CRANFIELD UNIVERSITY

SURG LT CDR TOM STEVENSON RN

BALLISTIC EXTREMITY WOUNDING: QUANTIFYING TISSUE DAMAGE ASSOCIATED WITH MILITARY FIREARMS

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PhD
Academic Year: 2018 - 2019

Supervisors:	Prof DJ Carr	2016-17
	Dr K Harrison	2016-18
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ABSTRACT

Gunshot wounding (GSW) is often the second most common mechanism of injury after explosive in war. With a large proportion of survivors typically suffering with extremity wounds, the clinical burden is often substantial. Following the recent Iraq and Afghanistan conflicts, this work set out to ascertain the clinical burden of GSW suffered by UK military personnel. A critical literature gap uncovered was pertaining to the effect of clothing on GSW patterns. A synthetic limb model was used to test the effect of UK military clothing on GSW patterns in a maximal and minimal state, as worn by front-line service personnel, using 7.62 x 39 mm and 5.45 x 39 mm ammunition types. Further work was then undertaken to develop a technique to facilitate precise examination of GSW patterns within an opaque target. Lastly, this led to the development of a cadaveric animal limb model to test the same military clothing states as with the synthetic model. Increased damage was found in the presence of the maximal clothing state within both models, which would translate clinically into a wound requiring more extensive surgical intervention. The relevance of these findings, along with critical appraisal of each model used are then discussed, with further work proposed.

Keywords: Gunshot, Wounding, Extremity, Clothing, AK47, AK74

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Other individuals are acknowledged at the end of the relevant chapters within the thesis.

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GLOSSARY

Anthropometry	"The branch of science that deals with the measurement of the human body is *anthropometry*, and anthropometrics is the term used for the application of such data" [1].
Axial plane	"Right angles to the long axis of the body i.e. denoting a horizontal plane through a standing patient at 90^{o} to the *coronal* and *sagittal planes*" [2].
Biofidelity	*Bio* – "relating to life or living beings" [3] *Fidelity* – "the degree of exactness with which something is copied or reproduced" [3].
Bloom strength	"A measure of the strength of a gel and is defined as the mass of a cylindrical probe with a diameter of 12.7 mm that is required to deflect the surface of the gel 4 mm. This test is carried out on a sample of gel with a concentration of 6.66% at a temperature of 10°C" [4].
Computed-Tomography (CT)	"A form of X-ray examination in which the X-ray source and detector (CT scanner) rotate around the object to be scanned and the information obtained can be used to produce cross-sectional images by computer" [2]. See *X-ray*.
Coronal plane	"A plane dividing the body into the dorsal (back) and ventral (front) parts" [2]. See *Axial* and *Sagittal plane.*
Debridement	"The process of cleaning an open wound by removal of foreign material and dead tissue, so that healing may occur without hindrance" [2].
Dissection	"The cutting apart and separation of tissues along the natural divisions of the organs and different tissues in the course of an operation" (or on cadaveric material) [2].

Doppler radar	*Doppler effect* – “an increase (or decrease) in the apparent frequency of waves as the source and the observer move towards (or away) from one another” [3]. *Radar* – “a system for finding the presence, direction and speed of an object by sending out pulses of radio waves which are reflected off the object back to the source” [3].
Excision (to excise)	To cut tissue out from the human (or animal) body [2].
Femur	Thigh bone. “A long bone between the hip and the knee” [2].
Gelatine	“A clear water-soluble substance obtained from animal bones” [3].
Neck length	Initial narrow wounding channel seen within a wound track caused by a projectile, before significant cavitation has taken place once the projectile has begun to yaw [5].
Neurovascular	*Neuro* – “combining form denoting nerves or the nervous system” [2]. *Vascular* – “relating to or supplied with blood vessels” [2].
Permanent cavity	An area of crushed and torn tissue left following the passage of a projectile or fragment [4]. See *Temporary cavity.*
Phantom cameras	High speed video camera system built by AMETEK Materials Analysis Division and Vision Research [6].
Sagittal plane	“A dorsoventral (front to back) plane running down the long axis of the body, dividing it into right and left parts” [2]. See *Axial* and *Coronal plane.*
Temporary cavity	“The energy that the bullet transfers to the medium accelerates the medium surrounding the path of the bullet away from it radially. This creates a hollow space behind the bullet and, initially, a vacuum. Because of inertia, the cavity only reaches its maximum diameter at any given point when the bullet has already passed that point” [4]. See *Permanent cavity.*

Ultrasonography (sonography)	“The use of *ultrasound* to produce images of structures in the human body. The ultrasound transducer probe sends out a short pulse of high-frequency sound and detects the reflected waves (echoes) occurring at interfaces within the tissues via piezoelectric crystals contained within the transducer probe, to convert into images” [2].
Ultrasound	See *ultrasonography*
Vickers hardness test	This microhardness test procedure specifies a range of light loads with the use of a diamond indenter to make an indentation which is then measured and converted into a value to represent hardness. Test samples must be highly polished to facilitate measuring the size of the impressions. A square base pyramid shaped diamond is used for testing in the Vickers scale, with indenter faces set at a 136 degree angle from one another [7].
X-ray	“Electromagnetic radiation of extremely short wavelength (beyond the ultraviolet), which pass through matter to varying degrees depending on its density" [2]
Yaw	“The linear oscillation of a bullet around the axis of the trajectory” [8].

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LIST OF ABBREVIATIONS

%	Percentage
^{o}C	Degrees Celsius
µm	Micro-metres
µs	Micro-seconds
3D	Three-dimensional
AIS	Abbreviated Injury Scale
AK	Automat Kalashnikov
ANOVA	Analysis of Variance
BB	Ball-bearing
BS	British Standard
BSN	(Camp) Bastion
C_{max}	Maximal clothing state (t-shirt, UBACS, smock, brassard)
C_{min}	Minimal clothing state (MTP trousers)
C_{nil}	Zero clothing state (bare)
CCU	Critical Care Unit
CIXT	Clinical Information and Exploitation Team
COTEC	Cranfield Ordnance Test and Evaluation Centre
CT	Computed Tomography
CURES	Cranfield University Research Ethics System
CV	Coefficient of Variation
D1	Distance to maximum height of temporary cavity
D2	Distance to maximum height of permanent cavity
DMICP	Defence Medical Information Capability Programme
DMRC	Defence Medical Rehabilitation Centre
DoP	Depth of Penetration
DoW	Died of Wounds
E1	Entrance wound
E2	Exit wound
EA	Exit Area
EDAX	Energy Dispersive X-ray Analysis
F	F-statistic
FMJ	Full Metal Jacket

fps	Frames per second
g	Grams
gr	Grains
g/m^2	Grams per square metre
GSW	Gunshot wound(s) / Gunshot wounding
H1	Maximum height of temporary cavity
H2	Maximum height of permanent cavity
HSD	(Tukey's) Honest Significant Difference
HSV	High Speed Video
Hv	Vickers Hardness
IBM	International Business Machine
IDF	Indirect fire
IED	Improvised Explosive Device
IJLM	International Journal of Legal Medicine
IQR	Inter-Quartile Range
ISO	International Organization for Standardization
IT	Information Technology
JTTR	Joint Theatre Trauma Registry
KE	Kinetic energy
kg	Kilograms
KIA	Killed In Action
KNEA	Killed Non-Enemy Action
kV	Kilovolts
LoS	Length of Stay
m	Metres
mls	Millilitres
mm	Millimetres
m/s	Metres per second
mAs	Milliampere-seconds
MHz	Megahertz
MoD	Ministry of Defence
MODREC	Ministry of Defence Research Ethics Committee
MOI	Mechanism of Injury

MPR	Multi-Planar Reconstruction
MRI	Magnetic Resonance Imaging
MTP	Multi-Terrain Pattern
MVC	Motor Vehicle Collision
NATO	North Atlantic Treaty Organisation
NL	Neck Length
NS	Not significant
ns	nanoseconds
NSN	NATO Stock Number
PPE	Personal Protective Equipment
PROMs	Patient Reported Outcome Measures
PYAR	Population Years At Risk
QEHB	Queen Elizabeth Hospital Birmingham
RCDM	Royal Centre for Defence Medicine
RNPCS	Royal Navy Personal Clothing System
RPG	Rocket-propelled grenade
S/N	Serial Number
SAF	Small Arms Fire
SD	Standard Deviation
SLR	Single Lens Reflex
SPSS	Statistical Programme for Social Sciences
TT	Total Track (length)
UBACS	Under Body Armour Combat Shirt
UK	United Kingdom
UKDS	United Kingdom Defence Statistics
US	United States
USA	United States of America
WIA	Wounded In Action
WNEA	Wounded Non-Enemy Action

1 INTRODUCTION

This PhD thesis is arranged as a thesis by papers. Each paper is either prepared for submission or published within a relevant journal. Where each paper appraises the relevant literature, this introduction provides the more global context in which each paper and this work as a whole sits.

1.1 Global epidemiology of Gunshot Wounding

Gunshot wounding (GSW) represents a health and societal problem in the majority of countries worldwide to varying degrees, within both the civilian and military context. Whilst UK figures are often much lower for civilian GSW, there has been a rise in injuries relating to firearms. The numbers of UK civilian casualties throughout the 1980s showed between 380-520 patients suffering GSW per year [1], though this has substantially increased since. The most recently published numbers available showed 1403 patients suffering GSW from 2016-17, of which 31 cases resulted in fatality [2]. Figures from other countries paint a very different picture. The USA has the highest rate of civilian death from GSW per year worldwide [3]. There are differences in reported rates of fatality and injury seen, for example, Barlett reported in 2000 that GSW fatalities annually were between 40,000 and 50,000 with the number of survivors suffering injury placed from 150,000 – 500,000 [4]. Other reports from the USA by Tasigiorgos, Dougherty, Lee, Morrison and Fowler place the number of deaths over multiple years consistently around 30,000 per year, and the number of injured ranging from 66,000 – 84,000 [3,5-8]. Cavazos in 2017 describes that in Mexico there were 11,514 gun murders seen during 2014 [9], and a paper from Bodalal in 2013 details the number of GSW cases seen in Libya during the 2011 war in the Al-Jalaa teaching hospital as being 1,761 [10]. When considering GSW of military casualties, the main difference is that the varying state of conflict will determine the number of casualties, so more variation is seen on a year-by-year basis rather than civilian statistics which tend to be more consistent. This is well illustrated by Coupland in 1999 whom cites the numbers of military casualties due to GSW from conflicts for the UK, USA, Israeli and Croatian militaries from the Second World War up until 1992 [11].

With these varying rates of GSW casualties seen among countries, what has become more apparent is the increasing use of military firearms against civilians. This is evidenced commonly in countries where gun laws are not strict, such as the USA, where mass shootings and school shootings have consistently been a problem throughout the decades [3,11]. The rise of terrorist activities associated with military firearms causing injury to civilian populations in recent years has increased the associated clinical burden upon civilian healthcare facilities [12,13]. Even since the commencement of this work, there have been several incidents in Europe and the USA involving mass shooting of civilians and / or the use of military firearms [14-17]. With survivors suffering life-changing injuries, the resource demand for their complex care from the point of wounding up until their final discharge from care is high.

1.2 The economic cost of GSW

Due to the heterogeneous nature of GSW, the economic costs of treating individuals can vary enormously. Cowey describes the cost of treating 187 patients with GSW in a UK hospital over a five year period from 1995 – 2000 as totalling £267,000 (though this included treatment of airgun injuries as a type of GSW). By contrast, when looking at the USA, Zawitz describes a cost of $260,000 to treat each survivor of GSW leading to a total cost of $63.4 billion during 1992 (noting that these costs include medical costs, insurance costs, emergency and civil service costs, mental health costs, decreased quality of life costs and loss of earnings) [18]. Bartlett breaks down Zawitz' data further to distil the figure of $2.7 billion a year when quality of life costs and loss of earning costs are removed [4]. The overall cost is placed much higher by Miller in 1997 at $126 billion (of which $40 billion are medical and public service costs), and higher still presented by Tasigiorgos and Lee in 2015 whom both describe total costs during 2010 as being $174 billion (with the medical costs alone ranging from $70 billion to $88.6 billion) [3,6]. Other recent studies from Morrison and Fowler in 2015 place annual costs a little more conservatively at $2 billion and $48 billion respectively, though there is no breakdown as to what these costs are made up from, so it can only be presumed it covers just the medical and / or public service costs [7,8].

1.3 Extremity injury

With regard to anatomical location of injuries for GSW, extremity wounds dominate amongst survivors. Porteous describes 74% of patients suffering extremity injuries from a 1997 paper detailing GSW casualties seen over two years within a UK London teaching hospital [1]. This is further corroborated by Persad whom presents data from the same hospital in 2004 covering a four year period noting that extremity wounds predominate with 70 extremity injuries to the 61 patients seen [19]. Bodalal from Libya reports on casualties treated during the 2011 war in a teaching hospital in Benghazi noting that 68% of injuries were to the extremity [10]. These numbers are similar to statistics from a hospital in Cordoba, Argentina, where 63% of all GSW casualties during one study period suffered extremity wounding, compared to 71.8% in a typical USA city trauma centre [5].

When considering UK military casualties from the recent conflicts in Iraq and Afghanistan, one study by Chandler et al. describes the rate of extremity injuries amongst all casualties sustained as 77% (for all mechanisms of injury, not just GSW) and another study by Penn-Barwell and Sargeant from 2009 – 2013 during the same conflicts listing extremity injuries in 56% of survivors [20,21]. Prior to the commencement of this PhD, there has not been a study found within the published literature which examines the clinical burden of GSW to UK forces throughout the complete period of the conflicts in Iraq and Afghanistan from 2003 to 2014.

1.4 Treating Gunshot Wounds

GSW from military firearms have the potential to produce significant tissue destruction. For this reason, surgical doctrine is that the length of the wound tract following this type of injury is fully explored and laid open with excision of damaged tissue [22-29]. This treatment strategy aims to remove necrotic tissue, presumed to lie throughout the wound tract, in order to prevent it becoming a culture medium for the growth of microbes as a result of contamination at time of injury [30]. The potential damaging effect of this extensive surgery is regarded as necessary to mitigate the risk of infection.

Surgical experience on combat casualty treatment also advocates the use of conservative management in selected cases of GSW caused by military firearms [5,21,31-33], with the observation of the loss of this corporate knowledge between conflicts time and again previously highlighted by Ogilivie [34,35]. Fackler cites numerous historical accounts written by several surgeons from the last century that argue against exploring uncomplicated soft tissue through and through wounds where there is no associated bony injury or damage to neurovascular structures [36]. This experience is supported by an experimental live animal study by Hopkinson in 1963 demonstrating uncomplicated through and through high energy soft tissue GSW in sheep limbs healing without infection and following no surgical intervention [37], and a similar study conducted by Mendelson in 1967 using goats [38]. Fackler had also been able to demonstrate experimentally the virtues of conservative treatment for such soft tissue wounds sustained by high velocity projectiles with a comparison of excision versus conservative treatment in two groups of swine demonstrating no difference between healing times [39]. This clinical practice is also corroborated by a number of civilian institutions in both the UK and USA which deal more predominantly with handgun-related injuries where patients have been successfully treated when employing this more conservative method [1,4,5,19]. A modern understanding of wound ballistics is shown when clinicians speak of managing the wound rather than the weapon, and can appreciate that energy transfer is more clinically relevant than the velocity of the projectile, i.e. a low energy transfer can be caused by a projectile travelling with a high energy if it perforates the target [32]. Similarly, a high energy transfer with devastating clinical consequences can be seen when a projectile travelling with a low energy delivers all of that energy to the tissues [40].

Therefore, to understand the nature of wounds sustained by military firearms may in turn provide an understanding of wound treatment options and raises the possibility of identifying those wounds that require less aggressive surgical management. If it were possible to accurately predict those wounds that do not require formal debridement, this would decrease the burden upon healthcare facilities globally.

1.5 Aims and objectives

1.5.1 Aim

To test the effect of UK military clothing on extremity wounding patterns occurring as a result of a soft tissue GSW, not involving bone or neurovascular structures, and to develop a method to identify those patterns.

1.5.2 Objectives

1. Identify and understand the extent of the clinical burden of soft tissue gunshot wounds on UK military troops from the conflicts in Iraq and Afghanistan (2003-2014) (chapter 2).

2. Build on an existing extremity GSW synthetic model, capable of testing the effects of UK military clothing layers, whilst identifying patterns of wounding from known ammunition types at specified engagement distances (chapter 3).

3. Identify appropriate techniques to examine GSW patterns within a cadaveric animal model (chapter 4).

4. Identify the effect on patterns of wounding in a cadaveric animal model from known ammunition types at specified engagement distances to determine the difference in patterns seen with clothing layers applied versus without (chapter 5).

5. Determine the wounding effect of projectiles yawing before striking a cadaveric animal limb target with clothing layers applied versus without (chapter 6).

1.6 PhD Academic Structure

This thesis is structured around the epidemiological data on GSW, as identified within the UK military clinical burden of GSW from recent conflicts, and also around the experiments required to test the effect of UK military clothing in both a synthetic and cadaveric animal extremity model using military firearms. The text below outlines this structure in more detail.

1.6.1 The clinical burden

Publication: Stevenson T, Carr DJ, Penn-Barwell JG, Ringrose TJ, Stapley SA (2018) The burden of gunshot wounding of UK military personnel in Iraq and Afghanistan from 2003-14. Injury 49:1064-1069 (chapter 2).

The aim of this work was to characterise the spectrum of GSW injuries and define their clinical burden to the UK military from the conflicts in Iraq and Afghanistan between 2003 and 2014.

1.6.2 Gelatine

Publication: Stevenson T, Carr DJ, Stapley SA (2018) The effect of military clothing on gunshot wounding patterns in gelatine. Int J Leg Med E-pub:1-11 (chapter 3).

After detailing the clinical burden of GSW injuries in chapter 2, the aim of this study was to characterise the effect of UK military clothing on GSW patterns in a synthetic extremity model using blocks of 10% by mass gelatine and two specific types of military ammunition fired from a fixed engagement distance.

1.6.3 Ballistic research techniques

Prepared for submission: Stevenson T, Carr DJ, Harrison K, Critchley R, Gibb IE, Stapley SA (2019) Ballistic research techniques: Visualising gunshot wounding patterns (chapter 4).

Following the work in chapter 3, the requirement to test a model with more anatomical biofidelity than gelatine necessitated prototyping. With visualisation of GSW patterns within an opaque target being challenging, the aim of this series of experiments was to ascertain the most effective method to measure GSW patterns in a cadaveric animal limb model.

1.6.4 Deer limbs

Prepared for submission: Stevenson T, Carr DJ, Gibb IE, Stapley SA (2019) The effect of military clothing on gunshot wound patterns in a cadaveric animal limb model (chapter 5).

Drawing together the work from chapters 3, 4 and appendix H, the aim of this work was to test the effect of UK military clothing on GSW patterns in a cadaveric deer limbs using two specific types of military ammunition from a fixed engagement distance. The clothing samples, ammunition types and engagement distance were the same as those used in chapter 3.

1.6.5 Yaw

Prepared for submission (as a technical note / short communication): Stevenson, Carr DJ, Gibb IE, Stapley SA (2019) Preliminary effect of yaw on extremity gunshot wounding in a cadaveric animal model (chapter 6).

Following the serendipitous use of a different gun barrel during one series of experiments, it was noted that projectiles were yawing prior to striking deer limb targets and that wounding patterns appeared substantially different to what would be expected with the different clothing states utilised in chapters 3 and 5. Therefore the aim of this preliminary study was to investigate whether projectile yaw occurring before penetration of a cadaveric deer limb model causes worse damage with or without UK military clothing layers present using 5.45 x 39 mm ammunition.

1.7 Experimental timelines

The work within this PhD thesis was undertaken to achieve the academic structure as laid out above. Data gathering and experiments were arranged around the availability of required facilities, personnel, resources and consumables. JTTR access required MODREC approval prior to commencing the database search and assistance from the Clinical Information and Exploitation Team (CIXT). Russian ammunition was procured via the Impact and Armour Group, ensuring batch control for the orders placed. Gelatine powder came from Germany. Clothing samples were sourced from HMS Nelson, Portsmouth dependent on their availability. Deer limbs were locally sourced in Worminghall, Oxfordshire, but were subject to availability during fallow deer hunting season. CT scanning was arranged out-of-hours at Queen Elizabeth Hospital Birmingham (QEHB) but was subject to clinical need and the availability of key technical staff. The unexpected announcement of the closure of the Impact and Armour Group with redundancy of almost all of the academic and technical personnel necessitated alternative arrangements. Several commercial ranges were explored, with Radnor Range providing invaluable assistance and use of their facilities, as well as use of Cranfield Ordnance Test and Evaluation Centre (COTEC). The goodwill of military colleagues at Shrivenham was also called upon to re-open the ranges under military jurisdiction to conduct experiments at short notice to fit the timelines of the many different facets needed to complete a full series of testing.

1.8 Declaration

I, Tom Stevenson, state that the work presented within this PhD thesis is my own. Guidance on model development, conducting the experiments, data interpretation and preparing manuscripts was provided by co-authors whom are acknowledged accordingly where relevant.

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2 THE BURDEN OF GUNSHOT WOUNDING OF UK MILITARY PERSONNEL IN IRAQ AND AFGHANISTAN FROM 2003-14

Stevenson T, Carr DJ, Penn-Barwell JG, Ringrose TJ, Stapley SA

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Additional epidemiological raw data for this work can be found in appendix B.

2.1 Abstract

Introduction: Gunshot wounding (GSW) is the second most common mechanism of injury in warfare after explosive injury. The aim of this study was to define the clinical burden of GSW placed on UK forces throughout the recent Iraq and Afghanistan conflicts. *Methods:* This study was a retrospective review of data from the UK Military Joint Theatre Trauma Registry (JTTR). A JTTR search identified records within the 12 year period of conflict between 19 Mar 2003 and 27 Oct 2014 of all UK military GSW casualties sustained during the complete timelines of both conflicts. Included cases had their clinical timelines and treatment further examined from time of injury up until discharge from hospital or death. *Results:* There were 723 casualties identified (177 fatalities, 546 survivors). Median age at the time of injury was 24 years (range 18-46 years), with 99.6% of casualties being male. Most common anatomical locations for injury were the extremities, with 52% of all casualties sustaining extremity GSW, followed by 16% GSW to the head, 15% to the thorax, and 7% to the abdomen. In survivors, the rate of extremity injury was higher at 69%, with head, thorax and abdomen injuries relatively lower at 5%, 11% and 6% respectively. All GSW casualties had a total of 2,827 separate injuries catalogued. A total of 545 casualties (523 survivors, 22 fatalities) underwent 2,357 recorded surgical procedures, which were carried out over 1,455 surgical episodes between admission to a deployed medical facility and subsequent transfer to the Royal Centre for Defence Medicine (RCDM) in the UK. This gave a median of 3 (IQR 2-5) surgical procedures within a median of 2 (IQR 2-3) surgical episodes per casualty. Casualties had a combined length of stay (LoS) of 25 years within a medical facility, with a mean LoS in a deployed facility of 1.9 days and 14 days in

RCDM. *Conclusion:* These findings define the massive burden of injury associated with battlefield GSW and underscore the need for further research to both reduce wound incidence and severity of these complex injuries.

