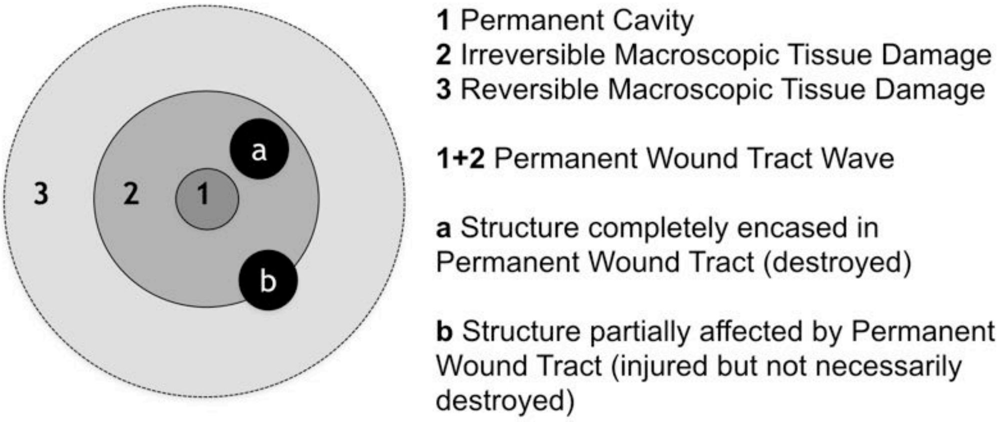


Figure 45: Diagrammatic representation of the results of these mechanisms of potential tissue damage. Clinically damage is patchy and does not form in such distinct layers.

10.10 Resultant injury prediction

Historically injury models have been based upon the concept of incapacitation, by which a soldier is unable to perform their role on the battlefield. To date no objective values for incapacitation have been agreed upon recognising that the level and location of injury is role and situation specific; for example blindness will prevent any soldier performing their role but damage to a leg may be of less importance to a military doctor working in a field hospital than an infantry soldier. In addition although the concept of incapacitation is important in comparing the relative effectiveness of different projectiles, it is less important to that of body armour, where death and morbidity are the desired variables. The use of AIS scores may potentially assist in scoring damage to individual structures but currently lacks clinical validation. The greatest difficulty will be in obtaining multidisciplinary consensus on the clinical effects of the interaction between individual anatomical structures and both permanent wound tract and temporary cavity.

10.11 Physical models (tissue simulants)

Ballistic grade gelatin remains the most commonly utilised ballistic testing medium and closely simulates both the density and viscosity of human and animal muscle tissue (Jussila, 2005; Fackler et al., 1988). Both 10% and 20% concentrations of gelatin have been stated as being comparable to pig muscle in terms of depth of penetration of bullets but insufficient evidence exists for comparisons with energised fragments. Other physical simulants such as soap or newer alternatives such as PermaGel ^{TM} are still rarely used due to difficulties in their manufacture in the former and a lack of evidence for their suitability with the latter (Table 39).

Simulant	**Advantage**	**Disadvantage**
Ballistic gelatin	Elasticity resembles muscle Translucent enabling high speed photography Cheap One use	Temporary cavity collapses so difficult to measure Shorter storage time and requires refrigeration
Ballistic soap	Temporary cavity remains after firing so can be measured Long shelf life Easy to handle Can be recycled	Opaque Requires factory production Expensive
PermaGel^{TM}	Can be recycled Easy to handle Long shelf life Transparent enabling high speed photography Cheap	Equivalence to 10% gelatin as marketed questioned Number of times can be melted and reformed without changing material properties unproven
Animal	Tissue properties likely to be close to human, especially if tested immediately post mortem Anatomical relationships of structures to one closer to humans in some body areas than others e.g. thigh (similar) versus neck (dissimilar)	Effect of time and storage post mortem on tissue properties unknown Ethical issues if live testing
Post mortem human subject	Anatomical relationships of structures to one another correct Material properties likely to be similar to live human for certain anatomical structures e.g. bones and skin	Effect of time and storage post mortem on tissue properties unknown Ethical issues Availability

Table 39: Most common physical models used in current terminal ballistics experiments comparing their individual advantages and disadvantages.

However all of these simulants are capable of representing the projectile factors produced by different types of FSP (Figure 44). The greatest advantage of translucent mediums such as gelatin is that it enables high- speed video analysis of cavitation and relate that to velocity reduction and thereby energy deposition along the projectile path (Figures 46 and 47).

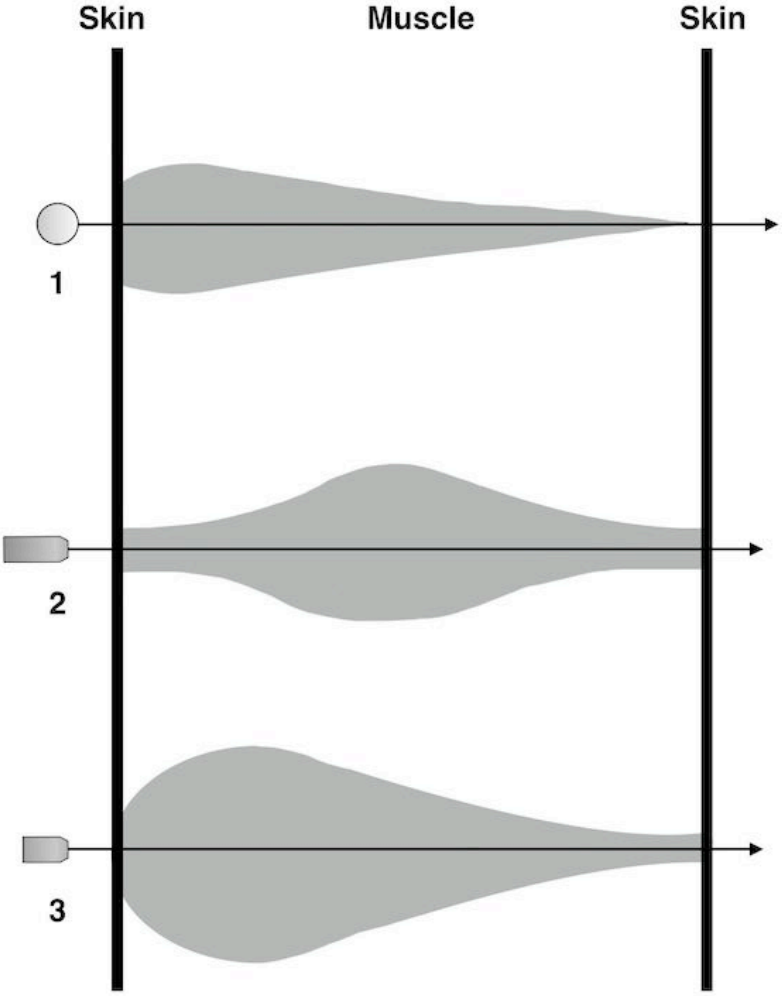


Figure 46: Stylised appearances of different shapes of temporary cavitation: (a) stainless steel spherical FSP, (b) stainless steel cylindrical FSP tumbling within tissue, (c) copper FSP deforming on impact.

Freshly slaughtered animal models may represent tissue effects more closely to that of a human but there is a lack of reproducibility in results (so called 'biological variation').

This means that large numbers of firings have to be undertaken to achieve any meaningful statistical analysis.

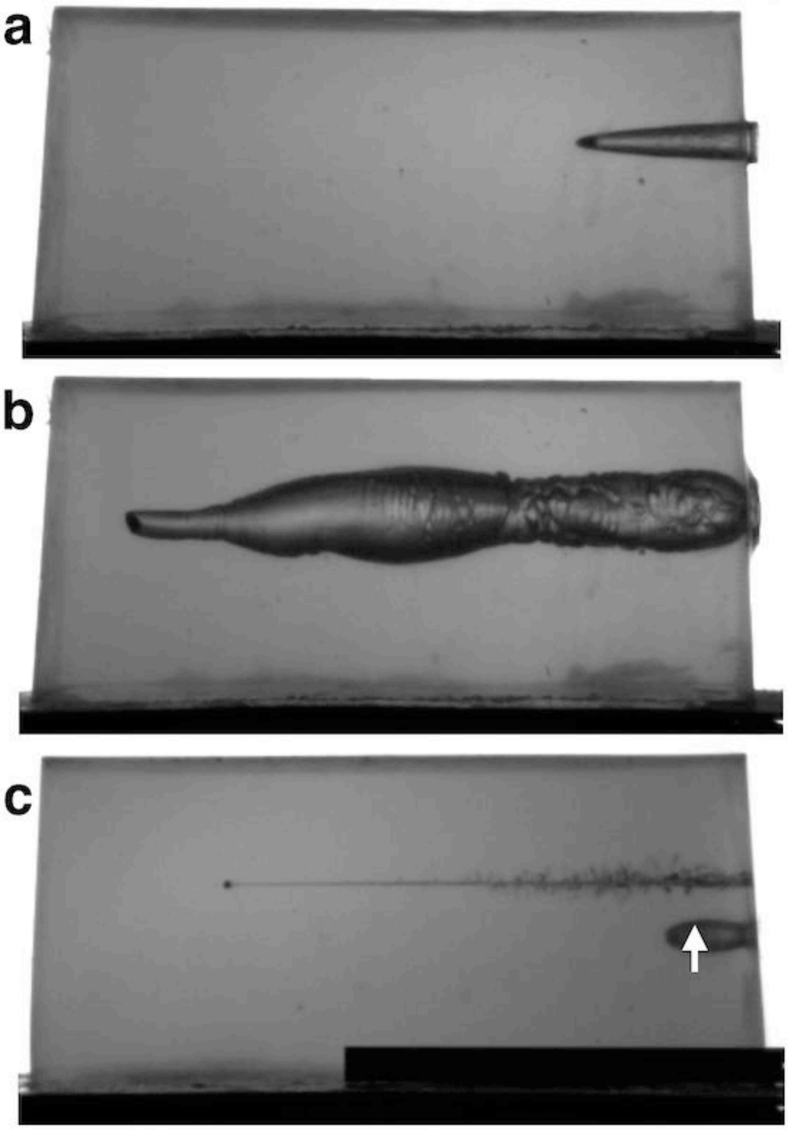


Figure 47: High- speed video stills of a 20% gelatin block being penetrated by a 5mm spherical FSP (a), demonstrating temporary cavity (b) and permanent cavity (c). Arrow marks the position of a temperature probe.

10.12 Potential numerical models for penetrating neck injury

Numerical injury models such as the historical UK model MAVKILL as well as the US model ORCA (Operational Requirement-based Casualty Assessment) represent the head/face/neck as a single homogenous unit. The acquisition of a three- dimensional mesh of human anatomy based upon the coordinates of structures generated from CT scans represents an exciting development in this respect (Figure 48). The Zygote has been scaled to a 50th percentile UK military Caucasian male using external anthropometric measurements derived from a population basis. In addition scaling of the dimensions of internal anatomical structures and distances from skin surface was undertaken by analysing CT scans of injured soldiers as described in Chapter 6. The Zygote has been used as the foundation for the two injury models that will be utilised in this thesis: the Interactive Mapping and Analysis Platform (Chapter 14) and the Coverage of Armour Tool (Chapter 15).

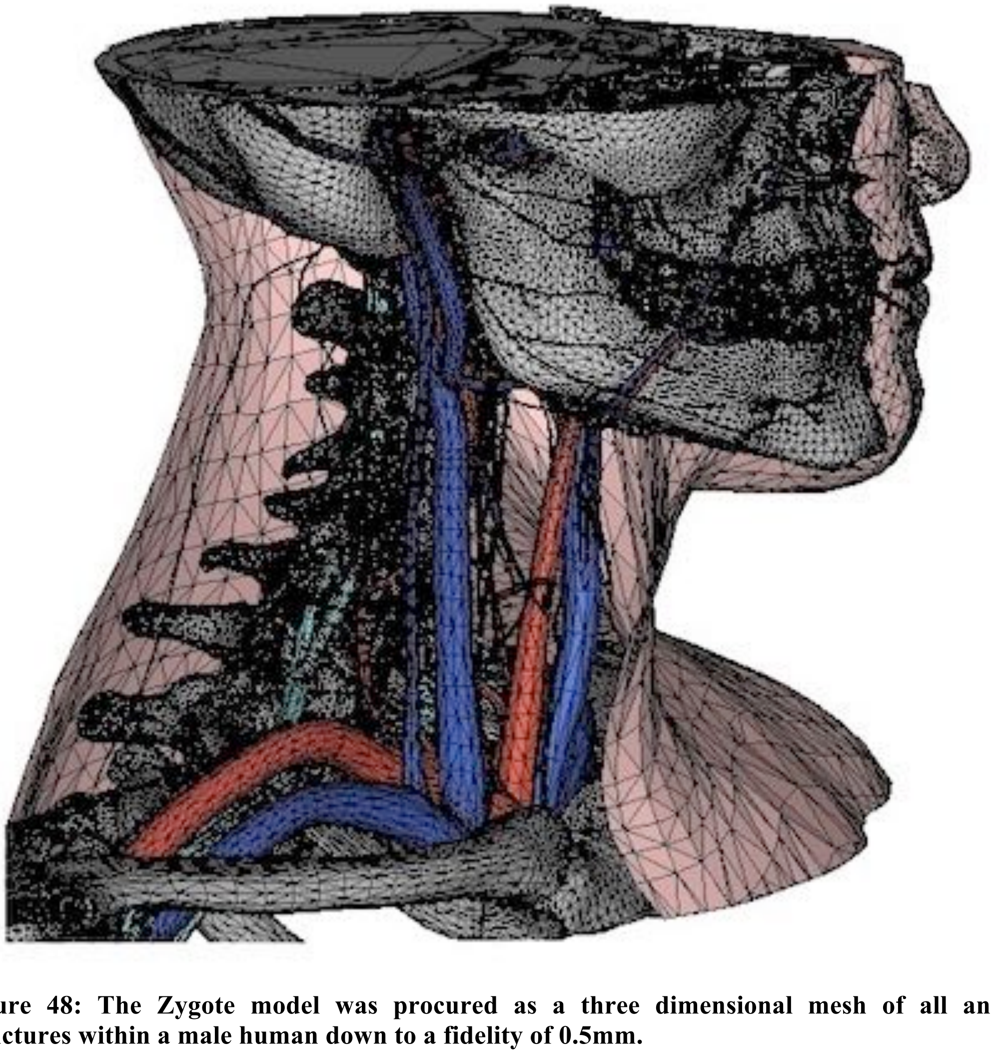


Figure 48: The Zygote model was procured as a three dimensional mesh of all anatomical structures within a male human down to a fidelity of 0.5mm.

10.13 Conclusions and recommendations

A summary is provided in Table 40 and provides the rationale for the research undertaken in subsequent chapters.

Conclusion	Recommendation
No single injury model can currently predict all of the complex interlinked variables required to compare the potential medical effectiveness of different designs of ballistic neck protection.	For the time being a combination of complementary models will provide the greatest confidence in potential injury mitigation between collars.
Finite element numerical models are likely to represent the future of human injury modelling but are still reliant for the time being on the physical models that inform their equations.	Testing of both animal models and tissue simulants should be undertaken to provide the equations necessary for underpinning the model. The suitability of PMHS in terms of material properties requires assessment.
The Zygote model has been used to produce an anatomical mesh of cervical neurovascular structures that is scaled to that of a 50th percentile male UK soldier.	This model should be used as the platform for future complementary injury models.

Table 40: Conclusions and recommendations based upon the findings from Chapter 10.

Chapter 11: Experimental determination of an equation to describe the velocity required for skin perforation by fragment simulating projectiles

Chapter summary

In the human neck, a layer of 2-4mm of skin is present which affects the retardation of smaller fragment simulating projectiles (FSPs) and therefore necessitates inclusion in any future injury model. Existing equations to describe skin perforation in the literature are limited by inconsistencies in terms of projectile used, velocity calculated or in the definition of skin perforation. 77 shots using three standardised FSPs were fired into freshly killed goat thighs and the results were added to those previous experiments identified in the literature. An equation describing the line of best fit was produced linking the velocity required for skin perforation for a range of FSP sizes, which can be used in future injury models. However valid future numerical simulations must not only match the perforation velocity but also mimic the mechanical properties of skin at high strain rates and further research is required to ascertain those values.

11.1 Aims of chapter

- To undertake a literature review to ascertain all existing results for the velocity required to perforate skin by FSPs for all types of physical models.
- To experimentally test three FSPs fired into goat skin backed by muscle and bone.
- To compare the experimental results to those found in the literature review to determine an equation for use in future numerical models.

11.2 Publications derived from this chapter

- Breeze J, Clasper JC. Determining the velocity required for skin perforation by fragment simulating projectiles: a systematic review. Journal of the Royal Army Medical Corps 2013; 159 (4): 265–270 (Breeze and Clasper, 2013a).
- Breeze J, James GR, Hepper AE. Perforation of fragment simulating projectiles into goat skin and muscle. Journal of the Royal Army Medical Corps 2013; 159 (2): 84–89 (Breeze et al., 2013c).

11.3 Collaborations

This chapter describes experimental testing of FSPs into goat skin. The trial was designed and undertaken by the author at Dstl Porton Down with the grateful assistance of Mr Greg James of Dstl.

11.4 Introduction

In the human neck, a layer of 2-4mm of skin is present (as determined in Chapter 6) which is known to affect the retardation of smaller FSPs and therefore necessitate inclusion in any future injury model. The process of a projectile breaking the skin surface is dependent on a number of variables, primarily mass, velocity, volume and the presented surface area (i.e. the area of the projectile that initially makes contact with the skin surface). Previous attempts to derive numerical equations to describe the relationships between all these variables have revolved around the testing of PMHS, animal and physical models (DiMaio, 1981). Of these potential physical models, goat skin is believed to be the most representative of human skin due to perceived similarities in biomechanical properties and thickness (Schantz, 1979; Bartell and Mustoe, 1989; Light, 1963).

Model	Advantage	Limitation
PMHS	Anatomical relationships correct	Effect of ageing and storage on material properties unknown. Testing performed to date on isolated skin. Very small data sets. Only used buckets and air rifle pellets
Animal	Material properties should be representative	Skin thickness very variable between species as well as breeds
Artificial simulant	Enables large amounts of testing to be undertaken	Limited evidence as to suitability and no internationally agreed material
Numerical	Unlimited testing can be undertaken	No internationally agreed equation to simulate FSP penetration of skin exists

Table 41: Types of physical and numerical models to represent human skin with their advantages and limitations.

Significant limitations exist with skin perforation testing to date in terms of both the models used (Table 41) and a lack of standardisation in the experimental methodology (Table 42). For example the terms 'penetration' and 'perforation' have been used interchangeably despite representing different outcomes. Experimentally the two are distinguished by examining the inner surface of the skin; if a hole is seen, or the projectile is visible, then it has perforated. This means that at the start of this thesis no agreed equation to describe the velocity required to perforate skin by an FSP existed.

Definition	Explanation
Perforation	A projectile that has passed through the whole thickness (all layers) of skin
Penetration	A projectile that has passed through less than all layers of the skin
Non perforation	A shot resulting in less than full perforation of the skin and will therefore inherently include shots classed as ‘penetration’
Threshold (V_{th}) velocity (m/s)	The lowest velocity at which perforation occurred. It dependent on a non-perforation and perforation being achieved with very similar velocities and does not account for non-perforations at higher velocities
V_{50} velocity (m/s)	The velocity at which 50% of projectiles perforate. This value is more statistically robust than the V_{th} and can be significantly higher than the V_{th}
Sectional density (*S*)	Projectile mass divided by presented area- a potential method of accounting for all projectile geometries, sizes and densities

Table 42: Explanations of definitions used in ballistic skin testing experiments.

11.5 Literature review to ascertain existing values for skin perforation by different projectiles

A systematic review of the open literature was undertaken using the PRISMA methodology (Moher et al., 2009), to identify all open source information quantifying the velocity required to perforate PMHS or animal skin by metallic projectiles. Database and internet searches were undertaken using the following keywords; skin, fragment simulating projectile, penetration, perforation and velocity. The references of any sources were requested to ensure no further studies were missed. Information pertaining to bullets was excluded, as was that for non-metallic projectiles. Projectile sectional density (mass over presented cross-sectional area) was plotted against the velocity required for skin perforation or penetration for all projectiles and an empirical equation describing the line of best fit was produced for all results.

Authors and date	Skin description	Storage	Projectile (mass and diameter in brackets if stated)	Velocity
(Krauss and McDonald, 1960)	Complete goat thigh	Not stated	Steel spheres (18g)	V_{th}
(Kokinakis and Sperrazza, 1965)	Isolated goat thigh skin (0.3mm)	Not stated	Steel spheres (0.06g) and cubes (0.26g, 1.0g, 4.1g)	Not stated
(Sperrazza and Kokinakis, 1968)	Isolated goat thigh skin (0.3mm)	Not stated	Steel spheres (1.0g, 2.0g and 10.0g), cubes + cylinders (dimensions and masses not stated)	V_{50}
(Lewis et al., 1978)	Isolated goat thigh skin over gelatin	Not stated	Steel spheres (0.06 g) + cubes (0.26g, 1.0g, 4.1g)	V_{50}
(MacPherson, 2005)	Isolated pig skin over gelatin	Not stated	Steel spheres (0.26g)	V_{th}
(Haag, 2010)	Pig abdominal skin over gelatin (0.9-1.6mm)	Fresh	Steel spheres (0.26g)	V_{th}

Table 43: Animal skin studies identified describing the velocity required to perforate skin by a fragment simulating projectile; g = grams, V_{th} = threshold velocity.

Authors and date	Skin description	Storage	Projectile (mass and/or diameter in brackets if stated)	Velocity
(Journee, 1907)	Complete limb	Fresh body	Lead spheres (8.50g)	V_{th}
(Grundfest et al., 1945)	Isolated abdominal skin	Fresh	Steel and lead spheres (0.42g)	V_{th}
(Sperrazza and Kokinakis, 1968)	Isolated thigh (0.3mm thick)	Not stated	Steel spheres (1.0g, 2.0g, 10.0g). Steel cubes + cylinders (dimensions not stated)	V_{50}
(Mattoo et al., 1974)	Complete thigh	"Relatively fresh"	Lead spheres (4.5g)	V_{th}
(Tausch et al., 1978)	Isolated skin (location not stated)	Not stated	Lead spheres (5.30g)	V_{th}
(Tausch et al., 1978)	Complete thigh	Fresh	Lead spheres (0.47g, 5.30g, 6.20g, 9.0g, 10.6g)	V_{th}
(DiMaio et al., 1982)	Complete thigh	Not stated	Steel air gun pellets (0.53g and 4.4mm, 1.07g and 5.46mm, 7.32g and 9.12mm)	V_{th}
(Missliwetz, 1987)	Complete thigh	"Fresh refrigerated"	Steel air gun pellets (0.54g, 4.5mm, 0.49g, 4.5mm). Brass spheres (0.3g, 4mm). Steel spheres (5.30g, 4mm)	V_{th}
(Rathman, 1987)	Isolated skin	Not stated	Steel spheres (0.26g), steel air gun pellets (1.07g and 5.46mm)	V_{th}
(Haag and Haag, 1987)	Isolated skin (location not stated)	Refrigerated	Steel spheres (0.26 g), brass spheres (0.31g), lead spheres (0.54g)	V_{th}

Table 44: PMHS skin studies identified describing the velocity required to perforate skin by a fragment simulating projectile; g = grams, V_{th} = threshold velocity.

16 studies were identified that gave results for skin penetration or perforation for either PMHS or animal skin (Tables 43 and 44). Very little consistency in methodology was found in terms of projectile used, velocity calculated or whether V_{th} or V_{50} velocities were calculated. Five authors described an empirical relationship describing the threshold velocity for either skin penetration or perforation (Lewis et al., 1978; Sperrazza and Kokinakis, 1968; Sellier and Kneubuehl, 1994; Mattoo et al., 1974; Tausch et al., 1978), again using a mixture of penetration and perforation as well as V_{th} and V_{50} velocities.

11.6 Experimental perforation of goat skin by three types of FSP

Three sizes of NATO STANAG 2920 steel chisel-nosed cylindrical FSPs (0.16, 0.49 and 1.10 g) were utilised (NATO Standardisation Agreement, 2003). The 0.49g and was chosen as it was the most representative of the FSPs retained in the neck (Chapter 5) and was similar to experiments using a 0.54 g cylinder (Jussila et al., 2005b) and 0.44 g cylinder (Light, 1963). A 1.10g FSP was chosen as this remains the industry standard for physical models and body armour protective material testing (Bellamy and Malinowski, 1988; Iremonger and Went, 1996). Finally the lightest FSP was chosen (0.16g) to test the potential importance of skin in the retardation of small projectiles. This FSP was the closest NATO standardised size to a previous experimeznt using a 0.2g cylinder (Bowyer, 1996) and is believed to be representative of the most common size of preformed fragmenting munitions (Hill et al., 2001; Ryan et al., 1991).

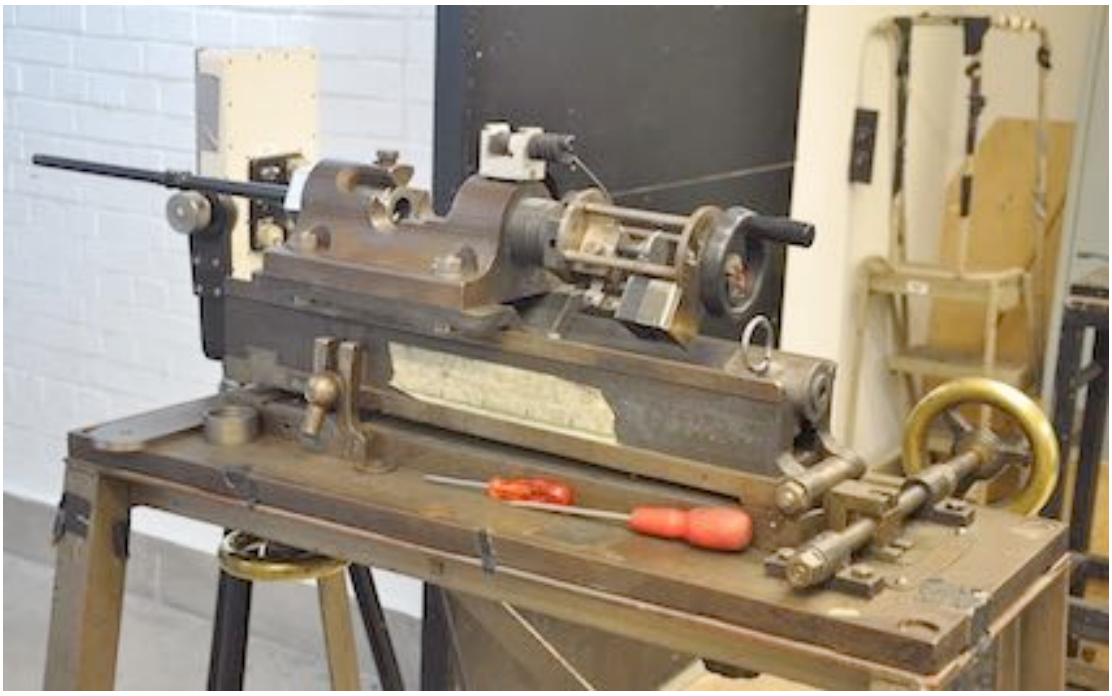


Figure 49: No. 3 proof housing fitted with a 7.62m rifled barrel used to fire fragment simulating projectiles.

The goat used was a 4-year-old Saanen breed (Capra Hircus) weighing approximately 60 kg. The animal was killed humanely using a Schedule 1 method and had its hind legs clipped to remove any hair. Ballistic testing started within 30 minutes of the animal being killed. Each leg was elevated in turn using rope until the leg was taut and shots aimed at the thigh. The animal was placed in front of a firing rig, with a 5 m distance between the end of the barrel and the target. FSPs were fired from a Pressure Housing weapon system, with a separate smooth bore barrel for each different diameter projectile (Figure 49). The projectiles were propelled using rechargeable 37 mm compressed air cartridges, using pressures of 3–20 MPa. Velocity was measured using optical equipment with a 1-metre separation between the velocity heads.

The Critical Perforation Analysis tool is a graphical user interface based on the statistical software package ‘R’ (R Foundation for Statistical Computing, Version 1, 2010, Vienna, Austria). This software calculates a V_{50} velocity with a 95% confidence interval. Perforation was determined as an FSP that traversed through the complete thickness of skin, but did not cause underlying muscle damage. Non-perforation was classed as anything less than full perforation of the skin such as the FSP bouncing off skin or penetrating a partial thickness of skin without breaking the posterior surface of the skin. Although statistically weaker, the V_{th} (the minimum velocity in which perforation occurred) was also calculated to allow comparison with any papers identified from the literature review that only provided this measurement and not V_{50}.

Shots were fired at the lateral thigh surface of all four limbs and filmed using high-speed video to ascertain if tumbling of the FSP occurred prior to impact. Due to the front legs being smaller than the rear, less shots were fired into the former (approximately 7-10 shots in each leg) than the latter (approximately 10-15 shots in each leg). A laser- targeting device attached to the rifle barrel enabled accurate shot placement to within approximately 5 mm, aiming for a minimum distance of 20 mm between skin impact locations at velocities unlikely to perforate skin in an attempt to maximise the number of shots but limit damage to adjacent skin. For those shots at higher velocities, a minimum of 40 mm between entry wounds was attempted to prevent overlapping of the wound tracts. All shots were fired at the posterior aspect of the leg and skin depth (surface of skin to surface of muscle) was measured with callipers at four points on each leg (superior, inferior, medial and lateral).

11.7 Determination of V_{50} and threshold velocities for goat skin compared to 20% gelatin

Skin thickness was found to be between 3.0 and 3.5 mm (mean 3.2). A total of 77 shots were fired using three sizes of FSPs. Values for V_{50} and V_{th} are demonstrated in Table 45. The velocity values for the same FSPs fired into 20% gelatin are included to represent the effects of having muscle with no skin. The methodology for the shots into 20% gelatin and pig tissue are described in the next chapter (Chapter 12) and V_{th} was determined by using the intersection of the line of best fit for the data points with the x axis if no value for non perforation was available. There was a significant difference ($p>0.05$) in the V_{th} velocity required to perforation goat skin compared to 20% gelatin for the 0.16g FSP only.

FSP mass (g)	**FSP presented area (cm^2)**	**FSP sectional density (g/cm^2)**	**V_{50} (m/s) + 95% CI goat skin**	**V_{th} (m/s) goat skin**	**V_{th} (m/s) pig skin**	**V_{th} (m/s) 20% gelatin**
0.16	0.057	2.79	121.1 (7.6)	101.7	209.5	84.2
0.49	0.126	3.89	103.7 (21.1)	66.0		64.9
1.10	0.229	4.80	97.8 (10.8)	76.0	125.3	88.4

Table 45: Skin perforation velocities in relation to dimensions and masses of FSPs. *S*= Sectional density, CI= Confidence interval.