Keywords: Ballistic, Gunshot, Wounding, Epidemiology, Military

2.2 Introduction

Between 2003 and 2014, UK military forces were engaged in conflicts in Iraq and Afghanistan. Gunshot wounding (GSW) was shown to be the second most common mechanism of injury (MOI) for UK personnel in warfare after injury from explosive weapons in these prolonged conflicts [1]. It has also been demonstrated however, that GSW form a much greater proportion of injuries during the initial phases of military operations i.e. 'theatre entry' operations [1, 2].

While a substantial proportion of recent UK military research has focused on blast injury [3-7], there has been far less examination of GSW. There are several studies from the USA looking at gunshot wounding epidemiological data within US military casualties throughout the same conflict period from Iraq and Afghanistan [8-14], and although some recent UK studies have examined other aspects of combat injury from Iraq and Afghanistan [1, 15-17], the burden and injury pattern of GSW to UK military personnel throughout the Iraq and Afghanistan conflict period has not previously been examined.

Quantifying the burden of injury is challenging; while mortality is clearly an extremely important measure, the use of mortality alone fails to capture the efforts required in treating survivors of GSW. Patient reported outcomes (PROMs) have been used to measure 'recovery', but only in specific injury sub-groups [18, 19]. Whilst PROMs do represent a measure of the success of reconstructive and rehabilitative efforts, the resources required in this process are not captured. This study therefore seeks to measure the injury burden of caring for large numbers of GSW casualties by examining the resources involved in their care. This has significant relevance for those in both the military and civilian sectors within the UK who may need to plan for the care of large numbers of GSW casualties.

The aim of the current study was to characterise the spectrum of GSW injuries and define their clinical burden in UK forces from the conflicts in Iraq and Afghanistan between 2003 and 2014.

2.3 Patients and methods

This study was a retrospective review of registry data using the UK Military Joint Theatre Trauma Registry (JTTR) under the guidance and with assistance of the Clinical Information and Exploitation Team (CIXT). Ethical approval was obtained (CURES/2076/2016).

The JTTR prospectively captures data on all trauma cases admitted to deployed UK military medical facilities who trigger a 'trauma alert', or are subsequently repatriated for treatment of their injuries [20]. The JTTR is operated by UK Defence Statistics (UKDS) and injuries are coded according to the 2005 military version of the Abbreviated Injury Scale (AIS) [21] by Trauma Nurse Coordinators in both deployed and UK medical treatment facilities. It is important to note that as per the AIS system, a single GSW can result in several injuries being coded separately. At the time of writing, there was no directly comparable civilian national trauma registry in use in the UK.

The JTTR was searched to identify records of all UK military casualties sustaining GSW during the Iraq and Afghanistan campaigns within the 12 year period of conflicts between 2003 and 2014. The dates were chosen to cover the invasion of Iraq on the 19th March 2003 and cessation of major combat operations by UK Forces in Afghanistan on the 27th October 2014, thus spanning the totality of both campaigns. The term 'casualty' refers to both those killed and those who were injured and survived. Killed in Action (KIA) and Killed Non-Enemy Action (KNEA) refers to those who died before receiving medical care; Died of Wounds (DoW) refers to those who die after reaching medical care. Wounded in Action (WIA) and Wounded Non-Enemy Action (WNEA) refers to those survivors whom received medical care for their injuries (Table 2.2). Data on GSW casualties was extracted to establish their clinical timelines and surgical treatment between injury up until discharge from hospital or death. The relationship between anatomical injury location and probability of survival was also assessed using the chi-squared test [22] and binomial confidence intervals [23] with a null hypothesis of no association between them.

To put casualty numbers in proportion to the number of deployed UK troops exposed to risk, Population Years at Risk (PYAR) figures were calculated for the study period. From UKDS data between 2008-14, the PYAR was based on computerised records of every day spent in either of the two operational theatres by each UK service person. These figures were summed for each calendar year and divided by 365 to give the PYAR i.e. the equivalent number of personnel deployed for 12-months. For 2003-7, detailed pay records were not available, therefore the information was extrapolated from Ministry of Defence (MoD) figures on troop levels contained in memoranda to the UK Parliament and is regarded as less precise [18].

A surgical procedure was defined as any procedure undertaken by surgical teams to treat a casualty’s wounds. Whilst the majority (92%) of this data set involved formal surgical procedures with at least one surgeon conducting the procedure, the remaining 8% of the data also included procedures such as central line insertion and dressing changes, which still required the use of personnel and resources within the operating theatre environment.

A surgical episode was defined as any visit to the operating theatre for a casualty under the care of a surgical team, where single or multiple procedures could take place within each surgical episode.

Length of stay (LoS) was defined as the amount of time in days spent within any medical treatment facility, worldwide, from the time of injury up until their discharge from the Role 4 treatment facility in the Royal Centre for Defence Medicine (RCDM), Birmingham, UK. This did not include any subsequent readmissions to RCDM following their initial discharge, and also did not include any time spent by casualties undertaking rehabilitation either with their home unit medical centres or at Defence Medical Rehabilitation Centre (DMRC) Headley Court.

2.4 Results

Over the 12-year study period, there were 2,986 British military casualties recorded in the JTTR. Explosive weapons remained the most frequent MOI, responsible for 1,694 casualties, or 57% of the total. The second most common MOI was GSW with 723 (24%) of the total casualties with further detail on MOI given in Table 2.1. Amongst the GSW casualties, there were 177 fatalities and 546 injured survivors. With GSW casualties representing the group of interest to this study, those injured by other mechanisms will not be discussed further.

Table 2.1 Mechanism of injury data

MOI	Number
Explosive	1694
GSW	723
MVC	163
Fall	111
Other	93
Crush	71
Aircraft Incident	67
Burn	43
Assault	21
Total	**2986**

[MVC = Motor Vehicle Collision]

The breakdown of casualties with GSW sustained by conflict location and by military casualty classification is summarised in Table 2.2. The median age of GSW casualties at the time of injury was 24 years (range 18-46 years), with all but three casualties being male. The proportion of GSW casualties sustained against all deployed UK troops in the form of PYAR data shows the variation in casualty numbers per year of the study period (Table 2.3). The worst year of conflict during the study period for GSW casualties, both survivors and fatalities, was 2010 where there were over 14 GSW casualties per 1,000 PYAR (140 survivors, 31 fatalities).

Table 2.2 GSW casualty classification

Casualty classification	Iraq	Afghanistan	Total
KIA / KNEA	38	115	153
DoW	11	13	24
WIA / WNEA	71	475	546
Total survivors	71	475	546

Casualty classification	Iraq	Afghanistan	Total
Total fatalities	49	128	177
Total casualties	**120**	**603**	**723**

Table 2.3 Population Years at Risk (PYAR) data

Year	PYAR	UK Casualties (all MOI)	UK GSW Survivors	UK GSW Fatalities	GSW Casualties Per 1000 PYAR
2003	17,820	94	18	20	2.13
2004	10,483	69	5	5	0.95
2005	10,767	100	3	2	0.46
2006	13,000	177	25	15	3.08
2007	13,300	410	85	27	8.42
2008	13,513	270	40	12	3.85
2009	11,909	543	77	20	8.15
2010	11,657	521	140	31	14.67
2011	11,771	349	61	14	6.37
2012	11,488	273	59	27	7.49
2013	7,679	145	24	4	3.65
2014	3,787	35	9	0	2.38
Total	**137,174**	**2986**	**546**	**177**	**5.27**

In terms of numbers of casualties, the different anatomical locations of injury were catalogued (Table 2.4) where the most common anatomical region for GSW was to the extremities, with 379 (52%) of all casualties suffering extremity GSW (237 or 33% of the total being lower extremity injuries and 142 or 20% being upper extremity), followed by 115 (16%) sustaining GSW to the head, 106 (15%) to the thorax and 49 (7%) to the abdomen. In survivors, the percentage rate of extremity injury was higher at 69% (43% lower extremity, 26% upper extremity) with head, thorax and abdominal injuries relatively lower at 5%, 11% and 6% respectively. The remaining anatomical regions of ‘face’, ‘neck’, ‘spine’, ‘other trauma’, ‘uncoded’ and ‘external’ recorded for GSW can be found within Table 2.4.

Table 2.4 Total GSW casualties by anatomical injury location

Injury Location	Total number of casualties (% of total)	Number of survivors (% of survivors)	Number of fatalities (% of fatalities)
Total Extremities	**379 (52%)**	**376 (69%)**	**3 (2%)**
Lower Extremity	237 (33%)	235 (43%)	2 (1%)
Upper Extremity	142 (20%)	141 (26%)	1 (1%)
Head	115 (16%)	30 (5%)	85 (48%)
Thorax	106 (15%)	58 (11%)	48 (27%)
Abdomen	49 (7%)	35 (6%)	14 (8%)
Face	26 (4%)	25 (5%)	1 (<1%)
Neck	23 (3%)	10 (2%)	13 (7%)
Spine	18 (2%)	11 (2%)	7 (4%)
Other Trauma	3 (<1%)	0 (0%)	3 (2%)
Uncoded	3 (<1%)	0 (0%)	3 (2%)
External	1 (<1%)	1 (<1%)	0 (0%)
Total casualties	**723**	**546**	**177**

A chi-squared test of association between injury location and survival or not gave a test statistic of 327 on 8 degrees of freedom ($p<0.001$), clearly rejecting the null hypothesis of no association and signifying that the anatomical injury location where a casualty was shot directly affected their chances for survival, as one would expect.

When the numbers of survivors were compared with fatalities by anatomical regions, all extremity casualties and casualties with facial injury were more likely to survive whereas head and neck casualties were more likely to die (Figure 2.1). With regard to abdominal and spinal injured casualties, although fewer in numbers compared with survivors, casualties had a marginally higher percentage of fatality in both groups (Table 2.4). Figure 2.1 shows the observed numbers of survivors for each anatomical location of injury, the observed percentage of survivors and the exact 95% confidence interval for the percentage of survivors in each case (using Minitab 16 statistical software). This demonstrates, for example, that casualties that sustained GSW to the extremities had a much higher probability of survival (we are 95% confident that the probability is between

96.98% and 99.90% for upper extremity casualties, and between 96.14% and 99.98% for lower extremity casualties) whereas those casualties sustaining GSW to the head had a much higher probability of fatality (we are 95% confident that the probability is between 64.90% and 81.66%), as would be expected.

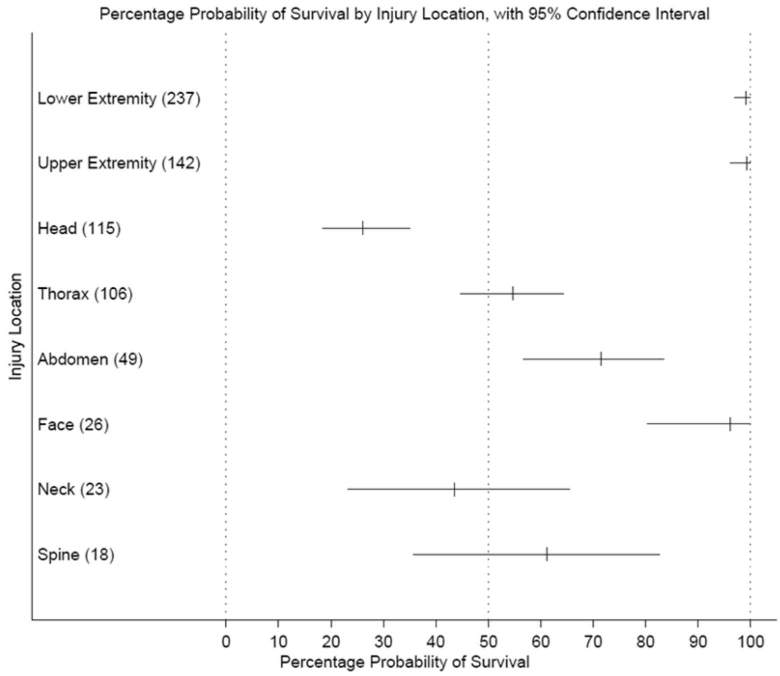

Figure 2.1 GSW survival probability

In terms of numbers of injuries within the 723 GSW casualties, there were 2,827 separate injuries recorded within the JTTR (Figure 2.2). Considering the data in this way takes into account the spread of injuries from casualties whom were injured in multiple anatomical regions. Once again, the anatomical region with the highest proportion of injury was the extremities (908 injuries or 32%). When considered separately as upper and lower extremity, then the highest proportion of injuries were to the thorax (22%), followed by lower extremity (19%), head (18%), upper extremity (13%) and abdomen (10%), with face, spine, neck, external and “other trauma” making up the remaining 18% of injuries (Figure 2.2).

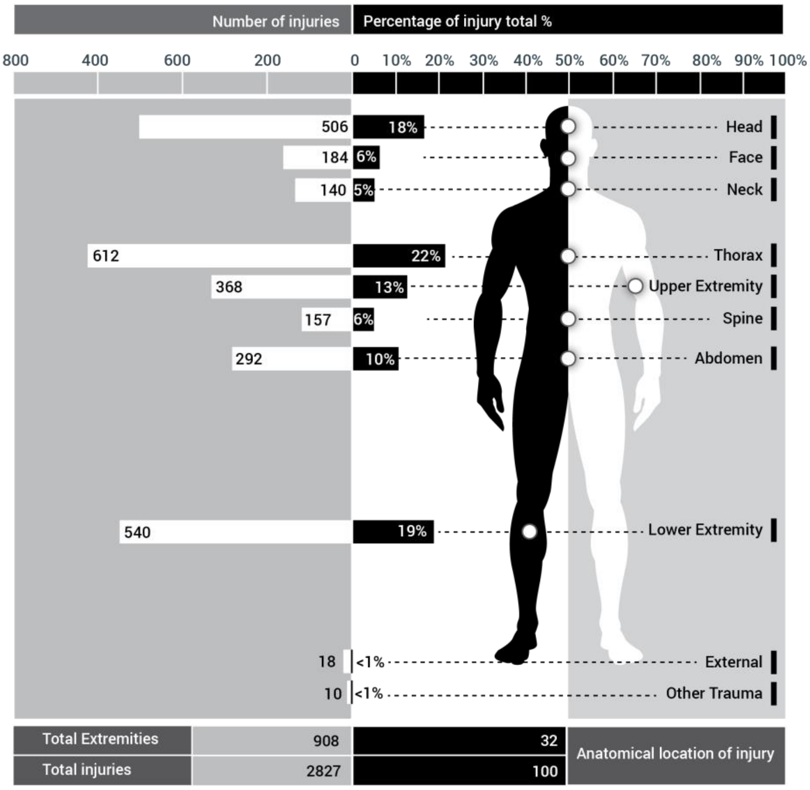

Figure 2.2 GSW injuries anatomy schematic

A total of 545 or 75% of all GSW casualties (523 survivors, 22 fatalities) required a total of 2,357 surgical procedures between admission to a deployed military surgical facility and subsequent transfer to RCDM in the UK. This equates to a median of 3 (mean 4.32, IQR 2-5) surgical procedures per casualty. These procedures were carried out over a total of 1,455 surgical episodes of which 646 (44%) episodes were conducted within a deployed military surgical facility and 809 (56%) episodes were undertaken at RCDM in the UK. Casualties could expect a median of 2 (mean 2.67, IQR 2-3) surgical episodes each. There was a mean time of 122 minutes per procedure though 1064 (45%) procedures had no operating time recorded. Casualties had a combined LoS of 25 years (9114 days) within a medical treatment facility, with a mean LoS in a deployed military surgical facility of 1.9 days and 14 days in RCDM (Table 2.5). The 22 fatalities were casualties whom died of their wounds in spite of surgical treatment carried out. Therefore the proportion of GSW casualties undergoing surgical procedures during their initial treatment period captured on the JTTR had a survival probability of 96% (523 out of 545, 95% Confidence Interval: 94.0% - 97.5%).

Table 2.5 Length of Stay data

Location	Total Days	Mean (days)	Median (days)	IQR
All Locations*	**9114**	**8.14**	**3**	**1-9**
Role 3 Bastion (BSN) Ward	**736**	**1.95**	**1**	**1-2**
Role 3 BSN CCU	37	1.76	1	1-1
Role 3 BSN Total	773	1.94	1	1-2
Role 4 RCDM Wards (all)	**6985**	**14.08**	**8**	**4-16**
Role 4 RCDM Ward 412	2587	13.13	7	4-14
Role 4 RCDM CCU	1037	9.97	6	2-11
Role 4 RCDM Total	8022	13.37	8	4-16

* Multiple locations across Afghanistan, Cyprus, Germany, Iraq, Pakistan and UK

2.5 Discussion

These results provide detailed information as to the injury pattern of GSW to the UK military and define the significance of the clinical burden of GSW over a prolonged period of conflict. Key statistics are summarised as follows: 24% of all British casualties within the study period were due to GSW, of which over half suffered injury to the extremity. Three quarters of the GSW casualties underwent a total of 2,357 surgical procedures which were carried out over a total of 1,455 surgical episodes (median of 3 surgical procedures carried out over a median of 2 surgical episodes per casualty undergoing treatment). Mean time per surgical procedure was 122 minutes. Casualties undergoing surgical procedures during the treatment period examined had a survival probability of 96%. Finally, casualties accumulated 25 years LoS across medical treatment facilities.

To calculate the numbers of surgical procedures or episodes and the accumulated length of stay of those casualties undergoing treatment, the 545 casualties examined consisted of troops whom were either WIA / WNEA or DoW, i.e. were successfully evacuated to receive medical treatment, and excluded those who were KIA / KNEA as they didn't receive any formal medical treatment.

With the spread of anatomical regions injured amongst all casualties, there is a higher percentage rate of head, neck and thorax injuries amongst fatalities compared with survivors for obvious reasons when considering the anatomical structures filling those regions; of interest is the large proportion of extremity injuries seen. With nearly 70% of survivors suffering extremity wounding, the subsequent workload to the Orthopaedic and Plastic surgeons both deployed and in the UK is clearly substantial. This rate of extremity injury sustained during conflict is comparable to data collected on extremity injured casualties of all MOIs which outlined the burden of treatment for these casualties and also compared the rate of extremity injury with other major conflicts over the last 50 years [24].

It is important to acknowledge the limitations in this study. Firstly, like any registry study, it is reliant on the quality of the data entry. It is believed that the data fidelity was higher from 2006 onwards [1]. This study recorded the number of surgical procedures and may risk overestimating the surgical treatment if the assumption was that each procedure required its own trip to the operating theatre; however this was mitigated by recording the number of distinct surgical episodes to demonstrate how many procedures would be conducted within each trip to the operating theatre. AIS coding can overestimate numbers of wounds to the head and neck with closely packed structures compared to the limbs. Data entry points could also be ambiguous, for example a procedure might be listed as “change of dressings” however this could have entailed a formal change of dressings within the operating theatre environment under the care of the surgeon or equally could have been a bedside change of dressings undertaken by the wound care specialist nurse within the ward environment. Though where these instances were so few and only represented 8% of the procedures undertaken, excluding these data points made almost no difference to the calculated means and medians for surgical procedures and episodes conducted upon the casualties and where the figures were presented as whole numbers rounded up, it actually made no difference at all whether they were included or not. Finally, the JTTR only captures data on military patients up until their death or their first time being discharged from the medical facility. Any subsequent readmission is not captured, therefore the onward disposal of these casualties is extremely difficult to ascertain and was not achievable within the scope of this study.

Aside from the potentially life-changing impact of GSW on the patients themselves, such injuries involve complex surgical care, often delivered over repeated surgical episodes and consequentially a prolonged surgical stay. The measure of success from such treatments comes in the form of examining the quality of life and functional outcomes of these casualties (e.g. PROMs). Quality of life and functional outcome study within UK military troops would require medium to long-term follow up data from this cohort of patients which is notoriously difficult to capture, especially where casualties have subsequently left military service, and is outside the scope of this study. Currently the care of UK military patients is transferred from the Defence Medical Services to the National Health Service upon military discharge. There is no formal method for the UK military to track these patients further once they have completed all formal medical treatment and therefore their long-term functionality is currently not known.

2.6 Conclusions

The findings of this study define the substantial size of the injury burden of GSW sustained in combat within the UK military and the resources required for their treatment. This work indicates the need for further research into the clinical management of GSW to UK military personnel.

In light of recent terrorist atrocities over the last few years in the UK, European mainland and the USA, there have been mass shootings of civilians by military style firearms leading to multiple fatalities and hundreds of injuries requiring hospital treatment. Whilst it should be remembered that a typical civilian population is unprotected by body armour so the spread of injury would be likely more variable with potentially higher numbers of fatalities and thus difficult to compare with a military population, the data presented in this paper may be useful to UK trauma centres that are planning for the appropriate resources required to treat GSW casualties should an event of this nature occur within the UK, in the absence of any other UK-based gunshot epidemiological research data available.

2.7 Conflict of interest statement

There are no conflicts of interest from any of the listed authors for this submission.

2.8 Acknowledgements

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3 THE EFFECT OF MILITARY CLOTHING ON GUNSHOT WOUNDING IN GELATINE

Stevenson T, Carr DJ, Stapley SA

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Further detail on the gelatine manufacturing process used in this chapter can be found at appendix C. Further detail on microhardness and elemental analysis of projectiles used in this chapter can be found at appendices D and E respectively. Further detail on fabric analysis conducted on clothing materials used in this chapter can be found at appendix F. Experimental raw data is included in appendix G.

3.1 Abstract

With no two gunshot wounds (GSW) being the same, novel research into wound ballistics is challenging. It is evident that the majority of previous wound ballistic research has been conducted without the presence of clothing. Whilst the effect of clothing on wound contamination has been explored, there is a paucity of literature examining the effect of clothing on GSW patterns. The aim of this study was to test the effect of Multi-Terrain Pattern (MTP) UK military clothing on GSW patterns within calibrated blocks of 10% by mass gelatine, using two types of ammunition commonly used in recent conflicts – 7.62 x 39 mm and 5.45 x 39 mm. In total, 36 blocks were shot; 18 by each projectile type, further divided into 6 with no clothing layers (C_{nil}), 6 with a single clothing layer (C_{min}) and 6 with maximum clothing layers (C_{max}) worn on active duty. Blocks were analysed with high speed video and dissection to capture measurements of damage, and results compared using Analysis of Variance (ANOVA). Results showed significantly different damage measurements within blocks with C_{max} for both ammunition types compared to the other clothing states. This may result in GSWs that require more extensive surgical management, inviting further study.