11.8 Derivation of an equation describing the velocity required to perforate skin

Prior to this thesis, five papers had described an empirical equation describing the range of velocities required to perforate skin by different fragment simulating projectiles into animal and PMHS (Figure 49). These previous equations all used results based on the 16 studies (described in Tables 42+43), although each only included some and not all 16.

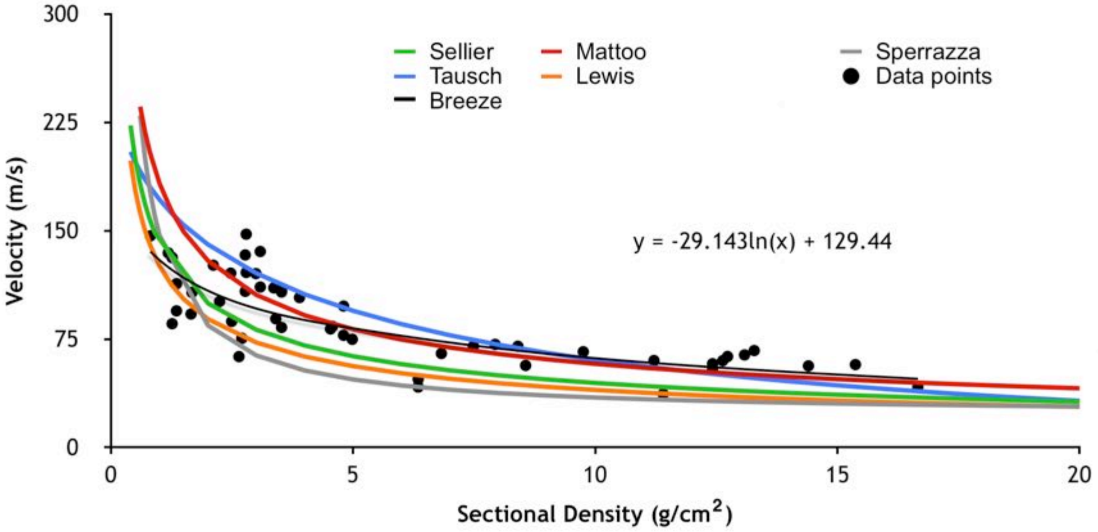


Figure 50: The data points from all 16 studies (including the three derived from this chapter have been re-plotted (a mixture of V_{th} and V_{50} data). Included are the 5 previous lines of best fit generated by proposed empirical equations; the new line entitled 'Breeze' is the first to include all of the data points.

No statistical difference was found between animal and PMHS skin. There were insufficient numbers of results for statistical analysis to be undertaken to compare types of animal skin to one another individually or to PMHS skin, but skin retardation by goat skin was generally less than found in comparable pig testing. There was also no statistical difference between the gradient of the lines of best fit between skin perforation by spheres and cylinders of equal sectional density. The original data points from all 16 studies plus those three data points generated by the experiments in this chapter were combined together. This produced a new empirical relationship derived from the line of best fit is generated (entitled 'Breeze' in Figure 50). The empirical equation to describe this line of best fit is demonstrated below (where V= threshold velocity, S= sectional density, ln= natural logarithm) and will be used to describe skin perforation by FSPs in future injury models.

$$\mathbf{V= -29.143 \ln(\mathit{S}) + 129.44}$$

11.9 Conclusions and recommendations

A summary is provided in Table 46 and provides the rationale for the research undertaken in subsequent chapters.

Conclusion	Recommendation
Significant heterogeneity was found in terms of previous methodology of skin testing with no conformity in terms of projectile used or measurement parameters.	Future testing of ballistic skin models should use NATO standardised FSPs, measuring the V_{50} velocity (not threshold velocity) for skin perforation (not penetration)
An equation describing the relationship between impact velocity required for skin perforation has been determined for a range of fragment simulating projectiles.	This equation should be utilised in future physical and numerical models of skin perforation.
Valid future numerical simulations must not only match the velocity for penetration but also mimic the mechanical skin properties, most importantly measured as tensile strength, strain and elasticity.	A systematic review should be undertaken to determine whether these values at high strain rates have been described in the literature and if not future experimental research should be undertaken to determine them.
Goat skin significantly increased the threshold velocity required for perforation compared to 20% gelatin for the 0.16g FSP.	Inclusion of a skin layer into future penetration models is required should this FSP necessitate further evaluation.

Table 46: Conclusions and recommendations based upon the findings from Chapter 11.

Chapter 12: Experimental determination of equations describing the velocity required for penetration of animal muscle and 20% gelatin by fragment simulating projectiles

Chapter summary

Muscle is the largest anatomical component of the neck, and therefore accurately representing its physical properties in terms of projectile retardation is essential to the accuracy of any future penetration injury model. Four sizes of FSP were fired into intact goat and pig thighs and necks at a range of velocities and compared to 20% gelatin. No significant difference was found between pig or goat muscle compared to 20% gelatin for the larger three FSPs. Equations describing depth of penetration produced at a range of velocities into these simulants were derived and are recommended for representing muscle in future injury models.

12.1 Aims of this chapter

- To undertake a literature review to determine any previous testing results of depth of penetration produced by firing of FSPs into animal models.
- To experimentally determine the depth of penetration produced by firing four FSPs into goat and pig muscle at a range of velocities.
- To experimentally determine the depth of penetration produced by firing four FSPs into 20% gelatin at a range of velocities.
- To compare the experimental results to those found in the literature review to determine an equation for use in future numerical models.
- To utilise those equations in conjunction with masses and depths of penetration of fragments retained within the necks of injured UK soldiers to estimate a range of probable impact velocities.

12.2 Publications derived from this chapter

- Breeze J, Hunt N, Gibb I, James G, Hepper A, Clasper J. Experimental penetration of fragment simulating projectiles into porcine tissues compared with simulants. Journal of Forensic and Legal Medicine 2013; 20 (4): 296–299 (Breeze et al., 2013b).
- Breeze J, James GR, Hepper AE. Perforation of fragment simulating projectiles into goat skin and muscle. Journal of the Royal Army Medical Corps 2013; 159 (2): 84–89 (Breeze et al., 2013c).

12.3 Collaborations

This chapter describes the experimental methodology and results of two trials, both undertaken at Dstl Porton Down. The author planned the trials, undertook the specimen dissection in conjunction with a consultant pathologist (Dr Nicholas Hunt) and assisted in the CT analysis with a consultant radiologist (Lieutenant Colonel Iain Gibb). The members of Dstl who kindly assisted in the undertaking of this trial are acknowledged as co-authors in the publications derived from this chapter.

12.4 Introduction

Muscle is the largest anatomical component of the neck, and therefore accurately representing its physical properties in terms of projectile retardation is essential to the accuracy of any future penetration injury model. Experiments to determine the retardation of bullets into pig muscle in the 1970s (Janzon and Seeman, 1988; Sellier and Kneubuehl, 1994; Berlin et al., 1977; Albreht et al., 1979) were demonstrated many years later by Jussila (Jussila, 2005) to be comparable to 10% gelatin. However the relationship between animal muscle and gelatin is less clear for energised fragments. A number of authors have compared the wounding effects of different shaped fragments on animal muscle (Wang et al., 1988; Liu et al., 1988; Feng et al., 1988; Ma et al., 1988), but only one paper has measured DoP for a fragment and compared that to gelatin (20% gelatin versus a 0.20g cylinder) (Bowyer, 1996). Although spheres produce greater reproducibility in results due to their regular shape, cylinders were shown in Chapter 4 to be the most common shape found in explosive events causing neck injury. Testing of a range of cylindrical FSPs is therefore necessary to inform any future injury model of penetration. The choice of animal muscle surrogate for this type of ballistic testing has historically included pigs, goats and dogs. Although dogs have been used by Chinese authors (Cheng et al., 1988; Liu et al., 1988; Ma et al., 1988; Feng et al., 1988), there are ethical issues in the Western world with using this type of surrogate. Goat thighs have been the most common medium for testing skin penetration to date due to the similarity of their skin to human in terms of thickness (mean 3-4mm) and layers. However goat thighs are less than 60mm in diameter in comparison to the mean male UK soldier's neck of 131mm (as derived in Chapter 6). Pig thighs have a greater diameter and higher proportion of muscle than comparable goat tissue, but are potentially hampered by thicker skin, which affects the perforation of smaller FSPs (Chapter 11). Testing with a combination of both goat and pig tissue could therefore overcome the limitations with using just one animal model alone.

Deriving probable impact velocities of fragmenting munitions is essential for both the testing of body armour materials as well as defining the parameters of injury models. The velocities of energised fragments are rarely published and most values are derived from either munitions manufacturer specifications, or from arena range trials in which the fragments from detonated munitions are collected. Care must be taken in equating exit velocities produced by the explosive event and the impact velocity of the fragment hitting the target. Even the most aerodynamic fragments such as spheres loose velocity rapidly, meaning that the impact velocity is highly dependent upon the proximity of the subject to the explosive device at the time of detonation. The initial (exit) velocity of fragments produced by a device has been stated as being virtually independent of the fragment mass (Kneubuehl et al., 2011). Instead exit velocity primarily relates to the charge size (Gurney, 1943), although it should be remembered that fragments of different masses loose velocity at different rates. Initial velocities may be very high (>1500 m/s) but because of irregular shape, velocities decline rapidly (Ryan et al., 1991).

Evidence of velocities produced by improvised explosive devices have rarely been openly published. However recent experimental evidence recreating the explosions produced by improvised explosive devices such as pipe bombs produced fragment velocities of 332 - 567 m/s, although some smaller devices produced velocities of as low as 51-191 m/s (Cummins and Goodpaster, 2014a; 2014b). Analysis of retained fragments identified on CT scans of soldiers injured in the neck undertaken in chapter 4 provided values for both their mass and depth of penetration into skin and muscle. By utilising equations relating such values derived from experimental firings at fixed velocities, it could potentially be possible to estimate the impact velocity of those retained fragments. Such an approach has recently been attempted for inert mediums such as fibre board (Jordan and Naito, 2010) but has never been undertaken on animal or human tissues.

12.5 Literature review

A systematic review of the open literature was undertaken using the PRISMA methodology (Moher et al., 2009), to identify all open source information quantifying the velocity required to perforate PMHS or animal skin by metallic projectiles. Database and internet searches were undertaken using the following keywords; skin, fragment simulating projectile, penetration, perforation and velocity. Information pertaining to bullets was excluded as was that for non-metallic projectiles.

Lead author and year of publication	Surrogate	Projectile	Comments
(Hall and Bamford, 1937)	Goat skin and muscle	0.14g metal fragments (shape not stated)	DoP through skin and muscle was 52 and 55 mm at 610 m/s. Composition of metal not stated. No equation provided.
(Light, 1963)	Goat skin and muscle (body area not stated)	Steel spheres of masses 0.44 g, 1.04 g, 3.59 g and 5.49 g	0.49 g sphere penetrated 190-400mm muscle at 488-1024 m/s. 1.04g sphere penetrated 180-600mm muscle at 524-1005m/s. No equation provided.
(Mendelson and Glover, 1967)	Gelatin (concentration not stated)	2.6g steel spheres	Very poor correlation between DoP and impact velocity noted. No equation provided.
(Charters and Charters, 1976)	Post mortem human subject	3.1mm steel spheres	Only 6 shots. Multiple projectiles fragmented so DoP not true representation.
(Rybeck and Janzon, 1976)	Dog skin and muscle (thigh)	6mm steel spheres	Only DoP for three shots described. No equation provided.
(Tausch et al., 1978)	Post mortem human subject (thigh)	5.3g lead spheres	Limited range of DoP against velocity described. Effect of projectile deformation unknown.
(Bellamy and Malinowski, 1988)	Pig skin and muscle (thigh)	6mm steel sphere	DoP for 5 shots provided. No fragmentation.
(Bowyer, 1996)	Pig skin and muscle (thigh) compared to 20% gelatin	0.2g steel cylinder	No statistical difference in DoP against velocity for this particular FSP.

Table 47: Previous published ballistic testing using fragment simulating projectiles into physical models (g = grams, DoP = Depth of Penetration).

In total 8 papers were identified that provided values for depth of penetration produced by FSPs into different physical models (Table 47). Only a single paper directly compared penetration of an FSP into animal tissue compared to gelatin (Bowyer, 1996), and only did so for a single size of standardised FSP (a 0.20g steel cylinder). Insufficient evidence was found to produce an equation predicting depths of penetration at varying velocities for any size or shape of FSP, necessitating further original experimental testing as described below.

12.6 Experimental firing of fragment simulating projectiles into goat muscle

The methodology utilised in this section was identical to that used for skin testing in Chapter 10, with 0.16g, 0.49g and 1.10g FSPs fired at a range of velocities into goat thighs. This experiment was undertaken in November 2010. DoP for each FSP perforating into muscle was determined using a metal rod with graduated measurements- depths were confirmed by taking plain radiographs to ensure that the rod was touching the FSP; should it be incorrect, the rod length could be adjusted. These radiographs often demonstrated fragments lying directly beneath the contralateral skin surface (Figure 51). This reflected the ability of skin to retard projectiles greater than muscle and demonstrated an identical appearance to that of radiographs taken at post mortems of humans wounded by ballistic projectiles (Warlow, 2004).

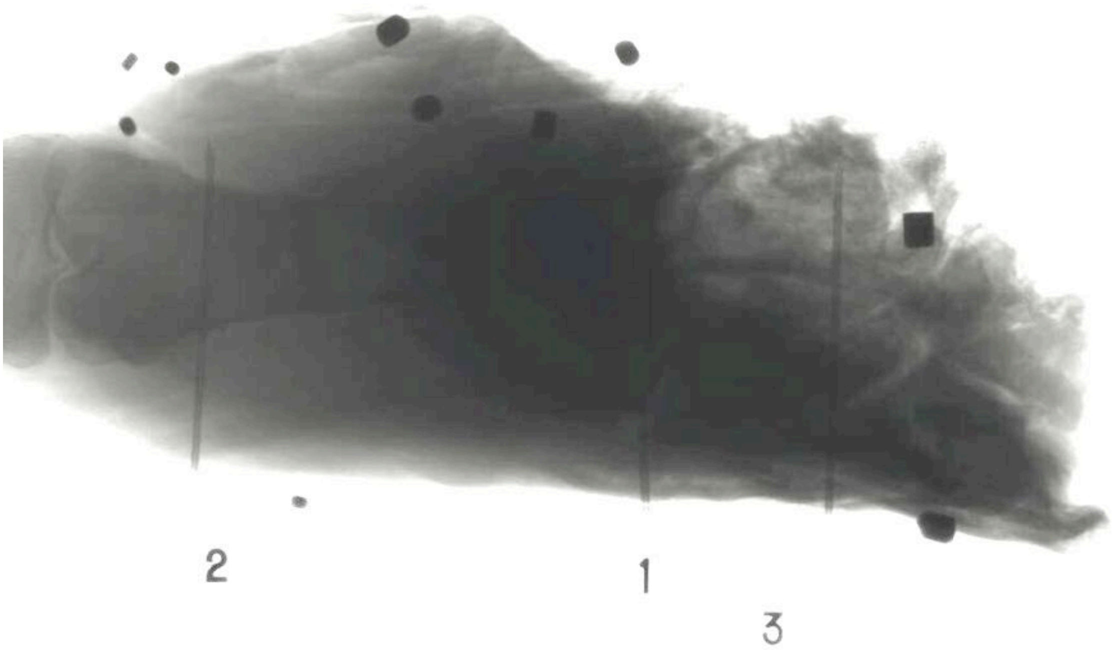


Figure 51: A plain radiograph of metal markers inserted into wound tracks; note FSPs lodged under contralateral skin surface.

12.7 Experimental firing of fragment simulating projectiles into pig muscle

0.16g, 1.10g and 2.84g cylindrical FSPs derived from STANAG 2920 (NATO Standardisation Agreement, 2003) were fired at a range of velocities (112-1652 m/s) into the thighs and necks of six pigs weighing between 45- 55 kg. The whole animal cadavers were placed on their back on a trolley in front of the firing rig using a stand and clamp to raise the limbs for leg shots. A pressurised cartridge system was used to fire the FSPs through a smooth bore barrel at low velocities and a 7.62mm rifled barrel and pyrotechnic propellant was used to fire the FSPs at higher velocities with a sabot to allow firing of the 1.10g and 0.16g fragments (Figure 48). Velocity was measured using optical equipment with a one-metre separation between the sensor heads. Firing commenced within 30 minutes post mortem. Subjects were imaged with a Philips Brilliance 16 slice CT scanner within 15 minutes of completion of firing and a consultant radiologist measured Depth of Penetration (DoP). The CT scanner was incorporated into a mobile trailer, which was parked adjacent to the range at Dstl Porton Down. The quality of the CT scans provided surface shaded rendering of the skin enabling accurate assessment of projectile entry locations (Figure 52).

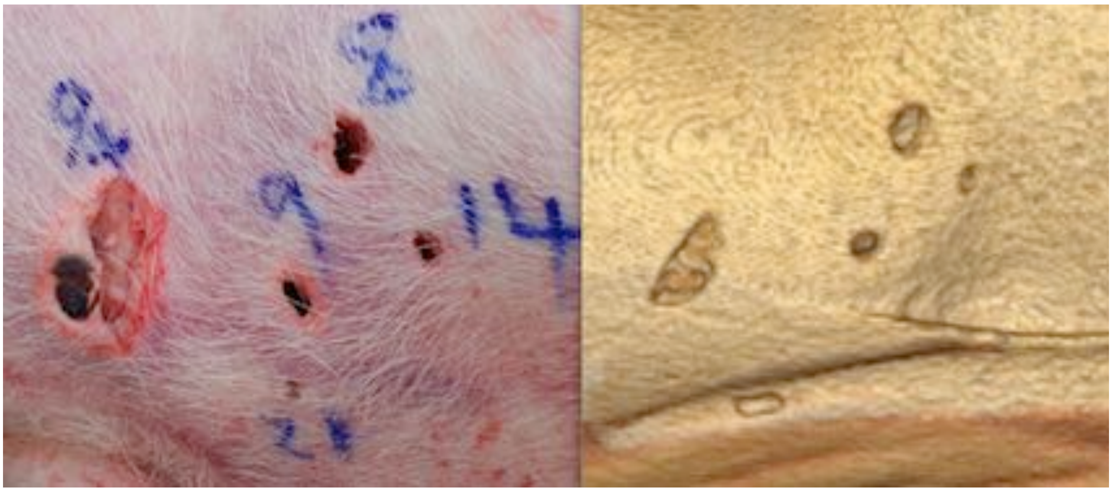


Figure 52: Surface shaded rendering of the skin enabled accurate assessment of projectile entry locations between that seen clinically (left) and radiologically (right).

In addition DoP was ascertained clinically by dissection along the wound tract from the front (presenting) face of the projectile to the skin surface (or point where skin would have been) along the wound track (Figure 53). DoP was determined using the value obtained from clinical dissection when the retained FSP could be found and a clear wound track to skin surface measured. For the remaining FSPs the DoP value used was that derived from CT. The DoP for all retained FSPs that hit bone at any point along the wound track or any FSP found immediately beneath the contralateral skin surface was discounted. When a Permanent Wound Cavity (PWC) was visible radiologically (seen as a discrete area of gas within tissue caught in the path of the projectile), its maximum diameter was measured perpendicular to the wound tract direction.

Figure 53: Coronal reformatted CT viewed using a bone window. Depth of Penetration is determined as the distance between points a and b. The measurement indicates the width of the Permanent Wound Cavity at this point.

12.8 Experimental firing of fragment simulating projectiles into 20% gelatin

Four sizes of cylindrical FSP (20 of each of the following 0.16g, 0.49g, 1.10g and 2.84g) were fired into 20% gelatin. Type A ballistic grade (250 bloom, 20% by mass) dry gelatin powder was mixed with distilled water at 70°C±5°C. The water was stirred while the gelatin flakes were added slowly. When all gelatin had been added, it was stirred for an additional 5 min. It was then covered and allowed to stand for 5 min. After this, it was stirred once more for 5 min, and then allowed to stand for a further 45 min. Excess foam that had formed on the surface of the gelatin was scraped off and the liquid gelatin decanted into molds. Following cooling to 20°C, the gelatin block was removed from the mold (dimensions 45 cm× 20 cm× 20 cm) and stored at a temperature of 10° +/- 2°C for 8-12 hours. DoP was measured using a 2 mm diameter metal rod and a ruler (Figure 54).

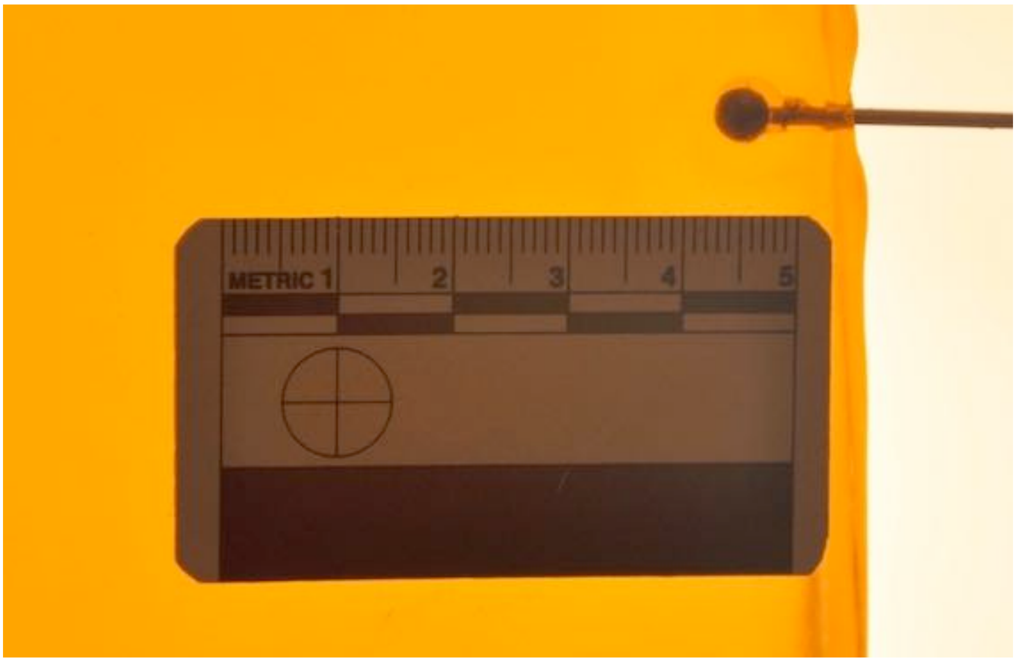


Figure 54: Measurement of fragment simulating projectile penetration into 20% gelatin. The diameter of the sphere is added onto the depth measurement.

12.9 Statistical analysis

Regression analysis was undertaken to determine the line of best fit for velocity versus DoP. The gradient of the line of best fit for each sized FSP into each simulant was compared with that of 20% gelatin using a Student t test with a significance of <0.05.

12.10 Cumulative results for pig, goat and gelatin testing

Results for DoP versus velocity for the four FSPs fired into pig and goat tissues compared to 20% gelatin can be seen in Figures 55-58. The point at which each line intersects the x- axis is the threshold velocity. Statistical significance between gelatin and animal tissue for the gradient of the line of best fit is demonstrated in Table 47. The greatest correlation between data points for all simulants (as demonstrated by R^2 values) was produced using natural logarithmic regression equations describing velocity versus DoP (Table 48). There was a significant difference ($p<0.05$) between the gradients and intercepts of the lines of best fit for both pig and goat compared to gelatin for the 0.16g, reflecting the importance of skin in the retardation of smaller fragments, particularly at low velocities. A visible PWC was only produced by the 2.84 g FSP. The maximum permanent cavity diameter varied between 6-14 mm at impact velocities of 451-1312 m/s.

Simulant	Variable	0.16g cylinder	0.49g cylinder	1.10g cylinder	2.84g cylinder
Pig	Was gradient of line of best fit significantly different from 20% gelatin	Yes		No	No
	R^2 value	0.71		0.87	0.85
Goat	Was gradient of line of best fit significantly different from 20% gelatin	Yes	No	No	
	R^2 value	0.87	0.62	0.73	
20% gelatin	R^2 value	0.70	0.95	0.96	0.98

Table 48: Significance of results of animal tissue penetration compared to 20% gelatin. Any grey boxes mean that simulant was not tested with that projectile.

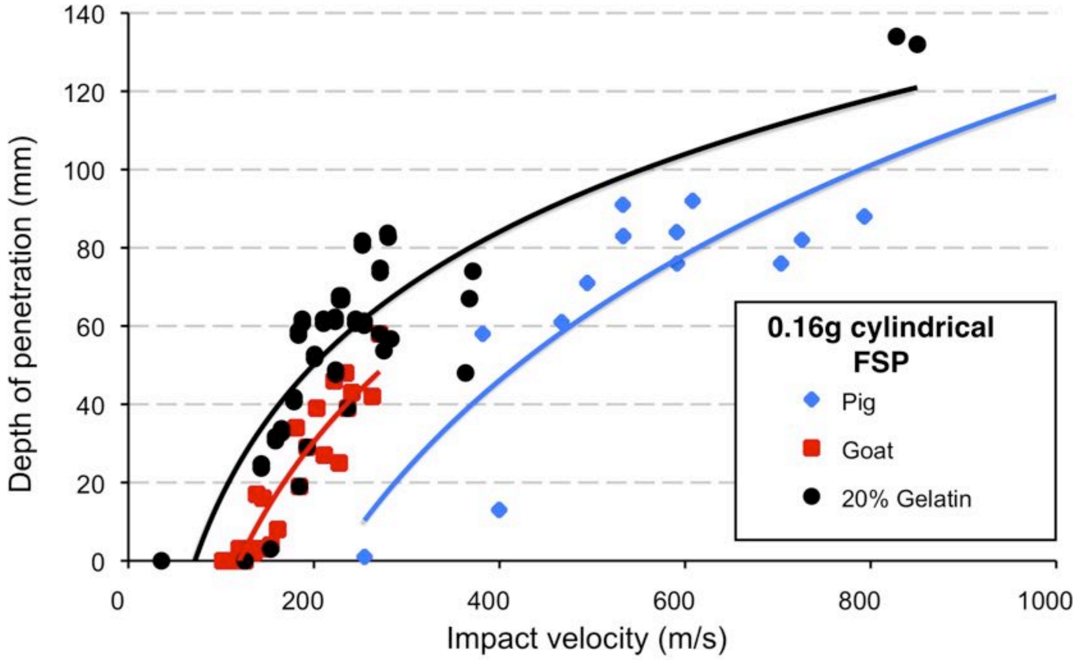


Figure 55: Depth of Penetration versus impact velocity for 0.16g FSP fired into fresh pig and goat tissue compared to 20% gelatin. Logarithmic trendlines are displayed for the data points.

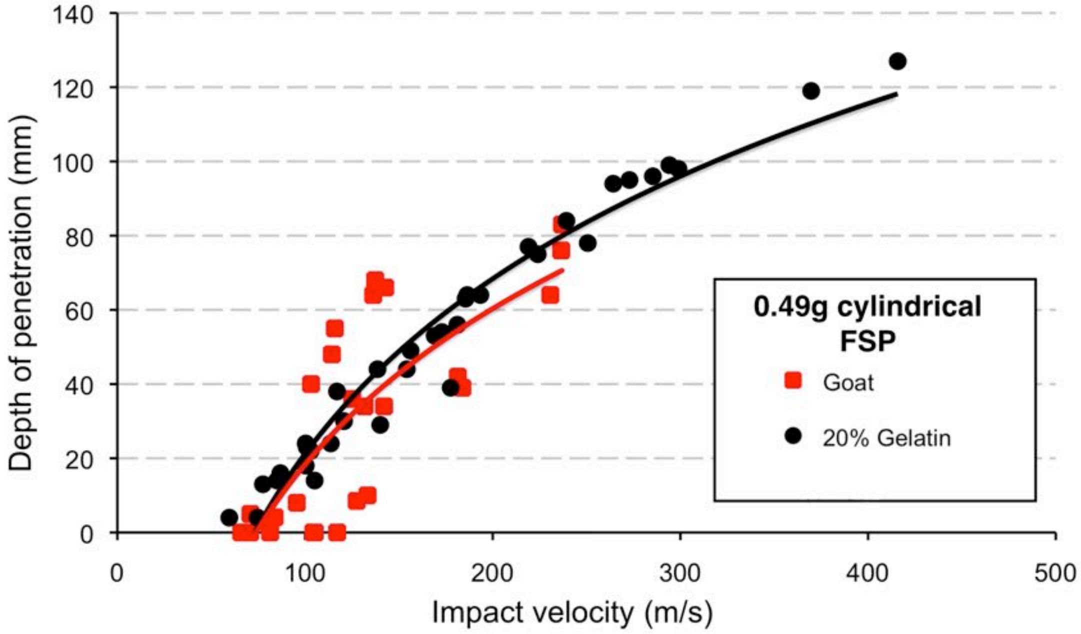


Figure 56: Depth of Penetration versus impact velocity for 0.49g FSP fired into fresh goat tissue compared to 20% gelatin. Logarithmic trendlines are displayed for the data points.

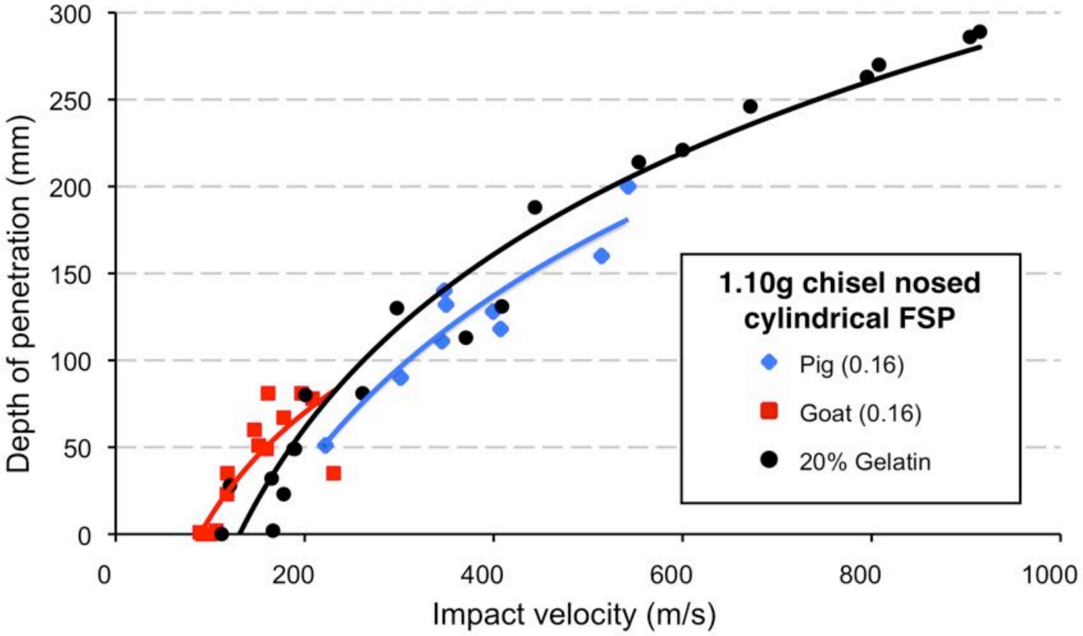


Figure 57: Depth of Penetration versus impact velocity for 1.10g FSP fired into fresh pig and goat tissue compared to 20% gelatin. Logarithmic trendlines are displayed for the data points.

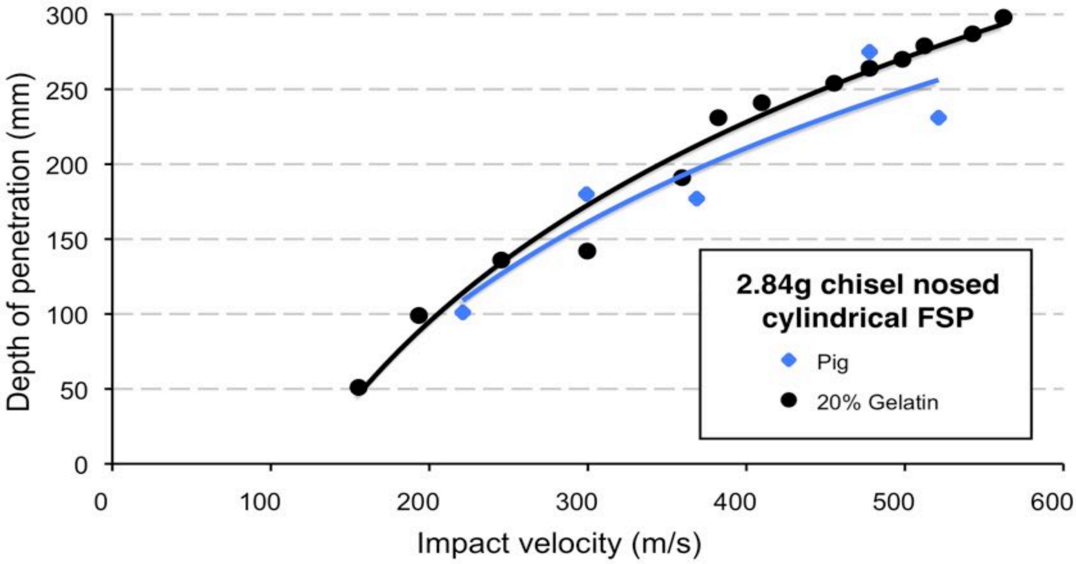


Figure 58: Depth of Penetration versus impact velocity for 2.84g FSP fired into fresh pig and goat tissue compared to 20% gelatin. Logarithmic trendlines are displayed for the data points.

12.13 Derivation of equations describing depth of penetration into muscle for a range of velocities

Equations were derived relating DoP for each FSP to velocity for goat muscle, pig muscle and 20% gelatin (Table 49). Good correlation was demonstrated between the line of best fit produced by the 0.16g FSP fired into pig muscle and results derived from the literature (Bowyer, 1996). Skin produced a significant retardation effect on projectiles, especially for the 0.16g FSP and therefore care must be taken in interpreting data using the equation derived from pig and goat tissue for this projectile; the curve for the 0.16g FSP into 20% gelatin would be recommended instead.

FSP Mass (g)	Pig tissue derived equation	Goat tissue derived equation	20% gelatin derived equation
0.16	DoP = (79.23 x ln Vel) - 428.57)	DoP = (59.17 x ln Vel) - 283.03)	DoP = (48.93 x ln Vel) - 209.09)
0.49		DoP = (60.63 x ln Vel) - 260.89)	DoP = (68.10 x ln Vel) - 292.44)
1.10	DoP = (144.39 x ln Vel) - 727.99)	DoP = (86.92 x ln Vel) - 390.55)	DoP = (144.21 x ln Vel) - 703.14)
2.84	DoP = (171.88 x ln Vel) - 819.05)		DoP = (192.28 x ln Vel) - 923.89)

Table 49: Equations relating Depth of Penetration (DoP, in mm) to velocity (Vel, in m/s) derived from the experiments in this chapter.

12.14 Using these equations to estimate probable impact velocities of the retained fragments identified in Chapter 4

In Chapter 5 it was demonstrated how the mass and depth of penetration of 146 fragments retained in the necks of 199 UK soldiers who had CT scans was estimated. These fragments were then grouped together in terms of their mass closest to the nearest FSP (Table 49). Using the equations describing DoP against velocity for each FSP (Table 50) it was therefore possible to work out the range of predicted impact velocities. The upper velocity estimation was derived using a DoP measurement one standard deviation greater than the mean (meaning that 95% of fragments of that mass range would be expected to have resulted in DoP one standard deviation above or below that mean). For example the DoP for fragments in the 0.49g mass grouping had a mean of 64mm and standard deviation of 21mm; therefore velocity was calculated using a DoP of 85mm. Using this method it would be expected that 95% of predicted impact velocities for retained fragments in injured UK soldiers were below 347.6 m/s.

FSP Mass (g)	Retained neck fragment mass range (g)	Mean DoP (in mm), standard deviation in brackets	Upper velocity estimation from pig equations (m/s)	Upper velocity estimation from goat equations (m/s)	Upper velocity estimation from gelatin equations (m/s)
0.16	0.04 - 0.32	28 (7)	347.6	215.9	146.7
0.49	0.33 - 0.79	64 (21)		300.3	301.9
1.10	0.80 - 1.96	78 (22)	309.3	282.5	262.2
2.84	1.97 - 3.22	94 (32)	244.3		235.1

Table 50: Estimated impact velocities of fragments retained in the neck derived using equations described in Table 48 in conjunction with depth of penetration (DoP). Any grey boxes mean that simulant was not tested with that projectile.

12.15 Conclusions and recommendations

A summary is provided in Table 51 and provides the rationale for the research undertaken in subsequent chapters.

Conclusion	Recommendation
No statistical difference was found between the gradients of the regression lines for the 0.49g and 1.10g FSPs between all three simulants. Results for DoP against velocity were also comparable to the only previous published data using similar projectiles.	20% gelatin was a suitable simulant of both pig and goat muscle for cylindrical 0.49g and 1.10g FSPs. Equations describing DoP against velocity for these FSPs should utilise that based on 20% gelatin as these demonstrated the highest correlation between data points.
A significant statistical difference between the gradients of the lines of best fit for both pig and goat tissue was found compared to 20% gelatin for the cylindrical 0.16g FSP. This likely reflected the importance of skin in the retardation of smaller fragments, particularly at low velocities.	Equations describing DoP against velocity into muscle for a cylindrical 0.16g FSP should use that derived from 20% gelatin.
Although the gradients of the regression lines for the chisel nosed cylindrical 2.84g FSP were similar between pig tissue and 20% gelatin, there were insufficient numbers for statistical analysis.	Equations describing DoP against velocity for the 2.84g FSP should use that derived from 20% gelatin unless future evidence is found that disproves its utility. Further testing of this FSP into animal tissue and 20% gelatin is therefore recommended.
Plain radiographs utilised during testing of goat tissues improved the confidence of correctly ascertaining the correct DoP. However the process of obtaining radiographs was time consuming and could not account for differences in angulation of the projectile.	The use of plain radiographs is recommended for measuring DoP in opaque homogenous simulants but not when bone is present.
The use of CT for the pig testing provided significant advantages over more traditional methods of wound ballistics analysis. However it was expensive and time consuming.	CT is essential for future testing of this kind but a way to overcome the expense should be sought, such as using scanners already held in institutions capable of undertaking ballistic testing.
The predicted impact velocities for 95% of the retained fragments in the necks of injured UK soldiers identified in Chapter 4 were estimated to be below 348 m/s. However this upper velocity measurement Includes that derived from pig tissue testing of the 0.16g FSP and may therefore be unrepresentative.	Until further information is found, a velocity of 348 m/s is recommended as the minimum to which ballistic neck protection materials as well as FSPs within injury models of neck penetration should be tested. Utilisation of equations excluding that derived from pig testing for fragments grouped around the 0.16g FSP would instead produce a 95% confidence interval for the upper limit of velocity being 310 m/s.
Insufficient evidence in the literature was found to substantiate the suitability of 20% gelatin in representing the penetration of spherical FSPs. The effect of tissue changes post mortem and the subsequent effect on projectile retardation is unknown.	Further testing using spherical FSPs as well as testing how tissue changes post mortem affect depth of penetration are recommended and will be undertaken in Chapter 12.

Table 51: Conclusions and recommendations based upon the findings from Chapter 12.

Chapter 13: Comparing the penetration of fragment simulating projectiles into fresh, refrigerated and frozen porcine tissue

Chapter summary

Testing with post mortem human subjects may provide subjects with correct anatomical relationships but no information exists about how post mortem tissue changes and storage conditions in humans or animals may affect projectile penetration. Two chisel nosed cylinders (0.49 g and 1.10 g) and a 0.51 g sphere were fired into three groups of porcine tissue (fresh, refrigerated and frozen then refrigerated) and compared to 20% gelatin. No difference in depth of penetration was found between porcine tissue stored in the different manners compared with 20% gelatin by impact velocities less than 100 m/s. Refrigerating or freezing porcine tissue followed by thawing has no effect on its ability to retard these projectiles. This would suggest that PMHS may be a valid future method of modelling penetrating neck injury from energised explosive fragments.

13.1 Aims

- To mimic those storage conditions that a PMHS would likely be subjected to with an animal surrogate.
- To compare the results of projectile penetration into refrigerate and frozen tissue to that of a fresh subject.
- To obtain experimental penetration data using a spherical fragment simulating projectile.

13.2 Publications derived from this chapter

Breeze J, Carr DJ, Mabbott A, Beckett S, Clasper JC. Refrigeration and freezing of porcine tissue does not affect the retardation of fragment simulating projectiles. Journal of Forensic and Legal Medicine 2015; DOI: 10.1016/j.jflm.2015.03.003 (Breeze et al., 2015e).

13.3 Collaborations

This chapter describes a trial undertaken at Cranfield University to determine if the effects of storage post mortem affect projectile penetration. The author derived the trial concept and approached Dr Debra Carr to help undertake the testing. Assistance was also gained from Alexander Mabbott in the testing and Dr Sophie Beckett who undertook the CT scanning and provided the DICOM images.

13.4 Introduction

Ballistic testing utilising PMHS is a potential method for ascertaining the effect of human anatomy on projectile penetration that cannot be assessed using animal or tissue simulants (Chapter 10). The use of PMHS in this regard has to date been extremely limited, predominantly revolving around testing of skin penetration or whole legs subjected to explosive blasts (Ramasamy et al., 2014). However the potential effects on material properties of tissue changes post mortem including that of projectile penetration is not known. In addition these specimens will be stored and transported in strict conditions post mortem to preserve their quality as described below but again the effects of these different types of storage conditions on penetration is also unknown. The author was able to discuss via third parties in Wayne State University and Dstl to those individuals likely to be responsible for PMHS procurement (Andrecovich et al., 2013), and the predicted storage conditions are as follows.

Preservation of PMHS generally begins 2-3 hours post mortem by refrigeration at 1 °C. Refrigeration continues for 24-48 hours prior to dissection. Following dissection, specimens can either remain refrigerated or may be frozen and can be transported in either condition to their final location. Specimens are transferred to a refrigerator for twenty-four hours prior to testing if frozen.

13.5 Method

Two sizes of NATO standardised chisel nosed cylinder were tested (0.49g and 1.10g) in conjunction with a 0.51g sphere. The firing apparatus and 20% gelatin preparation were identical to that used for muscle penetration testing in Chapter 11. In addition high-speed photography was undertaken with a Phantom V12 high- speed camera (Vision Research, New Jersey, USA; 6,240 frames/second) to map velocity within the specimen and measure exit velocity, if applicable (Figure 59).

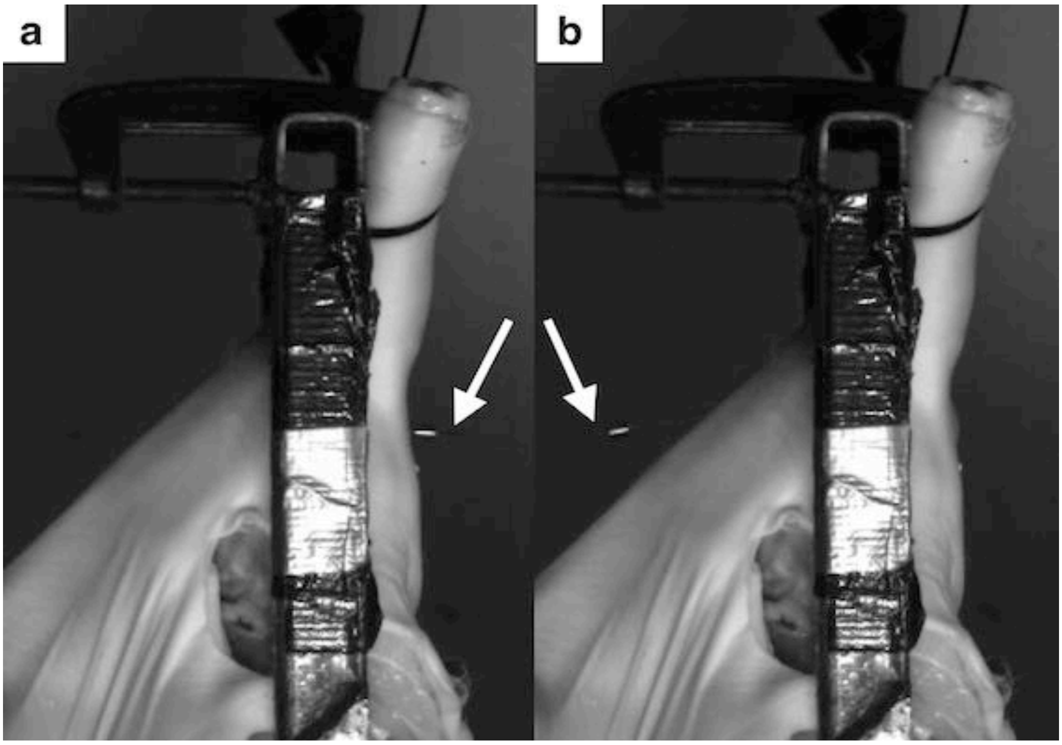


Figure 59: High speed video analysis used to demonstrate sites of impact (a) and exit (b) as well as yaw of projectile (arrowed).

13.5.1 Animal tissue preparation and methods of storage

The methodology used was designed to as accurately as possible mimic the predicted storage conditions of any future PMHS testing (as described in section 12.1). Animals were acquired from a Food Standards Agency approved slaughterhouse and had been killed in a humane manner. Three groups of specimens were used which varied according to methods of storage post slaughter (Table 52). For the firings of fresh pig tissue, testing started between 90-120 minutes post slaughter. For the stored animals, testing was undertaken 1 week after slaughter (2 animals were refrigerated for 7 days and 2 animals were frozen for 6 days and thawed for 1 day; testing occurred with specimens at room temperature). The primary sites for targeting were the skin overlaying the humerus or femur and the specimens were sectioned just above their articulation with the scapula and pelvis respectively thereby preserving joint integrity and muscle insertions. Eight thighs were used for each type of storage and between 3-5 FSPs were fired into each thigh with impact sites kept at least 50mm apart so wound tracts did not interact. For the 8 fresh thighs, the bone was removed from four of them prior to firing. All thighs were placed into custom made perspex containers of dimensions 120 mm height and 94 mm diameter (Figure 60); these corresponded to the maximum size of object that could be CT scanned using a one-panel scan.

Group	Number of thighs or blocks	Number of FSPs	Tissue types	Specifics
Fresh	4	20	Skin + muscle	Testing started 90-120 minutes post mortem
Fresh	4	16	Skin + muscle + bone	Testing started 90-120 minutes post mortem
Refrigerated	8	16	Skin + muscle + bone	Refrigerated within 90 minutes post mortem for 1 week at 4 °C
Frozen	8	10	Skin + muscle + bone	Frozen within 90 minutes post mortem for 6 days at -10 °C, then refrigerated for 1 day at 4 °C
20% gelatin	4	48	N/A	5mm spheres only. Results for 0.49 g and 1.10 g FSPs taken from Chapter 11

Table 52: Methods of specimen storage; those included were only those FSPs retained within the specimen or that did not perforate.

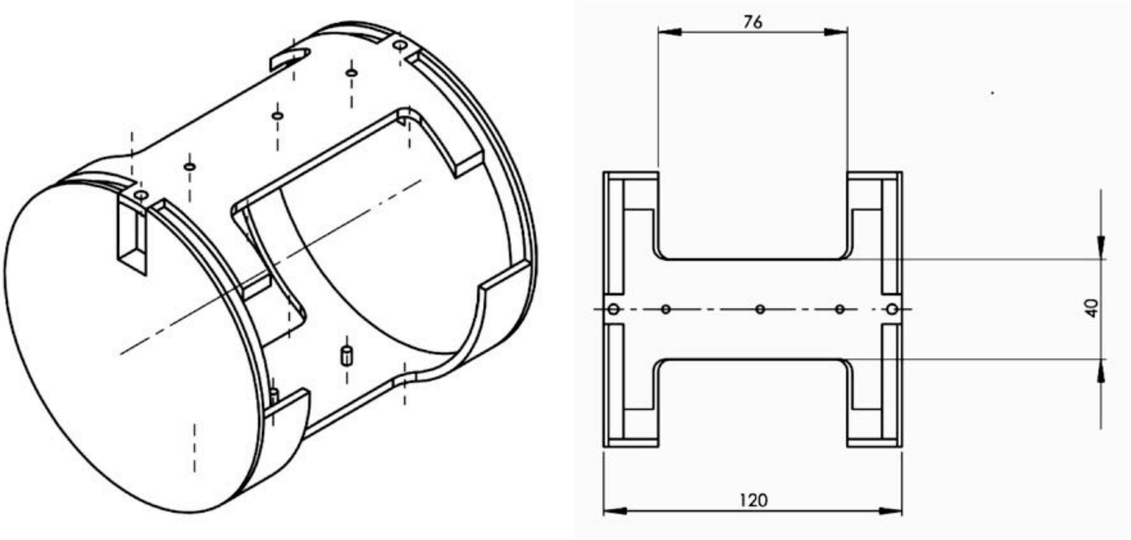


Figure 60: Custom made perspex containers used to hold thighs in position so that they did not move during or after firing.

13.5.2 Computed Tomography (CT) scanner

An industrial microfocus CT scanner (Nikon, XT H 225, Japan) was used to collect CT data. The equipment is held approximately 200 metres from the ballistics range so time delays between firing and CT scanning were minimised as much as possible. All data were collected using the following settings; tungsten target, 100 - 105 kV, 45 - 65 µA, 354 - 500 ms exposure, 720 projections, 2 frames per projection and a resultant voxel size of 0.12 – 0.14 mm. Scanning acquisition time was approximately 30 minutes. Corrections for beam hardening and noise reduction were applied during the volume reconstruction of the scan data. Digital Imaging Communications in Medicine (DICOM) files with a 0.3 mm slice distance were generated (Figure 61). This file format is the current industry standard for handling, storing and transmitting information in medical imaging. The DICOM files were reviewed using an open source specialist image processing software (OsiriX, OsiriX Foundation, Geneva, Switzerland) to measure DoP from skin surface entry wound to front surface of projectile.

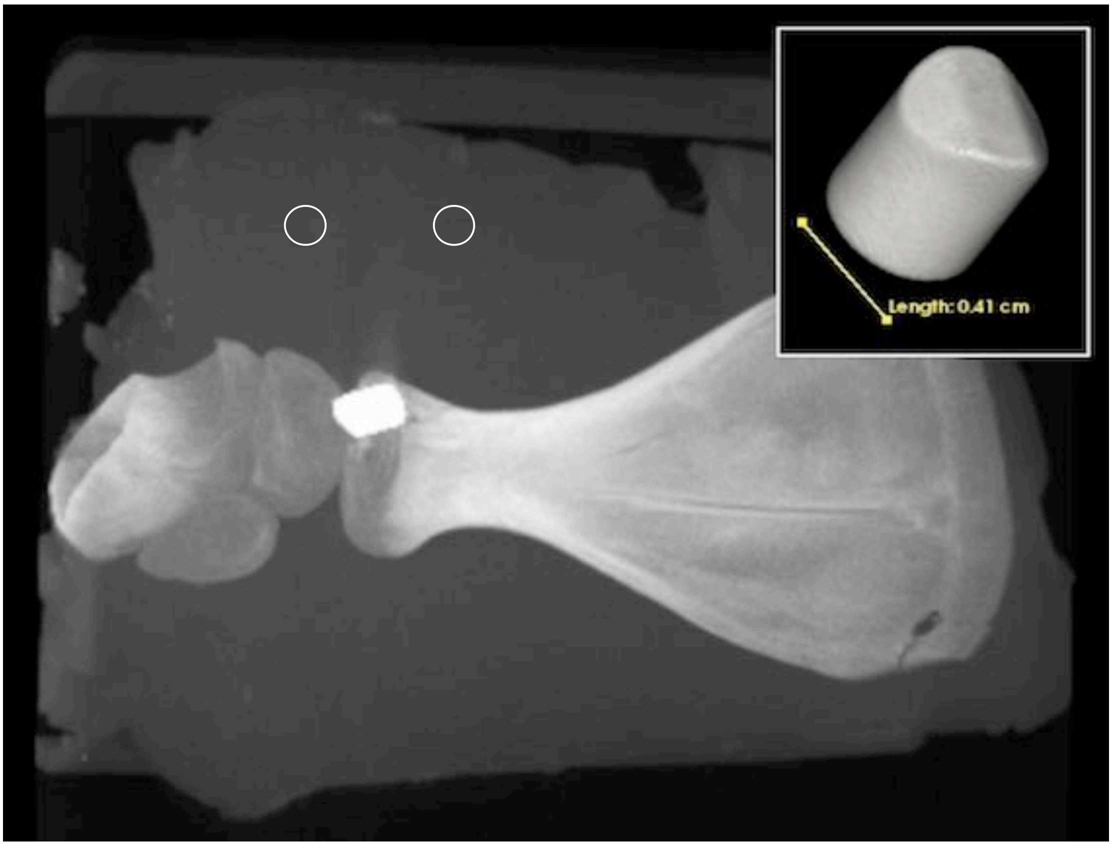


Figure 61: The 0.3mm slices available with this machine demonstrated excellent resolution, with equations that could manipulate the beam- hardening artefact produced by the metallic projectile (box insert).

13.5.3 Depth of penetration produced by each projectile in different simulants at a range of velocities

To determine the effect of simulant type (fresh, refrigerated and defrosted pig and 20% gelatine) on DoP, the following impact velocity ranges were utilised: 50-99 m/s, 100-149 m/s and 150-199 m/s. Results for DoP that could not be ascertained accurately from either CT or clinically were excluded, as well as any shots slower than 50 m/s and faster than 200 m/s. Analysis of variance (ANOVA) was used to determine whether mean DoP for different simulant types impacted by a single type of FSP were similar or significantly different. ANOVA was only conducted for velocity groups that contained a minimum of three retained FSPs to enable valid statistical analysis to be undertaken. When a statistical significant ANOVA result was obtained, Tukey's honest significant difference test (SPSS IBM Statistics version 21, Microsoft Corporation, Redmond, Washington, US) was used to find which means were significantly different from each other. Equality of variance and normality of residuals were determined for each analysis.

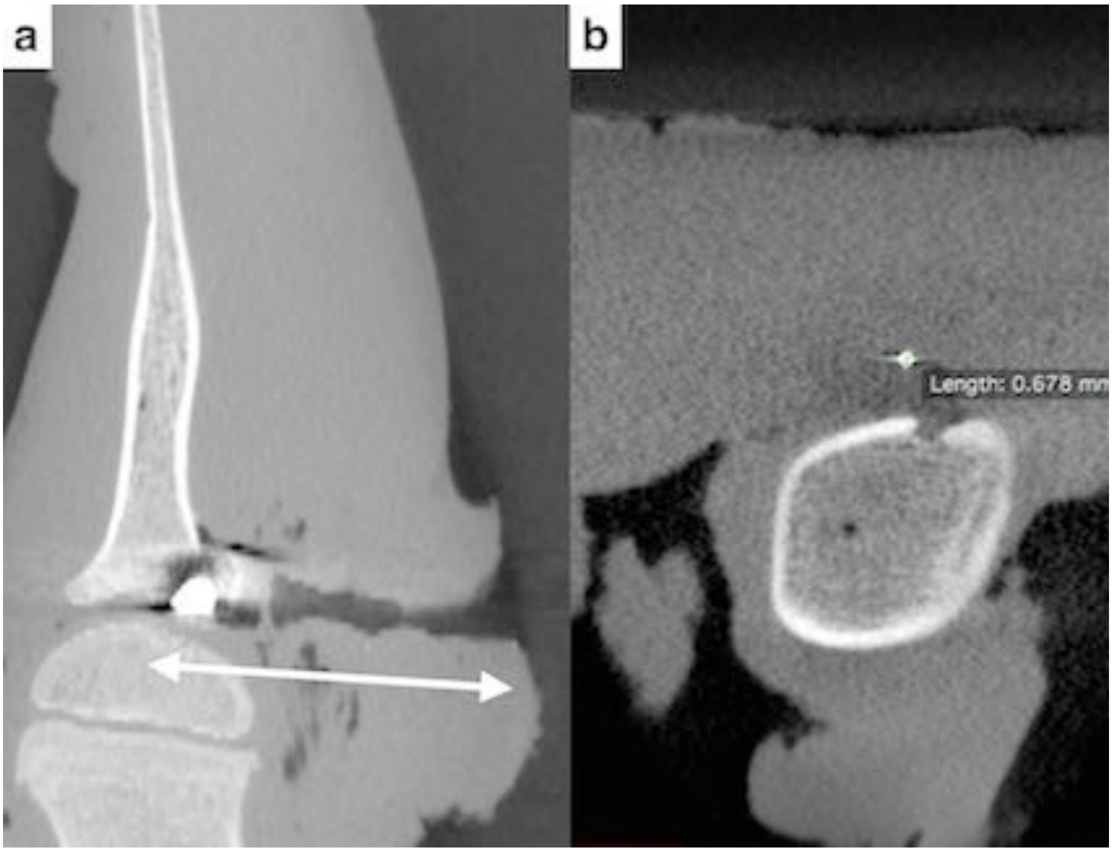


Figure 62: a) Depth of penetration (arrowed) measurements were discarded when bone impact (a) or fragmentation of the projectile (b) was observed on CT.

13.5.4 Kinetic energy absorption into tissues

Impact and exit velocities were determined from the high- speed video for 0.49 g CN FSPs impacting fresh pig. The kinetic energy (KE) of the projectile was calculated using the following equation: KE = 0.5 × mass × velocity^2. Energy deposition was therefore calculated as the KE on impact deducted from the KE on exit, on the assumption of conservation of mass of the projectile. Therefore the results of any projectile that could potentially have fragmented during their passage through tissues was excluded, which was determined by looking for any additional metallic debris on the CT scan. In addition any firing in which bone was seen to be damaged on CT was excluded (Figure 62). The deposited kinetic energy was divided by the thickness of that part of the specimen that the FSP travelled through to produce a value of energy deposited per mm travelled. This was then divided by the diameter of the presenting surface area of the projectile to produce a 'normalised' energy deposited per mm of projectile passage.

13.6 Results

Skin thickness ranged between 1-2 mm and was very pliable, particularly for the fresh pig. In seven shots the FSP could not be identified clinically to measure DoP. 4/7 of these shots had DoP measured using CT alone. In the remaining 3/7 the DoP was not measured because the entry location as derived from the high- speed photography footage could not be accurately correlated with the position on the CT. In one more additional shot, a small 0.7 mm metallic fragment was noted near to a retained FSP (Figure 62) and the DoP was therefore discarded.

13.6.1 Impact velocity versus depth of penetration

Impact velocity versus DoP for each of the three types of FSP is demonstrated pictorially in Figures 63-65. Good correlation between impact velocity and DoP was demonstrated for all of the 20% gelatin firings (R^2 values of 0.89-0.99), but correlation was poor with pig tissues except for the 0.49g FSP fired into tissue that had been frozen and defrosted (Table 53). FSPs with velocities less than 50 m/s bounced off the surface and that greater than 200 m/s perforated the pig specimens completely. In addition ANOVA could only be conducted for the 50-99 m/s group as this was the only velocity at which at least 3 FSPs were retained within each simulant to enable DoP to be measured and valid statistical analysis to be undertaken. For the 1.10 g cylinder, simulant type significantly affected DoP between 50-99 m/s ($F_{2, 8}= 6.91$; $p<0.05$). Tukey's test identified two overlapping groups; DoP was similar in i) gelatin and refrigerated pig and ii) fresh and refrigerated pig; however neither achieved statistical significance. DoP produced in fresh pig at matching velocities was significantly different to 20% gelatin ($p<0.05$). For the 5 mm sphere, there were only greater than 3 retained FSPs in the fresh pig and gelatin simulants at the 50-99 m/s range; no significant difference between these simulants was found in terms of DoP ($F_{1,\ 13}$= 1.91; p=NS). For the 0.49 g cylinder, all simulants could be compared as there were at least 3 retained FSPs in each at the 50-99 m/s range; no significant difference was found between any of these simulants in terms of DoP ($F_{3,\ 21}$= 0.57; p=NS), although the number of retained FSPs was not matched between groups.

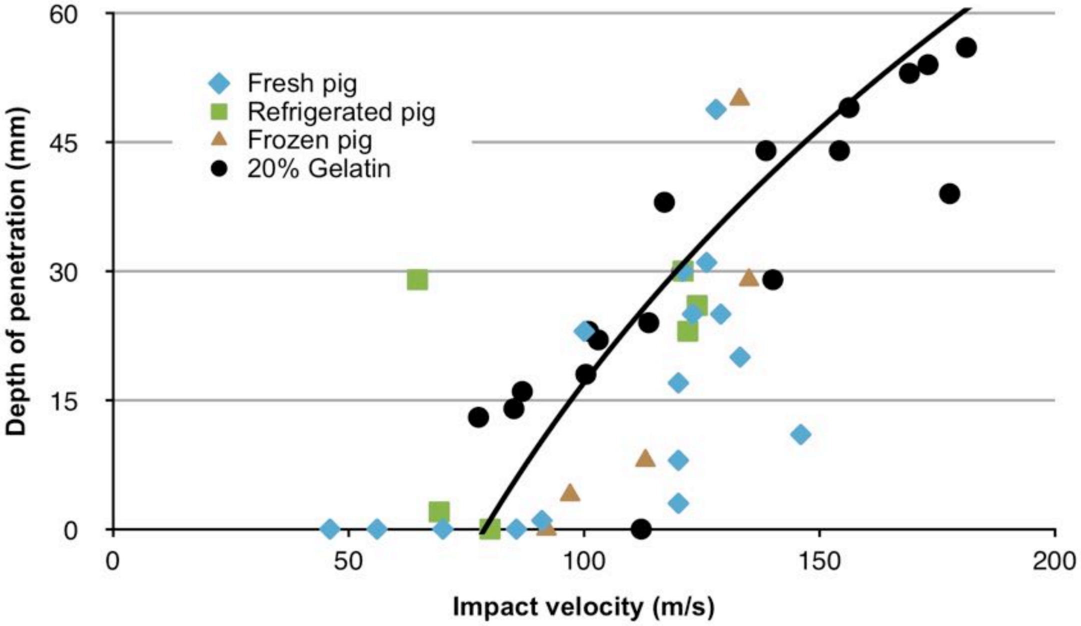


Figure 63: Depth of penetration (mm) versus velocity (m/s) for the 0.49 g chisel nosed cylinder for the different specimen storage types. A logarithmic trendline is displayed for the 20% gelatin data points.