Keywords: Gunshot, Wounding, Clothing, Gelatine, Military, AK47, AK74

3.2 Introduction

During the recent Iraq and Afghanistan wars (2003-14), the UK military suffered 723 gunshot wound (GSW) casualties with 177 fatalities and 546 survivors leading to a substantial clinical burden [1]. Historical review has demonstrated that clinical lessons learned from previous conflicts are often lost, leading to potentially avoidable higher morbidity amongst casualties [2,3]. It is therefore paramount that studies are undertaken using appropriate methods to continually test existing theory and research conducted over the last century, and help develop novel strategies to further understand wound ballistics. This may improve patient outcomes [4], and ultimately retain corporate knowledge gained previously and pass it on to the next generation of clinicians.

The majority of existing GSW research has been conducted on naked animals or cadavers or bare tissue simulants, e.g. [5-16]. Whilst the effects of clothing on GSW have been examined with respect to contamination e.g. [17-21], there remains a paucity of literature examining the effect of clothing on the wounding patterns, exceptions include separate works by Kieser, Carr, Mabbott, and Mahoney [22-25].

Gelatine has been used for wound ballistic research since the early 20th century, with different concentrations and configurations depending on the aims of the respective studies [26-34]. Research conducted at the Letterman Institute in the USA re-validated the use of gelatine as comparable to live swine thigh muscle tissue with regard to its response to ballistic testing. This can offer a useful way to visualize GSW profiles from different ammunition types [35-37]. Studies from the last five years have examined the difference in gelatine concentrations to determine positive and negative attributes for certain uses within wound ballistic research [24,38,39]. The use of gelatine in wound ballistic research has also recently been summarised and highlights the difficulty in accurately reproducing wounding patterns despite controlling as many variables as possible [4]. With clinicians often stating that no two GSWs are ever the same [40], such modelling poses a real challenge to the researcher in order to achieve their aim. As well as gelatine, other media used in ballistic modelling include ballistic soap, cadaveric animal and human tissue, live animal tissue and other synthetic tissue simulants, all of which have been subject of recent review [41].

It helps to consider wounding patterns that occur within gelatine blocks in several different stages which are explored in greater detail within Kneubehl's comprehensive text "Wound Ballistics" [42] and are summarised as follows:

- *Temporary cavity*: The temporary cavity is formed following transfer of kinetic energy (KE) from the projectile to the gelatine. The KE causes the gelatine to radially accelerate away from the projectile, generating negative pressure, drawing air in from the entrance (and / or exit) wound and forming the temporary cavity. The size of the temporary cavity can vary along the wound track and is determined by the amount of kinetic energy (KE) being transferred, which is in turn determined by the contact surface area of the projectile. Should the projectile yaw, expand and/or fragment, its contact surface area with the target is increased at that point, causing an increase in drag coefficient resulting in more rapid deceleration, and leads to greater delivery of KE and thus greater temporary cavitation. The temporary cavity, by the physical properties associated with its formation, is multiple times larger than the permanent cavity left behind.

- *Permanent cavity:* This consists of the track formed by the projectile crushing and cutting its way through the gelatine, and the damage caused by the formation and collapse of the temporary cavity. When a projectile of a certain type (for example, military projectiles, such as 7.62 x 39 mm) strikes a target nose on, an initial narrow wound channel (i.e. the neck length) is created whilst the projectile is still travelling symmetrically (and is arguably of the greatest surgical relevance as marginal to no surgical debridement of tissues is required [14,43]). There is little damage seen as the projectile's contact surface area with the gelatine is at its minimum. With a longer neck length, the projectile may go on to exit the target before yawing, and as such takes the majority of KE with it, leaving a potentially smaller and simpler wound profile behind – again, clinically this is important and will be revisited within the discussion section of this paper. It should be noted that other ammunition types, such as expanding projectiles may have little to no neck length at all with extensive cavitation seen. Other projectile types, such as ball bearings, are of a uniform spherical shape so will not yaw and also do not deform in shape and may only leave a narrow track following minimal temporary cavitation. Knowledge of these properties helps identify wound patterns attributable to those projectile types.

Understanding the wounding pattern helps facilitate calculation of the area or volume of gelatine damage seen. With respect to what measurements are relevant, this is variable and determined by the aim of the study. Examples include measuring the depth of penetration (DoP) of projectiles into the gelatine block, the dimensions of the temporary cavity using high speed video (HSV), the dimensions of the permanent cavity, the distance from entry to which the projectile yaws 90°, and imaging of wound tracks using medical imaging modalities [4,22,24,25,36,44-48].

The types of ammunition used in ballistic modelling are dependent on what the subject for study demands. Typically for modelling directed at the use of military grade firearms, high velocity rifle ammunition is used e.g. 7.62 x 39 mm, 7.62 NATO (7.62 x 51 mm), 5.45 x 39 mm and 5.56 NATO (5.56 x 45 mm). This list is by no means exhaustive; there are numerous studies examining different projectile types, such as steel ball bearings [24,49]. With physical, mechanical and ballistic properties of ammunition varying widely but rarely being discussed within the literature, it is preferential to use a single quarantined batch of required ammunition types and, if necessary, identify composition and microhardness [4].

The ballistic protective performance of winter issue military clothing has been reported, however this examined the failure of the clothing rather than any wounding patterns seen as a result of ballistic impact [50]. A study of rifle ammunition effects on tissues considered anaesthetized pigs clothed in Finnish military uniforms however made no comment on the effect of the presence of the clothing on the wounding patterns [51].

More recently published was a study that showed the presence of a layer of denim on a model of a deer femur embedded in 20% (by mass) gelatine led to an increase in the risk of indirect femoral fracture when shot by 5.56 NATO ammunition [22], followed by an increasing interest in examining clothing effects on wounding in ballistic research (e.g. [4,20,21,23,44,45]). Published research has demonstrated that intermediate layers (clothing or other personal protective equipment) can affect damage sustained by a gelatine block during ballistic testing e.g. [22,23,25,44].

Whilst it can be acknowledged that previous research on naked tissue and tissue simulants has been conducted, it is evident that professional troops going into active conflict in the modern era will be appropriately clothed. With respect to UK service personnel, that clothing is typically in the form of standard issue Multi-Terrain Pattern (MTP) clothing, with different layers worn depending on the climate and the nature of the operations being conducted. The effect of military clothing on wounding patterns does not appear to have previously been examined.

The aim of the current study was to characterise the effect of military clothing on GSW patterns in blocks of 10% by mass calibrated gelatine using 7.62 x 39 mm and 5.45 x 39 mm ammunition, whilst considering the clinical relevance of the results.

3.3 Materials and methods

Ethical approval for this work was granted through CURES (CURES/3579/2017).

3.3.1 Materials

Thirty-six blocks of 10% (by mass) gelatine were made in batches of six from Type 3 photographic grade gelatine (GELITA® AG, Uferstraβe 7, D-69412, Eberbach, Germany; Bloom strength 263). Moulding tins had inside dimensions of 250 x 250 x 500 mm, with a 1^o taper to facilitate set gelatine removal [44]. The blocks were conditioned at 4 ^oC for 24 hours after setting.

The MTP clothing selected for investigation was divided into different states to represent the minimal and maximal layers worn globally by UK personnel on combat and front-line duties. Firstly bare blocks of gelatine, or a zero clothing state (C_{nil}) was used for a control. The minimal clothing state (C_{min}) was represented by a single clothing layer taken from MTP trousers[1] (n = 6) (Figure 3.1). Finally, the maximal clothing state (C_{max}) involved several layers of clothing including a base layer standard issue t-shirt[2] (n = 6), upper arm sleeve pocket of Under Body Armour Combat Shirt (UBACS)[3] (n = 6), the upper arm sleeve pocket of an MTP smock jacket[4] (n = 6), and finally a brassard (upper arm protection). The brassard consisted of a fragment protective filler[5] manufactured from a para-aramid fabric, sealed in a light- and water-resistant cover. This was inserted into an outer carrier[6] which attaches to the body armour torso as part of the OSPREY body armour system (n = 12 for both items) (Figure 3.1) [52]. All clothing, excluding the brassards, was laundered (following procedure 8A of British Standard EN ISO 6330: 2001) by washing six times before drying informed by the care label provided in the garment and to ensure the removal of any finishing treatments and dimensional stability of the fabric [53][7].

[1] Trouser, combat, warm weather MTP – NATO Stock Number (NSN): 8415-99-317-8313
[2] T-shirt, combat, anti-static, light olive – NSN: 8415-99-813-3258
[3] Shirt, UBACS, MTP – NSN: 8415-99-317-8402
[4] Smock, combat, windproof, MTP – NSN: 8415-99-317-8386
[5] Filler Osprey Mk 2 – NSN: 8470-99-480-8055
[6] Osprey MKIVA (MTP) cover brassard – NSN: 8470-99-684-4613-4
[7] BEKO washing machine (model number WM84125W) used on a cotton cycle lasting 79 minutes per cycle with a water temperature of 40°C; BEKO tumble dryer (model number DSV64W) used on a 60 minute cycle at the standard factory set temperature (not listed).

Figure 3.1 Examples of MTP clothing used – clockwise from top left: MTP trousers; top right: t-shirt, UBACS, smock, and brassard as worn by service personnel; bottom: i. t-shirt, ii. UBACS, iii. smock and iv. brassard layers prepared for testing

Fabric samples of individual clothing layers were analysed (n = 5) in order to characterise their physical properties. Mass per unit area and thickness of the samples were measured [54,55], using Oxford A2204 scales to measure mass and a Mitutoyo C1012MB thickness gauge to measure thickness of the MTP trouser single layer for C_{min}, and the individual layers of the t-shirt, UBACS and Smock as part of C_{max}. The brassard and all combined layers for C_{max} were measured using Mettler PE16 scales for mass and a Shirley Thickness Gauge (Shirley Developments Ltd., 87137) for thickness.

In recent conflicts that UK Armed Personnel have participated in, a wide range of weapons systems were used. Two common weapons systems available in Iraq and Afghanistan (2003-14) that were used against UK Armed Forces were the AK47 and the AK74 [56,57]. The ammunition used with these weapons systems is 7.62 x 39 mm and 5.45 x 39 mm respectively. Therefore, these two types of ammunition were used in the current study. To help control the variability in ammunition batch production, batches of ammunition were quarantined for this study: 7.62 x 39 mm (7.62 x 39 mm Wolf Hunting Cartridges; lead core, 122 grain full metal jacket, Lot number F-570, made in Russia, 2006) and 5.45 x 39 mm (5.45 x 39 mm; mild steel core, 53 grain full metal jacket, Lot number 539-04, made in Russia, 2004) (Figure 3.2). Hardness was determined by sectioning and encapsulating projectiles in epoxy resin (n = 3), using a Struers Rotopol 15 to polish the sample projectiles, and an Indentec Highwood microscope with diamond tipped load point to measure hardness. Elemental composition was determined using a Hitachi SU3500 scanning electron microscope with EDAX analysis and TEAM software.

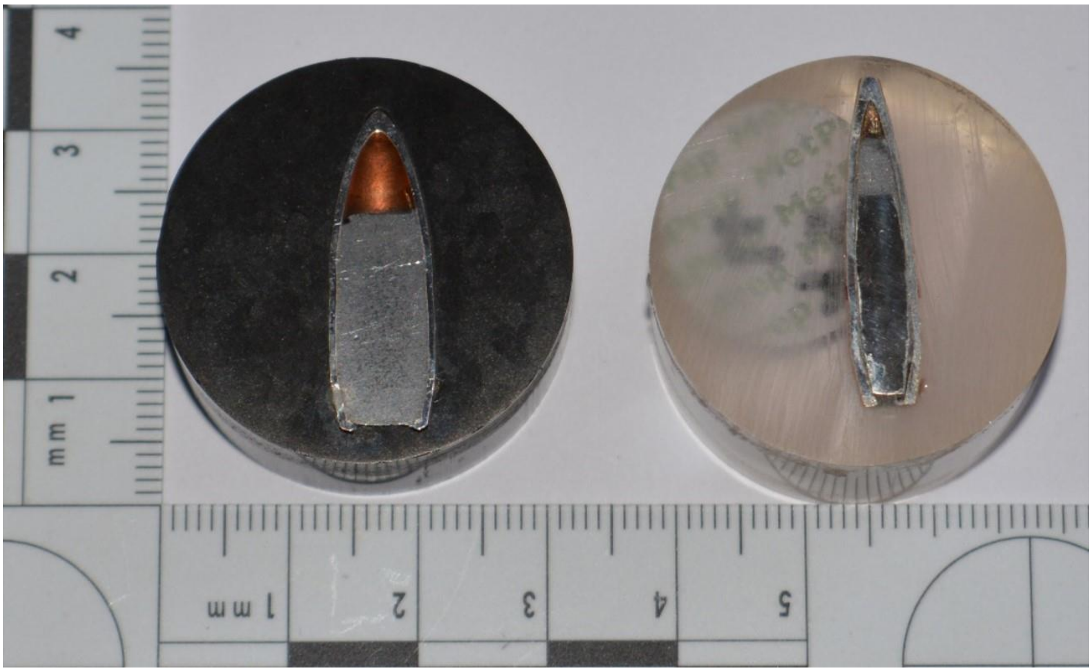

Figure 3.2 Mounted sections of 7.62mm (left) and 5.45mm (right) projectiles

3.3.2 Methods

Fabric samples for C_{min} were cut from laundered MTP trousers (250 x 250 mm) and pinned to the front face of the gelatine blocks (Figure 3.3). Fabric samples for C_{max} were measured and cut in relation to the upper sleeve pocket size on the UBACS and Smocks (200 x 150 mm), and placed in layers with the t-shirt layer innermost, then UBACS, smock and finally with the brassard then placed over the top of the other layers (Figure 3.3).

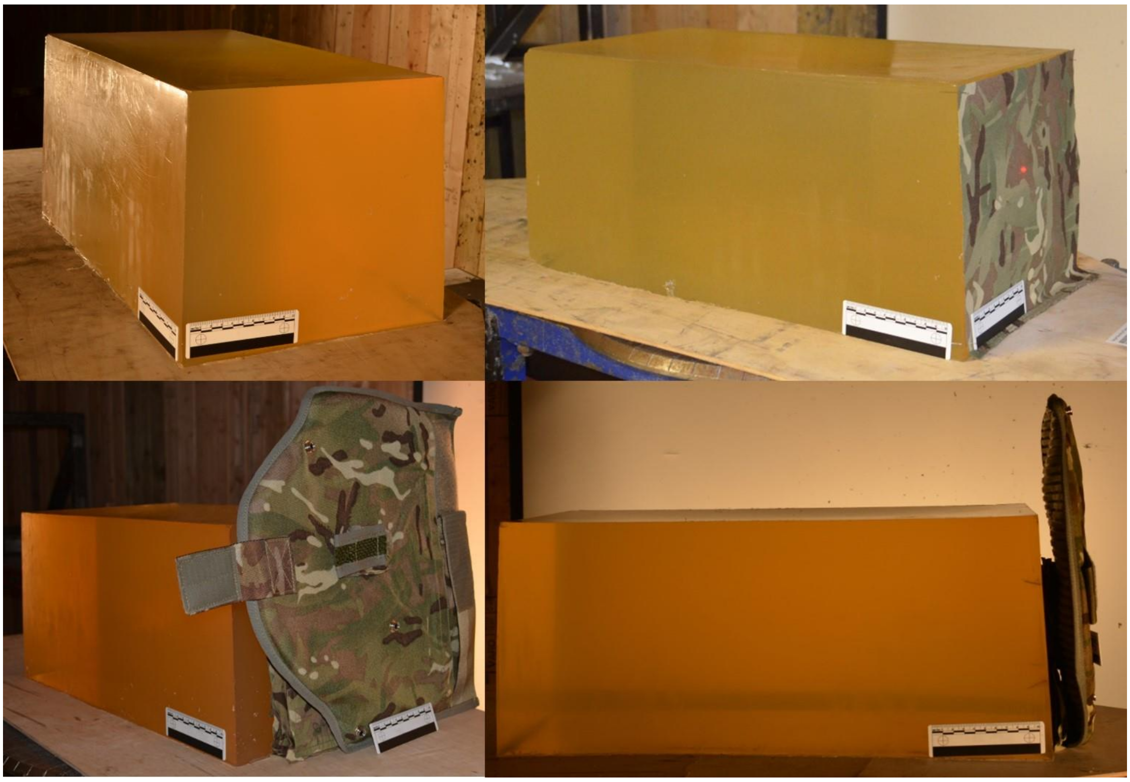

Figure 3.3 Clockwise from top left: C_{nil} oblique view; C_{min} oblique view; C_{max} side view; C_{max} oblique view

An indoor small arms range was used to fire projectiles from a number 3 proof housing where the end of the barrel was situated at 10 m from the target. The gelatine was calibrated by firing a 5.5 mm ball bearing into each block; DoP was measured and compared to previously published studies to ensure validity of the blocks used in this series of experiments [25,38,58]. Each block was then shot once with the test projectiles. Eighteen blocks were shot with 7.62 mm projectiles and the remaining 18 blocks were shot with 5.45 mm projectiles. Six blocks for each ammunition type had either C_{nil}, C_{min}, or C_{max} added to the impact face.

The impact velocity for each projectile was measured using Doppler radar (Weibel W700). HSV using a Phantom V1212 video camera (frames per second = 37,000, shutter speed = 5µs, resolution = 512x384) allowed visualisation of the wounding pattern and to record the formation of the temporary cavity. Measureable parameters taken from the HSV of this phenomenon using Phantom Software (Visions Research, Phantom Camera Control Application 2.6). These parameters included maximum height of the temporary cavity (H1) and distance to the maximum height of the temporary cavity (D1), where the latter corresponded to the point where the projectile was at maximum yaw of 90° [36], e.g. Figure 3.4a. Temperature of the gelatine blocks was recorded after shooting using a calibrated digital thermometer. Black food colouring was poured in via entrance wounds of the gelatine blocks to visually highlight wounds. Gelatine blocks were then dissected and any fragmentation of the projectiles noted and recovered. The damage to the gelatine block was photographed using a Canon D5100 Digital SLR camera (S/N 6773411). The parameters of damage measured were maximum height of the permanent cavity (H2), distance to maximum height of the permanent cavity (D2), and neck length (NL) e.g. Figure 3.4b.

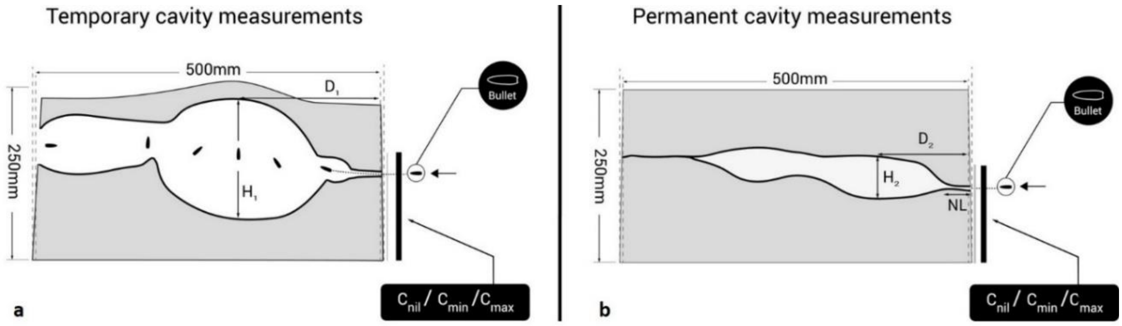

Figure 3.4 a Temporary cavity measurements schematic; b Permanent cavity measurements schematic

The International Business Machine Corporation's Statistical Package for Social Services version 24 (IBM SPSS Statistics v24), analysis of variance (ANOVA) was used to determine the effect of the different clothing states[8] on H1, D1, H2, D2 and NL. The two ammunition types were considered together and homogeneity of variance and normality of data were confirmed with a significance level of 0.05 applied. Significant differences due to ammunition type and/or clothing condition were identified using Tukey's honest significant difference (HSD) test. Main effects and significant interactions only are discussed in the Results section.

[8] The effects of C_{min} on GSW patterns were presented as a poster at the 30th International Symposium on Ballistics [45].

3.4 Results

Calibration of the gelatine blocks using 5.5 mm diameter ball bearings (mean impact velocity of 725 m/s, SD = 26 m/s; mean DoP = 361 mm, SD = 11 mm) was similar to previously collected data giving confidence in the consistency of the blocks (Figure 3.5). Mean impact velocity for the 7.62 mm projectiles was 648 m/s (SD = 8 m/s) and for the 5.45 mm projectiles was 883 m/s (SD = 14 m/s). Mean temperature of the gelatine blocks after testing was 6.8 ^{o}C (SD = 1.6 ^{o}C).

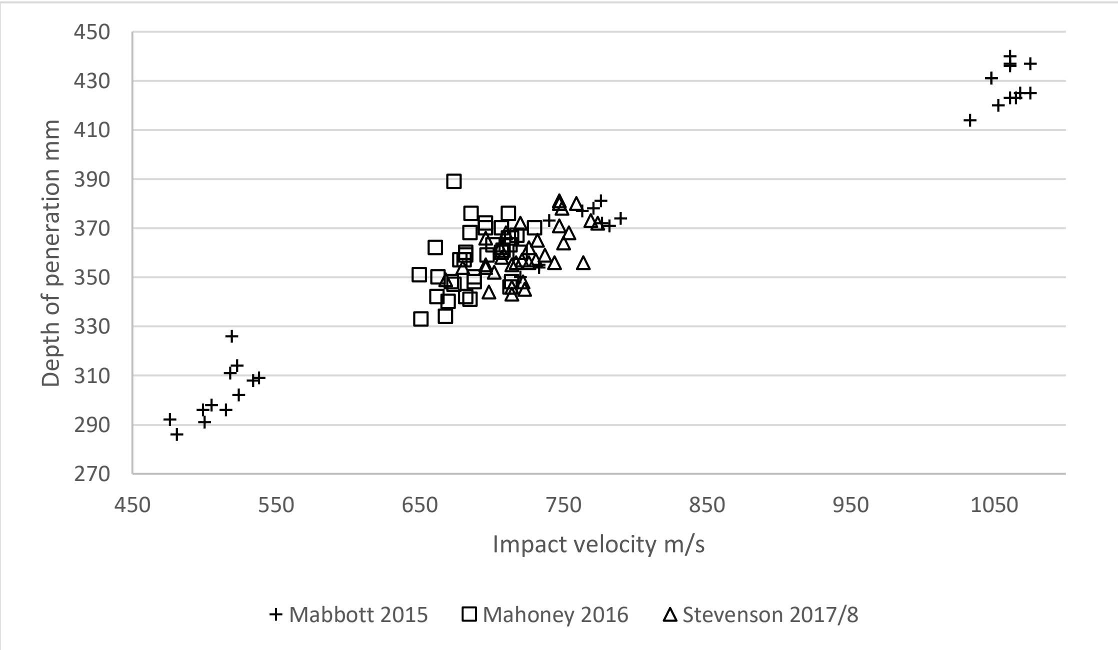

Figure 3.5 10% gelatine (4 ^{o}C) calibration data (Stevenson 2018 current study, compared to historical data [44,59]. Mabbott's data included calibration using different velocities, hence the outlying clusters of data points seen on the graph)

Ammunition characteristics are given in Table 3.1. As expected, both projectiles were jacketed in steel with copper washes and the lead core of the 7.62mm projectile was softer than the steel core of the 5.45mm projectile which had a soft lead tip.

Table 3.1 Characteristics for 7.62 x 39 mm and 5.45 x 39 mm ammunition

Projectile type		Core hardness (Hv)	Jacket hardness (Hv)	Tip hardness (Hv)
7.62 mm	**Mean**	7.39	184.57	N/A
	SD	0.86	9.91	N/A
	Composition	Lead, antimony	Steel (with internal / external copper wash)	N/A
5.45 mm	**Mean**	820.90	188.90	4.58
	SD	15.85	15.41	1.05
	Composition	Steel	Steel (with internal / external copper wash)	Lead

Mass per unit area and thickness for C_{min} and C_{max} are given in Table 3.2. The single trouser layer used for C_{min} was thinner and lighter than the combined layers used for C_{max} as would be expected. The C_{max} thickness and mass per unit area was calculated using all layers together, as would be worn in reality.

Table 3.2 Mass per unit area and thickness for clothing states

Clothing state		Mass per unit area (g/m^2)	Thickness (mm)
C_{min}	**Mean**	191.14	0.43
	SD	1.76	0.02
C_{max}	**Mean**	7735.17	32.26
	SD	86.02	0.97

Seventeen of the 7.62 mm projectiles and 10 of the 5.45 mm projectiles exited the blocks across all clothing conditions. For the 7.62 mm projectiles, all exits were via the rear face. For the 5.45 mm projectiles, one of the projectiles exiting exited via the rear face, four via the right face (as viewed from the impact face) and five exited via the top face. For projectiles that were retained, the DoP was measured: for the one 7.62 mm projectile retained, the DoP was 484 mm; for the eight 5.45 mm projectiles retained, the mean DoP was 423 mm (SD = 14 mm), though it was noted from the HSV that all those retained 5.45 mm projectiles except for one would have exited via the bottom face but instead were retained due to ricochet off the table the block was mounted on. The retained 7.62 mm projectile was in a gelatine block with C_{nil}, and the one truly retained 5.45 mm projectile (which did not ricochet of the base table) was in a block with C_{max}, therefore the clothing state was unlikely to have influenced the rate of projectile retention.

Seventeen of the 7.62 mm projectiles were seen to fragment on the HSV footage; 94% of those fragments were retained within the blocks and four of the seventeen shots that fragmented had more than one fragment, with a maximum of three fragments seen (Figure 3.6). Mass of fragments varied from 0.04 g to 0.61 g (mean = 0.30g, SD = 0.16 g). The difference seen in the number of projectiles that fragmented or the number of fragments seen among blocks with or without clothing layers was either non-existent or too small for statistical comparison. The mean DoP of the fragments was 350 mm (SD = 97 mm). None of the 5.45 mm projectiles fragmented. This data suggests that the clothing state did not influence the fragmentation of the projectiles, and that this was more likely due to the composition and construction of each ammunition type and the forces applied to the projectile during the interaction with the target.

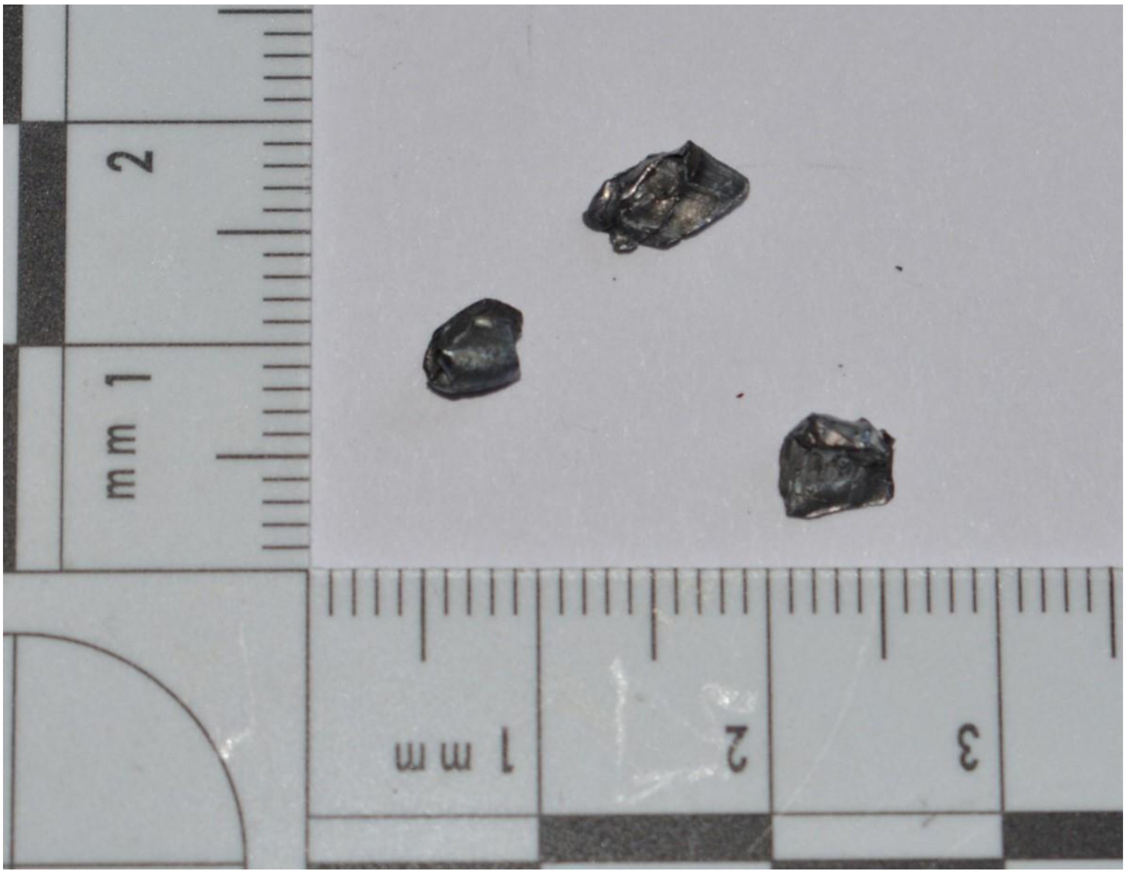

Figure 3.6 Typical fragmentation recovered from gelatine shot by a 7.62 mm projectile

The dimensions collected for the damage caused by the temporary and permanent cavities to the gelatine blocks are summarised in Table 3.3.

Table 3.3 Mean, Standard Deviation (SD) and Coefficient of Variation (CV) for dimensions measured

	NL			D1			H1			D2			H2		
Projectile / clothing state	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)
7.62 mm / C_{nil}	72.5	41.6	57.3	195.3	31.0	15.9	184.7	21.7	11.7	199.7	54.5	27.3	132.7	30.5	23.0
7.62 mm / C_{min}	74.5	58.3	78.3	191.0	63.4	33.2	192.8	13.6	7.0	178.0	69.8	39.2	133.2	29.0	21.8
7.62 mm / C_{max}	26.3	22.0	83.6	153.0	30.3	19.8	204.0	28.4	13.9	135.0	38.0	28.0	122.0	17.3	14.2
5.45 mm / C_{nil}	71.7	43.8	61.1	179.0	39.9	22.3	211.3	29.8	14.1	152.7	47.0	30.8	134.7	5.0	3.7
5.45 mm / C_{min}	51.0	12.1	23.8	182.0	18.5	10.2	181.7	8.5	4.7	163.0	44.7	27.4	126.7	7.6	6.0
5.45 mm / C_{max}	9.7	8.2	84.5	116.0	10.0	8.7	173.0	7.5	4.3	108.0	22.1	20.5	128.0	9.4	7.3

When considering the effect of clothing state on data variability from Table 3.3 for each ammunition type, no clear trends were observed except for the following:

- 7.62 mm – increasing variability in NL with increasing clothing state; decreasing variability in H2 with increasing clothing state
- 5.45 mm – increasing variability in H2 with increasing clothing state; decreasing variability in D1, H1 and D2 with increasing clothing state

ANOVA results are given in Table 3.4 below; data subgroups identified by Tukey's HSD are also included.

Table 3.4 ANOVA results

Measurement	ANOVA effects (F-statistic, P-value)		Data subsets found (Tukey's HSD)	
	Clothing state	Ammunition type	Group 1	Group 2
NL	$F_{2, 30} = 7.39$, $p \leq 0.01$	$F_{1, 30} = 3.10$, p = NS	C_{max}	C_{min}, C_{nil}
D1	$F_{2, 30} = 7.12$, $p \leq 0.01$	$F_{1, 30} = 6.05$, $p \leq 0.05$	C_{max}	C_{min}, C_{nil}
H1	$F_{2, 30} = 4.88$, $p \leq 0.05$	$F_{1, 30} = 6.96$, $p \leq 0.05$	C_{max}, C_{min}	C_{min}, C_{nil}
D2	$F_{2, 30} = 4.26$, $p \leq 0.05$	$F_{1, 30} = 6.75$, $p \leq 0.05$	C_{max}, C_{min}	C_{min}, C_{nil}
H2	$F_{2, 30} = 0.74$, p = NS	$F_{1, 30} = 0.26$, p = NS	No subgroups identified	

In all measurements apart from H2 it was demonstrated that the clothing state of C_{max} led to significantly different measurements when compared to C_{nil}. In the cases of NL and D1 measurements, C_{max} also led to significantly different measurements when compared to C_{min}.

3.5 Discussion

The clinical effects of a GSW will be dictated by both the ammunition effects and clothing effects together. When compared to an anatomical overlay (Figure 3.7), a projectile which might have otherwise passed through a limb before yawing significantly, would yaw sooner within that limb due to C_{max}. This would cause temporary cavitation to occur earlier and impart a greater amount of KE and subject those tissues to greater deformative stress. Crucially, the resultant effect would undoubtedly require an increased level of surgical intervention, bringing with it the associated risks of carrying out such surgery to the patient.

Interestingly, the effect of the ammunition on the temporary cavity varied with clothing state. That the temporary cavity height was smaller where 5.45 mm projectiles are used with C_{max} does not matter, because the damage still occurred earlier within the wound tract and was still greater than that seen within the neck length which exists at the same position in blocks with C_{min} and C_{nil} (Figure 3.7; Table 3.3)

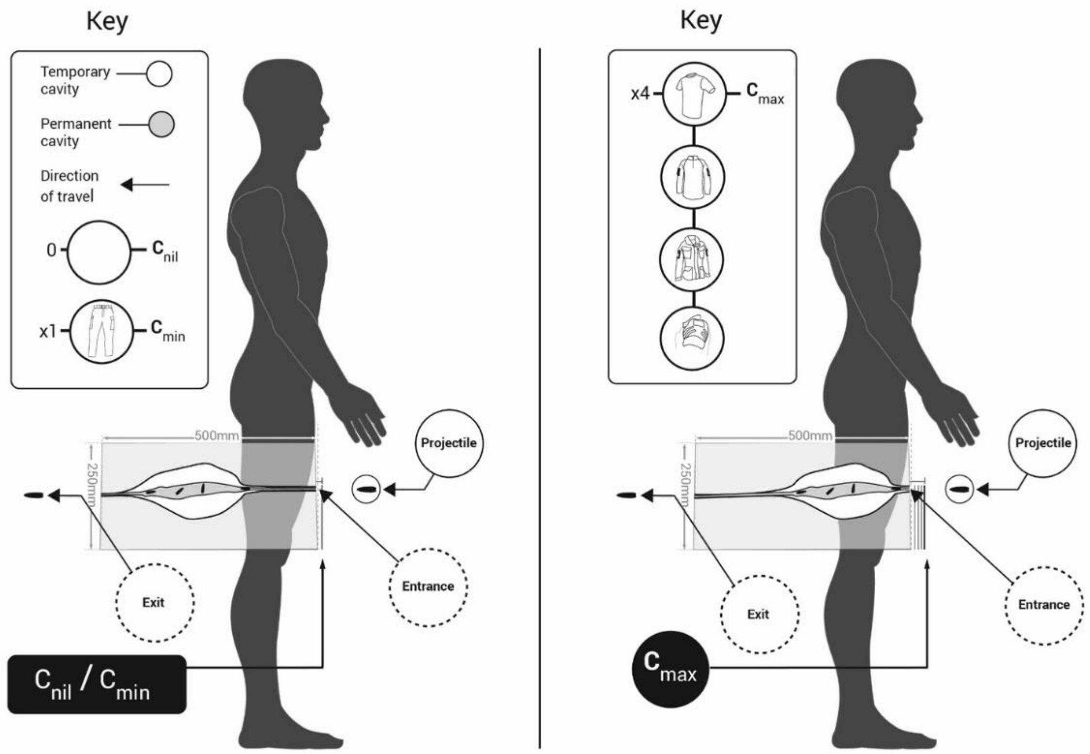

Figure 3.7 Anatomical overlay of GSW patterns – C_{nil} and C_{min} (left), C_{max} (right)

Introducing a layer of any material, such as clothing, between a projectile and its target brings further potential to alter the symmetry of flight of that projectile. The effect of intermediate layers has been reported previously, though not specifically on the effect of military clothing [22,23,25,44]. The presence of military clothing layers could mean an increased chance of the projectile yawing away from its central axis by several degrees within the microseconds following interaction with the material but before striking its target. This would increase the contact surface area of the projectile striking the target and thus lead to higher KE transfer and potentially subject that tissue to greater damage earlier on in the projectile/target interaction. This holds particular relevance with respect to the NL measurements, where the NL region of a body limb wound typically requires less surgical intervention. This translates to the NL being a key measurement of damage; the longer it is, the more likely the projectile has exited before imparting much of its KE and the chance is greater for a wound pattern requiring less clinical intervention.

The fragmentation of projectiles seen was exclusive to 7.62 mm, and most likely occurred due to the composition and construction of those projectiles rather than due to the clothing state. This was supported by the fact that the only 7.62 mm projectile not to fragment had passed through C_{max}, and by the fact that none of the 5.45 mm projectiles fragmented within blocks of all three clothing states. As the fragments were extremely small, the overall damage they contributed within the wounding patterns was negligible. Clinically, removing such fragments has the potential to cause more harm than benefit so, unless causing direct neurovascular injury, operating clinicians sometimes opt to leave them in situ.

Of qualitative interest was that the visual inspection of the HSV data showed a wounding pattern seen in real time that was grossly peculiar to each ammunition type irrespective of the presence of clothing layers as shown in the animations (Online resource 1, 2), though this observation in itself was not further quantified or statistically tested beyond the above results.

Online resource 1 – Typical GSW profile in bare gelatine block from 7.62 mm projectile

Online resource 2 – Typical GSW profile in bare gelatine block from 5.45 mm projectile

Microhardness and elemental analysis results suggested that both types of ammunition were manufactured consistently. This was also true of the fabric analysis results with regard to the use of the different layers of MTP for the relevant clothing states. To the knowledge of the authors of this work, the effect of UK military clothing on GSW patterns has not previously been considered within existing literature.

3.5.1 Limitations

One of the main limitations of this model is that gelatine is a synthetic medium and as such cannot in any way allow comment on tissue viability within such wounds as re-created in this study. As such, a number of assumptions have to be made when considering the clinical relevance of wounding patterns within synthetic modelling. It stands to reason that where maximal temporary cavitation occurs, tissues in a live subject would be exposed to greater stress and potential damage compared to an area in the tissue where temporary cavitation is minimal, i.e. the neck length, though without live tissue testing under the same conditions, it cannot be proven beyond the anecdotal experience of authors whom have seen such injuries within their clinical practice and can provide comment.

Another limitation is clothing type. Though in regular use on day to day active service for the UK military, the MTP clothing selected for this testing does not appear to have been previously discussed. This means there is no way to compare the results of this study directly with other studies at this time, although it does offer a point of comparison for future studies.

The ammunition types chosen also are a limitation where troops can be exposed to a plethora of different ammunition types during conflicts, depending entirely on the enemy logistical infrastructure. Even ammunition of the same type may have different physical properties and characteristics due to being of different batches or manufactured in different countries [4].

Other limitations include the fixed engagement distance and controlled projectile velocities; it is unlikely to expect that GSWs are sustained regularly at muzzle velocity with a projectile flying symmetrically in all combat scenarios. Engagement distances with the enemy will always vary, as will the subsequent velocity and potential asymmetry of the projectile in flight upon striking the target, thus the behaviour of the ammunition being fired is determined due to the number of external influences prior to impact. This further reinforces a need to control variables as a measure of scientific rigor to allow accurate testing, hence to why the above testing conditions were set, to try and minimise the amount of variability beyond that which was to be examined.

3.6 Conclusion

C_{max} significantly affected the damage sustained by a gelatine block shot by 7.62 mm or 5.45 mm projectiles raising the possibility of a more complicated surgical intervention being required for human casualties wearing such clothing combinations. C_{min} did not affect the damage sustained by a gelatine block shot by 7.62 mm or 5.45 mm projectiles. Neither iteration of MTP clothing layers appeared to affect the propensity of projectile fragmentation, retention, nor the path which was taken by the projectile after entering the gelatine block, though the latter was extremely difficult to quantify from the data collected.

3.7 Acknowledgements

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4 BALLISTIC RESEARCH TECHNIQUES: VISUALISING GUNSHOT WOUNDING PATTERNS

Stevenson T, Carr DJ, Harrison K, Critchley R, Gibb IE, Stapley SA

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Further detail on the development of the method of contrast CT scanning used in this chapter can be found in appendix H.

4.1 Abstract

There are difficulties associated with mapping gunshot wound (GSW) patterns within opaque models. Depending on the damage measurement parameters required, there are multiple techniques that can provide methods of "seeing" the GSW pattern within an opaque model. The aim of this paper was to test several of these techniques within a cadaveric animal limb model to determine the most effective. The techniques of interest were flash X-ray, ultrasound, physical dissection and computed-tomography (CT). Fallow deer hind limbs were chosen for the model with 4 limbs used for each technique tested. Quarantined 7.62 x 39 mm ammunition was used for each shot, and each limb was only shot once, on an outdoor range with shots impacting at muzzle velocity. Flash X-ray provided evidence of yaw within the limb during the projectile's flight, ultrasound though able to visualise the GSW track, was too subjective and was abandoned, dissection proved too unreliable due to the tissue being cadaveric so also too subjective, and lastly CT with contrast provided excellent imaging in multiple viewing planes and 3D image reconstruction; this allowed versatile measurement of the GSW pattern to collect dimensions of damage as required. Of the different techniques examined in this study, CT with contrast proved the most effective to allow precise GSW pattern analysis within a cadaveric animal limb model. These findings may be beneficial to others wishing to undertake further ballistic study both within clinical and forensic fields.

Keywords: Gunshot, wound, limb, X-ray, ultrasound, CT

4.2 Introduction

Damage caused to a target by the impact of a projectile in research can be measured in a number of ways, for example, depth of penetration (DoP), kinetic energy (KE) transfer, or calculation of area or volume of damage [1-12]. One of the challenges associated with gathering such data is to optimise the method(s) used for the target material under study. The last century has seen the use of target materials for ballistic research including, but not limited to, soap, gelatine, cadaveric human tissue, cadaveric animal tissue, and live animal tissue [13].

With synthetic models such as gelatine, the lack of opacity allows for visual analysis of gunshot wounding (GSW) using techniques such as high speed video (HSV) to capture the effect of the projectile on the target in real time [6,10,12,14]. With respect to the study of GSW in cadaveric or live tissue, one of the difficulties in the analysis of wounding patterns is the opacity of the surrogate.

This paper examines several techniques to ascertain the most effective method to measure GSW patterns in a cadaveric animal model.

4.2.1 Flash X-ray

Flash X-ray is a relatively expensive, non-portable method of capturing an image via a small dose of radiation. The use of flash X-ray allows a snapshot of what happens within opaque tissue during the ballistic event under study. With knowledge of the timing of imaging in relation to the projectile's position within or outside of the model, measurements of temporary cavity dimensions can be captured, as well as evidence of bone fracture, and yaw of the projectile [15-20].

4.2.2 Ultrasound

Ultrasound is a relatively cheap, portable, quick and non-invasive method of imaging within human or animal tissues (or synthetic materials). It also offers a non-irradiating method of imaging to try and visualise a GSW track within the target. Operation of ultrasound requires specialist knowledge with challenges of interpreting images including orientation and precision of measurements where the probe is used to sonographically collect the imaging. Within the clinical setting, ultrasound has been used with regard to GSW to determine the extent of internal haemorrhage or free fluid associated with thoracic, abdominal and pelvic injury to assist the decision-making process towards rapid surgical intervention [21]. With regard to mapping GSW tracks, the literature appears limited with examples of a case report [22] and a live animal model study [23]. There has been an increasing use of ballistic gelatine in models for ultrasound training, such as vessel cannulation or joint injection [24-28].

4.2.3 Dissection

Physical dissection remains a method to lay open a GSW track and allow direct visualisation of the tissues. The main disadvantage is that the tissue under study will be destroyed by dissection. To manage GSW in a clinical setting, surgical intervention is employed via appropriate expertise. The knowledge of what tissue to remove and what to leave behind has caused controversy over many years (e.g. [29-36]). With regard to investigating GSW in experiments, expert clinicians would frequently be used to excise damaged tissue. The total mass of excised tissue is then used as a measure of wounding severity [37-40]. Another use of excised tissue has been to determine the morphology of cells within the zone of injury, identify the border of damaged versus undamaged cells, or to determine the reversible or non-reversible changes seen with serial measurements over nominated time intervals [16-18,38,41-43]. With regard to this study, tissue viability was not under investigation as the animal tissue in question was cadaveric.

4.2.4 Computed-Tomography

As a radiological method, computed-tomography (CT) it is neither cheap, nor easily portable, and requires expert interpretation of images produced. CT scanning provides an in-depth and detailed method to precisely reproduce the anatomy of opaque tissues for study. When concerning GSW, CT scanning has previously been employed to attempt to map the path taken by a projectile in the acute clinical setting or for use in forensic analysis [44-47]. For the purposes of this study, a method was developed to inject contrast into the wound tracks and allowed for multi-planar reconstruction (MPR) and 3D reconstructed images for further analysis and can be found in more detail at [48].

4.3 Materials and methods

Ethical approval for this work was granted through CURES (CURES/3579/2017).