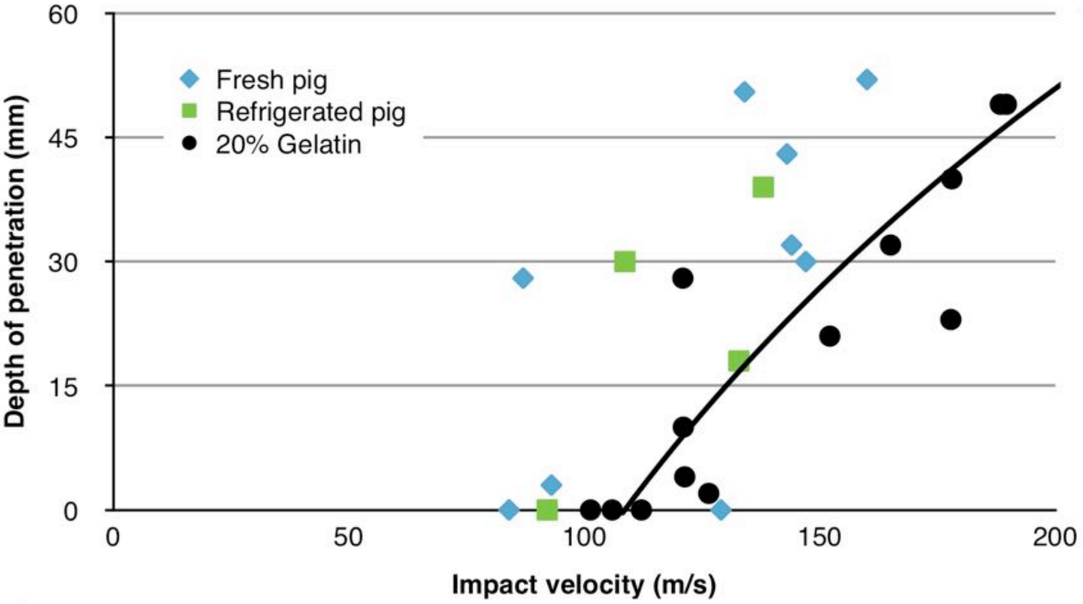


Figure 64: Depth of penetration (mm) versus velocity (m/s) for the 1.10 g chisel nosed cylinder for the different storage specimen types. A logarithmic trendline is displayed for the 20% gelatin data points.

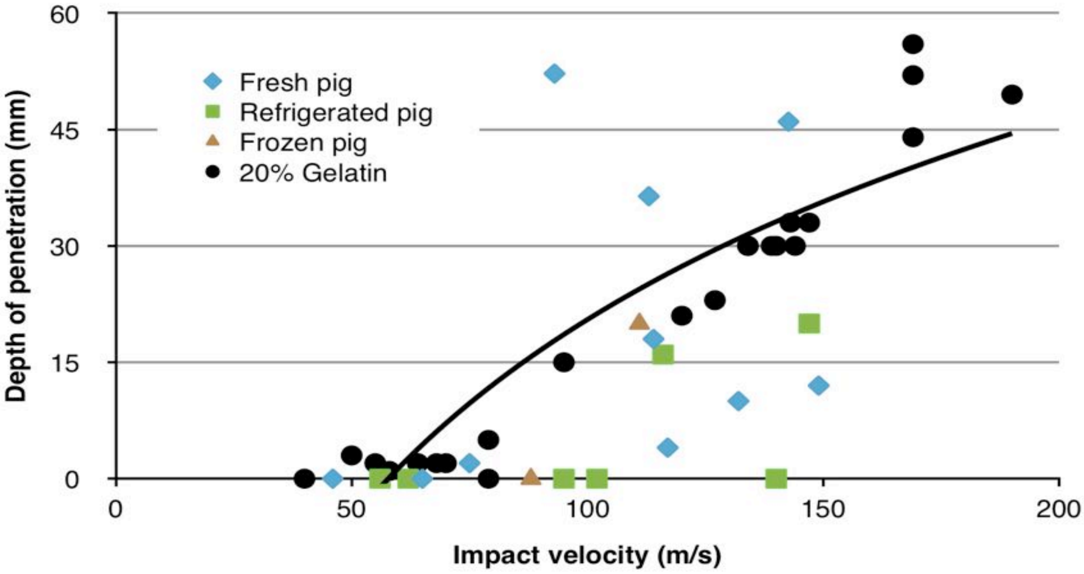


Figure 65: Depth of penetration (mm) versus velocity (m/s) for the 0.51 g sphere for the different specimen storage types. A logarithmic trendline is displayed for the 20% gelatin data points.

Fragment simulating projectile	**Correlation using R^2 values of natural logarithmic trend lines relating impact velocity to depth of penetration (number of FSPs lodged in tissue in brackets).**			
	20% gelatin	**Fresh pig**	**Refrigerated pig**	**Frozen pig**
0.51g sphere	0.99 (59)	0.51 (10)	0.51 (7)	N/A (3)
0.49g cylinder	0.98 (32)	0.56 (16)	0.42 (6)	0.98 (5)
1.10g cylinder	0.89 (15)	0.51 (10)	0.51 (4)	N/A (0)

Table 53: Correlation of natural logarithmic trend lines relating impact velocity to depth of penetration for each tissue type using. The number of FSPs lodged in tissue is shown in brackets; if <5 were lodged in tissue, a trend line could not be made and therefore no correlation coefficient is stated.

13.6.2 Kinetic energy absorption into tissues

Specimen thickness varied between 21-38 mm. With the exception of 2 shots from 5mm spheres, energy absorbed per mm of tissue consistently ranged between 0.13- 0.2 J/mm (Table 54). The energy absorption of the fresh tissue group and refrigerated tissue group were compared to one another, finding that the means and standard deviations were similar. However ANOVA could not be undertaken because the limited simple sizes meant that the data did not meet the requirements of equality of variance nor was it normally distributed.

Storage type	**FSP**	**Impact velocity (m/s)**	**Exit velocity (m/s)**	**Impact energy (J)**	**Exit energy (J)**	**Eabs (J)**	**Specimen thickness (mm)**	**Energy absorbed per mm tissue (J/mm)**
Fresh	0.49 g cylinder	172	111	7.25	3.02	4.23	23	0.18
		175	124	7.50	3.77	3.74	21	0.18
		170	103	7.08	2.60	4.48	23	0.19
		184	138	8.29	4.67	3.63	29	0.13
		176	134	7.59	4.40	3.19	21	0.15
		196	128	9.41	4.01	5.40	38	0.14
		176	111	7.59	3.02	4.57	31	0.15
	0.49g sphere	215	122	11.79	3.80	7.99	31	0.26
	1.10 g cylinder	146	85	11.72	3.97	7.75	38	0.20
Fridge	0.49g sphere	197	151	9.90	5.81	4.08	21	0.19
		166	114	7.03	3.31	3.71	23	0.16
		114	81	3.31	1.67	1.64	26	0.06
	1.10 g cylinder	124	40	8.46	0.88	7.58	38	0.20
		123	67	8.32	2.47	5.85	31	0.19
		140	106	10.78	6.18	4.60	29	0.16
		134	91	9.88	4.55	5.32	38	0.14
		136	98	10.17	5.28	4.89	29	0.17
		106	66	6.18	2.40	3.78	21	0.18

Table 54: Estimated kinetic energy (KE) absorption per millimetre penetration for those fragment simulating projectiles (FSPs) that fully perforated and CT did not demonstrate bone impact.

13.7 Conclusions and recommendations

The conclusions based upon this chapter and recommendations for future research are provided in Table 55.

Conclusion	Recommendation
There were insufficient sample numbers for statistical analysis to be undertaken for impact velocities greater than 100 m/s for all three projectiles as this often resulted in perforation of the specimen. This was directly related to the small physical size of the specimens, which in turn were chosen due to the size of the CT scanner available.	Animals should be of a larger size than the ones used in this trial, which would enable more projectiles to be retained for statistical analysis. This would however necessitate a full human sized scanner with reduced data acquisition time to potentially minimise any changes in material properties of the specimen post mortem.
The use of high-speed video in combination with doppler radar enabled both entry and exit velocities to be ascertained as well as confirming entry and exit locations which greatly assisted determining wound tract length. Although not statistically significant, the means and standard deviations for energy absorption of the fresh tissue group and refrigerated tissue group were similar.	Comparisons of energy deposition between tissue types for those projectiles that fully perforated the specimen is a potential method for increasing sample numbers. By normalising the projectile in terms of presenting area it may be possible to develop equations to predict energy deposition for any size of projectile and we would recommend this approach be developed in future trials.
The high resolution of this model of CT scanner provided the ability to identify fragmentation of projectile which would have potentially unknowingly invalidated any measurements based on that shot had it not been used.	Use of a CT scanner with a potential resolution of 0.3mm slices is recommended for future experiments to enable projectile fragmentation to be identified.
The trial in Chapter 11 utilised CT scans only after firing and demonstrated discrete radiolucent areas consistent with cavitation in the tissues. When such cavitation is noted along the path of the projectile, this could be ascribed to the production of the permanent wound cavity. The addition of pre firing CT scans in this trial demonstrated that air was present in some tissue planes before firing and therefore we believe care must be taken in assuming that all radiolucent areas in the path of the projectile is cavitation and making potential measurements for permanent cavity sizes from it.	We would recommend that future experiments utilise whole animals that are not sectioned to see how this affects the air within tissues. The use of CT scans pre and post firing is for the time being recommended should measurements of wound tracts be desired. This will be particularly important for any future testing of PMHS where such limited existing information exists.

Table 55: Conclusions and recommendations based upon the findings from Chapter 13.

Chapter 14: Use of Computerised Surface Wound Mapping to differentiate between neck protection prototypes

Chapter summary

A computerised three-dimensional representation of the skin surface of a human based upon the Zygote geometry termed the Interactive Mapping and Analysis Programme (IMAP) has been developed. This tool was used to graphically display the neck entry wound locations of all soldiers injured by penetrating energised fragments between 01 January 2010 and 31 December 2011. The OSPREY half neck collar, both neck collar prototypes and the three modified UBACS neck collar prototypes were imported into the tool. Comparisons between collars were made in terms of coverage from shot lines originating horizontally and from the ground. The use of IMAP alone would suggest that the most effective collar in terms of entry wound coverage of severe neck injuries was the three-piece collar prototype and the UBACS prototype 3.

14.1 Aims of this chapter

- To utilise a computerised representation of the human skin surface to which entry wound locations can be inputted and linked to JTTR.
- To prospectively collect the entry wound locations of all UK soldiers (survivors and those who died) and enter them into this wound mapping tool.
- To import different designs of neck protection prototypes into the tool.
- To attempt to relate entry wound location to clinical outcome for these different neck protection designs.

14.2 Publications derived from this chapter

- Breeze J, Midwinter MJ. Editorial: Prospective Computerised Surface Wound Mapping will Optimise Future Body Armour Design. Journal of the Royal Army Medical Corps 2012; 158 (2): 79–8 (Breeze and Midwinter, 2012).
- Breeze J, Allanson-Bailey LC, Hunt NC, Delaney R, Hepper AE, Lewis EA. Using computerised surface wound mapping to compare the potential medical effectiveness of Enhanced Protection Under Body Armour Combat Shirt collar designs. Journal of the Royal Army Medical Corps 2015; 161 (1): 22–26 (Breeze et al., 2015c).
- Breeze J, Allanson-Bailey LS, Hunt NC, Midwinter MJ, Hepper AE, Monaghan A, Gibbons AJ. Surface wound mapping of battlefield occulo-facial injury. Injury 2012; 43 (11): 1856–1860 (Breeze et al., 2012b).

14.3 Collaborations

This chapter describes how IMAP was utilised to validate differing designs of ballistic neck protection. IMAP is based upon the Zygote and was developed primarily by Dr Lucy Allanson Bailey at Dstl, who outsourced the software programming itself to a commercial company called RiskAware®. The author worked with Dstl at all points in the development of IMAP, providing the clinical information and surface wound locations required to populate its database. The user trial of IMAP by the author in Afghanistan provided the onus and many of the suggested requirements for the trimmed down version of the programme, IMAP Lite (Chapter 16).

14.4 Introduction

Surface wound mapping (SWM) is the process by which the wound locations of projectiles perforating the skin are graphically recorded. It has been attempted intermittently since World War I but never gained mainstream acceptance despite the potential for validation in coverage provided by differing designs of Personal Protective Equipment (Kosashvili et al., 2005; Gofrit et al., 1996; Oughterson et al., 1962). At the start of the neck protection programme it was recognised that SWM was a potential method for providing a rapid pictorial representation of the entry wound locations. The first attempt to undertake SWM was performed using the clinical and post mortem notes of soldiers suffering neck wounds between 01 January 2006 and 31 December 2009 (undertaken at the same time as data collection for Chapter 4). This involved producing a paper based template and dividing the neck into addition surgical zones for clarity (Figure 66) and to enable ease of comparison between designs.

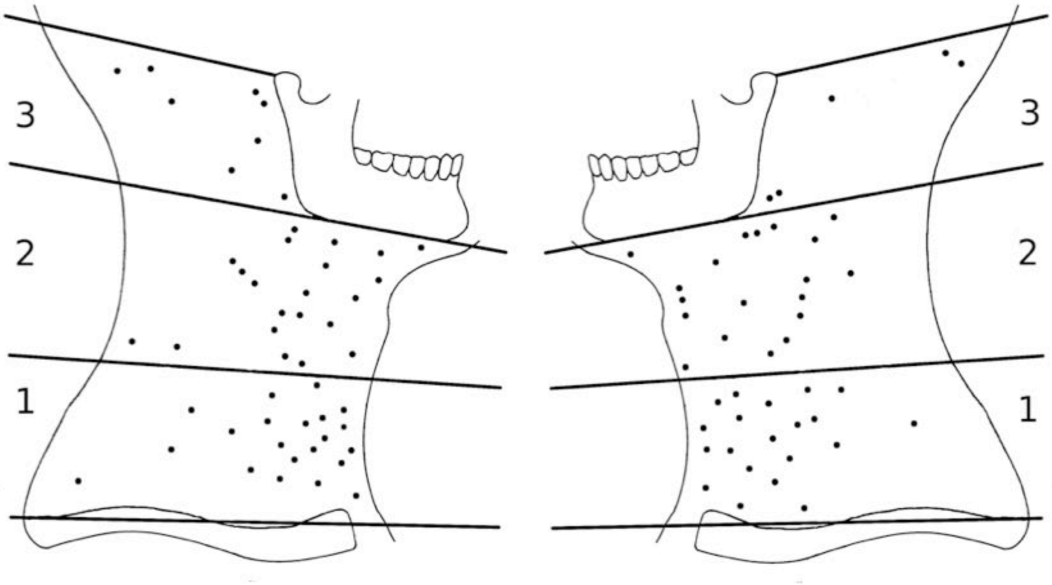


Figure 66: Paper based template for the gathering of impact locations demonstrating surgical neck zones using entry wound locations for soldiers sustaining neck wounds between 01 January 2006-31 December 2009.

Knowledge of neck zone coverage by each prototype enabled crude comparisons to be made. For example the greatest number of wound entry locations were to Zone 1, which all neck collar designs covered (with the exception of a small window anteriorly with OSPREY). Significant differences in the coverage of Zone 2 was noted between prototypes, but quantifying these differences was not possible (Table 56).

Conclusions attained from paper based surface wound mapping	Decisions for future wound mapping methodology
The retrospective nature of the analysis meant that entry wound location information was only available in 49% of soldiers sustaining a neck wound.	Prospective data collection should be undertaken.
Clinical information was limited for survivors, particularly those not evacuated back to the UK. Although those soldiers not requiring evacuation were likely to have insignificant wounds in terms of adverse outcomes, not including these would reduce the ability of wound mapping to identify the most susceptible areas of the neck requiring protection.	Wound mapping data collection should be focused on survivors, both in the field hospital in Afghanistan as well as on the ward in Birmingham. Wounds should be charted as soon after injury as possible to decrease error.
The best information was available for those who were killed due to the detailed available post mortem records that included clinical photographs.	No additional processes are required to map post mortem injuries.
Comparisons between protective equipment designs is difficult as separate data collection sheets are required for each design.	A numerical model in which different CAD files could be superimposed onto a representation of a human should be sought.
Wound locations and causative mechanisms could not be linked.	A method for linking causative mechanism, entry wound location and resultant injury should be sought.
All wounds were mapped from a single angulation (horizontal) and therefore could not assess threats from different trajectories.	A numerical simulation of a human that can be manipulated such that it can be viewed from different angulations is sought.

Table 56: Limitations to retrospective paper based surface wound mapping and potential solutions.

13.3 Method

In conjunction with Dstl Porton Down, a novel electronic SWM tool called the Interactive Mapping Analysis Platform (IMAP) has been developed. This was based upon a mesh of the skin surfaces described in the Zygote programme (Chapter 9) and was scaled to anthropometrically measurements derived from a 50th percentile UK male service person (Chapter 5). The IMAP software was placed onto a laptop classified with a restricted security status, collecting information as close to the point of wounding as possible (Figure 67).

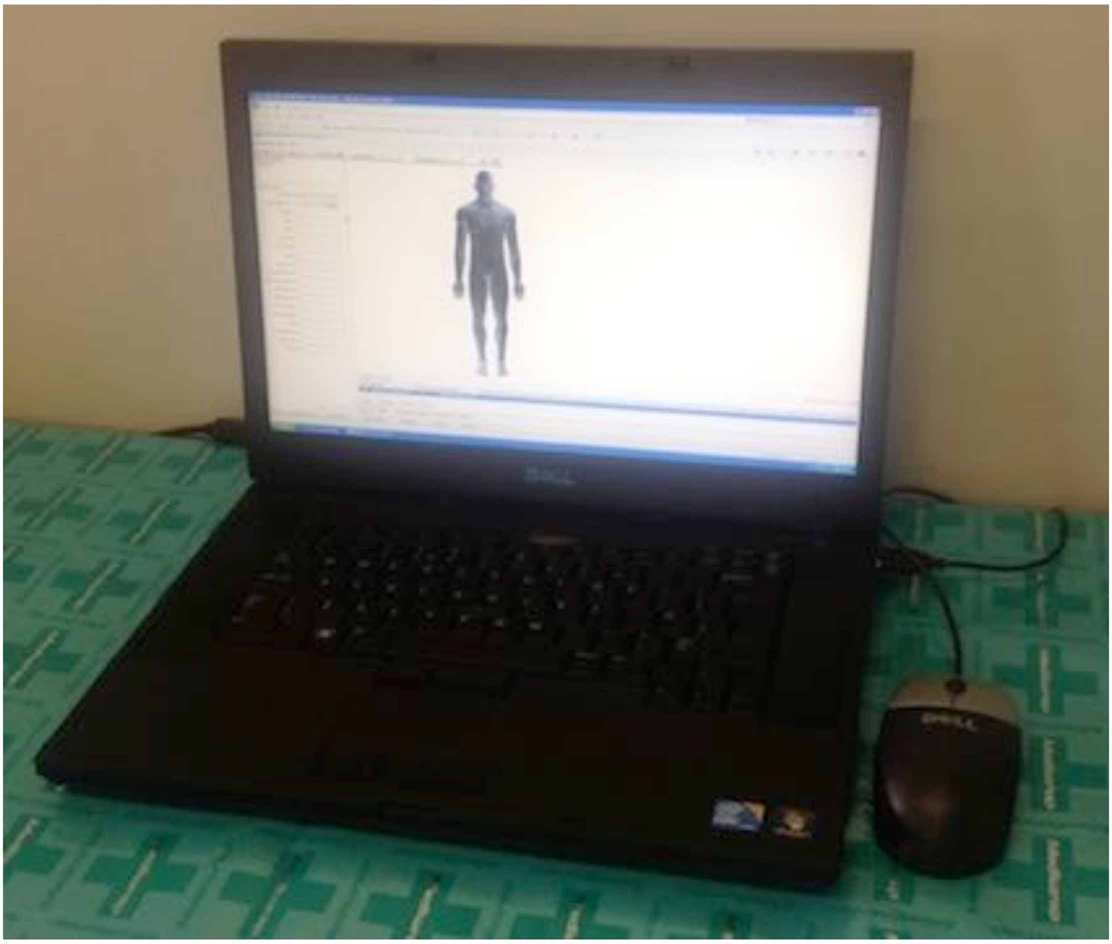
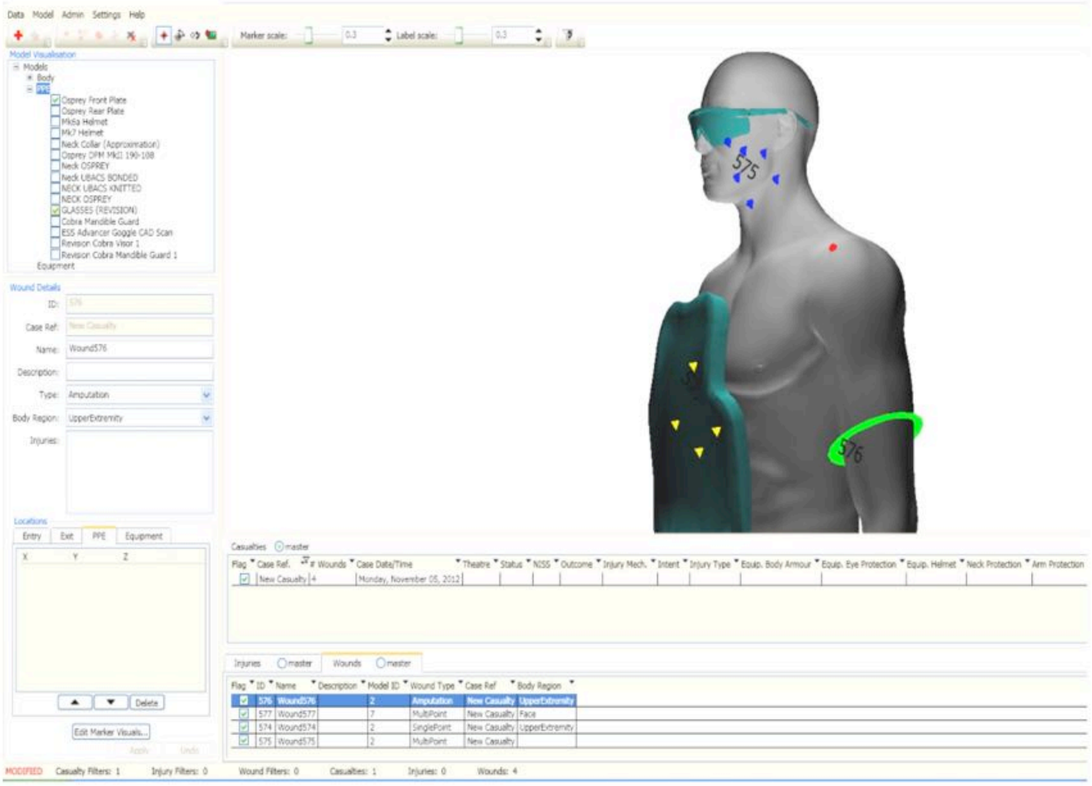


Figure 67: IMAP being used on the ward during the author's deployment to Afghanistan.

IMAP is aligned with the data fields available within the JTTR casualty database, with fields including casualty identifiers, injuries, protective equipment and causative mechanisms when known. Each surface wound location can be linked to an individual wound using the AIS score ascribed to that injury (Figure 68).



Marker scale: 0.3
Label scale: 0.3

☑ Osprey Front Plate
☐ Osprey Rear Plate
☐ Mk6a Helmet
☐ Mk7 Helmet
☐ Neck Collar (Approximation)
☐ Osprey DPM MkII 190-108
☐ Neck OSPREY
☐ Neck UBACS BONDED
☐ NECK UBACS KNITTED
☐ NECK OSPREY
☑ GLASSES (REVISION)
☐ Cobra Mandible Guard
☐ ESS Advancer Goggle CAD Scan
☐ Revision Cobra Visor 1
☐ Revision Cobra Mandible Guard 1

ID: 576
Case Ref: New Casualty
Name: Wound576
Description:
Type: Amputation
Body Region: UpperExtremity
Injuries:

Flag	Case Ref.	# Wounds	Case Date/Time	Theatre	Status	NISS	Outcome	Injury Mech.	Intent	Injury Type	Equip. Body Armour	Equip. Eye Protection	Equip. Helmet	Neck Protection	Arm Protection
☑	New Casualty	4	Monday, November 05, 2012												

Flag	ID	Name	Description	Model ID	Wound Type	Case Ref	Body Region
☑	576	Wound576		2	Amputation	New Casualty	UpperExtremity
☑	577	Wound577		7	MultiPoint	New Casualty	Face
☑	574	Wound574		2	SinglePoint	New Casualty	UpperExtremity
☑	575	Wound575		2	MultiPoint	New Casualty	

MODIFIED Casualty Filters: 1 Injury Filters: 0 Wound Filters: 0 Casualties: 1 Injuries: 0 Wounds: 4

Figure 68: Screen shot of IMAP with the body model and wound types demonstrated within it.

13.3.1 Gathering of prospective entry wound location information

Wound locations were charted for all UK service personnel deployed to Afghanistan (survivors, killed in action and died of wounds) who sustained a combat induced penetrating neck injury between 01 January 2010 and 31 December 2011. Where possible it was determined whether the service person was wearing an OSPREY neck collar and UBACS shirt at the time of injury. Entry wound locations were linked to injury using the AIS scores held within the JTTR database. As described in Chapter 3, each individual neck injury is ascribed an AIS score, ranging from 1 (minor) to 6 (maximal, currently untreatable). All wounds caused by energised fragments were charted pictorially and blunt wounds and those due to gunshot wounds were excluded. Wound locations for those evacuated to the UK were prospectively gathered by the author directly from examining the patient, either on the ward or in the Intensive Care Unit at the Queen Elizabeth Hospital, Birmingham. Wound locations for those soldiers who were killed were derived retrospectively using photographs contained in the post-mortem records in conjunction with the Home Office pathologists that originally undertook the post mortem examination.

13.3.2 Analysis using the Interactive Mapping Analysis Platform (IMAP) tool

The physical prototypes of the three modified UBACS neck collar prototype designs (Chapter 8), the two-piece and three-piece prototypes (Chapter 7) and OSPREY half collar (Chapter 6) were laser scanned. The UBACS prototype 1 collar (Figure 69) only reinforced the collar with ballistic protective material, leaving a potential gap in protection between collar and OSPREY vest. This was overcome in prototype 2, which incorporated an additional semicircle of ballistic protective material between the collar and OSPREY vest below the collar anteriorly and posteriorly. In terms of ergonomics assessment there was no difference in the acceptability or ability to perform military representative tasks between prototypes 1 and 2.

Figure 69: The modified UBACS prototype 1 has protective material in the collar alone, but there is still a gap between the OSPREY half collar and vest that is not covered by the OSPREY half collar. This gap is prevented by an additional semi circle of material below the collar in the UBACS prototype 2.

Each collar was superimposed over the entry wound locations in turn and the assumption made that any entry wound location (red dot) was covered by a collar (in green), then it was assumed to have stopped the fragment and was therefore discounted.

The number of entry wound locations left exposed when each collar was worn was ascertained for when the soldier was viewed in IMAP from the front with a shot line in the horizontal plane and one originating at a 45 degree angle from below; this second view was designed to represent projectiles originating from the ground in front of the target. In addition this procedure was repeated using only those entry wound locations that were associated with underlying neck wounds that resulted in AIS scores of 5 and 6 (i.e. only those wounds that were associated with death or likely significant morbidity). At the time of completion of this thesis IMAP did not have an intrinsic analytical capability and therefore all calculations were made by hand.

13.4 Results

During 01 January 2010 and 31 December 2011, neck wounds caused by energized fragments were present in 81/871 (9%) of injured UK service personnel deployed on operations in Afghanistan. 7 soldiers were excluded because the mechanism was blunt trauma and a further 4 soldiers were excluded because wound mapping information was not available (Figure 70). Of the 70 soldiers with penetrating wounds, 76 individual entry wound locations were charted in IMAP. Of these 76 entry wound locations, 59/76 were visible when viewed from the front in either a horizontal plane or a 45 degree angle from below (the remaining 17/76 were at the back of the neck and not visible).