4.3.1 Materials

Fallow deer (*Dama dama*) hind limbs were used in this work[1]. The similarity in morphology between deer femur bones and human femurs has been discussed [49], and it can be assumed that the soft tissue morphology is equally comparable. The muscular nature of deer with little subcutaneous fat and similar mass to that of a healthy human limb offers higher biofidelity to give comparison to a fit young soldier's limb, compared to porcine tissue which has a thicker layer of subcutaneous tissues [5,13,50,51]. Limb masses were 11-13 kg and measured approximately 280 mm x 700 mm x 100 mm (width x height x thickness), and were sectioned from the main carcass at the pelvis and the ankle (Figure 4.1). Total body mass for fallow deer are typically 46-94 kg for males and 35-56 kg for females [52]. The limbs were used as fresh targets (within 72-hrs of culling) and after being stored by freezing and defrosted before use depending on access to the ballistic test facilities and availability of the target material. Previous work has suggested that the difference in ballistic wounding to fresh versus defrosted tissues is likely to be negligible [53]. In order to judge the suitability of fallow deer limbs to be used as a human tissue surrogate representative of UK service personnel, appropriate anthropometric data sources were examined to provide comparison. One survey provided data for the UK population aged between 19-65 years and gives a mean 50th percentile body mass of 69 kg for men and women (as a combined group) [54]. Another anthropometric survey specifically of UK service personnel gives mean 50th percentile body mass of 74 kg (all service personnel, male and female). With a single thigh accounting for 14.2% of total body mass this would imply an approximate typical thigh mass of 10.5 kg

[1] Deer were culled for entry into the human food chain, not specifically for research purposes

[55]. This data suggests that the comparison of fallow deer limb mass against mean thigh mass of UK service personnel is reasonable for this study. Limbs were examined either during or after shooting using flash X-ray, ultrasound, dissection or CT (n = 4 limbs for each technique). All limbs were shaved prior to testing.

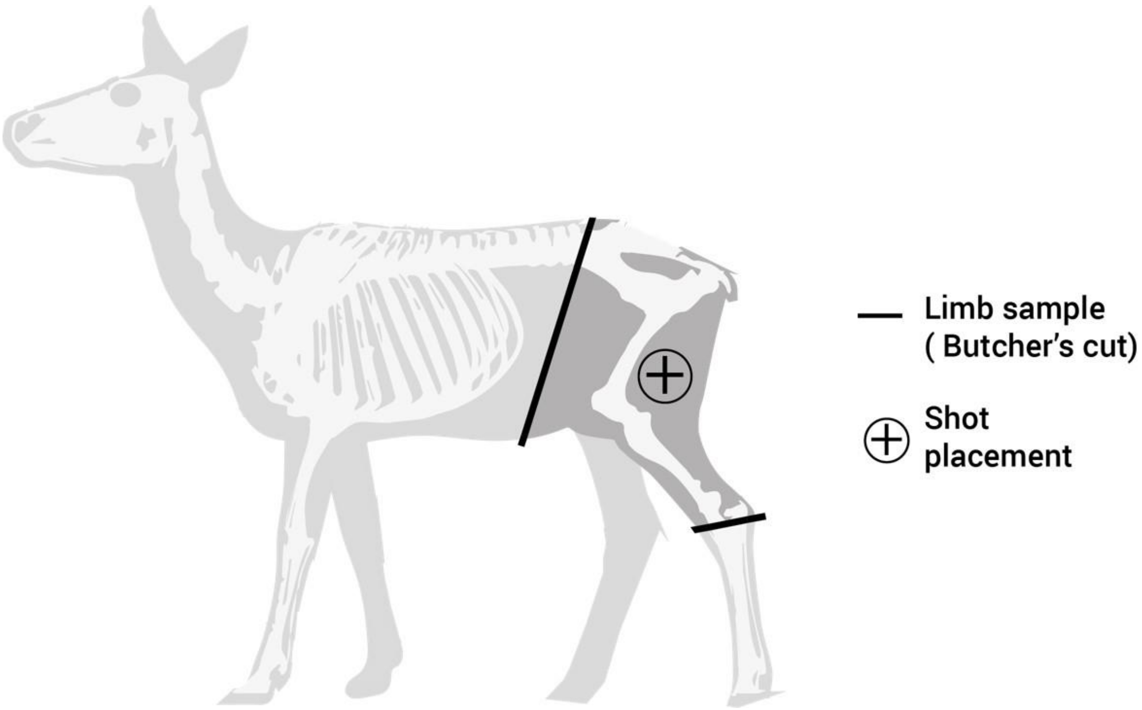

Figure 4.1 Fallow deer anatomy schematic demonstrating limb preparation and shot placement

The ammunition used was from a single batch of 7.62 x 39 mm (7.62 x 39 mm Wolf Hunting Cartridges; lead core, 122 grain full metal jacket, Lot number F-570, made in Russia, 2006). This ammunition type was a typical example faced by UK military service personnel throughout the most recent conflicts in Iraq and Afghanistan [10,12,56,57].

4.3.2 Methods

Ammunition physical and mechanical properties were determined in a previous study (Figure 4.2, [12]).

Figure 4.2 Mounted section of 7.62mm projectile. Mean core hardness 7.8Hv (SD 0.6Hv, n = 3), lead mixed with antimony. Mean jacket hardness of 184.4Hv (SD 12.3Hv, n = 3), steel with internal and external copper washes [12].

Shots were taken using Enfield number 3 proof housing fitted with an appropriate barrel from a range of 10 m with two high speed video (HSV) cameras used to capture the event of the entrance and exit of the projectile through the limb (Figure 4.3)[2]. Each limb was shot once through the shaved lateral surface of the limb, to traverse the posterior thigh soft tissue muscle group.

[2] All testing was conducted at COTEC, Cranfield University

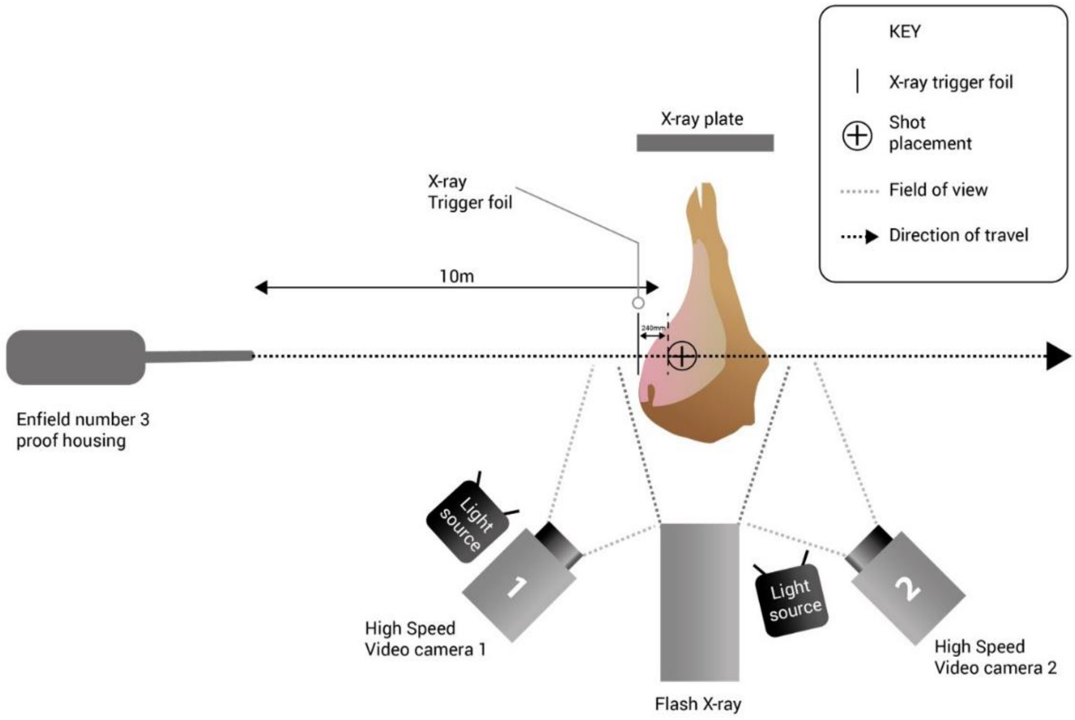

Figure 4.3 Experimental range set up including flash X-ray positioning[3]

4.3.2.1 Flash X-ray

Flash X-ray (Scandiflash XT 150, Serial No. 320184) was utilised in an attempt to capture the projectile mid-way through the deer limb to determine if the projectile yawed away from its central axis or not. Flash X-ray strength was 150 kV for all shots, with the X-ray heads situated 2 m from the target, and the exposure plates as close to the target as able. The trigger foil was placed 240 mm in front of the target's centre, and X-ray exposure time was 35 ns for each use (Figure 4.3).

4.3.2.2 Ultrasound

Limbs underwent ultrasound scanning before and after shooting using a Sonosite M-Turbo ultrasound machine (FUJIFILM Sonosite Ltd., Bedford, UK) with a L38X

[3] HSV camera 1: Phantom V12 video camera, frames per second = 28,000, shutter speed = 4µs, resolution = 512x384; HSV camera 2: Phantom V1212 video camera, frames per second = 37,000, shutter speed = 5µs, resolution = 512x384

10-5 MHz transducer to obtain images, with measurements taken using the in-built software. This ultrasound was also used to scan the limbs undergoing the CT scanning technique, both before and after contrast injection (Figure 4.4).

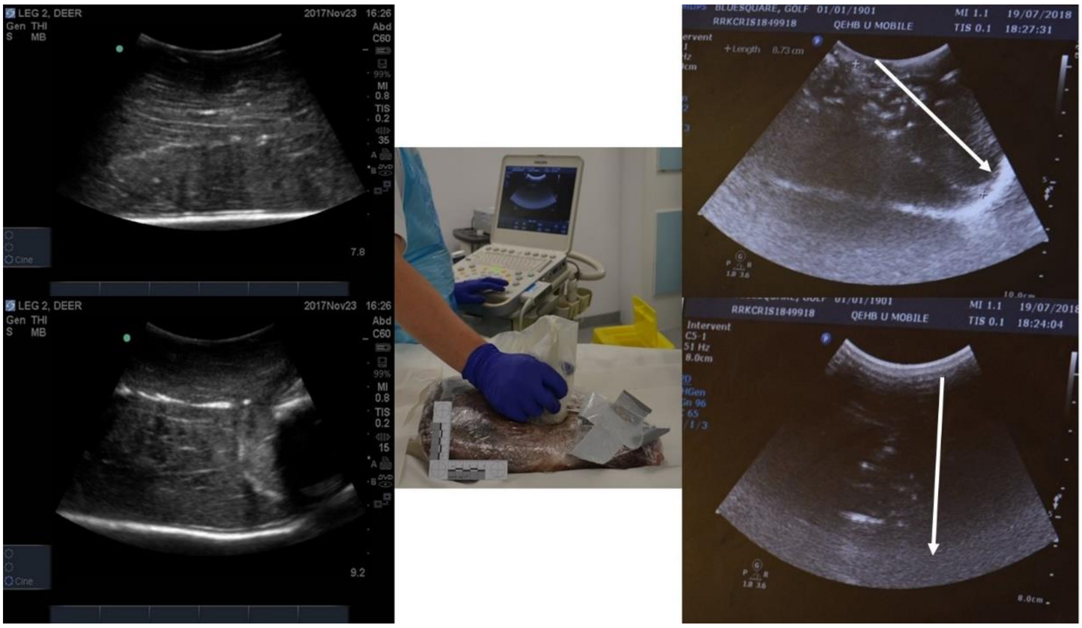

Figure 4.4 Left, top and bottom – pre-contrast, pre-shoot ultrasound images; Centre – Ultrasound in progress, demonstrating probe compression into limb soft tissue; Right, top and bottom – post contrast injection ultrasound, highlighted areas represent GSW track, arrows indicate projectile direction of travel

4.3.2.3 Dissection

Following shooting, limbs were dissected to identify features of the GSW track, such as track length and width using a steel ruler, and to provide general comment on any other physical properties of the wounds seen, such as evidence of projectile fragmentation.

4.3.2.4 Computed-Tomography

CT scanning was undertaken for limbs post shooting. Due to the availability of the scanner, limbs were frozen immediately after shooting until 72 hours prior to the scan date when they were then defrosted. The scanner used was a dual source (2 x 64 slice) Siemens SOMATOM Definition MSCT scanner (System SOMATOM Definition AS, 64622, Siemens AG, Wittelsbacherplatz, DE – 80333

Munchen, Germany). Scans using a standard adult pelvis protocol (exposure figures were 120 kV and 25-32 mAs) with 1.0 mm slice soft tissue and bony reconstructions in the axial, sagittal and coronal planes. The limbs were wrapped in Clingfilm and scanned initially in situ without contrast. For each limb, a small hole was then made over the entrance wound and 10-20 mls of Omnipaque 300 contrast (OMNI300, GE Healthcare) was subsequently injected whilst simultaneously probing the wound track via a 5” mixing tube connected to a 50 ml Omnifix Luer Lock Solo syringe. The hole was then sealed with duct tape to prevent leakage of the contrast, and the limb re-scanned. Scanned images were viewed best for conducting measurements within multi-planar reconstruction (MPR) as part of the Syngo CT2012B software package provided with the CT scanner [48].

Analysis for each technique was qualitative (and quantitative where possible) with advantages and disadvantages towards use of each considered. Attempted measurements from the wound patterns seen included a neck length or initial narrow section of the wound channel seen (NL), the maximum height of the permanent cavity (H2), the distance from entry to that maximum height (D2), and lastly the total track length (TT) as well as any other relevant features for comment.

4.4 Results

Projectiles for all shots had a mean velocity of 735 m/s (SD = 6.6 m/s). All shots perforated with no retained projectiles or projectile fragmentation within limbs.

4.4.1 Flash X-ray

Flash X-ray successfully captured the projectile travelling mid-way through the target with all four limbs. With HSV to capture the entrance and exit of the projectile to see if the projectile would strike the target symmetrically and exit with any obvious yaw, the flash x-ray was able to complement this by demonstrating the yaw as the projectile passed through the mid-point of the limb (Figure 4.5). Entrance wounds were small and symmetrical, however exit wounds were much larger and more varied (Figure 4.6). No further measurements could be taken with regards to the wounding pattern dimensions using flash x-ray.

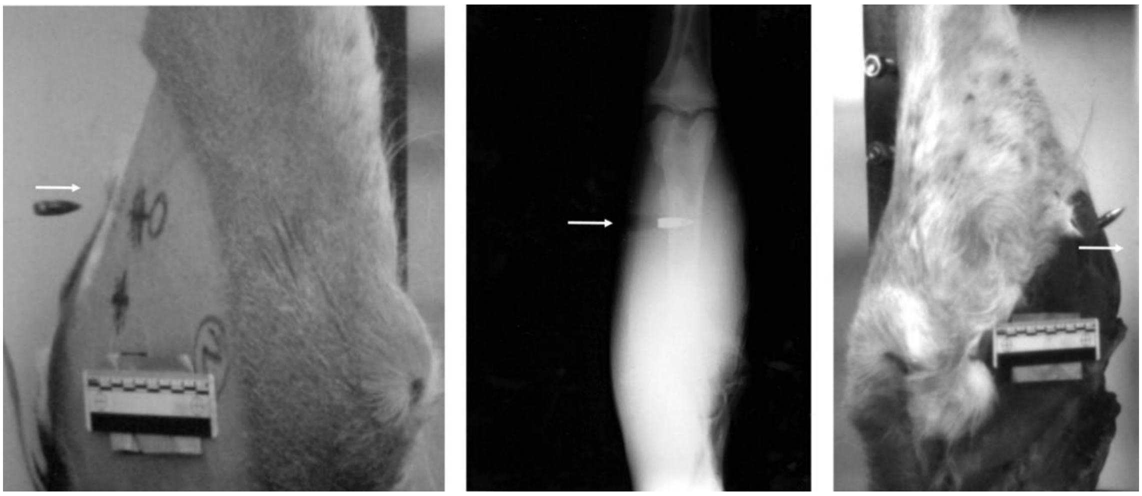

Figure 4.5 Arrow indicates projectile direction of travel – Left: oblique view of front face of deer limb with 7.62 mm projectile about to strike symmetrically; Middle: Flash X-ray imaging demonstrating 7.62 mm projectile travelling through suspended deer limb, yawing slightly; Right: oblique view of rear face of deer limb with 7.62 mm projectile exiting deer limb, yawing significantly

Figure 4.6 Example of large exit wound seen following yawing projectile exit the deer limb, indicated by dotted circle

4.4.2 Ultrasound

No tangible measurements of wounding pattern dimensions could be taken from the deer limbs using ultrasound. Image quality received was variable. Soft tissue musculature was displayed with relatively homogenous density, making it difficult to identify or measure obvious damage. Wound tracks were difficult to identify unless they had significant gas presence, or had contrast material injected to help delineate the GSW track from the other tissues (Figure 4.4).

4.4.3 Dissection

Of the four limbs which underwent dissection, total track (TT) lengths were measured and recorded in Table 4.1, and GSW tracks were laid open. All projectiles had perforated the deer limbs through a single wound track, with no physical evidence of secondary fragmentation tracks and no projectile fragmentation recovered. Although this study was of the soft tissue, it was noted that there were no bone fractures, either direct or indirect, that were sustained in any limb. Due to the cadaveric nature of the model, tissue viability could not be examined (Figure 4.7). No other tangible measurements of wound pattern dimensions could be taken. All limbs were destroyed following dissection.

Table 4.1 Deer limb total track length measurements with mean, SD and CV

Deer limb number	TT (mm)
1	108
2	96
3	90
4	102
Mean	99
SD	7.7
CV	7.8

Figure 4.7 Dissected tissues of cadaveric deer limb, blue arrows point at the GSW track in situ

4.4.4 Computed-Tomography

Limbs undergoing CT produced a series of comprehensive images as exampled in Figures 4.8-4.10. The presence of contrast allowed precise delineation of the GSW track in multiple planes of view. This, alongside the measurement tools within the software package used to view the images, allowed dimensional measurement of the complete GSW tracks from each limb scanned, which are displayed as mean with standard deviation (SD) and coefficient of variation (CV) for each measurement (Table 4.2). Wound patterns from projectiles were observed to enter from the lateral thigh surface, traverse the posterior muscle compartment of the thigh (hamstring muscles) whilst crossing an intermuscular plane around the midway point, before exiting via the medial thigh surface.

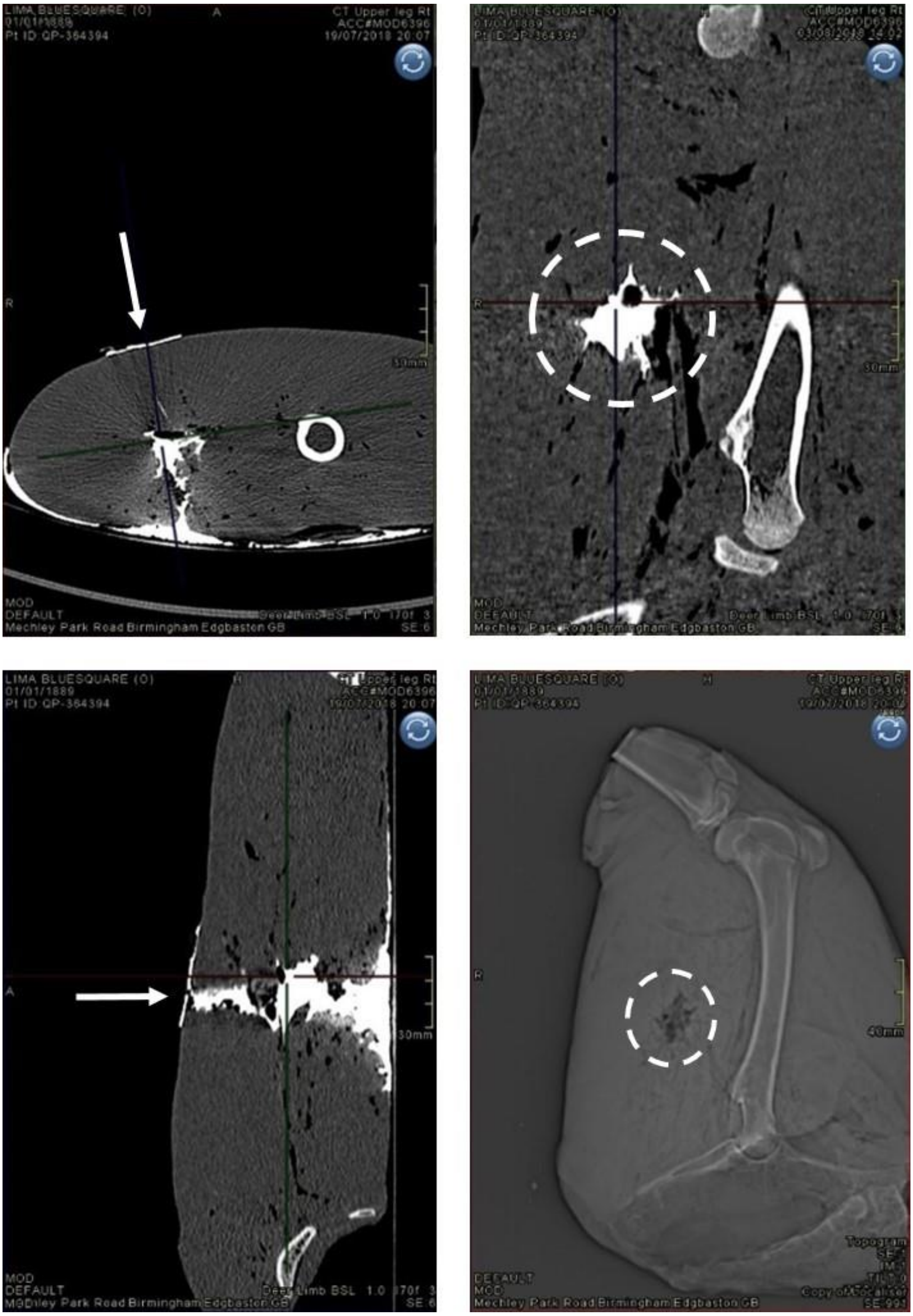

Figure 4.8 Arrows indicate projectile direction of travel, dotted circles indicate coronal section view of GSW track – Clockwise from top left – Contrast image, axial plane; contrast image, sagittal plane; X-ray scout view, sagittal plane; contrast image, coronal plane