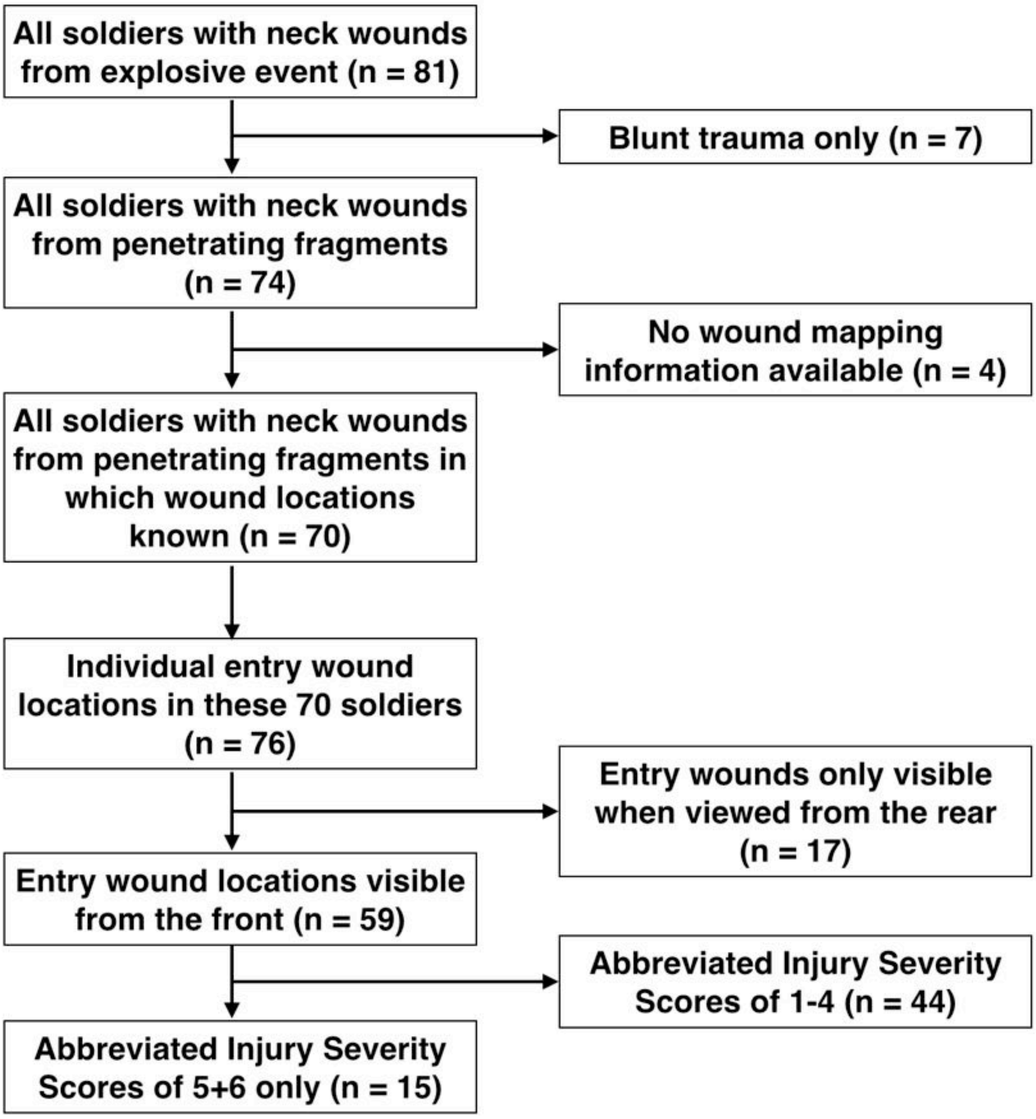


Figure 70: Flowchart demonstrating how the number of potentially visible entry wound locations was determined within the Interactive Mapping Analysis Platform (IMAP).

13.4.1 Modified UBACS Prototypes analysis

74/74 (100%) of casualties sustaining penetrating neck injuries from energised fragments during this period were wearing their standard UBACS at the time of injury. Demonstration of the numbers of neck entry wound locations that each prototype would cover is demonstrated in Figure 71 and Table 57. The addition of a semicircle of ballistic protective material under the collar in the modified UBACS Prototype 2 reduced the number of visible wound entry points over Prototype 1, in both directions and with all both sets of AIS scores. In both the horizontal and ground based shot lines prototype 3 (cross over collar) covered more entry wound locations than prototype 2. This was particularly evident from the ground based shot line due to the projection of the prototype 3 collar from the skin surface. When entry wound locations associated with AIS scores 5 + 6 only were displayed, the prototype 3 was even more effective as it provided greater coverage of the top of the neck on the lateral aspect (Zone 2), which was most associated with these AIS scores.

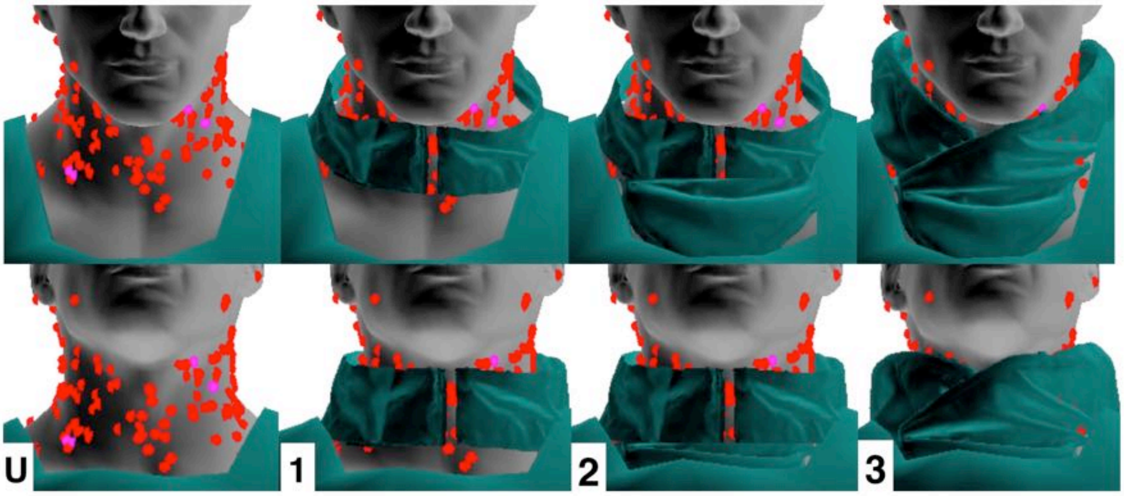


Figure 71: Screenshots from IMAP with all neck wound entry points displayed for the following: Standard UBACS (U), Prototype 1 (1), Prototype 2 (2), Prototype 3 (3).

Predicted projectile origin	**Abbreviated Injury Severity (AIS) Scores**	**UBACS alone (no ballistic protection)**	**Prototype 1**	**Prototype 2**	**Prototype 3**
Horizontal shot line from front	1-6 (all neck wounds)	59	28	23	14
	5+6 only (mortality + morbidity)	15	7	5	3
Ground based shot line from front	1-6 (all neck wounds)	59	23	18	13
	5+6 only (mortality + morbidity)	15	5	4	1

Table 56: Number of entry wound locations still visible and not covered on the assumption that every entry location covered by a collar would have stopped the wound.

13.4.2 Ballistic neck collar analysis

None of the 70 casualties sustaining penetrating neck injuries from energised fragments where the wound location was known during this period were wearing an OSPREY ballistic neck collar at the time of injury. The results for the comparison of potential coverage between the OSPREY half collar, two piece and three piece collars derived from the IMAP tool is demonstrated in Figure 72 and Table 58. When all 59 neck wounds were included (AIS scores 1-6), the OSPREY half collar was the most effective in both horizontal and ground based shot lines. However when only the 15 neck wounds with AIS codes 5+6 were included, both the prototypes were more effective than the OSPREY half. This reflected the tight fit of the collar to the top of the OSPREY vest (covered by the additional semi circle of ballistic protective material in the modified UBACS Prototype 2 design). The three-piece collar was slightly more effective than the two-piece collar for all AIS codes and in all for both horizontal and ground based shot lines.

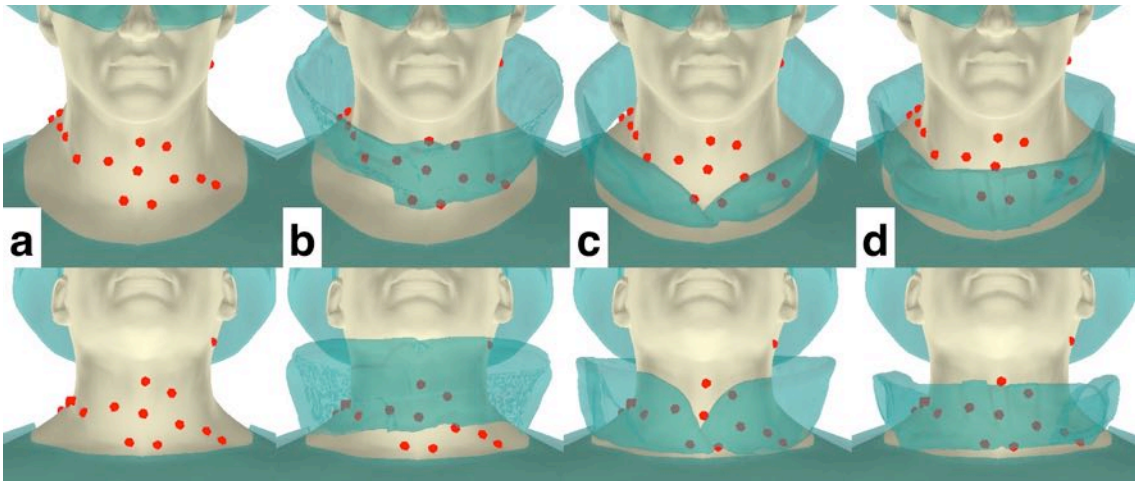


Figure 72: Screenshots from IMAP with only AIS score 5 and 6 neck wound entry points displayed for the following: a) no collar, b) OSPREY half, c) two-piece prototype collar, d) and three-piece prototype collar.

Predicted projectile origin	Abbreviated Injury Severity (AIS) Scores	No neck collar	OSPREY half collar	Prototype two- piece collar	Prototype three- piece collar
Horizontal shot line from front	1-6 (all neck wounds)	59	25	36	33
	5+6 only (mortality + morbidity)	15	2	10	9
Ground based shot line from front	1-6 (all neck wounds)	59	14	23	20
	5+6 only (mortality + morbidity)	15	5	2	1

Table 58: Number of entry wound locations still visible and not covered on the assumption that every entry location covered by a collar would have stopped the wound.

14.5 Conclusions and recommendations

Table 59 summarises the conclusions based upon the process of computerised wound mapping alone. Table 60 summarises those conclusions based upon the neck protection research itself made using the IMAP tool.

Conclusion	Recommendation
Computerised wound mapping using the IMAP tool provided a quick, simple and easily understandable comparison as to the potential medical effectiveness of different neck collar designs. Linking such information to the JTTR can relate coverage to injury mechanism and outcome.	The ability to demonstrate entry wound locations related to protective equipment is a successful concept and should be encouraged in the future. Collection of data should be undertaken by TNCs at the time of collecting clinical data to be coded as AIS scores into the JTTR.
The IMAP tool in its current iteration lacks the functionality to automatically ascertain reductions in hit locations by each prototype.	Investment into the tool should be made to enable this functionality so as to provide the user with a simple comparison between prototypes as to effectiveness.
Limiting entry wound locations to those resulting in death or significant morbidity (AIS scores of 5+6 alone) enabled prototypes to be assessed by their design features and gave clinical relevance. It meant that those prototypes with greater surface area were not necessarily the most effective.	The technique demonstrated how different parts of the neck were more susceptible to injury. This highlighted the importance of representing those underlying anatomical structures within a model. The use of AIS scores alone may enable the relative susceptibility of different anatomical structures to be ascertained without requiring clinical and post mortem information.
Viewing coverage from different angulations again demonstrated the importance of different design features, such as stand off for the skin increasing coverage from ground based threats.	The ability to alter the shot line is an essential tool in any future injury model.
Overlaying body armour designs in this manner must assume that the ballistic protective material was capable of stopping every projectile.	A method for differentiating penetrating of protective equipment based upon projectile type, size and velocity should be sought.
Only the skin surface was included with no relationship between projectile trajectory and underlying anatomy.	The Zygote model includes coordinates for the underlying internal anatomy, which should be developed to provide this utility.
The outcomes used in this approach may potentially be very specific to this conflict (ie Iraq and Afghanistan) and not represent that seen in future conflicts. For example the weapon mechanisms may change or the access to medical treatment may differ, such that an injury to a particular skin region may result in a different clinical outcome in a future conflict.	A method by which injury outcomes can be compared by injury mechanism, projectile trajectory, anatomical vulnerability and the differing retardation of projectiles by different tissues is required.

Table 59: Conclusions and recommendations based upon the process of computerised wound mapping alone.

Conclusion	Recommendation
A gap in ballistic protective material is noted between the undersurface of both OSPREY neck collars and the OSPREY vest. Both the two-piece and three-piece collars are flush with the vest such that no gap exists.	Both the two-piece and three-piece collars designs are recommended for protection in this area instead of the existing OSPREY collars.
When a standard UBACS collar was reinforced with ballistic material alone (Modified UBACS Prototype 1), the gap in the ballistic protective material between the undersurface of both OSPREY neck collars and the OSPREY vest remains. This gap is removed by the addition of semicircles of ballistic protective material in the UBACS Prototype 2 design or by the shape of the collar in the UBACS Prototype 3 design.	Should reinforcing the collar of the existing UBACS be chosen as either an interim measure or in addition to a standard collar, it should include additional semicircles of ballistic protective material at the front and rear.
When all 59 neck wounds were included (AIS scores 1-6), the OSPREY half collar was the most effective, with both the horizontal and ground based shot lines, reflecting its greatest surface area. However when only the 15 neck wounds with AIS codes 5+6 were included, both the prototypes were more effective than the OSPREY half.	When covering wounds entry points of clinical relevance, the OSPREY half collar was the least effective despite its larger size. Development of the smaller prototypes with the more successful design features should be encouraged.
The three-piece collar was slightly more effective than the two-piece collar for all AIS codes and both shot lines.	Surface wound mapping would suggest that the prototype that should be developed further is the three-piece design.

Table 60: Conclusions and recommendations based upon the neck protection research itself made using the Interactive Mapping Analysis Platform tool.

Chapter 15: Use of the Coverage of Armour Tool to differentiate between three neck protection prototypes

Chapter summary

The Coverage Of Armour Tool (COAT) is a shot line numerical model incorporating a three-dimensional representation of those cervical anatomical structures determined from Chapter 3 to be responsible for mortality and morbidity. Coverage of these structures by the same three collar designs tested in Chapter 13 was compared in a variety of azimuths and elevations. COAT demonstrated that despite the OSPREY half collar having almost double the surface area of ballistic protective material than the two prototype collars, it only had 2-4% greater coverage of the vulnerable cervical structures than the prototypes. Significant limitations in the tool do exist in that a shot line approach cannot represent the temporary cavity and permanent wound tract. In addition all protective materials and anatomical structures have equal material properties so that neither tissue nor projectile factors are represented. COAT is recommended for future comparisons of body armour designs but a finite element model approach is recommended as a more ideal long- term solution.

15.1 Aims of this chapter

- To import those cervical anatomical structures believed to be responsible for mortality and morbidity into a novel injury model.
- To use this model to compare the predicted clinical effectiveness of the same three ballistic neck collars utilised in Chapter 14.
- To ascertain if the tool can reflect design and surface area differences to that of predicted medical effectiveness.

15.2 Publications derived from this chapter

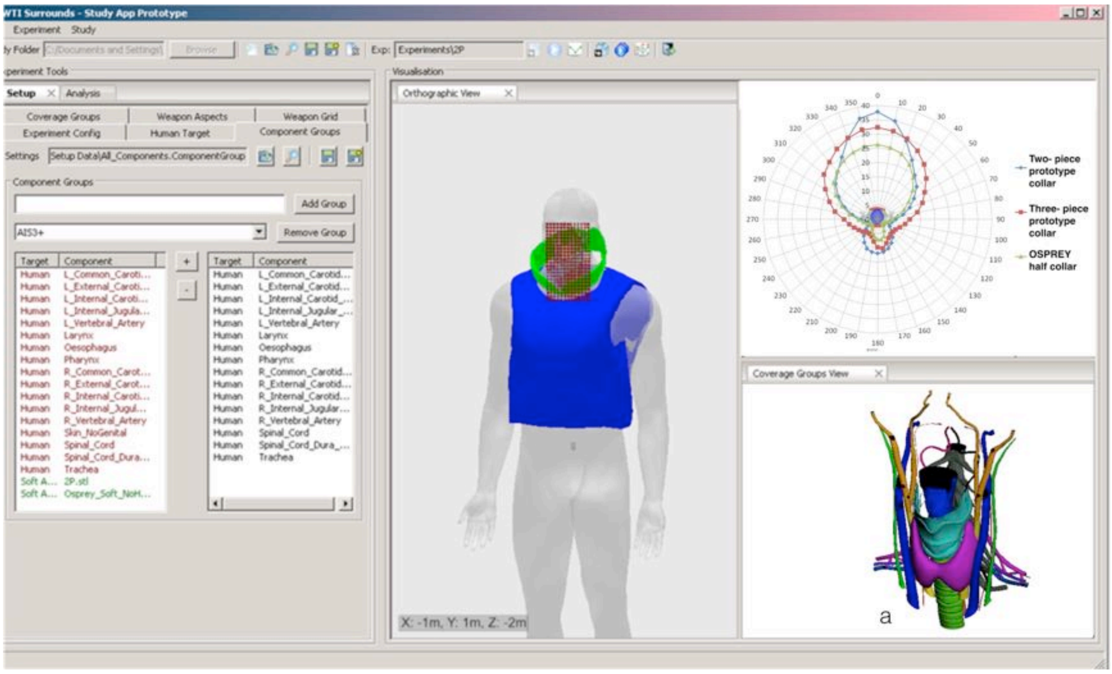
- Breeze J, Fryer R, Hare J, Delaney R, Hunt NC, Lewis EA, Clasper J. Clinical and post mortem analysis of combat neck injury used to inform a novel Coverage of Armour Tool. Injury 2015; DOI: 10.1016/j.injury.2015.01.045 (Breeze et al., 2015f).
- Breeze J, Baxter D, Carr D, Midwinter MJ. Defining combat helmet coverage for protection against explosively propelled fragments. Journal of the Royal Army Medical Corps 2015; 161 (1): 9–13 (Breeze et al., 2015d).

15.3 Collaborations

This chapter describes how COAT was utilised to validate differing designs of ballistic neck protection. The geometry within COAT is again based upon the Zygote, with the tool itself having been developed by Dr Rob Fryer and Dr Jon Hare of Dstl. The author worked with Dstl in the development of IMAP, providing the clinical information and prototypes used to validate its predictions.

15.4 Introduction

The Coverage Of Armour Tool (COAT) has been developed in conjunction with Dstl as another method for objectively comparing the ability of different designs of body armour to cover vulnerable anatomical structures (Figure 73). It is based upon the same Zygote human mesh (Chapter 14) as is used in IMAP; however it also includes not only the skin but a mesh of surfaces representing all anatomical structures down to the smallest named nerves and vessels. The same CAD files of body armour used in IMAP can also be incorporated and overlaid onto these anatomical structures. COAT was developed to overcome some of the limitations in wound mapping, primarily that SWM requires accurate knowledge of both the wound location and the trajectory of the projectile, both of which are often not known.



Folder: C:/Documents and Settings\

Exp: Experiments\2P

Settings: Setup Data\All_Components.ComponentGroup

AIS3+

Target	Component
Human	L_Common_Caroti...
Human	L_External_Caroti...
Human	L_Internal_Caroti...
Human	L_Internal_Jugula...
Human	L_Vertebral_Artery
Human	Larynx
Human	Oesophagus
Human	Pharynx
Human	R_Common_Carot...
Human	R_External_Carot...
Human	R_Internal_Caroti...
Human	R_Internal_Jugul...
Human	R_Vertebral_Artery
Human	Skin_NoGenital
Human	Spinal_Cord
Human	Spinal_Cord_Dura...
Human	Trachea
Soft A...	2P.stl
Soft A...	Osprey_Soft_NoH...

Target	Component
Human	L_Common_Carotid...
Human	L_External_Carotid...
Human	L_Internal_Carotid_...
Human	L_Internal_Jugular_...
Human	L_Vertebral_Artery
Human	Larynx
Human	Oesophagus
Human	Pharynx
Human	R_Common_Carotid...
Human	R_External_Carotid...
Human	R_Internal_Carotid...
Human	R_Internal_Jugular...
Human	R_Vertebral_Artery
Human	Spinal_Cord
Human	Spinal_Cord_Dura_...
Human	Trachea

Figure 73: A screenshot of the Coverage of Armour tool being used to compare the coverage of three different types of neck collar.

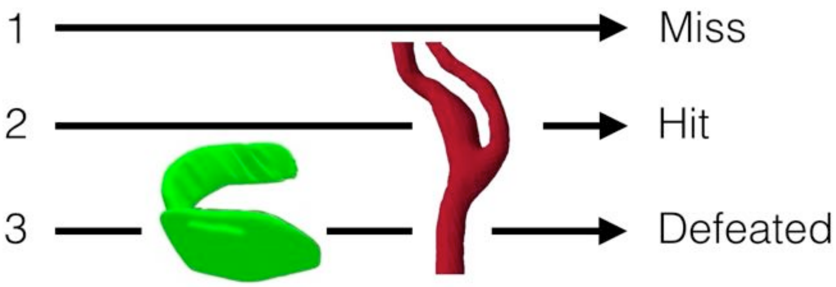


Figure 74: Concept of a shot- line analysis utilising a neck collar potentially protecting the carotid arteries from different projectile trajectories.

COAT uses the concept of a 'shot-line' analysis, meaning that projectiles are assumed to be fired from outside the body and pass through the body in an infinitely thin straight line (Figure 74). A mesh of these shot- lines, generally with 2mm spacing between them, is superimposed over the body area being examined (e.g. the neck) in different angulations about the subject in the horizontal (azimuth) and vertical (elevation) planes

(Figure 75). For example in the horizontal plane, 0^o corresponds to a shot-line originating from in front of the body, 90^o to a shot-line from the subject's right side, 180^o to shot-line from behind and 270^o to shot-lines originating from the subject's left side. In the vertical plane, 0^o represents the shot-line being directed horizontally and -90^o as if the projectile was directed from the ground going directly upwards through the subject.

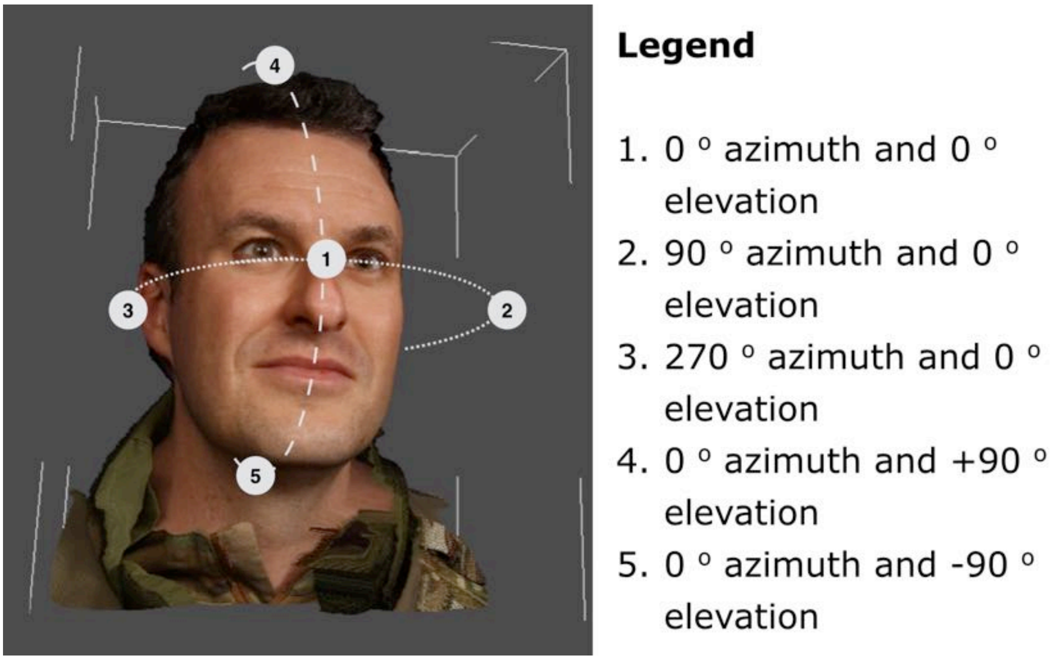


Figure 75: Concepts of azimuths and elevations within the COAT tool. The rear of the head (not visible) would be a 180 ^{o} azimuth and 0 ^{o} elevation.

The clinical and post mortem review described in Chapter 3 identified all those structures responsible for mortality and morbidity and the mesh outlines of these structures were identified within COAT (Figure 76). To remind the reader these structures were the vertebral and carotid arteries (common and internal), brachial plexus, larynx, trachea and spinal cord. It was important to differentiate which structures actually require protection as many anatomical structures are neither responsible for mortality or morbidity. The inclusion of all anatomical structures within the body region being analysed by COAT would merely result in those designs of body armour with the greatest surface area having the most effective coverage. COAT in turn ascertains the percentage of these anatomical structures remaining exposed when overlaid by different designs of personal armour.

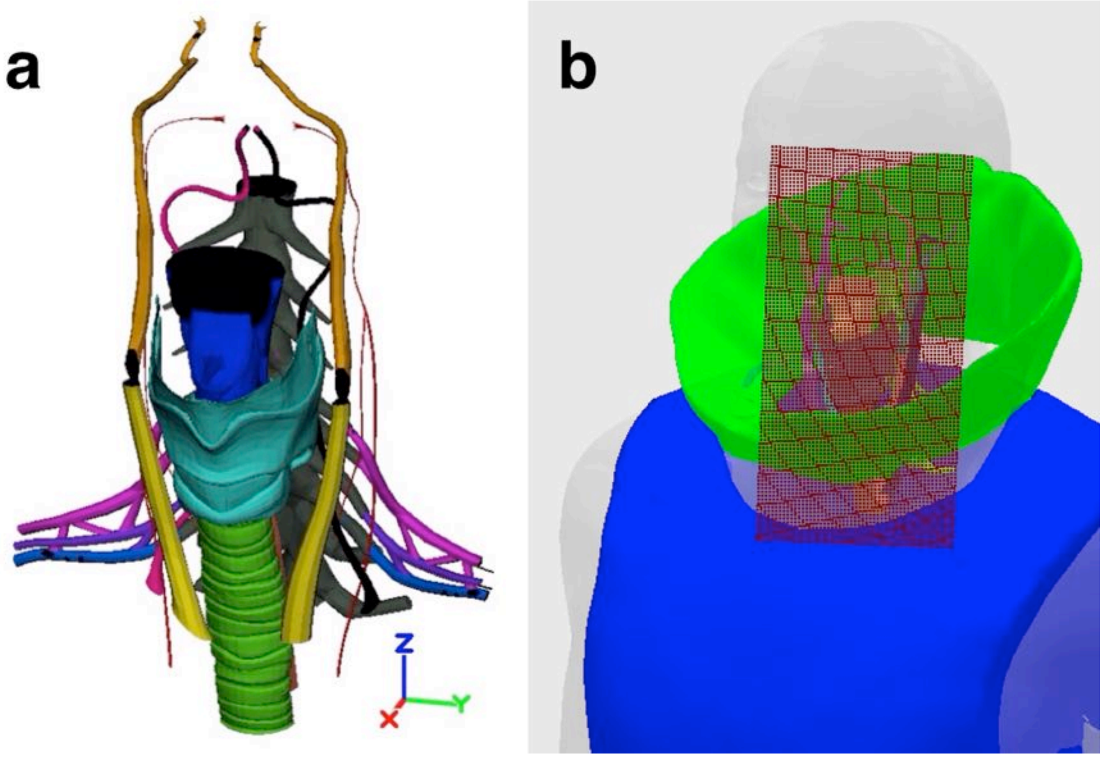


Figure 76: a) Cervical anatomical structures described in the Zygote model responsible for mortality or morbidity; b) With grid superimposed.

15.5 Method

Comparisons of the coverage of the anatomical structures identified as being responsible for either mortality or morbidity were made using the same three collars as in the last chapter on SWM (Chapter 9) to provide a direct comparison (Figure 77). As a reminder to the reader, the OSPREY half collar was made of two overlapping segments with a surface area of $0.0608m^2$. The two- piece and three- piece prototype collars both had a total surface area ($0.026m^2$) as demonstrated in Chapters 6 and 8.

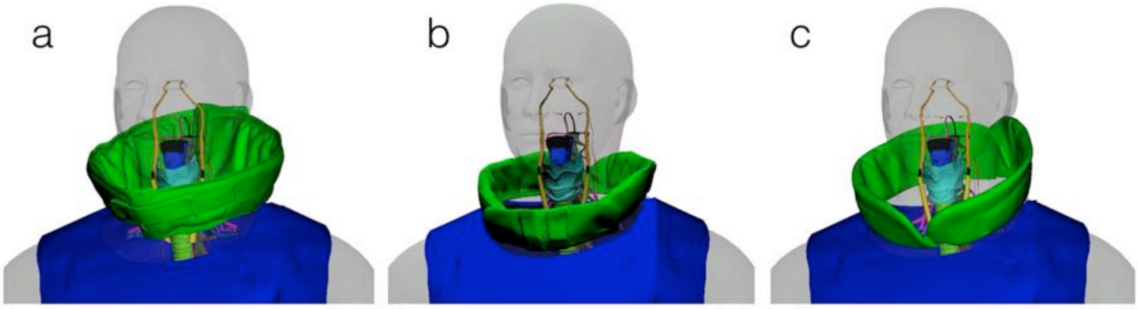


Figure 77: COAT being used to compare collar designs using those anatomical structures identified by post mortem records analysis to be responsible for death or morbidity at 1 year; a) OSPREY half collar, b) Three- piece prototype collar; c) Two- piece prototype.

In another direct comparison to the methodology utilised in the previous chapter, it was again decided to predict coverage that the neck collars would provide against energised fragments originating from the ground, either directly beneath the subject or in front of them. COAT generates a grid that covers those anatomical structures previously determined as requiring protection for one particular shot- line (Figure 76). This grid is then rotated in increments of 10^{o} for a full 360^{o} around the subject in the horizontal (azimuth) plane and from -80^{o} to $+ 10^{o}$ in the vertical plane (elevation). If a shot- line missed the identified anatomical structures then it was discounted (Group a). If it passed through a structure it was classed as a hit (Group b). If the shot- line passed through a neck collar or the soft filler vest prior to passing through any of the structures then the shot- line was counted as being defeated (Group c). The percentage of structures exposed by a particular collar was calculated by subtracting Group c from Group b and then dividing by group b and multiplying by 100. The percentage exposed in all desired shot- lines was then averaged. For example, if 10 out of 50 shot- lines intersect the vulnerable structures without intersecting a protective structure first, that would correspond to 20% exposed.

15.6 Results

COAT predicted that the OSPREY half collar was the most effective of the three collars in that it provided the lowest percentage of the vulnerable anatomical structures left exposed (11.6%). The second most effective was the two- piece prototype (14.4% of vulnerable anatomical structures exposed) and the least effective was the three- piece prototype (16.3% of vulnerable anatomical structures exposed). This effect is pictorially demonstrated in the radial (azimuth) plot which superimposes the coverage of these anatomical structures provided by all three collars (Figure 77) in the horizontal (azimuth) plane over all elevations.