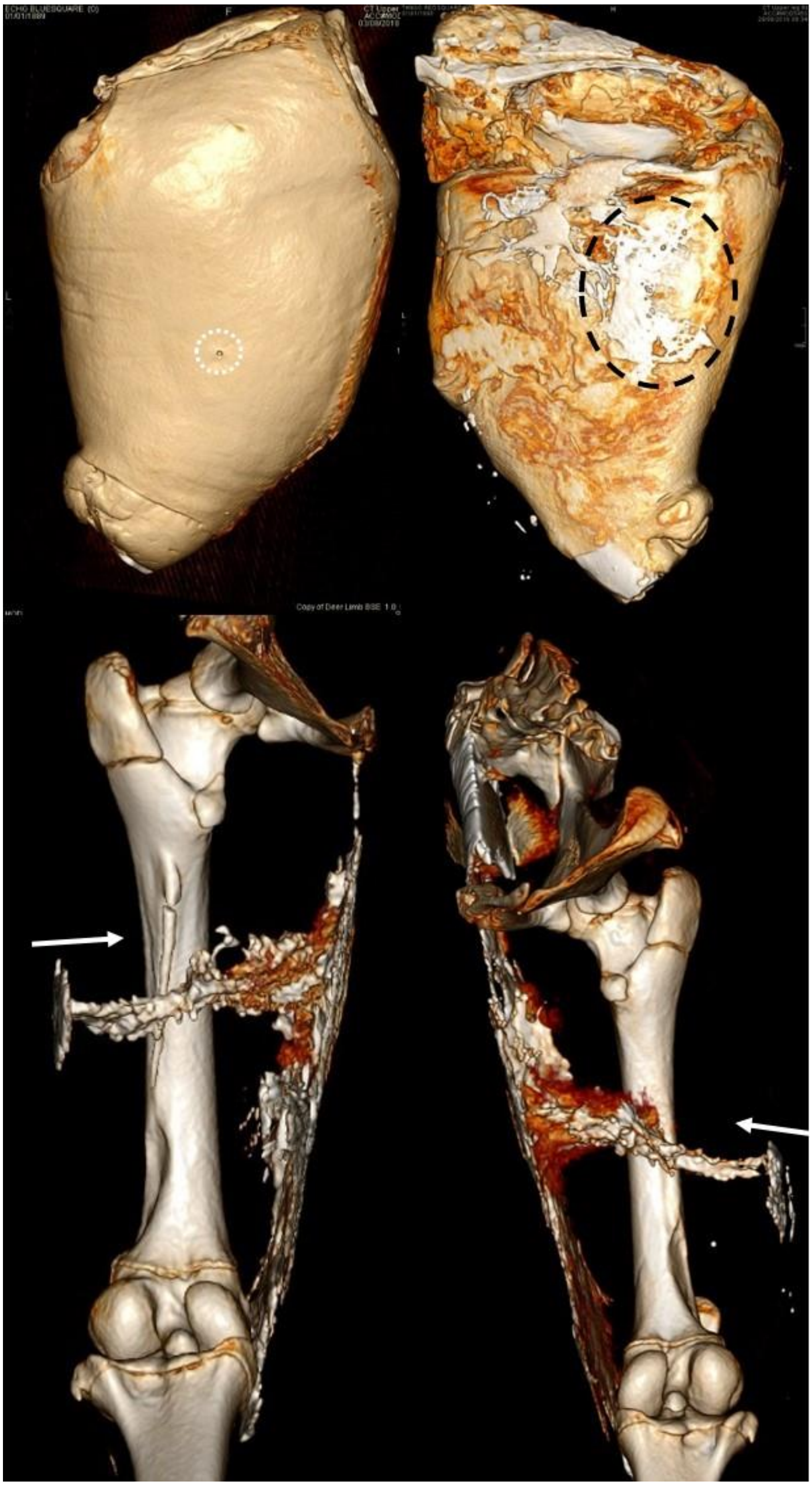

Figure 4.9 3D reconstructed images, arrows indicate projectile direction of travel, white dotted circle indicates entrance wound, black dotted circle indicates exit wound – Clockwise from top left: Front face of deer limb without digital subtraction, rear face without digital subtraction, right limb wound profile, left limb wound profile

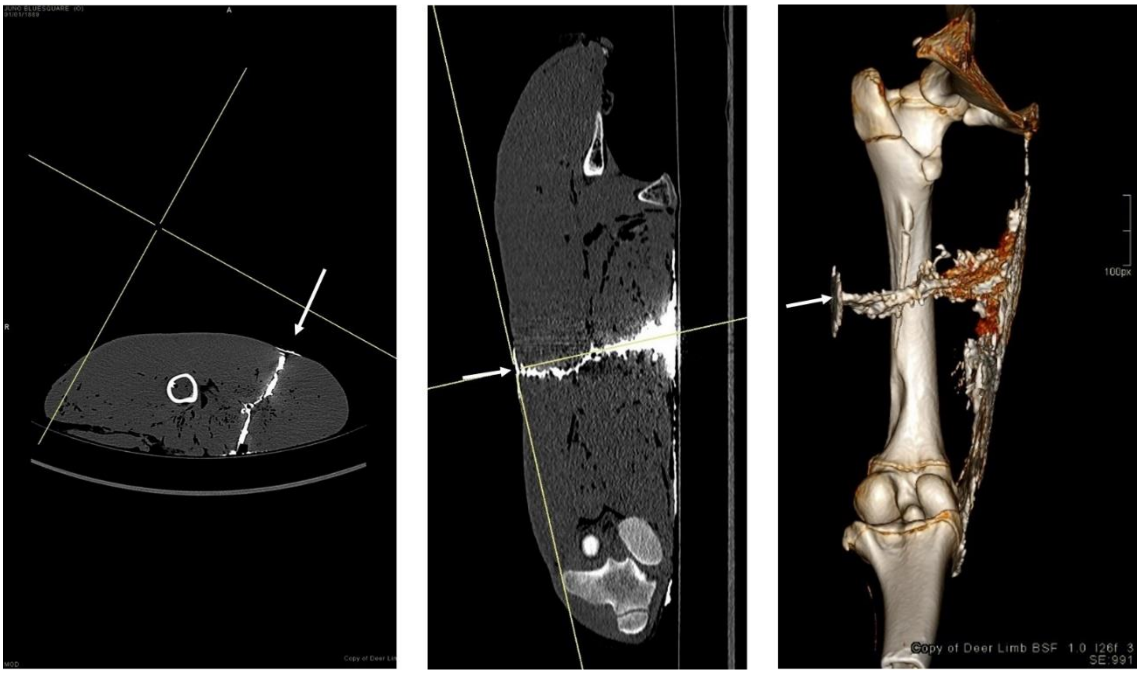

Figure 4.10 Arrows indicate projectile direction of travel – Left: Axial view with contrast; Middle: Coronal view with contrast; Right: Corresponding 3D reconstruction image in coronal view

Table 4.2 Mean, SD and CV for dimensions measured on CT imaging of deer limbs post shooting

		NL			H2			D2			TT		
Projectile	CT view	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)
7.62 mm (n = 4)	Axial	32.5	13.2	40.6	14.9	4.5	30.1	59.7	25.2	42.1	90.5	3.0	3.4
	Coronal	31.9	14.9	46.8	17.8	4.6	25.7	46.9	7.0	14.8	90.4	4.6	5.1

Contrast medium successfully penetrated each complete wound track to allow visualisation on CT images. CVs for NL, H2 and D2 are relatively large as would be expected due to the variability seen within GSW patterns even under controlled circumstances.

4.5 Discussion

The different techniques examined highlight the complexities which can be found when examining GSW within an opaque model. Within this cadaveric animal limb model, the focus was on mapping the GSW track and demonstrating the behaviour of the projectile. A limitation of the model is that the use of fallow deer hind limbs in ballistic research has not previously been validated. Each technique is discussed below separately.

4.5.1 Flash X-ray

Flash X-ray provided information about projectile yaw but also could have been utilised to collect data on temporary cavitation, as demonstrated in previous studies [15-17,19]. This yaw would allow for an increase in the KE delivered to the tissues and likely accounted for the larger and more variable exit wounds seen in this study. Building a dynamic picture of a GSW profile helps allow understanding of the nuances of wounds caused by different ammunition types and how one ammunition type will not always result in the same wound each time, even with conditions controlled experimentally [2]. This makes flash X-ray a versatile technique for visualising GSW patterns within opaque materials such as a cadaveric animal model. One significant disadvantage of flash X-ray use was the cost, which was relatively expensive. Flash X-ray technology also required trained expertise to operate, though was sometimes unreliable in its function. It could quite easily mistime exposure or fail to trigger, leading to wasted limb samples and mounting costs. Although the data captured was useful, the above difficulties meant that overall its sustainability within a research project would require cautious planning.

4.5.2 Ultrasound

With respect to the use of ultrasound for mapping GSW tracks, the difficulties encountered outweighed the benefits. Light and portable, the use of ultrasound is versatile, and is relatively cheap, however the variation in images seen made it challenging to demonstrate a scientifically reproducible series of results when examining the cadaveric animal material in this study. The addition of contrast improved the quality of images gathered, as the identification of fluid within a material of fixed echogenicity is where ultrasound is able to excel [21,24,25,27,28]. GSW tracks with contrast injected could be found within the deer limbs with relative ease, however with difficulty in orientation or taking an appropriate reference point, measurements in GSW track dimensions were extremely subjective. Another crucial disadvantage for taking wounding pattern dimensional measurements was that the ultrasound operator had to manually compress the tissues upon which the probe was placed (Figure 4.4), thus distorting the tissue and invalidating the precision of measurements taken using the software measuring tools provided. Ultrasound images, although captured with relative ease, also proved difficult to open on a desktop computer with compatibility issues found on multiple occasions. This made retrospective or repeat analysis challenging to manage. Appropriate training was also required to operate the equipment and interpret the images for analysis. Owing to these difficulties and the failure to gain precise measurements, this technique was therefore abandoned. Whilst not providing reproducible data in this study, as a technique for ballistic research experiments, its potential for use still merits further investigation.

4.5.3 Dissection

Dissection was found to be of little value within this study. Although it has historically provided useful data with respect to damaged tissue excised from live animal models [37-40], its use in a cadaveric model such as this was limited due to the fact that without live tissue, determining what tissues had been damaged apart from the direct wound track was not possible. Also, measuring dimensions within the GSW pattern, apart from total track length, was challenging due to the need to directly open the wound track with a knife, which meant distorting the track. This made measurements subjective and lacking in reproducibility across the four limbs taken for dissection. Dissection had to be completed within a short timeline due to the decomposition of the cadaveric material, which in itself provided an unpleasant working environment for the researcher. Other disadvantages also included difficulty maintaining orientation throughout the respective tissue planes traversed by the projectile. The final problem was with the limb effectively being destroyed following dissection, precluding any repeat analysis, thus rendering the technique futile.

4.5.4 Computed-Tomography

CT scanning of limbs following direct percutaneous injection of contrast and MPR gave demonstrable results with precise mapping of the GSW track within the samples scanned. Specific wound pattern traits that were measured (as shown in Table 4.2) are comparable to data collected within other studies examining GSW patterns [5,8,10,12]. Whilst the application of CT for GSW within forensic fields is already proven [45-47], by collecting precise dimensional GSW pattern data using the method outlined in this study, contrast CT scanning offers a further tool for data capture to the ballistic researcher, particularly within opaque materials under study, e.g. animal or human tissues. Despite these advantages, a significant disadvantage was the availability of appropriately trained personnel and the scanner itself. This could have potentially caused difficulty with a narrow timeline for data collection, though in this study was not an issue. Whilst no significant cost was incurred for this study due to the affiliations of authors with the institute utilised, other researchers may not be able to benefit from such an arrangement. The software for image reconstruction was also complex and required a user not only trained in its use, but also proficient with it in order to facilitate image analysis. Contrast penetration of the true wounding pattern was assumed, though it would be possible for elements of the wound profile and the distorted anatomy to prevent complete contrast penetration to all areas. This must be considered upon reviewing the images collected.

4.6 Conclusion

Of the different techniques examined in this study, each provides merit within an appropriate scenario, however under these test conditions, CT with contrast proved the most effective to allow precise GSW pattern analysis within a cadaveric animal limb model. These findings may be beneficial to others wishing to undertake further ballistic study both within clinical and forensic fields.

4.7 Acknowledgements

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5 THE EFFECT OF MILITARY CLOTHING ON GUNSHOT WOUND PATTERNS IN A CADAVERIC ANIMAL LIMB MODEL

Stevenson T, Carr DJ, Gibb IE, Stapley SA

In draft for submission: (2019) Int J Leg Med

Experimental raw data can be found within appendix G. Further detail on the method of contrast CT scanning used in this chapter can be found in appendix H.

5.1 Abstract

With the majority of gunshot wounds (GSW) in survivors being of the extremities, novel wound ballistic research is encouraged to try and capture corporate knowledge in what has been learned about these injuries during recent conflicts and understand the wounding patterns seen. With recent work examining the effect of UK military clothing on extremity GSW patterns in a synthetic model, a model with greater biofidelity is needed for ballistic testing. The aim of this study was to test the effect of UK military clothing on GSW patterns using a cadaveric animal limb model using two types of ammunition commonly used in recent conflicts – 7.62 x 39 mm and 5.45 x 39 mm. In total, 24 fallow deer hind limbs were shot, 12 by 7.62 mm projectiles and the remaining 12 shot by 5.45 mm projectiles, further divided into 4 with no clothing layers (C_{nil}), 4 with a single clothing layer (C_{min}) and 4 with maximum clothing layers (C_{max}) as worn on active duty by UK military personnel. Limbs were analysed using contrast CT scanning to capture measurements of permanent cavity damage, and results compared using Analysis of Variance (ANOVA). Results showed significantly different damage measurements within limbs with C_{max} for both ammunition types compared to the other clothing states. This may result in GSWs that require more extensive surgical management, and invites further study.

Keywords: Gunshot, wound, limb, clothing, CT

5.2 Introduction

Extremity gunshot wounds (GSW) are responsible for extensive numbers within military casualty statistics throughout numerous major conflicts, and have seen the rapid evolution of clinical practice to try and mitigate the complex nature of these injuries [1-10]. Novel research into wound ballistics is therefore paramount to continue to try and improve overall patient outcomes as well as to maintain corporate knowledge already gained. Experimental models for such research come in a variety of forms, such as cadaveric human or animal, live animal, or synthetic mediums such as soap, or gelatine, many of which have been the recent subject of review [11].

With respect to synthetic modelling, the use of gelatine in research is a relatively cheap and reliable method to investigate wound ballistics, with 10% by mass gelatine validated against live swine thigh muscle tissue and previous research into mapping wounding patterns from various ammunition types conducted [12-15]. However, the use of a homogenously dense material in this way does not offer sufficient biofidelity with respect to the anatomy found within human and animal subjects, i.e. bone, neurovascular structures, skeletal muscle, muscle fascia, subcutaneous fat and skin [11]. As such the use of human or animal tissue is sometimes required to understand the complex interactions faced with a projectile when it enters the anatomy [16-20].

With regard to examining the effect of clothing within these models, there is literature which reports on contamination of wounds (e.g. [19,21-24], though there are only a small number of studies which investigate the effect of clothing on the wounding pattern itself (e.g. [25-29]).

The aim of this study was to test the effect of UK military clothing on GSW patterns using a cadaveric animal limb model.

5.3 Materials and methods

Ethical approval for this work was granted through CURES (CURES/3579/2017).

5.3.1 Materials

Previous work by this research group has tested the effect of UK military clothing on a 10% by mass gelatine model using quarantined ammunition to represent the typical threat faced by UK service personnel within recent conflicts [6,29,30]. For the purposes of the current work, the same quarantined ammunition types were chosen[1,2].

With regard to clothing, the same standard issue Multi-Terrain Pattern (MTP) UK military clothing was chosen, to provide clothing states of: a nil clothing state, i.e. no clothes (C_{nil}), a minimal clothing state, i.e. a single clothing layer taken from MTP trousers (C_{min}) or a maximum clothing state (C_{max}), i.e. clothing layers taken from a t-shirt, Under Body Armour Combat Shirt (UBACS), smock, and upper arm brassard as worn by UK service personnel (Figure 5.1).

[1] 7.62 x 39 mm Wolf Hunting Cartridges; lead core, 122 grain full metal jacket, Lot number F-570, made in Russia, 2006; with a core composition found to be lead mixed with antimony, and jacket composition found to be steel with internal and external copper wash; mean hardness was 7.8 Hv for the core and 184.4 Hv for the jacket [29].

[2] 5.45 x 39 mm; mild steel core, 53 grain full metal jacket, Lot number 539-04, made in Russia, 2004; with a core composition of steel; a core tip composition of lead was found, and for the jacket, the composition found to be steel with internal and external copper wash; mean hardness was 814.9 Hv for the core, 3.6 Hv for the core tip, and 188.8 Hv for the jacket [29].

Figure 5.1 Examples of MTP clothing used – clockwise from top left: MTP trousers; top right: t-shirt, UBACS, smock, and brassard as worn by service personnel; bottom: i. t-shirt, ii. UBACS, iii. smock and iv. brassard layers prepared for testing. Laundering detail and fabric analysis data for this clothing used within these experiments is detailed in previously published work [29]

Animal tissues selected for testing were fallow deer (*Dama dama*) hind limbs. These were ethically sourced and hunted for entry into the human food chain rather than directly for these experiments. Total body mass for fallow deer is typically 46-94 kg for males and 35-56 kg for females [31]. Fallow deer limbs were chosen due to their muscular nature, with little subcutaneous fat and similar mass to that of a healthy human, making them more biofidelic to compare to a fit young soldier's limb, rather than porcine tissue which has a thicker layer of subcutaneous tissues [11,32,33]. Femurs from deer are similar in morphology with human femurs [34], and therefore it can be assumed that soft tissue morphology should follow suit. In order to judge the suitability of fallow deer limbs to be used as a human tissue surrogate representative of UK service personnel, appropriate anthropometric data sources were examined. One survey provided data for the UK population aged between 19-65 years gave a 50th percentile body mass of 69 kg for men and women (as a combined group) [35]. Anthropometric data for surveyed UK service personnel gave a 50th percentile body masses for males of 81 kg and 67 kg for females (combined mean of 74 kg). With one thigh accounting for 14.2% of stature this would suggest an approximate typical thigh mass of 10.5 kg [36]. This suggested that fallow deer limb mass was of reasonable comparison to UK service personnel for this study. The fallow deer limbs were culled for entry to the human food chain rather than specifically for research use, and were prepared by a professional butcher (Figure 5.2). Limbs were of a mass between 9.5-13 kg and measuring approximately 280 mm x 700 mm x 100 mm (width x height x thickness). Limbs were used both as fresh targets (within 72 hours of culling) and also stored by freezing and subsequently defrosted over a 72 hour period for use, due to differences in availability of range facilities and the acquisition of limbs. The difference in ballistic effects to fresh versus frozen cadaveric tissue can be considered negligible [37].

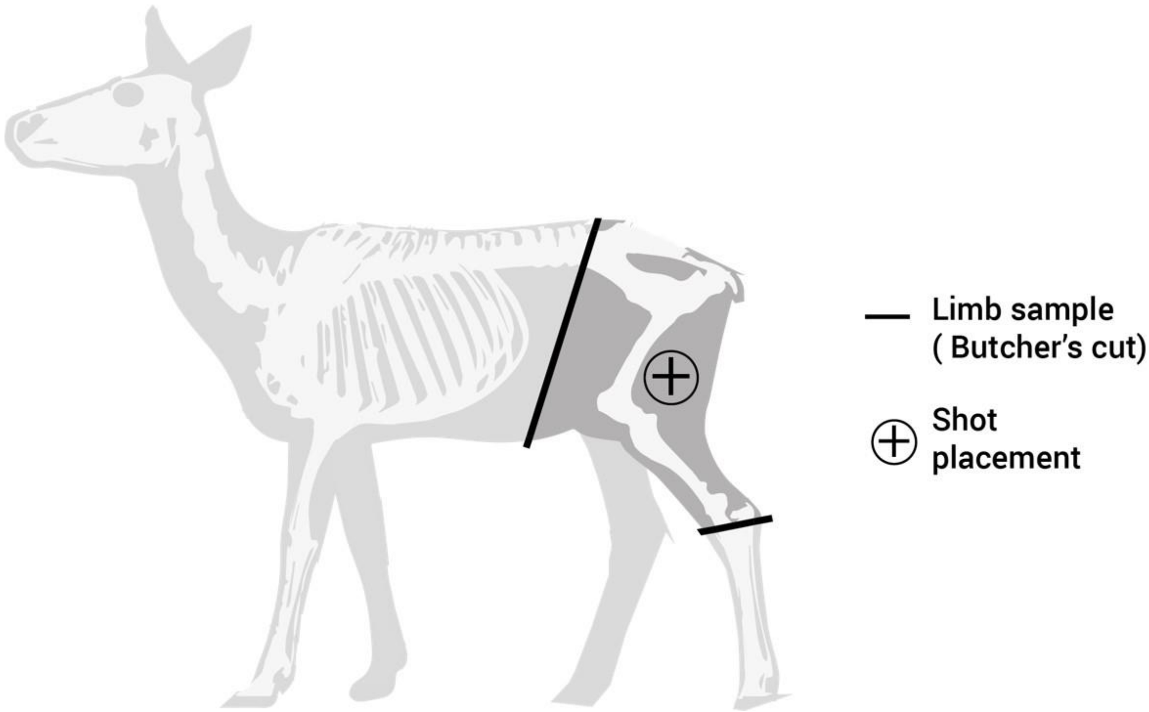

Figure 5.2 Fallow deer anatomy schematic demonstrating limb preparation and shot placement

5.3.2 Methods

Fabric samples for C_{min} were cut from laundered MTP trousers (250 x 250 mm)[3] and pinned to the front face of the relevant deer limbs (Figure 5.3, top right image). Fabric samples for C_{max} were measured and cut in relation to the upper sleeve pocket size on the UBACS and Smock (200 x 150 mm)[4], and placed in layers with the t-shirt layer innermost, then UBACS, smock and finally with the brassard then placed over the top of the other layers (Figure 5.1 lower image, and Figure 5.3 lower images).

Limbs were suspended upside down using an "S"-shaped metal hook looped between the distal tibia and fibula at the ankle joint.

[3] C_{min} mean thickness = 0.43 mm; mean mass per unit area = 191.14 g/m^2 [29]
[4] C_{max} mean thickness = 32.26 mm; mean mass per unit area = 7735.17 g/m^2 [29]

Figure 5.3 Clockwise from top left: C_{nil} front view; C_{min} front view; C_{max} front view; C_{max} side view

An indoor small arms range was used to fire projectiles from a number 3 proof housing where the end of the barrel was situated at 10 m from the target. Each limb was shot once with the test projectiles, where all limbs were shaved prior to shooting. Twelve limbs were shot with 7.62 mm projectiles and the remaining 12 limbs were shot with 5.45 mm projectiles. Four limbs for each ammunition type had either C_{nil}, C_{min}, or C_{max} added to the impact surface of the required limb.

The impact velocity for each projectile was measured using Doppler radar (Weibel W700). High Speed Video (HSV) allowed visualisation of the wounding patterns external to the limbs from both the entrance[5] and exit[6] surfaces, with

[5] Phantom V12 video camera (frames per second = 28,000, shutter speed = 4µs, resolution = 512x384)
[6] Phantom V1212 video camera (frames per second = 37,000, shutter speed = 5µs, resolution = 512x384)

dynamic recordings of the wounding pattern evolving. Qualitative examination of GSW patterns was conducted using Phantom Software (Visions Research, Phantom Camera Control Application 2.6).

A schematic of the experimental setup is shown at Figure 5.4.