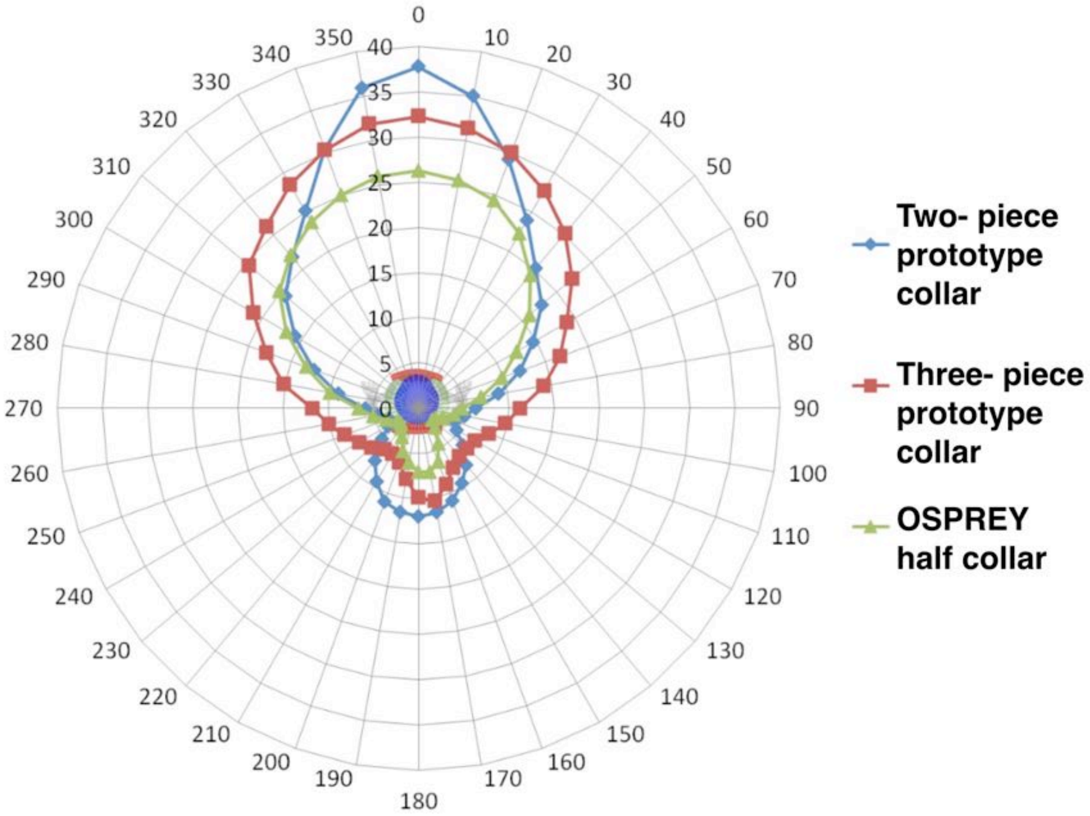


Figure 78: An azimuth plot demonstrating exposure of structures by each neck collar design in a 0 to 360 ° horizontal (azimuth) plane and -80 to +10° vertical plane (elevation).

Hence the further the outline is from the centre of the plot the higher the percentage of vulnerable group that is exposed and the less effective that design of armour is at providing coverage from that particular azimuth. For example from the front (0°) the two-piece prototype has the highest exposure (blue line) but from the sides it is the three-piece prototype (red line) that has the highest exposure. The OSPREY half collar demonstrates the least exposure from all directions.

15.7 Conclusions and recommendations

The following summary is provided in Table 61 and provides the rationale for the research undertaken in subsequent chapters.

Conclusion	Recommendation
COAT demonstrated its ability to objectively quantify the potential effectiveness of body armour designs in providing coverage of vulnerable anatomical structures from different shot line orientations.	The use of COAT should be investigated to ascertain its potential utility in comparing the coverage of different types of personal protective equipment in covering other parts of the body.
Unlike SWM, COAT is not reliant on knowledge of wound locations and therefore can be used for the remaining body where such information has not been collected. COAT is also not reliant on threat specific data, hence can be used to assess situations post Afghanistan where no wounding data will be available initially or to plan with. However this will still require outcome data for damage to anatomical structures of the remaining body, which is not always known.	A quick way of non- clinicians identifying those structures relevant for modelling mortality and morbidity is potentially to use AIS and Functional Capacity Index (FCI) scores respectively. However, it is recognised that the use of such scoring systems, of which anatomical damage predictions only make up one component of their utility, in this manner is not a validated approach and further research should be directed at gaining accurate military specific clinical and post mortem data for the remaining body.
COAT demonstrated that despite the larger OSPREY half collar having almost double the surface area of material than the other two collars, it only reduced the percentage of vulnerable cervical structures left exposed by 2-4% for the prototype collars.	Both prototype collars have little difference to the OSPREY half collar in terms of coverage of structures causing mortality and morbidity and are recommended. The three- piece prototype would appear to be slightly more effective than the two-piece and is recommended over it.
COAT treats all structures and ballistic protective materials as equal, with every protective material completely stopping every projectile and every anatomical structure retarding the projectile equally.	A method of being able to differentiate between the relative retardation produced by different ballistic protective materials and different anatomical structures is required. This should also be dependant upon the mass, shape and impact velocity of the projectile.
COAT uses a grid of infinitely thin shot lines which do not reflect either projectile or tissue factors.	A model should ideally be able to accurately represent both the permanent wound tract and temporary cavity, which are the two mechanisms that result in potential tissue damage.

Table 61: Conclusions and recommendations based upon the findings from Chapter 15.

Chapter 16: Discussion, future directions and the introduction of new neck protection designs for UK armed forces in Afghanistan

Chapter summary

The primary aim of this thesis was to develop more acceptable methods of ballistic neck protection that could replace the existing OSPREY ballistic neck collar. Clinical and post mortem injury analysis, computed tomography interpretation and ergonomics assessments were undertaken, resulting in the recommendation of two prototype designs to the MoD. These two prototypes have subsequently been renamed the Enhanced Protection UBACS (EP-UBACS) and the Patrol collar. Both items are now issued to all UK armed forces deploying on operations overseas. The secondary aim of this thesis was to develop methods to validate the potential medical effectiveness of future body armour designs. Three new novel numerical injury models have been designed using an anthropometrically accurate three- dimensional representation of cervical anatomical structures. Penetration of representative fragment simulating projectiles through skin and muscle was determined experimentally using physical and animal simulants. COAT is being used in the current MoD VIRTUS procurement programme to rule out future body armour designs on clinical grounds.

16.1 Publications derived from this chapter

- Breeze J, Midwinter MJ, Pope D, Porter K, Hepper AE, Clasper J. Developmental framework to validate future designs of ballistic neck protection. British Journal of Oral and Maxillofacial Surgery 2013; 51 (1): 47–51 (Breeze et al., 2013f).
- Breeze J, Allanson-Bailey L, Hunt NC, Delaney R, Hepper AE. Development of the new ballistic neck collar to protect UK soldiers from explosive fragmentation injury

in Afghanistan. Personal Armour Systems Symposium 2014; Cambridge, UK (Breeze et al., 2014a).

- Breeze J, Allanson-Bailey L, Hepper AE, Midwinter MJ. Demonstrating the effectiveness of body armour: a pilot prospective computerised surface wound mapping trial performed at the Role 3 hospital in Afghanistan. Journal of the Royal Army Medical Corps 2015; 161 (1): 36–41 (Breeze et al., 2015a).
- Breeze J, Allanson-Bailey L, Hepper AE, Lewis EA. Novel method for comparing coverage by future methods of ballistic facial protection. British Journal of Oral & Maxillofacial Surgery 2015; 53 (1): 3–7 (Breeze et al., 2015b).

16.2 Introduction

The primary aim of this thesis was to develop more acceptable methods of ballistic neck protection that could replace the existing OSPREY ballistic neck collar. Concerns regarding the acceptability of the neck collar were first identified in January 2009 following a review by the author. This demonstrated a large difference in the incidence of neck wounds sustained by UK soldiers compared to their US counterparts (Chapter 2) and led to the start of this thesis in June 2010. With the assistance of the Defence Academy based at Cranfield University, the first ergonomics trial was undertaken in July 2010 and demonstrated potential design and equipment integration problems with the collar. A six-month detachment away from clinical duties to Dstl Porton Down began the analysis of post mortem records and the implementation of SWM. A further ergonomics trial was undertaken in March 2012, which highlighted two possible acceptable neck collar designs as well as the potential utility of the integrating ballistic protective material into the collar of a UBACS. Both the two-piece and three-piece prototype OSPREY neck collars were equally acceptable in terms of ergonomics and no method of objectively determining potential differences in their medical effectiveness existed. By March 2012, electronic SWM had advanced to a stage where it could be used to objectively compare the medical effectiveness of prototypes. The recommendation to DE&S of the three- piece collar prototype as a more acceptable form of neck protection fulfilled the first aim of this thesis (Table 62). In addition a modified neck collar within the UBACS was demonstrated in the field trial in Afghanistan to be a highly acceptable method of providing additional protection (Figure 84).

Figure 79: The author evaluating one of the modified UBACS neck collar prototypes in a field trial in Afghanistan.

Aims of thesis	Solution
To develop more acceptable methods of ballistic neck protection that could replace the existing OSPREY ballistic neck collar.	Clinical and post mortem injury analysis, computed tomography interpretation and ergonomics assessments were undertaken, resulting in the recommendation of two prototype designs to the MoD. These two prototypes have subsequently been renamed the Enhanced Protection Under Body Armour Combat Shirt (EP-UBACS) and the Patrol collar. Both items are now issued to all UK armed forces deploying on operations overseas.
To develop methods to validate the potential medical effectiveness of future body armour designs.	The development of three new novel numerical injury models using an anthropometrically accurate three- dimensional representation of cervical anatomical structures. The Coverage of Armour Tool is currently being used in the VIRTUS procurement programme to rule out future body armour designs on medical grounds.

Table 62: Primary and secondary aims of this thesis and the solutions developed to fulfil those aims.

It is the opinion of the author that ergonomic assessments remain the key in determining both equipment integration as well as long-term user acceptability. However the financial costs and logistical requirements of such assessments often limit the numbers of designs that can be evaluated. For example the modified UBACS neck collar assessment was undertaken over a two-week long period in Afghanistan in order to recreate truly representative conditions and required over 30 persons to set up and carry it out. Two novel injury models have been developed to objectively compare between the potential clinical effectiveness of different armour designs (Table 62). The use of one or both of these models therefore has the potential to rule out certain future designs on clinical grounds early in their development, thereby greatly reducing the number of prototypes requiring ergonomics assessment (Figure 85). A similar framework will be used for the VIRTUS programme, which aims to procure the personal protective equipment used by UK armed forces in the future and will replace the current OSPREY.

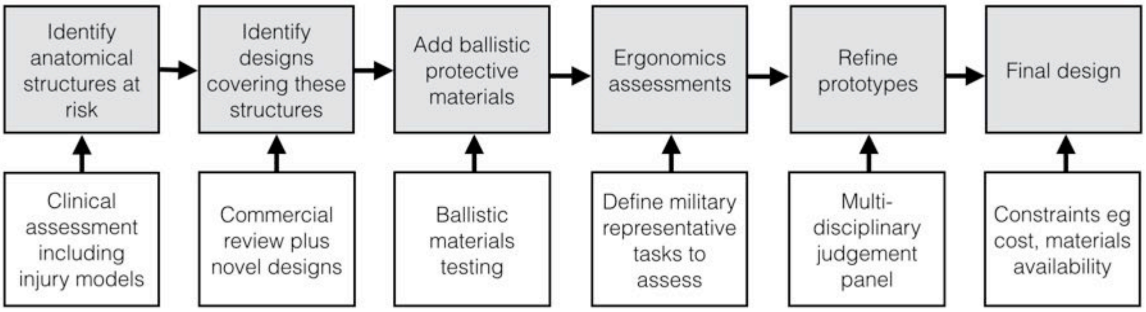


Figure 80: A suggested developmental framework for the design evaluation of future body armour used by UK armed forces in the future.

16.3 Future directions and likely utility for the Interactive Mapping Analysis Platform (IMAP)

Following the initial evaluation of IMAP in Dstl Porton Down to assess the neck protection prototypes (Chapter 14), it was taken by the author on deployment to Camp Bastion in September 2012 to ascertain its practicality when used on a daily basis. Although clinicians could see the potential utility of the tool, the inputting of data was felt to take too much time and the laptop was unwieldy. It was however possible to undertake a prospective trial of full body surface wound mapping, which objectively demonstrated for the first time the effectiveness of other types of body armour worn by UK forces (Figure 81).

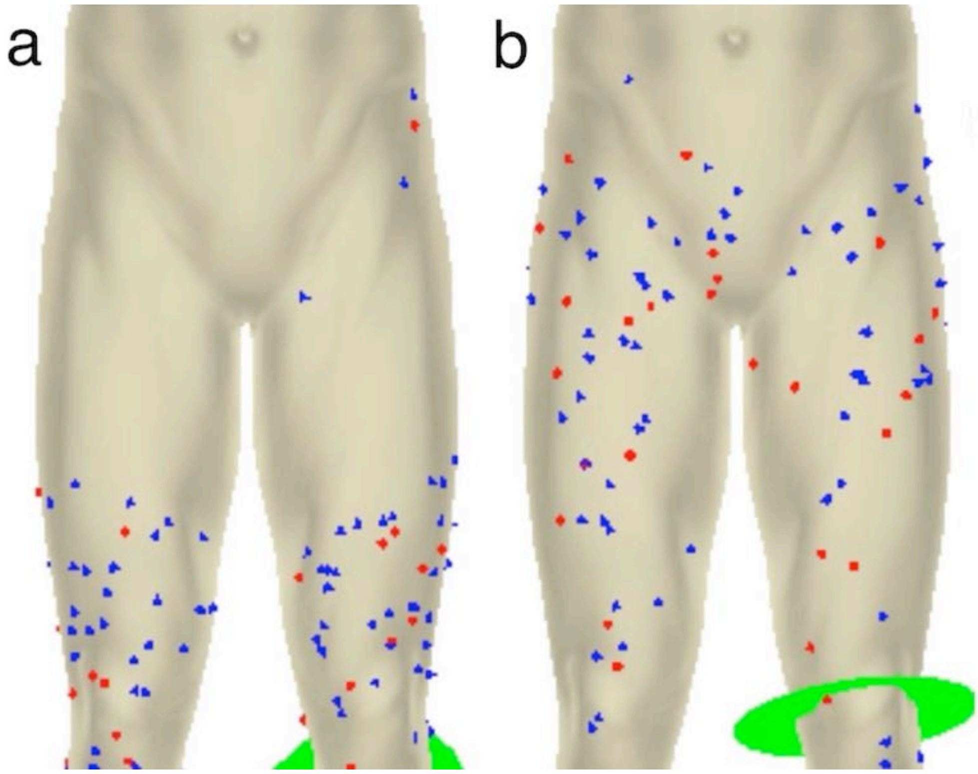


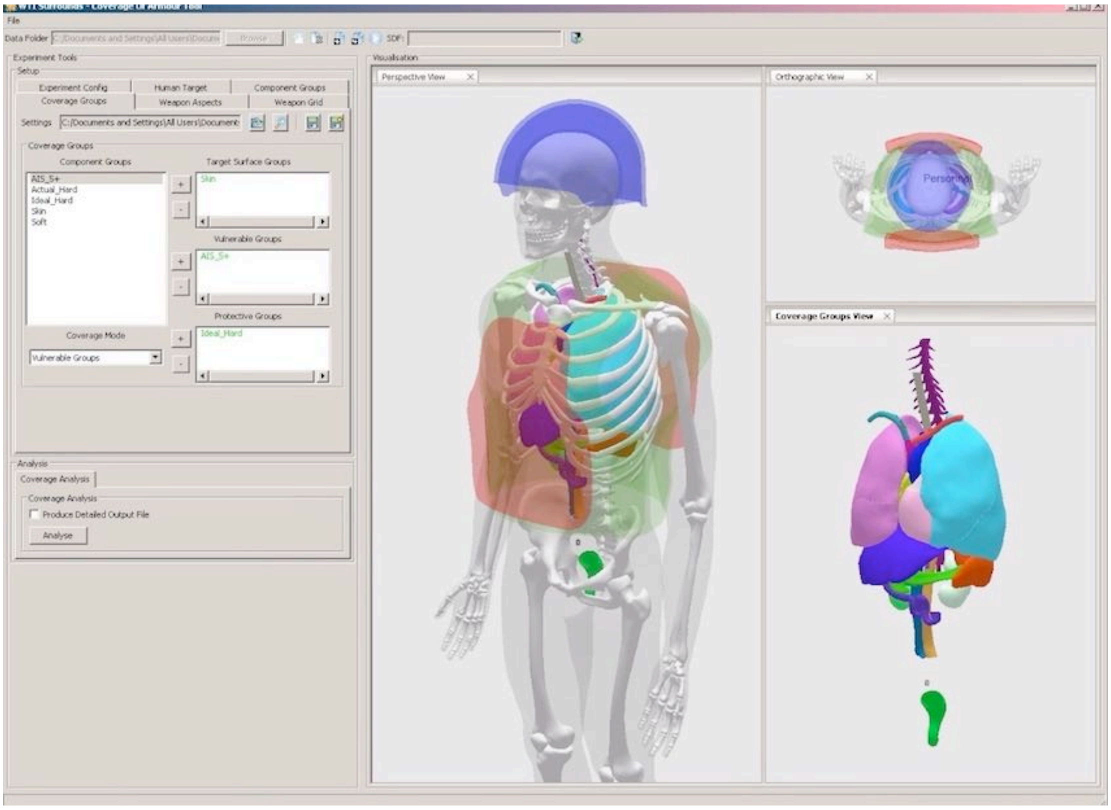
Figure 81: Entry wound locations in casualties: (a) wearing tier 1 or 2 pelvic protection; (b) unprotected casualties. Red dot = fragment large enough to excised; blue triangles = fragments seen clinically or radiologically not excised or removed by scrubbing, green disc = amputation.

In response to the comments from this pilot trial, a simplified version of the tool known as IMAP Lite has been developed by Dstl (Allanson-Bailey et al., 2014). This tool is designed to be used on a tablet style device, with a simplified touch screen data entry process enabling wound information to be inputted in less than one minute per casualty. Outlines of each piece of protective equipment are now included so that entry wound locations can be accurately related to protection (Figure 82). It is expected that these tablets with IMAP Lite will be issued to all Trauma Nurse Coordinators both on deployment and back in the UK to collect JTTR and wound mapping information in future conflicts.

Figure 82: A screenshot of the 'IMAP Lite' software currently running on a portable tablet device demonstrating outlines of ECBA and OSPREY plates on the Zygote. Images kindly provided by Miss Lucy Allanson Bailey, Dstl Porton Down.

16.4 Future directions and likely utility for the Coverage Of Armour Tool (COAT)

In November 2013 it was confirmed by DE&S that COAT would be used to provide the medical comparisons between body armour designs for the VIRTUS programme, which aims to procure the body armour worn that will replace the current OSPREY. As of the completion of this thesis in October 2014, COAT is being utilised in the assessment of the potential commercial soft armour components of VIRTUS. The author has completed a literature review to identify those thoracic and abdominal anatomical structures that require protection using a methodology similar to that described in Chapter 4, which will be used to compare potential designs of ceramic plates (Figure 83).


Data Folder: C:/Documents and Settings/All Users/Docum
Settings: C:/Documents and Settings/All Users/Document

Component Groups: AIS_5+, Actual_Hard, Ideal_Hard, Skin, Soft
Target Surface Groups: Skin
Vulnerable Groups: AIS_5+
Protective Groups: Ideal_Hard
Coverage Mode: Vulnerable Groups
☐ Produce Detailed Output File

Figure 83: The COAT programme being used to compare the anatomical coverage provided but the current OSPREY plate using the vulnerable structures identified by the author. Image kindly supplied by Dr Rob Fryer, Dstl.

16.5 Development of a finite element numerical neck model

Although IMAP and COAT are successful tools that have already proven their worth in enabling objective medical comparisons of body armour designs to be made, each has a number of inherent limitations to their capability that cannot be overcome. In response to this, development of a Finite Element (FE) model has begun, again using the neck as a starting point due to the considerable amount of work that has already been invested into this body area by the author. In terms of the numerical capabilities potentially available to the Ministry of Defence, an FE approach may be considered as the highest fidelity method for modelling the problem of energised fragments penetrating the neck. A model is currently under construction by Dstl that utilises the same three-dimensional mesh of cervical anatomical structures demonstrated to be responsible for mortality and morbidity as utilised in the COAT model. However in this approach, the meshes of anatomical structures, neck protection prototypes and fragment simulating projectiles, are represented by discrete parallelopoid 'elements' (Figure 84). The elements comprising each cervical anatomical structure are assigned an appropriate ‘material model’ from which the stresses and strains due to dynamic loading are determined. A 'material model' can be thought of as a set of equations that represent the specific biomechanical responses of that individual tissue or material under ballistic impact

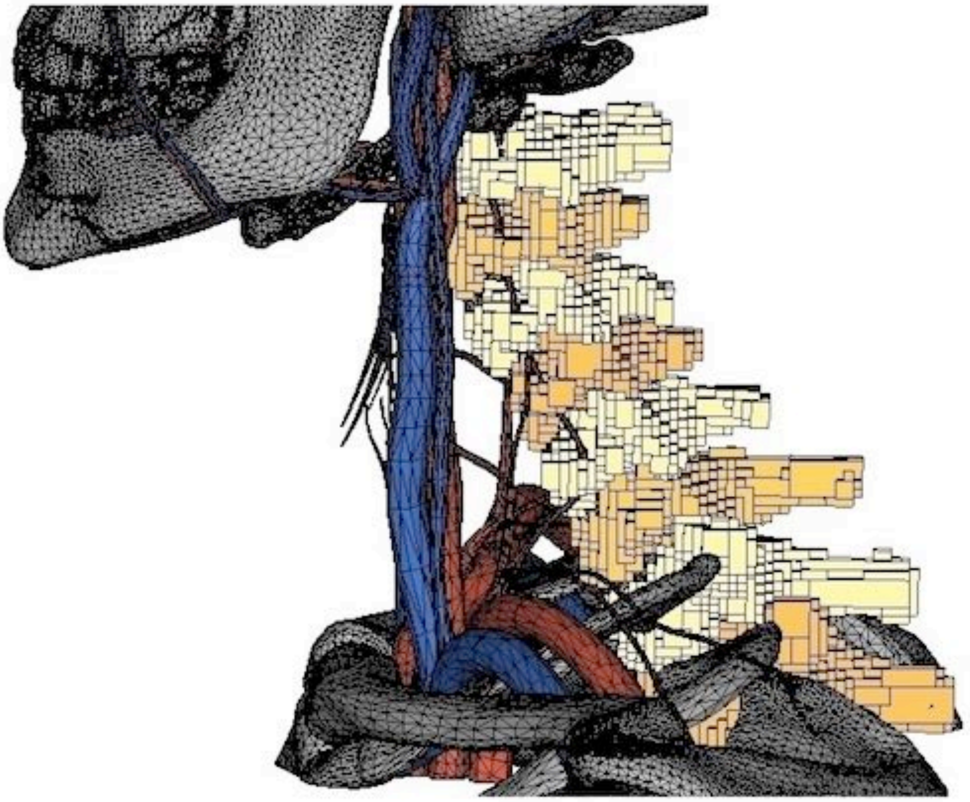


Figure 84: A three-dimensional mesh of cervical neurovascular structures in which the spinal cord is undergoing discretisation into elements that can each be assigned a material model for the tissue type it represents. Image kindly supplied by Dr Dan Pope, Dstl.

One significant advantage of this FE approach is that the properties of every component of the model can be tailored, including the body armour and projectile (Figure 85). In addition the fidelity of the model can potentially be increased by subdividing a structure into its component parts. For example a blood vessel could, at its simplest, be considered as a cylindrical tube of a single tissue type (requiring a material model to represent it) surrounding a single type of fluid representing blood requiring a second material model. The fidelity of the model can be increased by representing the blood vessel wall in its true three individual layers instead of a single homogenous layer; however each layer in turn will require its own material model to represent its individual biomechanical properties, greatly increasing the complexity of the model. A basic material model for each tissue type requires a value for the density of the material as well as two additional types of equations. The first describes the ‘strength’ of the material, representing strain versus stress in different directions. The second equation is the 'Equation of State' (EoS) of the material, representing how pressure develops under a given level of hydrostatic compression as well as any accompanying change in internal energy due to such deformation.

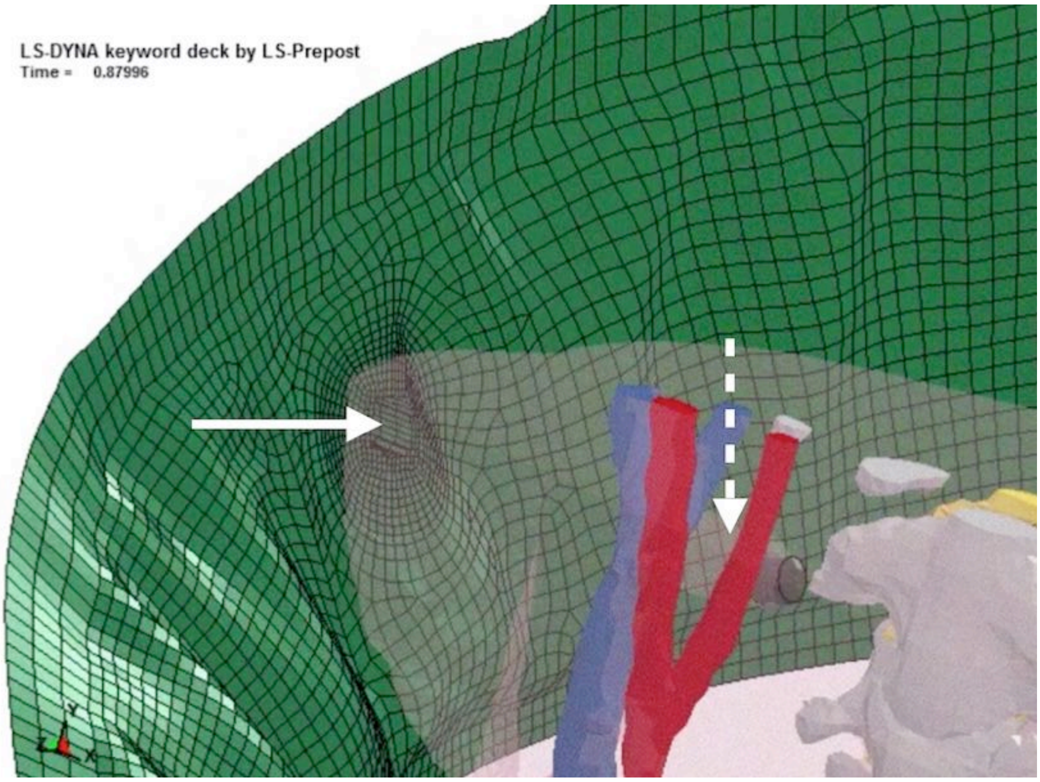


Figure 85: FE model demonstrating the deformation in para- aramid neck collar (solid arrow) and permanent cavity produced by FSP interacting with the internal carotid artery (dashed arrow). Image kindly supplied by Dr Dan Pope, Dstl.

Ascertaining the values experimentally required to populate these material models is still highly challenging as the high compressive strain rates (100-2500/s) and large deformations characteristic of typical impact scenarios require a fresh sample of each tissue type, utilising techniques that have only been developed relatively recently (Van Sligtenhorst et al., 2006; Trexler et al., 2011). A review of the open literature by the author demonstrated very limited original experimental data from which to derive these material models (Table 63).

Anatomical structure	**Density (g/cm^3)**	**Closest available material model**
Spinal cord	1.03	Human spinal cord (Bilston and Thibault, 1996)
Cortical bone	1.850	Human cortical bone (McElhaney, 1966)
Cancellous bone	0.65	Human cancellous bone (Shim et al., 2005)
Muscle	1.06	20% gelatin (Aihaiti and Hemley, 2014)
Muscle	1.06	Bovine muscle (Van Sligtenhorst et al., 2006)
Skin	1.03	Porcine skin (Shergold et al., 2006)
Adipose tissue	0.94	Porcine fat (Comley and Fleck, 2012)
Artery and vein walls	1.07	Human artery (Prendergast et al., 2003)
Blood	1.06	Water (Trexler et al., 2011)
Nerve	1.03	Human spinal cord (Bilston and Thibault, 1996)

Table 63: Material models used to represent anatomical structures within the latest iteration of the finite element neck model.

The first iteration of the model will use a material model for all structures based on that of 20% gelatin, which has in this thesis been demonstrated to reproduce the penetration of FSPs into animal muscle (Figure 86). Comparisons between the size and shape of the permanent cavity produced in the numerical model demonstrated excellent correlation to that produced from high speed video images of firings into 20% gelatin (Figure 87).

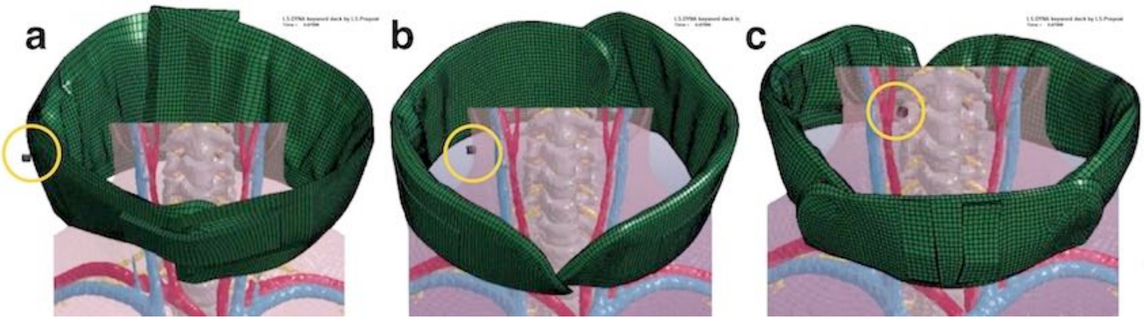


Figure 86: The OSPREY half collar (a), two-piece (b) and three-piece prototypes (c) incorporated into the FE model being run with the same 1.10g FSP (circled).

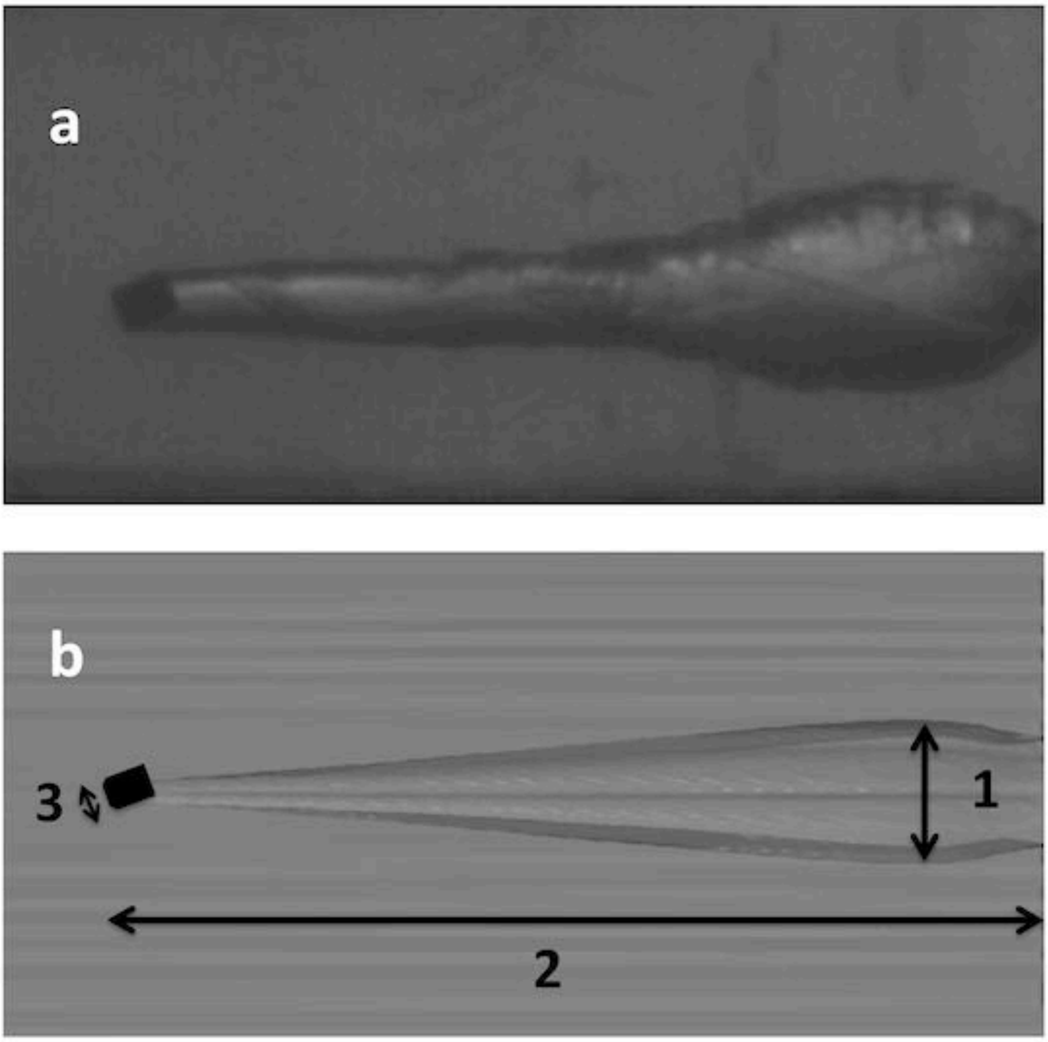


Figure 87: The material model identified for 20% gelatin provided excellent correlation between that produced by a projectile experimentally (a) and numerically (b); Permanent Cavity Width (1), Depth of Penetration (2) and Projectile Width (3).

The intention is to replace the material models for 20% gelatin with individualized ones identified in Table 60. However concerns regarding the suitability of the equations used in the models as well as a lack of models on structures such as bone mean that further experimental testing will be required. A preliminary trial testing fresh pig tissue at high strain rates was undertaken in May 2014, which demonstrated that ascertaining these values will be highly challenging due to the small size and sensitivity of the equipment required (Figure 88).

Figure 88: A sample of pig skin (left) has been placed into a device capable of generating a constant strain (right) causing distortion of the tissue measured using digital image correlation.

The ability to compare even a few test shots using the FE model against the most representative physical model possible would provide great reassurance as to its predictions. In response to this requirement for a method of potential validation, testing of the neck region of PMHS started at Wayne State University USA in March 2013. As of the completion of this thesis, tests on three of the planned ten subjects have been carried out (Figure 89).

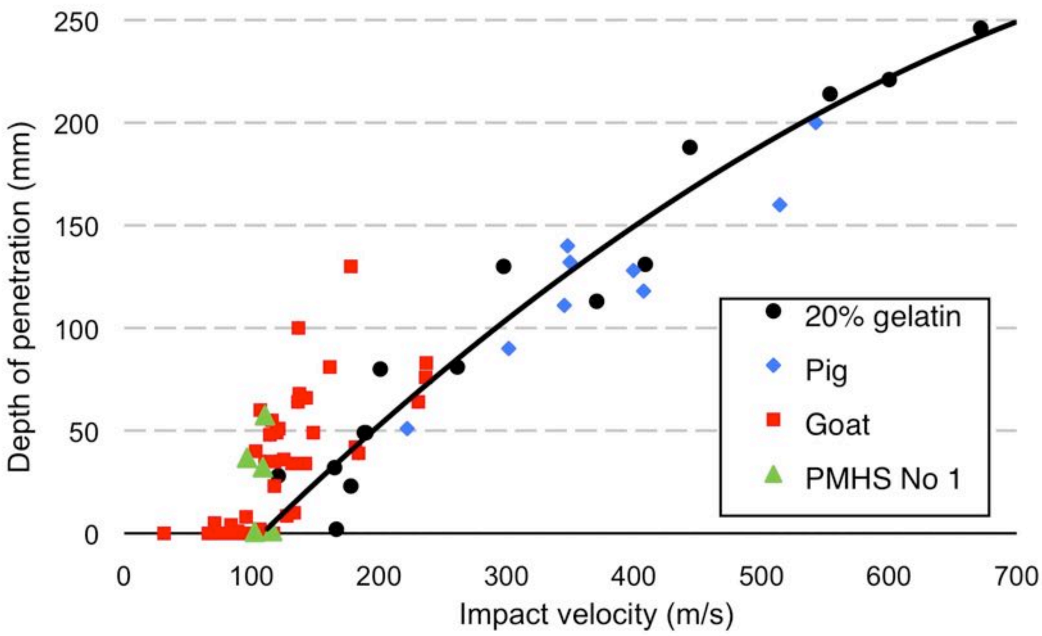


Figure 89: Testing into the neck of PMHS specimen number 1 undertaken at Wayne State University using a 0.49g cylindrical FSP compared to results from Chapter 11.

CT scans of each subject have been taken before and after completion of firing to enable accurate analysis of projectile passage through tissues and exclude bone impacts (Figure 90). These scans could then be converted into a three- dimensional mesh of the anatomical structures analogous to the Zygote model. This could in turn be converted into finite elements and populated with representative material models. It would then be possible to compare in three dimensions the predicted passage of each projectile to that seen experimentally.

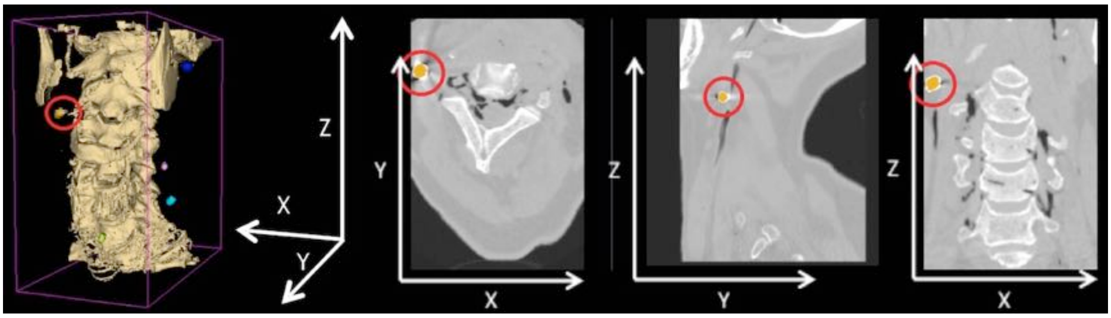


Figure 90: Computed Tomography scans taken after testing into the neck of PMHS specimens number 1 using a 0.49g cylindrical FSP.

The final requirement for the FE model is to provide an objective method for quantification of potential damage such that prototypes can be compared. Currently the model only includes those anatomical structures known to be responsible for mortality and long-term morbidity. Currently the FE model uses the assumption that any overlap of the permanent cavity means that the structure is destroyed, with no recognition of the effects of irreversible tissue damage lateral to that. An experimental trial has been planned in which tissue around the wound tract after firing is examined histologically, and an attempt made to correlate that to clinical outcome.

16.6 Introduction of Enhanced Protection UBACS (EP-UBACS) for use by UK armed forces in Afghanistan

Following the research described in Chapters 8 and 9, the modified UBACS Prototype 1 design was turned into a pre-production model and underwent an independent ergonomics trial run by ITDU between 21-27 October 2012 (Thorp, 2013). When used in conjunction with the three-piece neck collar prototype, no gap in ballistic protective material was seen above the OSPREY vest and therefore the additional semi circles of ballistic protective material below the collar were not required. The modified UBACS Prototype 1 design was formally renamed the Enhanced Protection UBACS (EP-UBACS) and was adopted into service by DE&S to replace the standard UBACS on 10 October 2013 for all UK soldiers deploying to Afghanistan on Operation HERRICK 19. The function of the revised neck collar within the EP-UBACS is to act as an irreducible minimum of protection (Tier 1), with the more traditional neck collar attached to the ballistic vest used in situations of greater threat or in static positions (i.e. providing Tier 2 level of protection). The full DE&S manufacturer specifications can be found in

Appendix D but the revised collar incorporates a layer of UHMWPE felt with a height recommended from the anthropometric assessment described in Chapter 6 (Figure 86).

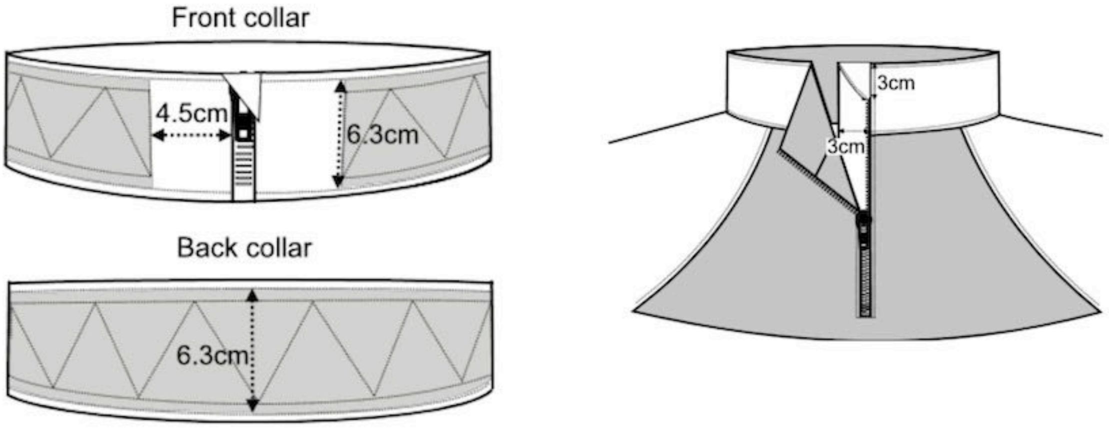


Figure 91: Manufacturer design specifications described by DE&S for the collar within the EP-UBACS. A full description is in Appendix D.

There is little change in the external appearance of the garment (Figure 92), with the exception of making the whole shirt in the Modified Terrain Pattern. In order to reduce chaffing of the skin under the chin when the collar portion is fully zipped up, a slip of material that covers the zip in this position has been added (as recommend in Chapter 8). Informal conversations with soldiers deploying on the last tour to Afghanistan before the drawdown (Operation HERRICK 20), found that users did not notice any change in the performance of the garment compared to its predecessor. The EP-UBACS has become a core piece of equipment for the UK armed forces and it is intended that it will be worn in conjunction with the new VIRTUS body armour when it is procured in the future.

Figure 92: The EP- UBACS issued to all UK armed forces since November 2013 incorporates UHMWPE felt in the neck collar (box insert). Note Modified Terrain Pattern is used throughout and a slip of material covers the zip at the top (circled).

16.7 Introduction of the Patrol Collar for use by UK armed forces in Afghanistan

At the time of the commencement of this thesis in June 2010, UK soldiers deploying on operations to Afghanistan were issued with two sizes of neck collar to attach onto the OSPREY vest (Figure 88). These collars had remained unchanged since the introduction of the OSPREY system in 2006, despite a generalised dislike of the design by soldiers on the ground. The research described in this thesis identified this problem to those responsible for body armour procurement at DE&S and work towards the development of a more acceptable replacement ensued.

Figure 93: The full (a) and half (b) neck collars used in the OSPREY Mark IV system immediately prior to the introduction of the three- piece prototype subsequently renamed the 'patrol' collar (c).

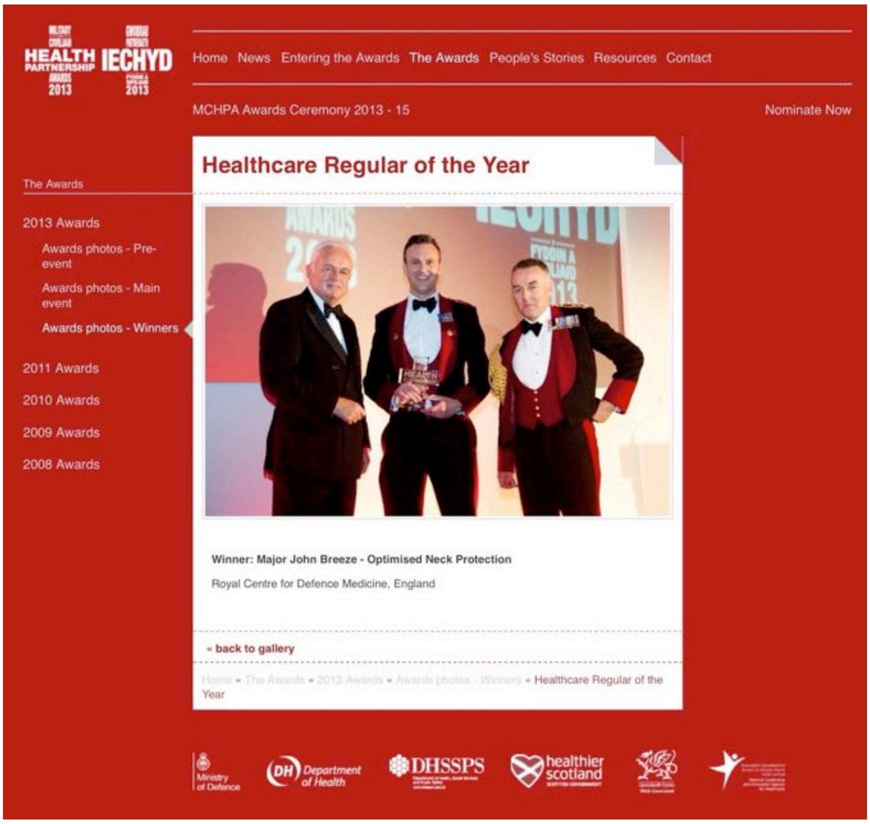
Following ergonomics assessment of a number of experimental prototypes (Chapters 8 and 9) and SWM analysis available at the time, the three- piece prototype was selected as the most successful candidate. The three-piece prototype was turned into a pre-production model and underwent an ergonomics trial run by ITDU between 21-27 October 2012 which the author of this thesis helped to run (Thorp, 2013). A number of problems were identified that necessitated further modifications before it could be considered for operational use. The collar was visibly not flush with the OSPREY vest at the front, which was solved by the addition of two press- stud loops. In addition the three segments of the collar collapsed after repeated use, which was subsequently solved by the addition of Velcro strips between them. The three- piece prototype has subsequently been renamed the 'Patrol collar' and since 13 February 2014 has been issued to all UK soldiers deploying to Afghanistan on Operation HERRICK 20 (Figure 89). Excerpts from the updated DE&S manufacturer specification for OSPREY, which includes the Patrol collar, can be found in Appendices E and F.

Figure 94: UK soldiers on foot patrol in Afghanistan in March 2014 during Operation HERRICK 20 wearing both the Patrol collar and an EP-UBACS beneath the OSPREY Mark 4 vest.

16.8 A final word

The Patrol Collar is not intended to be the ultimate solution in the design of ballistic neck collars and limitations do exist. The clinical data from which the design was based upon, as well as the role in which it was developed to perform, may be quite specific to Afghanistan and not necessarily be applicable to future conflicts. Indeed when the requirement for the VIRTUS procurement programme to replace OSPREY was put into open commercial tender, the author assisted DE&S in ensuring that the specifications defined only the optimal anatomical coverage for each part of the body. In this way manufacturers will have free reign over the actual designs, potentially maximising both clinical effectiveness and ergonomic considerations. At the time of completion of this thesis in October 2014, the soft armour components for VIRTUS were in the process of being down- selected, with the COAT tool being used by the MoD in commercial tender to provide the basis for optimal anatomical coverage. The anatomical structures within the neck used for the VIRTUS assessments were taken from this thesis. It will therefore be of great interest to see what designs of neck protection these commercial companies have developed when compared to those developed for this thesis and when not limited by the existing shape of the OSPREY vest.

It is the authors hope that the adoption of both the Patrol Collar and the EP-UBACS will reduce the considerable burden of neck injuries from energised fragments sustained by UK soldiers in future conflicts. COAT is currently being utilised by DE&S as the primary method for comparing the potential medical effectiveness of commercial body armour design tenders for the VIRTUS programme. In recognition of this research, the author was very privileged to be awarded Military Healthcare Person of the Year 2013 following nomination by Brigadier Gaunt of DE&S (Figure 97). In March 2015 he was also awarded the Mitchener Medal by the Royal College of Surgeons for the development of the Patrol collar.



Healthcare Regular of the Year

Winner: Major John Breeze - Optimised Neck Protection

Royal Centre for Defence Medicine, England

Figure 95: The author being presented the Healthcare Regular of the Year award on 26 June 2013 at the national Military and Civilian Healthcare Partnership Awards ceremony in Cardiff, Wales.

16.9 Stop press

One week before the final submission of the thesis, and following the viva and corrections in March 2015, the soft armour components for VIRTUS were finally announced by MoD. The provisional design is demonstrated in the DE&S 'Desider' magazine (Appendix G), confirming that the VIRTUS neck collar will be a three- piece design almost identical to that developed in this thesis.

Chapter 17: Conclusions

Relevance of neck injuries to future combat operations

- During the conflicts in Iraq and Afghanistan, neck wounds were present in 11% of injured soldiers.
- 79% of neck wounds were from energised fragments but only 7% of soldiers were wearing their issued OSPREY neck collars at the time of injury.
- In 64% of soldiers killed with a penetrating neck wound, the neck was contributory to death, primarily from spinal cord or vascular damage with a smaller contribution from airway compromise.
- 16% of survivors sustaining a neck wound had an injury that caused functional, aesthetic or psychological consequences at one year post injury, primarily from brachial plexus damage and trauma to the larynx or its innervations.

Fragment simulating projectile selection

- CT scans can potentially increase the number of retained fragments that can be measured and their mass and shape determined to select appropriate FSPs.
- Strong evidence was found for the use of cylindrical FSPs, with additional evidence that a 0.49g may supplement the existing 1.10g in testing materials to protect the neck.

Neck protection designs identified through ergonomics assessments

- The following design features were identified from the most successful prototypes: overlapping segments, stand-off from neck skin, coverage no greater than the base (Zone 1) of the neck.

- Nape pads are not supported due to prevention of the soldier lying in the prone position.
- The development of thermistors incorporated in protection designs and clothing are encouraged to enable continuous monitoring of physiological data.
- Incorporation of ballistic protective material into the collar of a UBACS represents an acceptable method of providing a baseline level of neck protection (Tier 1).
- A novel three- piece collar that attaches to the OSPREY vest was the most acceptable method for providing enhanced (Tier 2) neck protection.

Physical stimulant testing

- Goat skin significantly increased the threshold velocity required for perforation compared to 20% gelatin for the 0.16g FSP, necessitating inclusion of a skin layer into future penetration models should this FSP necessitate further evaluation.
- 20% gelatin was demonstrated to reproduce the depth of penetration for 0.49g-2.89g cylindrical FSPs and a 0.51g sphere fired into animal muscle.
- Early experimental evidence produced in this thesis would suggest that differing storage methods post mortem do not affect projectile retardation but further testing is required to confirm this hypothesis.

Surface would mapping using IMAP

- Computerised wound mapping linked to JTTR provides a simple but robust method for pictorially representing the entry wound location of any penetrating energised fragment.
- Wound entry locations can be related to armour coverage and thereby provide some indication as to the effectiveness of differing designs.

- The further development of a handheld touch screen device carrying IMAP Lite is encouraged to enable rapid data collection at the time of observing the wound directly.

Coverage of armour assessments using COAT

- Superimposition of armour designs onto an anthropometric three- dimensional representation of those anatomical structures causing mortality and morbidity is a powerful tool in comparing their potential medical effectiveness.
- Despite having half the surface area of the OSPREY half collar, both prototype collars were demonstrated to have little difference in terms of coverage of these vulnerable anatomical structures.
- The three- piece prototype has slightly better coverage than the two- piece collar in terms of covering structures causing mortality alone and is therefore recommended over the two-piece collar.

Future directions and implementation of novel methods of neck protection into service

- IMAP Lite is available on a touch screen hand held tablet with the intention for it to be used by TNCs in future conflicts as the primary data entry device for all JTTR data as well as wound mapping information.
- Based upon its success in this thesis, COAT is being used as the main method in the VIRTUS procurement programme for comparing the potential medical effectiveness of body armour designs.

- The three- piece prototype collar has been designated the Patrol collar by DE&S and has been issued to all deploying UK forces instead of the previous OSPREY collar since February 2014.
- The reinforced UBACS has been designated the Enhanced Protection UBACS by DE&S and has been issued to all deploying UK forces instead of the standard UBACS since October 2013.

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Appendix A: Excerpts from the original OSPREY Mark 4 body armour user instructions

Osprey Mk 4 Body Armour

de&s

JOINT SUPPORT CHAIN

USER CARE AND ASSEMBLY INSTRUCTIONS

MINISTRY OF DEFENCE

Osprey Mk 4 Body Armour

Body Armour Cover- Vest Front- x1

Body Armour Cover- Vest Back- x1

OPS Panel & T Bar fittings - x1

Waistbands Set - x1

Shoulder Guards, Pair
Left & Right with
elasticated fittings - x1

Brassards, Pair
Left & Right with
elasticated
fittings - x1

Cummerbunds, Pair Left & Right - x1

2 Piece Full Collar - x1

Ancillaries Set - x1

2 Piece Half Collar - x1

Blanking Panels,
Pair - x1

Accessories & Parts Listing

Front Armour
Plate - x1

Back Armour
Plate - x1

Pair Small Armour
Plates - x1

Front Plate Cover - x1

Back Plate Cover - x1

First Aid
Pouch
x1

Commanders
Pouch
x1

Water
Bottle Pouch
x1

LMG 100
Round Pouch
x1

UGL 8
Round Pouch
x1

Utility
Pouch
x1

SA80 2 Mag
Ammo Pouch
x4

SA80 Single Mag
Ammo Pouch
x3

SA80 Single Mag
Ammo Pouch
x3

Sharpshooter
3 Mag Ammo Pouch
x1

9mm Pistol
Ammo Pouch
x2

AP Grenade
Pouch
x2

Smoke Grenade
Pouch
x2

NB: A set of Soft Armour is also included but has not been illustrated.

Light Fighting Order

Complete Fighting Order

Appendix B: Subjective questionnaire for modified neck collar UBACS ergonomics assessment

Reinforced UBACS Neck Collar Prototypes Trial Questionnaire V2

Candidate number:			Assessor:	
Date:			Time:	
Temperature at start:			Configuration number:	

Please **circle** the colour which best describes your experience

Comfort

The neck collar was comfortable to wear during the assessments

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

Additional Comments:

Equipment integration

The collar fitted together well with the other clothing and equipment when carrying out the functional assessments

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

Additional Comments:

Heat dissipation

The collar made you feel more hot when carrying out the functional assessments

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

Additional Comments:

Acceptability

The collar would be acceptable to wear when patrolling in Afghanistan

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

Additional Comments:

Ability to reduce injuries

The collar would mean that you are less likely to get injured when patrolling in Afghanistan

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

Additional Comments:

Appendix C: Excerpts from the manufacturer specifications for the Enhanced Protection Under Body Armour Combat Shirt (EP-UBACS)

DC/MS/6584-2 Issue 05
15 April 2013

Manufacturing Specification for
SHIRT, ENHANCED PROTECTION, UNDER BODY ARMOUR, COMBAT (EP-UBACS), Multi-Terrain Pattern (MTP), Personal Clothing System (PCS), Combat Uniform (CU)

Defence Clothing (DC)

PROPERTY OF
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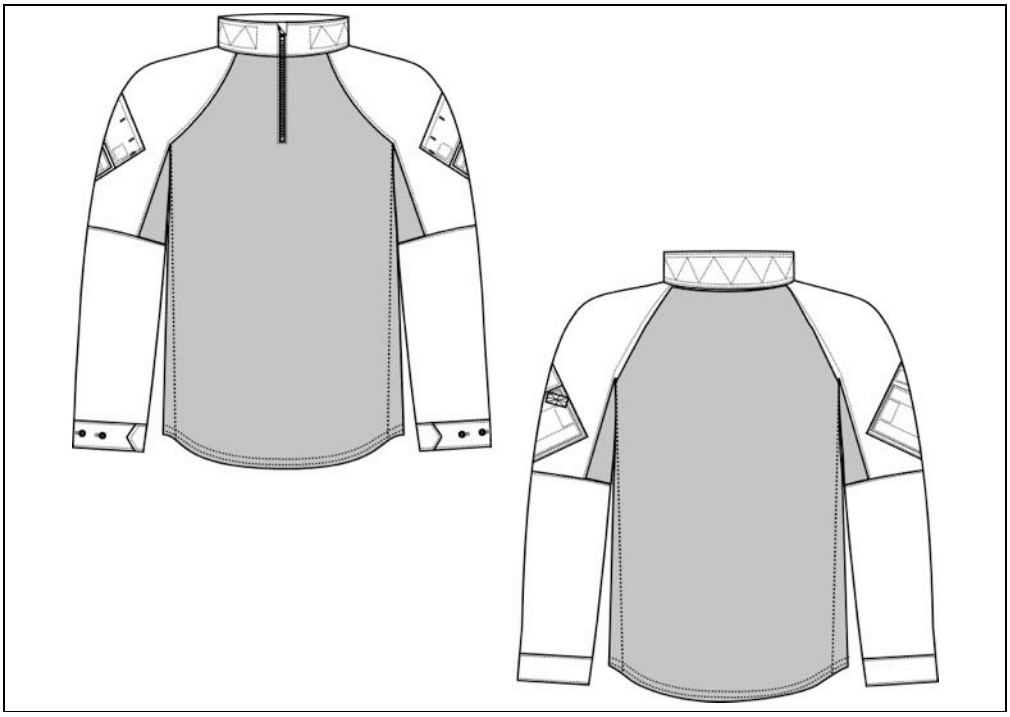
Defence Equipment & Support

MINISTRY OF DEFENCE

THE PRODUCT

Item Description	**NATO Stock No(s)**	**Pattern No.**
SHIRT, ENHANCED PROTECTION, UNDER BODY ARMOUR, COMBAT, (EP-UBACS), Multi-Terrain Pattern (MTP), PCS, CU		
Insect repellent treated	8415-99-488-8932 to 8938	D02223
Untreated	8415-99-488-8939	D02223TG

Technical Support	Defence Clothing



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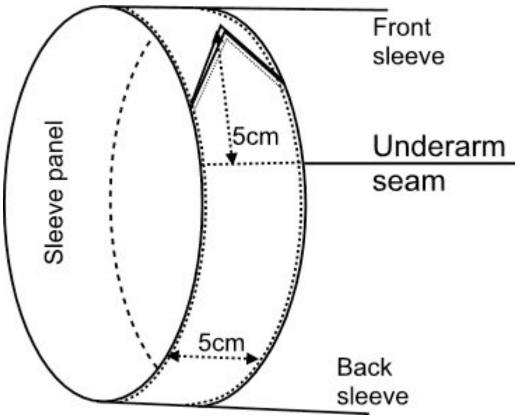
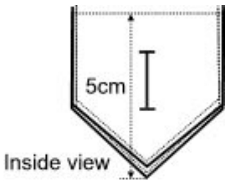
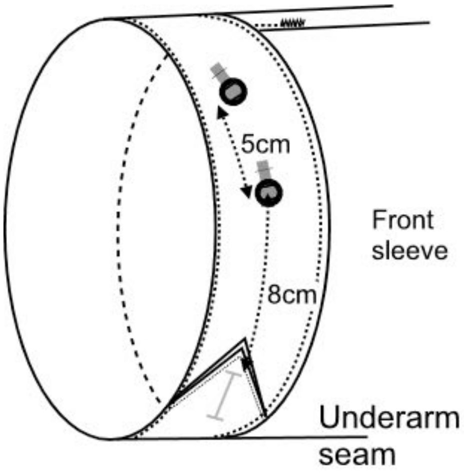
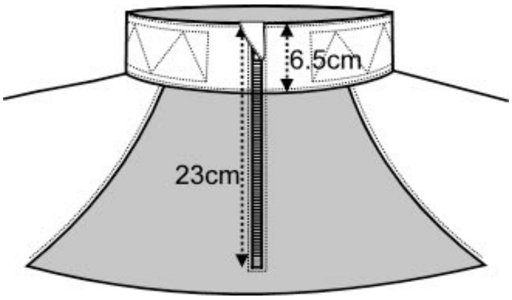
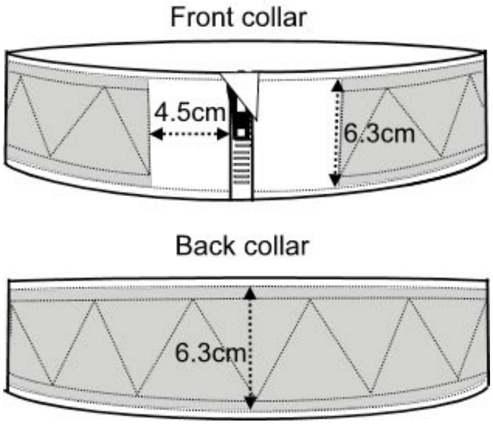
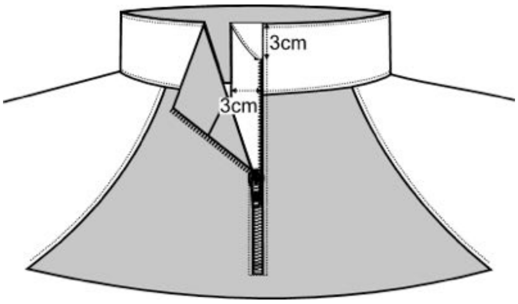
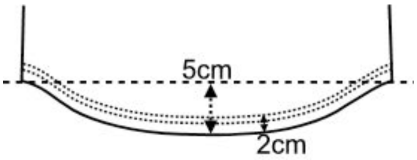
1. ISSUE RECORD