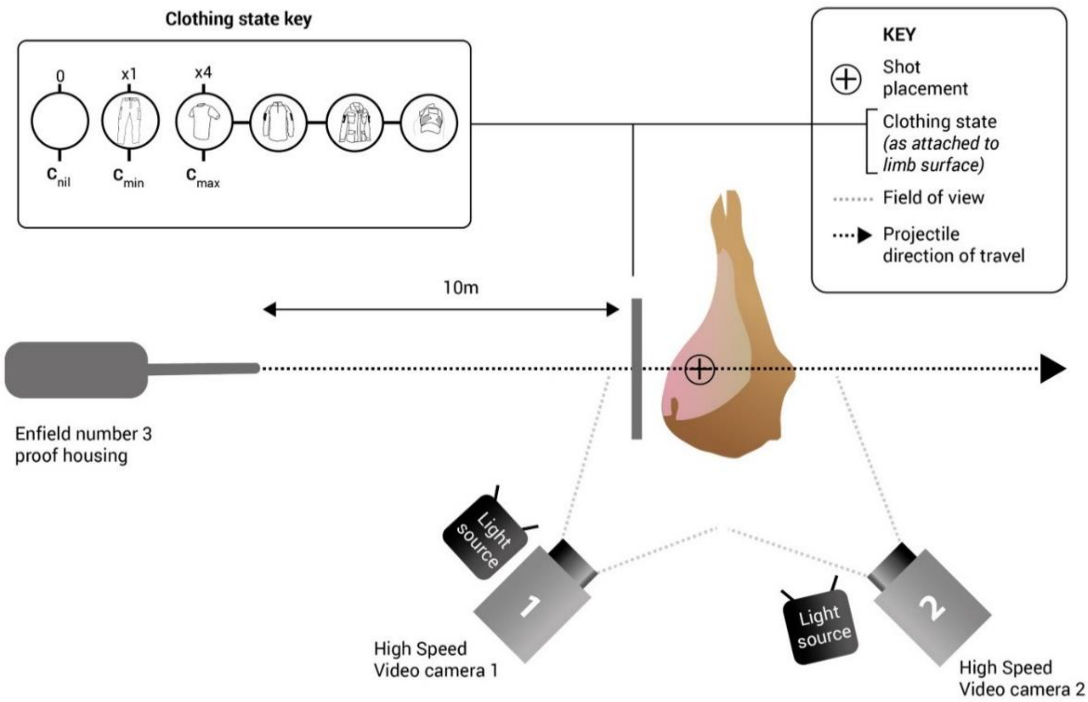

Figure 5.4 Schematic demonstrating the setup of limbs for shooting with each projectile type

The damage to the deer limbs was photographed using a Canon D5100 Digital SLR camera (S/N 6773411). Damage to the deer limbs was measured using CT scanning with contrast for which the scanning protocol developed during this process can be found in detail at [38]. A dual source (2 x 64 slice) Siemens SOMATOM Definition MSCT scanner (System SOMATOM Definition AS, 64622, Siemens AG, Wittelsbacherplatz, DE – 80333 Munchen, Germany) was used. Scans used a standard adult pelvis protocol (exposure figures were 120 kV and 25-32 mAs) with 1.0 mm slice soft tissue and bony reconstructions in the axial, sagittal and coronal planes. The parameters of damage were measured from multi-planar reconstructed (MPR) images came from axial and coronal viewing planes (Figure 5.5), as part of the Syngo CT2012B software package provided with the CT scanner. These parameters were the neck length (NL) of the GSW, maximum height of the permanent cavity (H2), distance to maximum height of the permanent cavity (D2), entry wound diameter (E1) and exit wound diameter (E2) (Figure 5.6). The parameters were chosen in conjunction with other research quantifying damage from GSW [14,25,27-29,39,40].

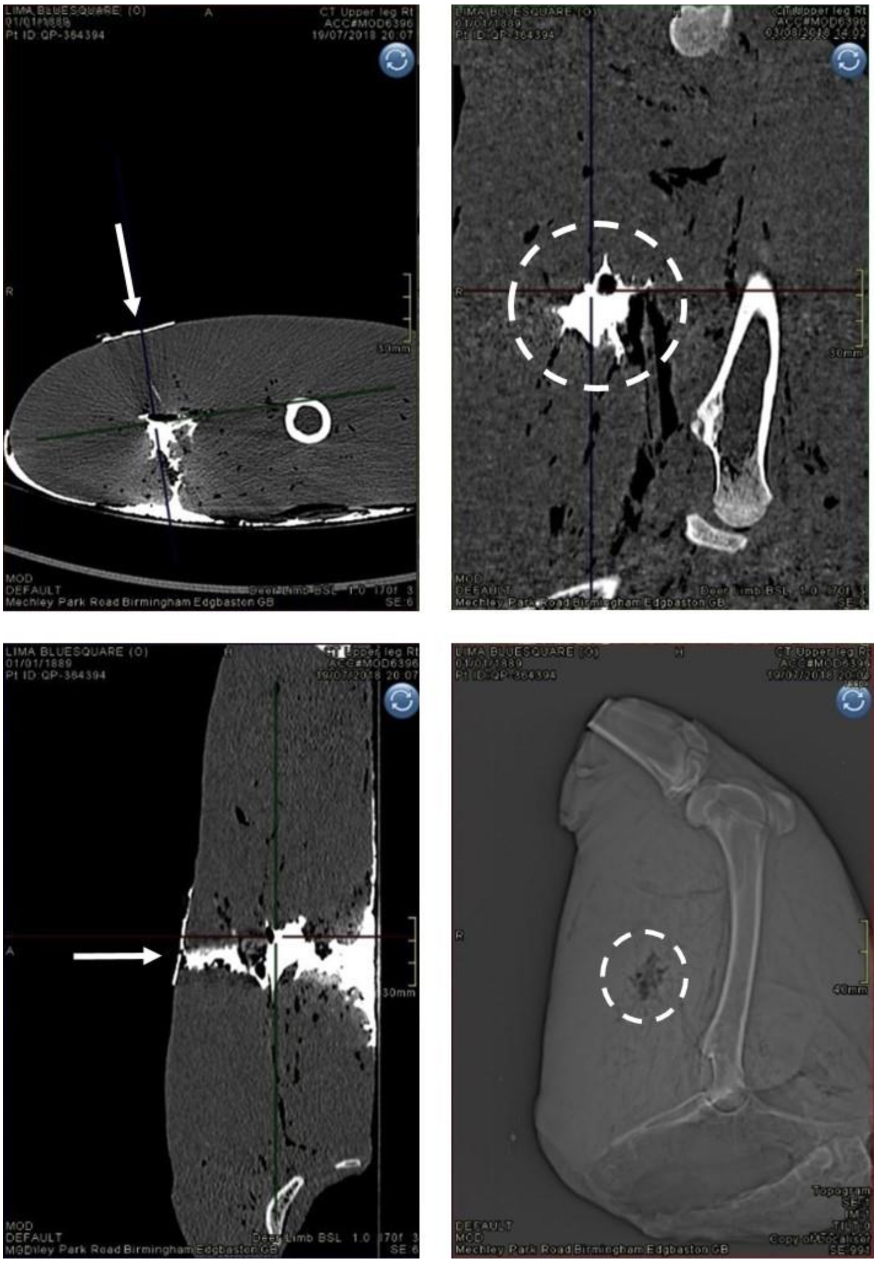

Figure 5.5 Arrows indicate projectile direction of travel, dotted circles indicate coronal section view of GSW track – Clockwise from top left – Contrast image, axial plane; contrast image, sagittal plane; X-ray scout view, sagittal plane; contrast image, coronal plane

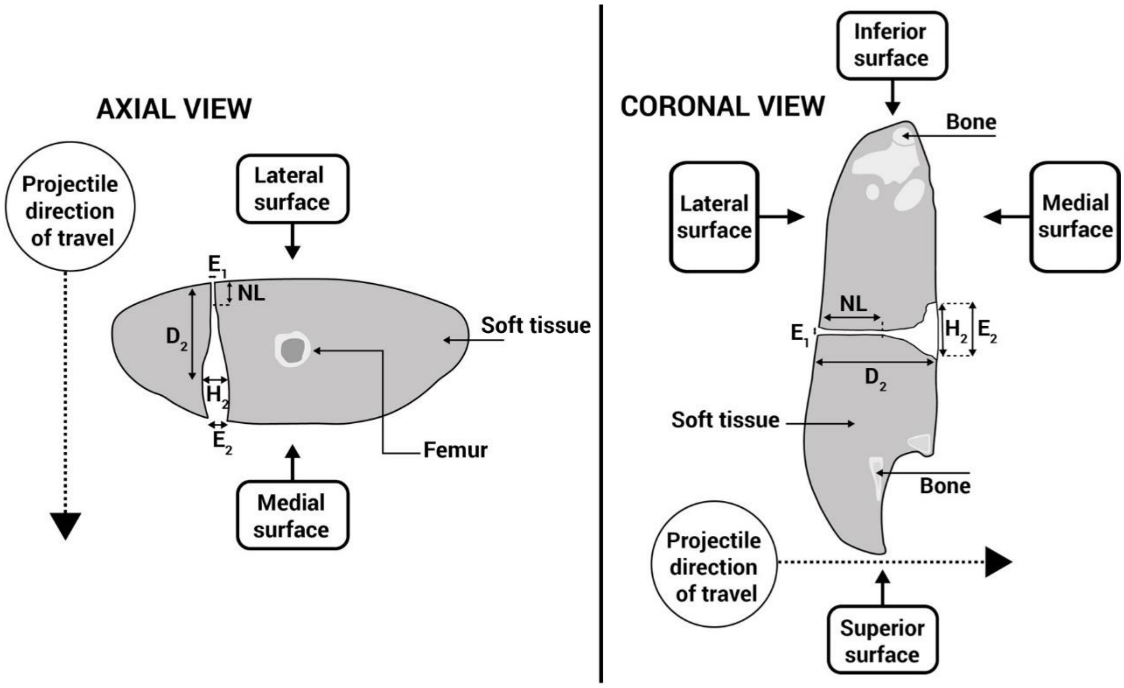

Figure 5.6 Schematic demonstrating CT scan measurements taken in axial and coronal planes of view

The International Business Machine Corporation's Statistical Package for Social Services version 24 (IBM SPSS Statistics v24), analysis of variance (ANOVA) was used to determine the effect of the different clothing states on NL, H2, D2, E1 and E2. The two ammunition types were considered together, as well as the different clothing states and the two different CT scan viewing planes where measurements were taken from. Homogeneity of variance and normality of data were confirmed with a significance level of 0.05 applied. Significant differences due to ammunition type and/or clothing condition were identified using Tukey's honest significant difference (HSD) test. Main effects and significant interactions only are discussed in the results section.

5.4 Results

Mean impact velocity for the 7.62 mm projectiles was 645 m/s (SD = 8 m/s) and for the 5.45 mm projectiles was 907 m/s (SD = 25 m/s).

Evidence of bullet wipe and yarn pull-out on the surfaces of the fabric samples was consistent with that described within the literature [33,41,42].

The dimensions collected for the damage to limbs caused by projectiles of both ammunition types for all clothing states are summarised in Table 5.1. Where an inequality of error variance in ANOVA testing for exit wound (E2) dimensions was found, likely due to the relatively high coefficients of variation (CV) seen, ellipsoid areas (EA) of the exit wounds were calculated. The means, standard deviations (SD) and CVs of EA are shown in Table 5.2.

Table 5.1 Mean, Standard Deviation (SD) and Coefficient of Variation (CV) for dimensions measured

	NL			D2			H2			E1			E2		
Projectile / clothing state	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)
7.62mm / C_{nil}	44.0	16.1	36.5	81.6	4.7	5.7	21.3	12.3	57.7	5.4	0.6	11.9	9.8	3.1	31.8
7.62mm / C_{min}	31.2	15.8	50.8	50.0	9.1	18.2	14.6	2.1	14.2	4.6	0.7	15.8	10.9	3.3	30.5
7.62mm / C_{max}	35.8	10.2	28.4	68.2	24.6	36.1	26.6	13.4	51.0	5.2	1.1	20.8	24.6	25.6	104.3
5.45mm / C_{nil}	33.5	21.5	64.1	56.7	13.1	23.2	23.8	3.8	15.9	3.5	0.9	24.9	19.1	7.6	39.6
5.45mm / C_{min}	32.2	37.2	115.3	41.4	22.4	54.1	17.0	5.8	34.2	3.0	1.1	36.4	14.7	5.1	34.4
5.45mm / C_{max}	37.2	24.3	65.2	80.1	14.5	18.1	31.2	8.4	26.7	4.9	1.3	27.3	22.9	8.6	37.7

ANOVA results are given in Table 5.3 below; data subgroups identified by Tukey's HSD are also included.

Table 5.2 Mean, Standard Deviation (SD) and CV for exit wound ellipsoid areas (EA)

	EA		
Projectile / clothing state	**Mean (mm)**	**SD (mm)**	**CV (%)**
7.62 mm / C_{nil}	155.7	83.0	53.3
7.62 mm / C_{min}	182.9	76.9	42.1
7.62 mm / C_{max}	1143.8	1456.1	127.3
5.45 mm / C_{nil}	528.3	307.0	58.1
5.45 mm / C_{min}	308.2	41.2	13.4
5.45 mm / C_{max}	884.4	567.1	64.1

Table 5.3 ANOVA results

Measurement	ANOVA effects (F-statistic, P-value)			Data subsets found (Tukey's HSD)	
	Clothing state	**Ammunition type**	**Viewing plane**	**Group 1**	**Group 2**
NL	$F_{2, 36} = 0.38$, p = NS	$F_{1, 36} = 0.16$, p = NS	$F_{1, 36} = 1.44$, p = NS	No subgroups identified	
D2 (5.45 mm)	$F_{1, 17} = 12.47$, $p \leq 0.01$	N/A	$F_{1, 17} = 6.43$, $p \leq 0.01$	C_{max}	C_{min}, C_{nil}
H2	$F_{2, 35} = 8.14$, $p \leq 0.01$	$F_{1, 35} = 1.60$, p = NS	$F_{1, 35} = 2.14$, p = NS	C_{max}, C_{nil}	C_{min}, C_{nil}
E1	$F_{2, 36} = 6.91$, $p \leq 0.01$	$F_{2, 36} = 18.61$, $p \leq 0.01$	$F_{1, 36} = 0.24$, p = NS	C_{max}, C_{nil}	C_{min}, C_{nil}
EA	$F_{2, 16} = 3.54$, p = NS	$F_{1, 16} = 0.10$, p = NS	N/A	No subgroups identified	

When considering the ANOVA results, H2 was significantly affected by the presence of C_{max} compared to C_{min}. The size of the entrance wounds was also significantly affected by the presence of C_{max} compared to C_{min}, and also by the difference in ammunition used, i.e. larger entrance wounds seen from 7.62 mm projectiles compared to 5.45 mm projectiles. D2 was affected by clothing state and viewing plane only when 5.45mm projectiles were considered alone. NL was unaffected by clothing for either ammunition type; D2 where 7.62 mm projectiles were used was also unable to satisfy Levene's test. Exit wounds (E2) were unable to be statistically analysed due to the increased CVs and size of standard deviations in relation to the different sub groups for analysis meaning Levene's test of equality of error variances could not be satisfied, i.e. the error variance was not equal for each different group, therefore rendering them incomparable using ANOVA. This was overcome by calculating EA with which ANOVA then demonstrates that clothing state and ammunition type had no effect on the size of those exit wound EAs.

5.5 Discussion

With regard to the clinical implication of these results, what is important is the dimensions of the GSW pattern. Despite the presence of C_{max} not affecting NL, importantly it does lead to a significantly larger H2 for both ammunition types. This suggests that wearing more clothing layers leads to a wound of larger proportions taking place within the limb model. Translated into a living subject, wounds of a larger proportion imply greater damage has been sustained, or at the very least, more tissue has been involved (Figure 5.7). This would necessitate more extensive surgical management such as wound debridement or excision of dead or severely damaged tissue [9,10]. With a greater amount of tissue loss clinically, either from GSW or from surgery, the resultant effect to the casualty will be increased morbidity, with the risk of further procedures and a prolonged recovery or rehabilitation process [6,8]. The overall finding of worse damage in the presence of C_{max} correlates with recent findings on the effect of MTP clothing in a synthetic limb model [29].

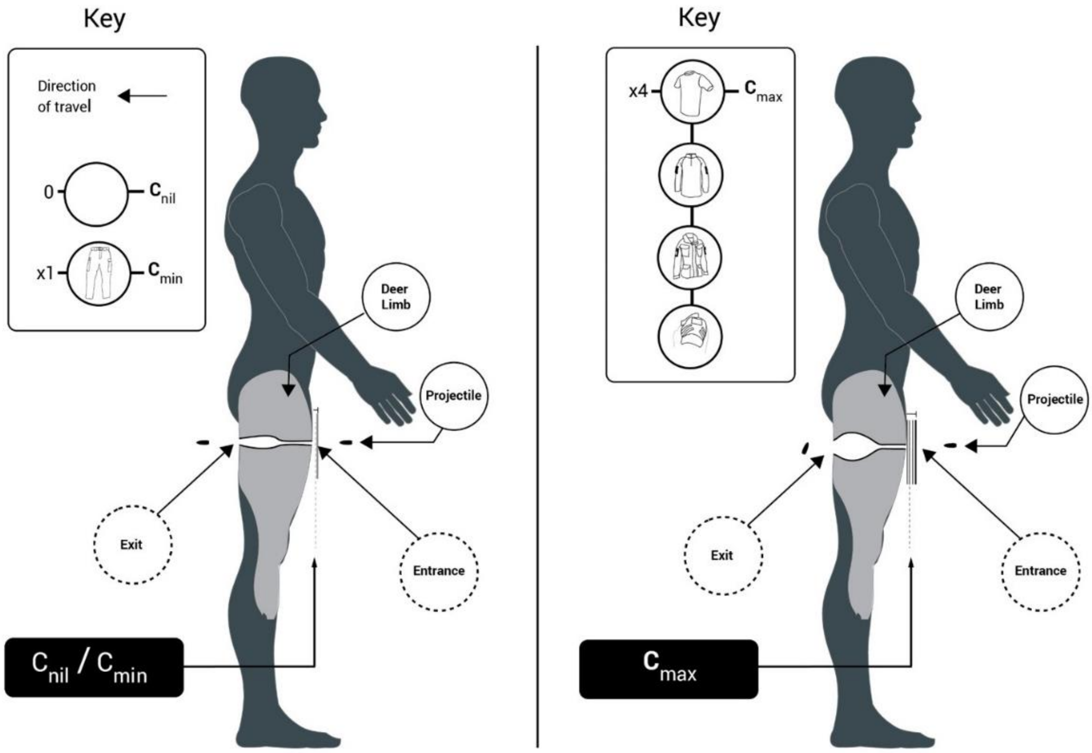

Figure 5.7 Human anatomical schematic overlaying deer limb GSW patterns – C_{nil} and C_{min} (left), C_{max} (right)

Clothing effects also showed some differences on wounding patterns across the two ammunition types. The use of 5.45 mm projectiles saw a significant effect with C_{max} on D2 whereas the effect with 7.62 mm projectiles could not be reliably judged. The 5.45 mm projectiles were of a lower mass and of a mild steel core compared to the heavier, lead core 7.62 mm projectiles. This difference in physical properties, in tandem with the respective different velocities of each ammunition type, i.e. 5.45 mm projectiles travelling faster, would suggest that the 5.45 mm projectiles had travelled further before imparting an increased amount of damage when C_{max} was present, even though the NL was not statistically different across clothing states. This finding is in part corroborated with previous research demonstrating that 5.45 mm projectiles are externally more resistant to fragmentation and deformation and as such tend to leave a globally more simple wound profile behind [12,15].

It is crucial to note that with the model being cadaveric, there cannot be any comment upon tissue viability following wounding. This therefore requires several assumptions to be made with respect to the wounding patterns seen. It seems reasonable that where the parameters of measurable damage were greater within the permanent cavity, that greater temporary cavitation must have taken place [33]. This, coupled with qualitative analysis of the HSV footage, would suggest that more of the limb tissue was involved with the wounding process. However it may be that in live tissue, the subsequent recovery of tissue which has been exposed to this level of deformation may be partial or even complete. This notion is observed and well described within one important study by Hopkinson published in 1963 [16]. The study involved using 0.22 inch (5.6 x 35 mm) hornet projectiles to create a soft tissue GSW in live skeletal muscle of sheep limbs and demonstrated that, without any surgical intervention, soft tissue wounds healed well and by three months had replaced all necrotic tissue with new connective tissue and a tiny amount of fibrotic scar tissue. This would be difficult to prove in human casualties beyond the anecdotal experience of those whom have surgically managed casualties with GSW [6,10], and warrants further study.

5.5.1 Limitations

There were several limitations to this work. The clothing type selected was a limitation where there currently is only one previous study discussing the effects of MTP clothing on GSW patterns [29]. However, added to this study, there is an evolving baseline of results for future comparison studies.

The ammunition types chosen could be considered as a limitation where troops will inevitably be exposed to a plethora of different ammunition types during conflicts, dependent upon enemy logistics. Even ammunition of the same type may have different physical properties and characteristics due to being of different batches or manufactured in different countries [14].

Other limitations include the fixed engagement distance and controlled projectile velocities where it is unrealistic to expect that GSWs are sustained by symmetrically flying projectiles at the same distance and velocities. The natural variation of the above factors will influence the subsequent behaviour of the ammunition being fired and the wounding pattern seen as a result. This necessitates the importance of controlling variables as a measure of scientific rigor to allow accurate testing, hence to why the above testing conditions were set, to try and minimise the amount of variability beyond that which was to be examined

5.6 Conclusion

C_{max} significantly affected the damage sustained by a cadaveric deer limb shot by 7.62 mm or 5.45 mm projectiles raising the likelihood of a more complicated surgical intervention being required for human casualties wearing such clothing combinations. C_{min} did not affect the damage sustained by a cadaveric deer limb shot by 7.62 mm or 5.45 mm projectiles. Neither iteration of MTP clothing layers appeared to affect the propensity of projectile fragmentation or retention, nor the risk of femur fracture, though the latter was not quantified further.

5.7 Acknowledgements

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6 PRELIMINARY EFFECT OF PROJECTILE YAW ON EXTREMITY GUNSHOT WOUNDING IN A CADAVERIC ANIMAL MODEL

Stevenson T, Carr DJ, Gibb IE, Stapley SA

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This chapter came from an experiment that lead to the unexpected observation of empirically worse wounds during qualitative HSV analysis of the limb-shooting events for all clothing states. This important observation also noted projectiles yawing before striking targets which, upon completion of the experiments, was found to be due to the serendipitous use of a larger diameter gun barrel firing the intended smaller 5.45 mm projectile. This caused projectiles to exit the barrel with an unexpected flight pattern. Raw data is included in appendix G and further detail on the method of contrast CT scanning used in this chapter can be found in appendix H.