Issue No	Comments	Issue Date
5	Table 2 – correction to Absorption & Evaporation values in line with DC/MS/6578 Combat T-shirt spec (requested by manufacturer) Table 10 – change to mass and thickness values of felt insert (requested by manufacturer) Page 10 – correction to fastener length from 9cm to 13cm on blanking plate	15 April 2013
4	New design with felt padding in collar – details reference throughout spec Removal of forearm pocket and Neoprene pads Page 6: Sleeve length increased on smaller sizes, grade now 3cm instead of 5cm Page 9: Change of design of bellow patch pocket to include fold over design Page 9 & 10: Blanking plate touch and close changed to “picture frame” construction Page 10: Change of position of Union Flag on Blanking Plate Page 15: Addition of `Do not iron’ touch and close fastener on Care Label Page 16: Change of wording to Swing ticket to just neck collar fragment protection Page 21: Knitted body material changed to MTP Page 30: Felt properties added (Table 10)	21 March 2013
3	BS EN ISO 6330 requirements updated	03 October 2012
2	Change of pad protection pockets from single to double pocket	05 July 2012
1	New specification derived from DC/MS/6584 Issue 7	21 June 2012

5. CONSTRUCTION continued

CUFF  	• Cuff band cut single ply in main fabric • 5cm wide with a pointed extension 5cm long • Bottom edge of the cuff is laid on top of the bottom end of the sleeve panel and attached • Top edge of cuff sewn to the sleeve panel • Extension positioned on the underarm seam • Point facing towards the front sleeve • Extension is to be double layered • Buttonhole 2.2cm long worked in the under layer of the extension • The eye 1.6cm from the point	1.06.02 1.04.01
	• Two buttons attached centrally to the cuff spaced 5cm apart on front of the cuff band • First button positioned 8cm from the eye of the covered buttonhole	
COLLAR AND SLIDE FASTENER OPENING 	• Stand collar cut two ply • Outer collar cut in main fabric, inner collar cut in knitted fabric (**reverse side of fabric must be next to skin)** • Depth 6.5cm • Top and bottom edge of collar edge stitched • Slide fastener 23cm long • Sewn between front edges of collar and front opening	

5. CONSTRUCTION continued

COLLAR AND SLIDE FASTENER OPENING (cont)  	Felt insert • Collar to have an additional felt layer • Felt cut 6.3cm deep and 4.5cm shorter than collar at the front on both sides. • Sandwiched between outer and inner collar • Securely attached to the outer collar • Stitched all the way around the edge and zigzagged along its full length as on diagram	
 	• Fastener guard cut two ply main material 3cm wide • Guard stitched behind fastener on the left hand side as worn • To extend 3cm above opening and stitched back into the collar • Front opening topstitched	
HEM  	• Front and back dipped hem • Dip to be 5cm at centre front and centre back • Upturn 2cm • Twin needle chain stitch finished	6.02.07

BILL OF MATERIALS continued

Light Olive components are to closely match Pantone shade 18-0820TC			
Components	Size/Colour	Reference/Description	Notes/NATO Stock No.
Felt Collar insert	White	UHMWPE (Ultra High Molecular Weight) 100% Polyethylene To comply with Table 10	
Slide fastener	Light Olive 23cm	FRONT OPENING Lightweight polyester, polyamide, spiral chain, closed end, auto-locking slider, top stop, 11mm stringer	UK/SC/4559
Button	Light Olive 19mm (30 ligne)	BUTTON Slotted matt finish	UK/SC/5121 Pattern No 28988 to guide
Fastener tape	Light Olive	Tape fastener, hook and loop pile Selvedges are to be finished/sealed to prevent fraying	DEF STAN 83-86
	20mm	BLANKING PLATE	
	25mm	BICEP POCKETS	
Cord	Light Olive 9mm	BUTTON ATTACHMENT Braided nylon	UK/SC/4782 Pattern No 9483E
Union Flag		BLANKING PLATE Badge, Organisation Arm Union Flag	8455-99-978-8929 Pattern number 24805 to UK/SC/5929
Identification/ care label	White	Refer to Section 6	BS 5742 Paragraph 3 BS EN ISO 3758 Max change 3 in colour change of fabric and print after 5 x BS EN ISO 105 CO6:C2S wash cycles
Swing Ticket	Card	Refer to section 6	
Thread	Light Olive	Polyester/cotton corespun	BS EN 12590
	Metric Ticket No		
	75	ALL OTHER SEWING	
		OVEREDGE STITCHING	
	120	Polyester on needle threads	
	180	Continuous filament textured polyester on looper threads	

Appendix D: Excerpts from the manufacturer specifications for the Patrol Collar addition to Mark 4 OSPREY Assembly

UK/SC/6706 Issue 05
13 February 2014

Technical Specification for COVER & FILLER BODY, ARMOUR, OSPREY MK4A (MTP) COVER & FILLER BODY, ARMOUR CIVILIAN OSPREY MK4A (BLUE)

Survivability Delivery Team (SDT)
Soldier System Programmes (SSP)

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Defence Equipment & Support

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PREFACE

TABLE 1 – PRODUCT LIST

Product Name	**COVER BODY ARMOUR OSPREY MK4A (MTP)** **COVER BODY ARMOUR CIVILIAN OSPREY MK4A (BLUE)**		
Development File No			
Item Name	**Size**	**Multi-Terrain Pattern**	**Civilian Blue**
Cover Ensemble Body Armour	170/100	8470-99-684-4611	8470-99-396-2394
Cover Ensemble Body Armour	170/112	8470-99-684-4612	8470-99-396-2395
Cover Ensemble Body Armour	180/104	8470-99-684-4613	8470-99-396-2396
Cover Ensemble Body Armour	180/116	8470-99-684-4614	8470-99-396-2397
Cover Ensemble Body Armour	190/108	8470-99-684-4615	8470-99-396-2398
Cover Ensemble Body Armour	190/120	8470-99-684-4616	8470-99-396-2399
Cover Ensemble Body Armour	200/116	8470-99-684-4617	8470-99-396-2400
Cover Ensemble Body Armour	200/124	8470-99-684-4618	8470-99-396-2401
Cover Ensemble Body Armour	Outsize	8470-99-684-4619	N/A

TABLE 1 – PRODUCT LIST continued

Product Name	**FILLER BODY ARMOUR OSPREY**	
Supplier	**1**	
Size	**OSPREY FILLER FRONT**	**OSPREY FILLER BACK**
170/100	8470-99-746-6689	8470-99-746-6697
170/112	8470-99-746-6690	8470-99-746-6698
180/104	8470-99-746-6691	8470-99-746-6699
180/116	8470-99-746-6692	8470-99-746-6700
190/108	8470-99-746-6693	8470-99-746-6701
190/120	8470-99-746-6694	8470-99-746-6702
200/116	8470-99-746-6695	8470-99-746-6703
200/124	8470-99-746-6696	8470-99-746-6704

Product Name	**FILLER ANCILLARIES BODY ARMOUR OSPREY** **Comprising of – Full Collar, Half Collar, Brassards & Shoulder Guards**
Supplier	**1**
Size	**NATO Stock Number**
Small	8470-99-746-6705
Medium	8470-99-746-6706
Large	8470-99-746-6707

TABLE 1 – PRODUCT LIST continued

Product Name	**FILLER BODY ARMOUR OSPREY**	
Supplier	**2**	
Size	**OSPREY FILLER FRONT**	**OSPREY FILLER BACK**
170/100	8470-99-746-6670	8470-99-746-6678
170/112	8470-99-746-6671	8470-99-746-6679
180/104	8470-99-746-6672	8470-99-746-6680
180/116	8470-99-746-6673	8470-99-746-6681
190/108	8470-99-746-6674	8470-99-746-6682
190/120	8470-99-746-6675	8470-99-746-6683
200/116	8470-99-746-6676	8470-99-746-6684
200/124	8470-99-746-6677	8470-99-746-6685

Product Name	**FILLER ANCILLARIES BODY ARMOUR OSPREY** **Comprising of – Full Collar, Half Collar, Brassards & Shoulder Guards**
Supplier	**2**
Size	**NATO Stock Number**
Small	8470-99-746-6686
Medium	8470-99-746-6687
Large	8470-99-746-6688

TABLE 1 – PRODUCT LIST continued

Product Name	**PATROL COLLAR COVER & FILLER BODY ARMOUR OSPREY (MTP COVER ONLY)**
Item Name	**NATO Stock Number**
Patrol Collar Cover Ensemble	8470-99-339-5412
Patrol Collar Side Protection Cover	8470-99-339-5410
Patrol Collar Front Protection Cover	8470-99-339-5411
Patrol Collar Filler Ensemble	8470-99-339-5415
Patrol Collar Filler Side Protection	8470-99-339-5413
Patrol Collar Filler Front Protection	8470-99-339-5414

Any colour shown in this document is for representation and must not be used for colour matching.

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TABLE 2 – ISSUE RECORD

Issue No	Comments	Issue Date
5	Modification of pouches, ties added to zip pullers, additional T Bars Patrol collar assembly added Inclusion of Cover Body Armour Civilian Osprey MK4A Blue Inclusion of all Osprey Filler requirements BS 5690 deleted and superseded by BS EN ISO 12947 Part 2	13 February 2014
4	Amendment of NATO Stock Numbers Do Not Bleach care symbol updated to reflect the changes to BS EN ISO 3758 Wash/Dry procedure updated to reflect the changes to BS EN ISO 6330	18 September 2012
3	NATO Stock Numbers for all elements of the Osprey Cover inserted	25 July 2012
2	New NATO Stock Numbers for MKIVA B/A Cummerbund deleted Details of Side Plate Pocket inserted NATO Stock Numbers for all pouches included Related specifications updated All drawing numbers inserted	23 April 2012
1	New specification	01 March 2011

PART 1

1. THE PRODUCT

a. Use of the Product. Cover, Ensemble, Body Armour Osprey, complete with Side Plate Pocket, Cover for Full Collar & Patrol Collar(MTP Cover Only); Cover for Brassard and Shoulder Pads supplied in pairs. Plate Sleeve and Pouches as listed below.

b. All parts are designed to enable the appropriate size of Osprey filler to be inserted and removed.

c. The size schedule provides for eight sizes.

d. Assembly Items: The items listed below make up the various sizes of the complete Ensemble of the Cover Body Armour Osprey MK4A.

ENSEMBLE

Item Name	Size	Components	Size
Body Armour Cover MTP NSN: 8470-99-684-4611 Civilian Blue NSN: 8470-99-396-2394	170/100	Waistband Brassard Shoulder Pad Full Collar Half Collar Patrol Collar (MTP Only)	Small Small One Size One Size One Size One Size
Body Armour Cover MTP NSN: 8470-99-684-4612 Civilian Blue NSN: 8470-99-396-2395	170/112	Waistband Brassard Shoulder Pad Full Collar Half Collar Patrol Collar (MTP Only)	Medium Small One Size One Size One Size One Size
Body Armour Cover MTP NSN: 8470-99-684-4613 Civilian Blue NSN: 8470-99-396-2396	180/104	Waistband Brassard Shoulder Pad Full Collar Half Collar Patrol Collar (MTP Only)	Small Medium One Size One Size One Size One Size

FILLERS continued

Item Name	Size	NSN	Quantity
Filler Body Armour Osprey Back	170/100	As Per Contract	1
Filler Body Armour Osprey Back	170/112	As Per Contract	1
Filler Body Armour Osprey Back	180/104	As Per Contract	1
Filler Body Armour Osprey Back	180/116	As Per Contract	1
Filler Body Armour Osprey Back	190/108	As Per Contract	1
Filler Body Armour Osprey Back	190/120	As Per Contract	1
Filler Body Armour Osprey Back	200/116	As Per Contract	1
Filler Body Armour Osprey Back	200/124	As Per Contract	1
Filler Ancillaries including – Full Collar, Half Collar, Brassards & shoulder Guards	Small	As Per Contract	1 Pair of each item
Filler Ancillaries including – Full Collar, Half Collar, Brassards & shoulder Guards	Medium	As Per Contract	1 Pair of each item
Filler Ancillaries including – Full Collar, Half Collar, Brassards & shoulder Guards	Large	As Per Contract	1 Pair of each item
Filler Patrol Collar Side Protection	N/A	8470-99-339-5413	1 Pair
Filler Patrol Collar Front Protection	N/A	8470-99-339-5414	1
Filler Patrol Collar Ensemble	N/A	8470-99-339-5415	1

TABLE 5 – PRODUCT CONSTRUCTION continued

OSPREY MK4A - BODY ARMOUR COVER, VEST; ALL SIZES			
Item	**Length**	**Quantity**	**Position**
FULL COLLAR (LEFT AND RIGHT)			
20mm Hook Velcro	12cm	2 off	Inner collars filler access opening
20mm Loop Velcro	12cm	2 off	Inner collars filler access opening
30mm Hook Velcro	8cm	1 off	Inner collar front - right
30mm Loop Velcro	10cm	1 off	Outer collar front fasten strap - left
50mm Hook Velcro	14cm	1 off	Inner collar back -right
50mm Loop Velcro	14cm	1 off	Inner collar back -left
MAT0004B 25mm MTP 9350 25mm Black	12cm	1 off	Right collar back attach stud web strap
30mm Loop Velcro	8½cm	4 off	Outer collars neck edge
30mm Loop Velcro	5cm	1 off	Left outer collar behind pull tab
HALF COLLAR			
PATROL COLLAR OUTER COVER (MTP ONLY)			
50mm Loop Velcro	18 cm	2 off	Side Protection outer panels (cut to shape)
50mm Loop Velcro	4cm	2 off	Side Protection outer panels front (cut to shape)
MAT0004B 25mm MTP	12cm	1 off	Side Protection back fixing strap
25mm Hook Velcro	2.5cm	1 off	Side Protection back fixing strap
25mm Loop Velcro	3.5cm	1 off	Side Protection back fixing strap
50mm Loop Velcro	6cm	1 off	Front Protection outer panel
MAT0004B 25mm MTP	13.5cm	2 off	Front Protection attach straps(stud 7.5, 9.5cm)
25mm Hook Velcro	3cm	2 off	Front Protection attach straps
50mm Hook Velcro	4cm	2 off	Front Protection inner panels sides (cut to shape)
MAT0004B 25mm MTP	20cm	2 off	Front Protection sides straps (Mark 12cm)
25mm Hook Velcro	10cm	2 off	Front Protection sides straps

Appendix E: Osprey Mk 4A Patrol Collar Fitting and Assembly Instructions

Osprey Mk 4A Patrol Collar

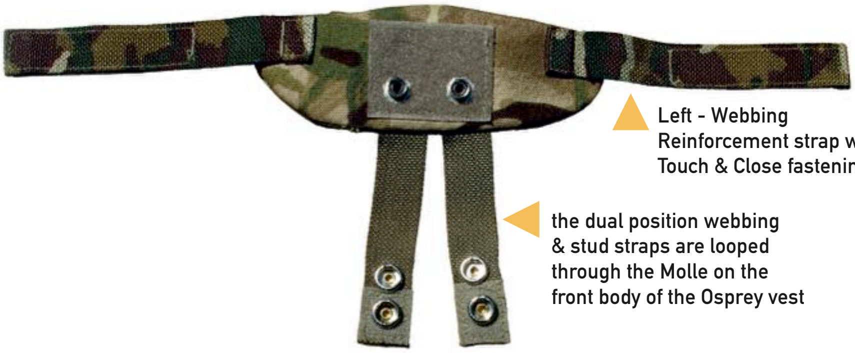
de&s
LAND EQUIPMENT

FITTING AND ASSEMBLY INSTRUCTIONS

MINISTRY OF DEFENCE

Osprey Mk 4A Patrol Collar

Front Collar Component

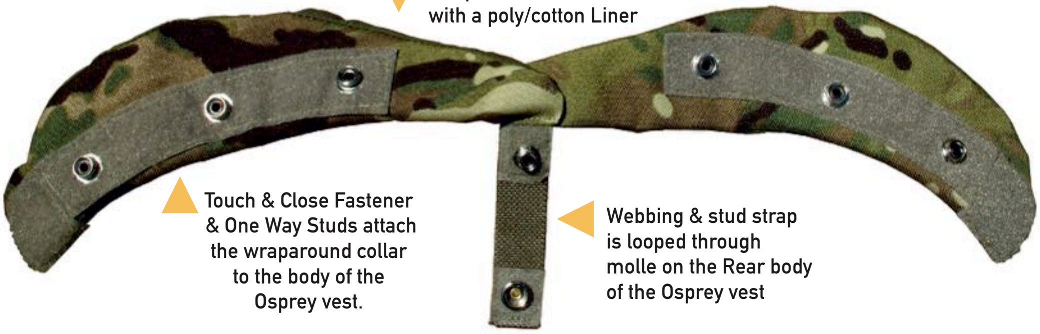


The Front Collar is lined with a poly/cotton Liner

Left - Webbing Reinforcement strap with Touch & Close fastening

the dual position webbing & stud straps are looped through the Molle on the front body of the Osprey vest

Side Collar Component



Wraparound Collar is lined with a poly/cotton Liner

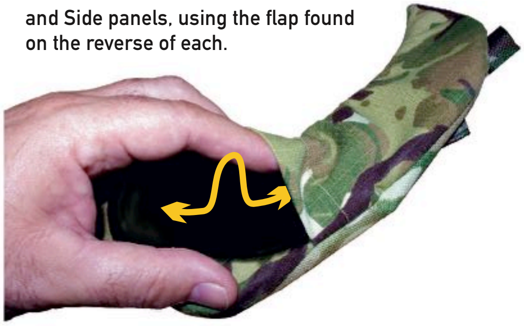
Touch & Close Fastener & One Way Studs attach the wraparound collar to the body of the Osprey vest.

Webbing & stud strap is looped through molle on the Rear body of the Osprey vest

The assembled Patrol Collar when correctly fixed to the Osprey vest offers additional ' 'All Round' protection to the neck and throat.

Inserting the Filler

The fillers are inserted in both the Front and Side panels, using the flap found on the reverse of each.



Attaching the Patrol Collar to the Osprey Body

1

Attach the Side Collar to the collar flap which features on the body of the Osprey vest, using the Touch & Close Fastening and the One Way studs (three studs per side).

2

Loop the webbing and stud strap through the central molle 'handle strap' at the top of the Osprey Vest back.

Close the One Way stud to complete fixing of the Side Collar to the vest.

3

Whilst the Front Collar is still loose, loop the two webbing and stud straps through the top layer molle straps on the front of the Osprey vest. Close the studs.

4

On the reverse corners of the Front Collar there feature hook touch & close fasteners, attach these to the corners of the main Side Collar. These can be adjusted for comfort.

5

To complete the assembly.

The Front Collar reinforcement straps can now be attached to the Side Collar.

This securely locks the whole collar in position for maximum protection.

6

For additional comfort to the user, the webbing & stud straps of the Front Collar is provided with an additional set of studs to enable attachment in a choice of positions.

Maintenance & Cleaning

THE COVER AND FILLER MUST BE SEPARATED IN ACCORDANCE WITH THE FITTING INSTRUCTIONS BEFORE CLEANING

Cover The cover is washed in accordance with the manufacturers instructions.

Filler To clean the filler, wipe the surface of the protective cover using a damp cloth.

DO NOT IMMERSE IN WATER

Dry thoroughly before inserting back into the cover.

Regular inspection of the fillers and covers should be made annually at a minimum.
On the occasion of any physical contact with objects likely to cause damage, inspection should be made at the earliest convenient time.

NATO Stock Numbers

OSPREY MKIVA MTP
PATROL COLLAR, SIDE
ENS: 8470-99-339-5412
8470-99-339-5410, DC4/4062

OSPREY MKIVA MTP
PATROL COLLAR, FRONT
ENS: 8470-99-339-5412
8470-99-339-5411, DC4/4062

COLLAR FILLER ENSEMBLE
ENS: 8470-99-339-5415

COLLAR FILLER SIDE PANEL
ENS: 8470-99-339-5413

COLLAR FILLER FRONT PANEL
ENS: 8470-99-339-5414

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Appendix F: Extract from Defence Equipment and Support "Desider" magazine March 2015 confirming design of neck collar in VIRTUS will be identical to that designed in this thesis

Kit moves on

The Survivability team in Soldier Training and Special Programmes at DE&S has signed a contract for Virtus, a new personal protection and load carriage system, providing significantly improved capability for UK soldiers. *Robin Clegg* reports

After an intensive assessment phase of almost two years, DE&S has committed to buy 9,000 Virtus systems in a contract worth an initial £14.69 million. High readiness Air Assault and Commando Brigades will be the first units to be provided with the new kit in the coming months.

The complete system is made up of a scalable body armour vest, helmet, and face protection, including ballistic glasses, ballistic goggles and a visor. There is also a 40L and 45L daysack, a 90L rucksack, pelvic protection, webbing and pouches, knee pads, extremity protection (arm and collar) and a hydration system.

Because of the dedicated work of the STSP team at Abbey Wood, the new equipment also provides better value for money for taxpayers than the current in-service equipment.

Major General Paul Jaques, Director Land Equipment at DE&S, said: "DE&S is committed to supporting the Armed Forces by providing them with a high standard of equipment and this new personal protection and load carriage system meets that requirement.

"In challenging troop trials we found it performed exceptionally well and was a step change improvement on the in-service equipment. Key is the integrated nature of the system that enables the soldier to operate far more effectively."

The new system helps close existing capability gaps relating to the ability of troops to change the level of protection they wear dependent on the threat. The new system is integrated which will improve the wearer's ability to perform the full range of military tasks. There is also a quick release mechanism, providing the wearer with the ability to remove the body armour vest quickly allowing escape from water and confined spaces, as well as enabling medical personnel easy access to the body should the wearer require emergency treatment.

In extensive user trialling, managed by the Infantry Trials and Development Unit, the system performed significantly better than the other bidding systems and the current in-service equipment.

It was found to be more comfortable, better integrated both as a system and with other items of military equipment and, importantly, lighter than the other systems tested.

The new kit was put through its paces in a series of tests in a range of climatic conditions in the UK and abroad involving more than 200 members of the tri-service commands, monitored by the Defence Science and Technology Laboratory and the Institute of Naval Medicine.

The full range of trials took the team from a climate controlled setting at Boscombe Down to the searing heat of a derelict ammunition compound in Dhekelia, Cyprus. Timed mobility tests over obstacle courses and sensor-controlled biometric assessments also measured levels of stress placed on the body.

Armed Forces involved in the trials were constantly monitored and completed questionnaires on all aspects of the kit's performance and usability after each stage of the five-month process. Overall, after a thorough and wide ranging set of technical tests and trials the Virtus system performed consistently better than the current system and its three competitors.

Major Chris Dadd, DE&S STSP, who co-ordinated the series of trials, said: "We wanted to replicate the whole range of military conditions that a soldier would be exposed to in order to gain the maximum amount of information, using all available technologies.

"Throughout the series of tests, in a myriad of conditions, Virtus was the best system by a long way. It performed exceptionally well when kit integration and all the human factors were taken into account. In the end, you need the right kit to do the job properly and this absolutely enables us to do just that."


Eyewear (Glasses/Goggles) - 0.41kg
Helmet - 1.42kg
40L daysack - 2.45kg
Harness & Pouches - 3.56kg
Scalable Tactical Vest - 3.99kg
Pelvic Protection - 3.20kg

Annex G: Peer reviewed open publications generated from this research

1. Breeze J, Carr DJ, Mabbott A, Beckett S, Clasper J. Refrigeration and freezing of porcine tissue does not affect the retardation of fragment simulating projectiles. Journal of Forensic and Legal Medicine 2015; DOI: 10.1016/j.jflm.2015.03.003.

2. Breeze J, Fryer R, Hare J, Delaney R, Hunt NC, Lewis EA, Clasper J. Clinical and post mortem analysis of combat neck injury used to inform a novel Coverage of Armour Tool. Injury 2015; DOI: 10.1016/j.injury.2015.01.045.

3. Breeze J, Allanson-Bailey L, Hepper AE, Lewis EA. Novel method for comparing coverage by future methods of ballistic facial protection. British Journal of Oral & Maxillofacial Surgery 2015; 53 (1): 3–7.

4. Breeze J, Allanson-Bailey LC, Hunt NC, Delaney R, Hepper AE, Lewis EA. Using computerised surface wound mapping to compare the potential medical effectiveness of Enhanced Protection Under Body Armour Combat Shirt collar designs. J R Army Med Corps 2015; 161 (1): 22–26.

5. Breeze J, Allanson-Bailey L, Hepper AE, Midwinter MJ. Demonstrating the effectiveness of body armour: a pilot prospective computerised surface wound mapping trial performed at the Role 3 hospital in Afghanistan. J R Army Med Corps 2015; 161 (1): 36–41.

6. Breeze J, Newbery T, Pope D, Midwinter MJ. The challenges in developing a finite element injury model of the neck to predict the penetration of explosively propelled projectiles. J R Army Med Corps 2014; 160(3): 220-5.

7. Breeze J, Clasper JC. Ergonomic assessment of future methods of ballistic neck protection. Mil Med 2013; 178(8): 899-903.

8. Breeze J, Midwinter MJ. Editorial: Prospective Computerised Surface Wound Mapping will Optimise Future Body Armour Design. J R Army Med Corps 2012; 158 (2): 79–8.

9. Breeze J, Baxter D, Carr D, Midwinter MJ. Defining combat helmet coverage for protection against explosively propelled fragments. J R Army Med Corps 2015; 161 (1): 9–13.

10. Breeze J, Grainger C, Pearkes T, Clasper JC. Ergonomic Assessment of Enhanced Protection Under Body Armour Combat Shirt Neck Collars. J R Army Med Corps 2014; 160(1): 32-7.

11. Breeze J, James G, Mouland M, Hepper AE. Perforation of Fragment Simulating Projectiles into Goat skin and muscle. J R Army Med Corps 2013; 159: 84-89.

12.Breeze J, Leason J, Gibb I, Hunt NC, Hepper A, Clasper J. Computed tomography can improve the selection of fragment simulating projectiles from which to test future body armor materials. Mil Med. 2013; 178(6): 690-5.

13. Breeze J, Sedman AJ, James GR, Hepper AE. Determining the Wounding Effects of Ballistic Projectiles to Inform Future Injury Models: a systematic review. J R Army Med Corps 2014; 160 (4): 273–278.

14. Breeze J, Clasper JC. Determining the velocity required for skin perforation by Fragment Simulating Projectiles: a systematic review. J R Army Med Corps 2013; 159(4): 265-70.

15. Breeze J, Leason J, Gibb I, Hunt NJ, Hepper A, Clasper J. Characterisation of explosive fragments injuring the neck. Br J Oral Maxillofac Surg 2013; 51(8): e263-6.

16. Breeze J, Hunt NC, Gibb I, James GR, Hepper AE, Clasper JC. Experimental penetration of fragment simulating projectiles into porcine tissues compared with simulants. J Forensic Leg Med.2013; 20: 296-299.

17. Breeze J, Helliker M, Carr DJ. An integrated approach towards future ballistic neck protection materials selection. Proc Inst Mech Eng H 2013; 227(5) 581-587.

18. Breeze J, West A, Clasper J. Radiological anthropomorphic assessment of cervical neurovascular structures to explosive fragmentation. Clin Radiol. 2013; 68(1): 34-8.

19. Breeze J, Masterton L, Banfield G. Outcomes from Penetrating Ballistic Cervical Injury. J R Army Med Corps 2012; 158(2): 96- 100.

20. Breeze J, Midwinter MJ, Pope D, Porter K, Hepper AE, Clasper J. Developmental framework to validate future designs of ballistic neck protection. Br J Oral Maxillofac Surg 2013; 51(1): 47-51.

21. Breeze J, Allanson- Bailey LS, Hunt NC, Delaney RJ, Pearce MJ, Hepper AE, Clasper J. Mortality and morbidity from UK combat neck injury. J Trauma 2012; 72: 969- 74.

22. Breeze J, Watson C H, Horsfall I, Clasper J. Comparing the human factors of neck collars in different military body armour systems. Mil Med 2011; 176(11): 1274-7.

23. Breeze J, Gibbons A, Shief C, Banfield G, Bryant D, Midwinter M. Combat-related craniofacial and cervical injuries: Five- year review from the British Military. J Trauma 2011; 71 (1): 108-13.

24. Breeze J, Horsfall I, Clasper J. Face, neck, and eye protection: adapting body armour to counter the changing patterns of battlefield injury. Br J Oral Maxillofac Surg 2011; 49: 602-606.

25. Breeze J. Editorial: The problems of protecting the neck from combat wounds. J R Army Med Corps 2010; 156 (3): 137-8.

Annex H: Oral presentations produced by this research

International

2013 **British association of Oral and Maxillofacial Surgeons (BAOMS) Conference, Dublin, Ireland:** Characterisation of explosive fragments injuring the neck

2011 **British association of Oral and Maxillofacial Surgeons (BAOMS) Conference, Nice, France:** Mortality and morbidity from UK combat neck injury

2010 **American association of Oral and Maxillofacial Surgeons (AAOMS) Conference, Chicago, USA:** Head Face and Neck injuries sustained by British Service Personnel

National

2013 **UK Radiology Conference (UKRC):** Characterisation of explosive fragments injuring the neck

2012 **British association of Oral and Maxillofacial Surgeons (BAOMS) Conference:** Radiological anthropomorphic assessment of cervical neurovascular structures to explosive fragmentation

2012 **British association of Oral and Maxillofacial Surgeons (BAOMS) Conference:** A developmental framework to validate future designs of ballistic neck protection

2012 **Military Surgery UK** Radiological characterisation of ballistic fragmentation injury

2012 **Military Surgery UK** Ergonomic assessment of novel methods of ballistic neck protection

2012 **International association of Oral and Maxillofacial Surgeons (BAOMS) Conference** Validation of ballistic cervical protection through the development of a novel numerical model

2011 **Military Surgery UK** Mortality and morbidity from UK combat neck injury

2010 **British association of Oral and Maxillofacial Surgeons (BAOMS) Conference:** Head Face and Neck injuries sustained by British Service Personnel in Iraq and Afghamistan

2010 **Military Surgery UK** Face and Neck Protection- adapting military body armour to counter the changing patterns of battlefield injury

Annex I: Poster presentations produced by this research

2014 **Personal Armour Systems Symposium (PASS)** Development of the new ballistic neck collar to protect UK soldiers from explosive fragmentation injury in Afghanistan

2014 **British Association of Oral and Maxillofacial Surgeons (BAOMS) conference** Clinical and post mortem analysis of combat neck injury used to inform a novel Coverage of Armour Tool

2012 **UK Radiology Conference (UKRC)** Radiological characterisation of ballistic fragmentation injury using a porcine model

2012 **UK Radiology Conference (UKRC)** Radiological anthropometric assessment of cervical neurovascular structures against explosive fragmentation

2012 **Military Surgery UK** Qualifying the wounding effects of penetrating fragments for injury modelling

2011 **British Association of Oral and Maxillofacial Surgeons (BAOMS) conference, Nice France** Comparing the human factors of neck collars in military body armour systems

2011 **Military Surgery UK** Comparing military performance restriction of neck collars from body armour

2010 **British Association of Oral and Maxillofacial Surgeons (BAOMS) conference** Face and Neck Protection- adapting military body armour to counter the changing patterns of battlefield injury