6.1 Abstract

Gunshot wounding (GSW) is capable of causing devastating tissue injuries by delivering kinetic energy (KE) through the contact surface area of a projectile. The contact surface area can be increased by yaw, deformation and fragmentation, all of which may be caused by any intermediate layers struck by the projectile prior to entering its target. The aim of this study was to investigate whether projectile yaw occurring before penetration of a cadaveric animal limb model causes worse damage with or without clothing layers present using 5.45 x 39 mm projectiles. In total, 12 fallow deer hind limbs were shot, further divided into 4 with no clothing layers (C_{nil}), 4 with a single clothing layer (C_{min}) and 4 with maximum clothing layers (C_{max}) as worn on active duty by UK military personnel. Contrast CT scanning captured measurements of permanent cavity damage to allow limb analysis, and results were compared using Analysis of Variance (ANOVA). No significant differences were found among clothing states for each series of measurements taken. Projectile yaw is therefore a key variable with regard to causation of damage within this extremity wound model.

Keywords: Yaw, Gunshot, Wounding, Clothing, Extremity, AK74

6.2 Introduction

Wound ballistics study can be challenging to the modern researcher. With the variables that require control in order to preserve objectivity and scientific rigour, reproducing high quality experiments is arduous for any researcher, no matter how well funded. With previous studies having explored or commented upon the survivorship burden from conflicts throughout the 20th century, extremity GSW are often noted to make up the largest proportion of injuries [1-8].

With previous research from this group having modelled extremity GSW to test the effects of UK military clothing on wounding patterns, key variables such as velocity, engagement distance and yaw have been controlled [9,10]. When considering military projectiles such as 7.62 x 39 mm or 5.45 x 39 mm, unopposed projectiles in flight are base-heavy and ultimately will yaw away from the central axis and lose flight stability [11]. With respect to wounding potential, the greater the contact surface area of a projectile (i.e. its shape, stability and integrity e.g. deforming or fragmenting) with its target will mean a greater amount of kinetic energy (KE) delivered over a fixed distance by a known velocity and mass of the projectile [12-19]. One study by Wen et al. in 2017 describes the effect of preliminary yaw from a computer model using 7.62 x 39 mm projectiles based on a gelatine model. The study observed that greater projectile yaw on striking the target leads to the projectile reaching maximum yaw (90^{o}) over a shorter penetration depth and therefore delivering a greater KE load to the model [20]. Intermediate layers such as clothing can destabilise projectiles in flight such that they yaw sooner than if they struck a bare target [9,10,20]. This would also therefore lead to yaw occurring sooner within the target and thus allowing for a greater delivery of KE and subsequently greater wounding potential.

The aim of this preliminary study was to investigate whether projectile yaw occurring before penetration of a cadaveric animal limb model causes worse damage with or without clothing layers present using 5.45 x 39 mm projectiles.

6.3 Materials and methods

Ethical approval for this work was granted through CURES (CURES/3579/2017).

6.3.1 Materials

The materials chosen for study were from previous work by this group [9,10,22]. Using Multi-Terrain Pattern (MTP) UK standard issue military clothing to provide the intermediate layers, the clothing was prepared in two states, the minimal state (C_{min}) and the maximal state (C_{max}), to be compared with a bare control (C_{nil}) (see methods below). Ammunition was quarantined by batch to ensure physical property differences could be kept to a minimum [23]. The ammunition type selected was a 5.45 x 39 mm mild steel core projectile, a typical threat faced during recent conflicts by UK forces [5,24], and used in previous work by this group[1]. Animal tissue chosen for testing was fallow deer (*Dama Dama*) hind limbs. The animal choice was justified by previous research demonstrating similar morphology of the human femur to that of a deer [25]. Limbs were of a mass of 9.5-13 kg and measured approximately 280 mm x 700 mm x 100 mm (width x height x thickness). UK anthropometric data demonstrated that this mass and size is comparable to that of human thighs, particularly those of a UK military population [26,27]. With fit young military personnel being of a muscular stature, cervine limbs also being of a muscular nature were preferable to other animals such as porcine. Porcine limbs have a thick layer of subcutaneous tissue and thicker skin compared to humans, which is a disadvantage of their use for testing [28]. Limbs were culled for entry into the human food chain rather than specifically for research, and prepared by a professional butcher (Figure 6.1). Limbs were used as both fresh targets (within 72 hours of culling) and also defrosted from freezer storage over a 72 hour period due to availability of range facilities versus limb acquisition. Differences in ballistic effects between fresh and defrosted frozen cadaveric material have previously been shown to be negligible [29].

[1] 5.45 x 39 mm; mild steel core, 53 grain full metal jacket, Lot number 539-04, made in Russia, 2004; with a core composition of steel; a core tip composition of lead was found, and for the jacket, the composition found to be steel with internal and external copper wash; mean hardness was 814.9 Hv for the core, 3.6 Hv for the core tip, and 188.8 Hv for the jacket [9].

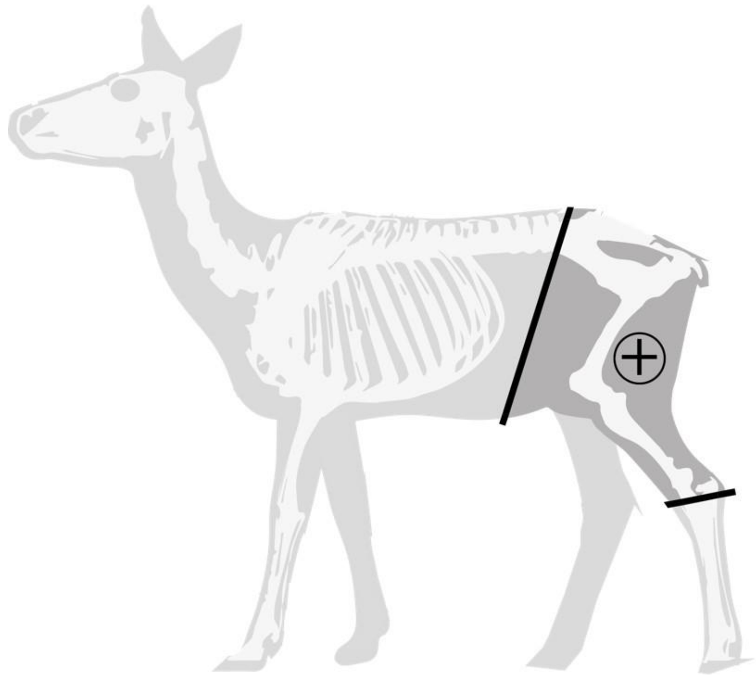

Figure 6.1 Fallow deer anatomy schematic demonstrating limb preparation and shot placement

6.3.2 Methods

The method for laundering and preparing the clothing states and preparing the limbs was as used in previous work and shown in the figures below [9]. A minimal clothing state (C_{min}) was required, consisting of a single layer of MTP clothing taken from issued trousers, and also a maximal clothing state (C_{max}) consisting of the combined layers of clothing taken from an issued t-shirt, Under Body Armour Combat Shirt (UBACS), smock, and upper arm brassard as worn on duty by UK service personnel (Figure 6.2). These were then compared to bare samples with a zero clothing state (C_{nil}) as a control. Fabric samples for C_{min} were cut from laundered MTP trousers (250 x 250 mm)[2] and pinned to the front face of the relevant deer limbs (Figure 6.3, top right image). Fabric samples for C_{max} were measured and cut in relation to the upper sleeve pocket size on the UBACS and Smock (200 x 150 mm)[3], and placed in layers with the t-shirt layer innermost,

[2] C_{min} mean thickness = 0.43 mm; mean mass per unit area = 191.14 g/m^2 [9]
[3] C_{max} mean thickness = 32.26 mm; mean mass per unit area = 7735.17 g/m^2 [9]

then UBACS, smock and finally with the brassard then placed over the top of the other layers (Figure 6.2 lower image, and Figure 6.3 lower images).

Figure 6.2 Examples of MTP clothing used – clockwise from top left: MTP trousers; top right: t-shirt, UBACS, smock, and brassard as worn by service personnel; bottom: i. t-shirt, ii. UBACS, iii. smock and iv. brassard layers prepared for testing. Laundering detail and fabric analysis data for this clothing used within these experiments is detailed in previously published work [9]

Figure 6.3 Clockwise from top left: C_{nil} front view; C_{min} front view; C_{max} front view; C_{max} side view

Four limbs were prepared for C_{min} and C_{max} clothing states, compared to four limbs with C_{nil} (i.e. bare limbs) giving a total of 12 limbs. Limbs were all shaved on the lateral surface, and suspended upside down using an “S”-shaped metal hook looped between the distal tibia and fibula at the ankle joint.

Projectiles were fired from a number 3 proof housing on an indoor range. Projectile yaw prior to striking the target, was induced serendipitously by the firing from a 5.6 mm barrel. The resultant precession and nutation prevented flight stabilisation, and allowed projectiles to yaw by several degrees prior to striking the targets. No facility to measure yaw angle was present as it had not been a part of the initial experimental design. Each limb was perforated once by a 5.45

mm projectile, with shots aimed to strike the lateral surface of the hind limb, travelling through the soft tissue compartment posterior to the femur, with limbs set at 10 m from the end of the barrel (Figure 6.4).

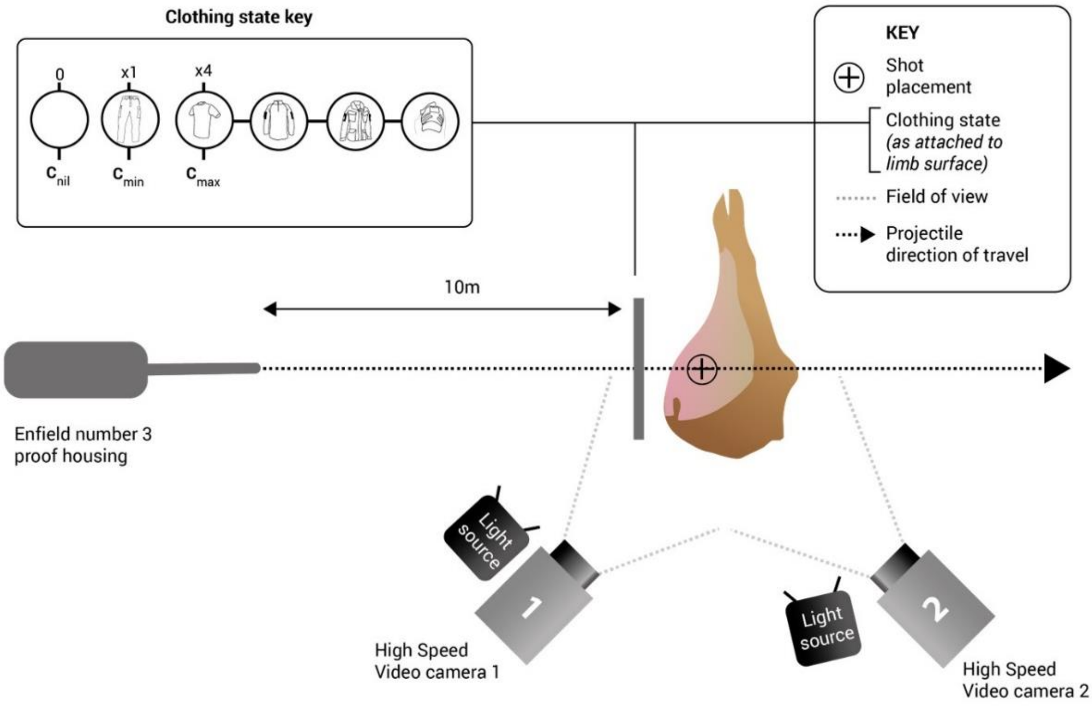

Figure 6.4 Schematic demonstrating the experimental set up

Impact velocities for all projectiles were measured using Doppler radar (Weibel W700). High Speed Video (HSV) was used to capture the event in real-time, showing wounding patterns external to the limbs from both the entrance[4] and exit[5] surfaces. GSW patterns were qualitatively examined using Phantom Software (Visions Research, Phantom Camera Control Application 2.6).

All limbs underwent photography post-shoot, using a Canon D5100 Digital SLR camera (S/N 6773411). Damage within limbs was measured using contrast enhanced Computed Tomography (CT) scanning with a protocol developed in previous work [30]. The CT scanner used was a dual source (2 x 64 slice) Siemens SOMATOM Definition MSCT scanner (System SOMATOM Definition

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[4] Phantom V12 video camera (frames per second = 28,000, shutter speed = 4µs, resolution = 512x384)
[5] Phantom V1212 video camera (frames per second = 37,000, shutter speed = 5µs, resolution = 512x384)

AS, 64622, Siemens AG, Wittelsbacherplatz, DE – 80333 Munchen, Germany). Scans with and without contrast used a standard adult pelvis protocol (exposure figures were 120 kV and 25-32 mAs) with 1.0 mm slice soft tissue and bony reconstructions in the axial, sagittal and coronal planes. Contrast injected into wounds consisted of 10-20 mls of Omnipaque 300 contrast (OMNI300, GE Healthcare). The dimensions of damage measured were in both axial and coronal viewing planes using multi-planar reconstruction (MPR) images (Figure 6.5) as part of the Syngo CT2012B software package provided with the CT scanner. The damage dimensional measurements of the GSW patterns were as follows: the neck length (NL), maximum height of the permanent cavity (H2), distance to maximum height of the permanent cavity (D2), entry wound diameter (E1) and exit wound diameter (E2) (Figure 6.6).

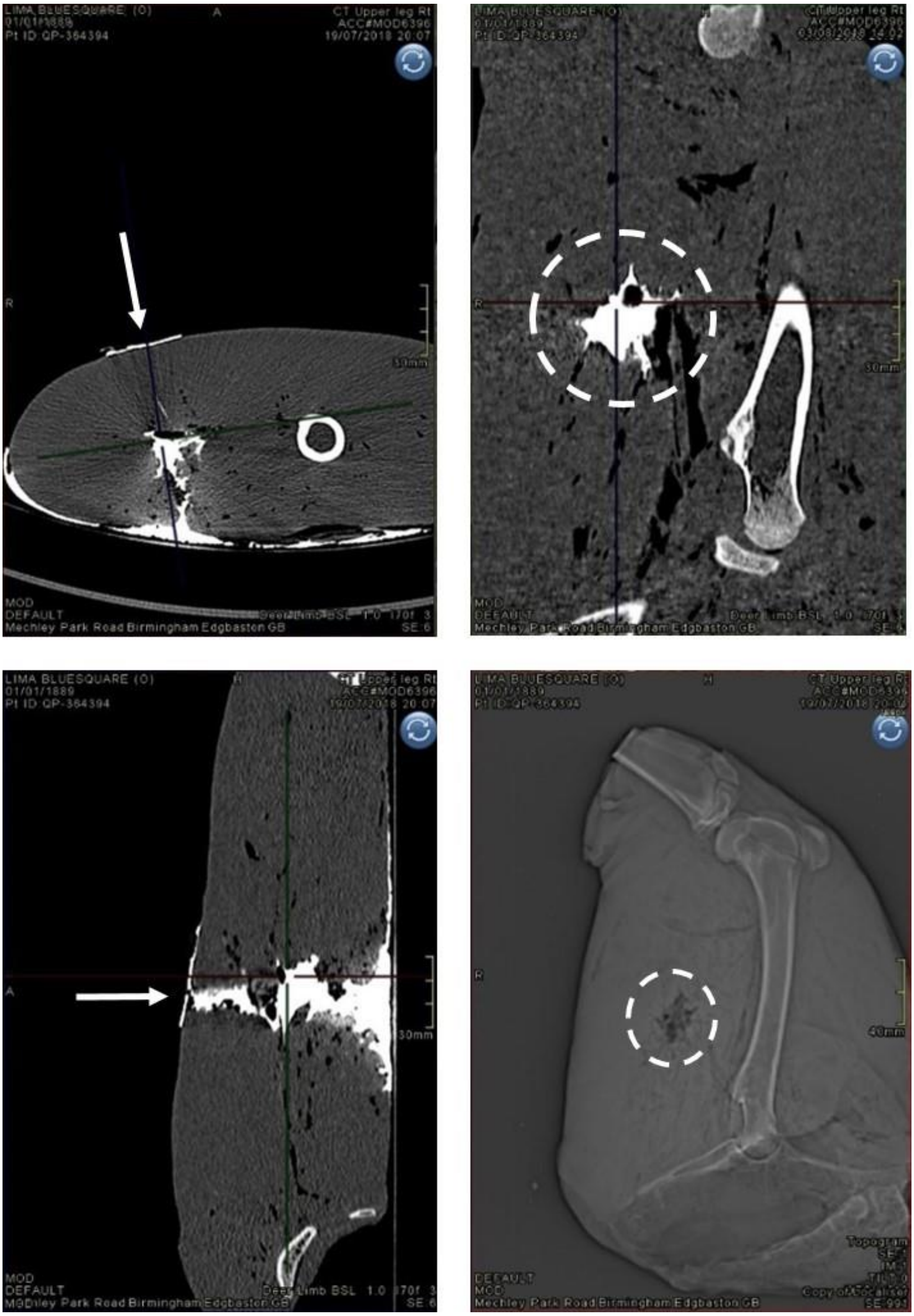

Figure 6.5 Arrows indicate projectile direction of travel, dotted circles indicate coronal section view of GSW track – Clockwise from top left – Contrast image, axial plane; contrast image, sagittal plane; X-ray scout view, sagittal plane; contrast image, coronal plane

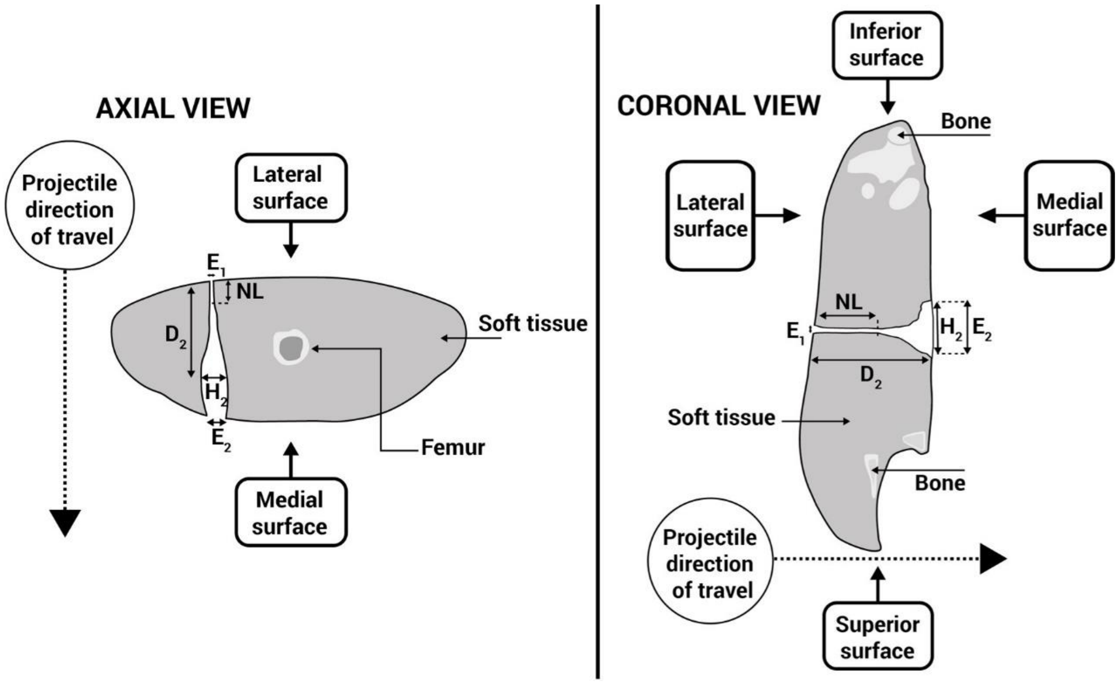

Figure 6.6 Schematic demonstrating CT scan measurements taken in axial and coronal planes of view

The International Business Machine Corporation's Statistical Package for Social Services version 24 (IBM SPSS Statistics v24), analysis of variance (ANOVA) was used to determine the effect of the different clothing states on NL, H2, D2, E1 and E2. The two different CT scan viewing planes where measurements were taken from were considered together, as were the different clothing states. Homogeneity of variance and normality of data were confirmed with a significance level of 0.05 applied. Significant differences due to clothing state were identified using Tukey's honest significant difference (HSD) test. Main effects and significant interactions only are discussed in the results section.

6.4 Results

Mean impact velocity for the 5.45 mm projectiles was 907 m/s (SD = 6 m/s). Each limb was perforated by its respective projectile. No projectiles appeared to fragment from review of the HSV, and of those projectiles recovered from the bullet trap there did not appear to be evidence of deformation or fragmentation.

Evidence of bullet wipe and yarn pull-out on the surfaces of the fabric samples was consistent with that described within the literature [11,31,32].

The dimensions collected for the damage to limbs caused by projectiles of both ammunition types for all clothing states are summarised in Table 6.1. Where an inequality of error variance in ANOVA testing for exit wound dimensions was found due to the relatively high coefficients of variation (CV) seen, areas of the exit wounds were calculated (EA) and are shown, along with raw exit wound dimensional data in Table 6.2.

Table 6.1 Mean, Standard Deviation (SD) and Coefficient of Variation (CV) for dimensions measured

	NL			D2			H2			E1			E2		
Projectile / clothing state	**Mean (mm)**	**SD (mm)**	**CV (%)**	**Mean (mm)**	**SD (mm)**	**CV (%)**	**Mean (mm)**	**SD (mm)**	**CV (%)**	**Mean (mm)**	**SD (mm)**	**CV (%)**	**Mean (mm)**	**SD (mm)**	**CV (%)**
5.45 mm / C_{nil}	44.4	22.5	50.6	69.7	19.8	28.5	17.2	3.7	21.5	5.1	0.9	18.4	18.9	3.7	19.4
5.45 mm / C_{min}	31.4	31.9	101.6	68.6	22.1	32.2	16.6	4.0	24.0	6.7	3.8	56.9	15.6	5.8	37.0
5.45 mm / C_{max}	18.8	21.5	114.7	62.5	26.9	43.1	22.7	8.9	39.4	7.9	4.3	53.7	23.4	9.1	39.0

Table 6.2 Exit wound dimensional measurements taken from CT scans

	Clothing State											
	C_{nil}				C_{min}				C_{max}			
Limb number	1	2	3	4	5	6	7	8	9	10	11	12
Exit (axial view) (mm)	22.2	15.5	22.0	16.0	17.4	9.3	22.7	13.0	30.0	27.3	13.0	n/a
Exit (coronal view) (mm)	34.9	20.3	29.0	20.7	25.0	9.3	9.7	38.0	30.8	28.2	12.6	16.7
Ellipsoid Area of exit (EA) (mm^2)	1217.1	494.3	1002.3	520.3	683.4	135.9	345.9	776.0	1451.6	1209.4	257.3	n/a

ANOVA results are given in Table 6.3 below; data subgroups identified by Tukey's HSD are also included.

Table 6.3 ANOVA results

Measurement	ANOVA effects (F-statistic, P-value)		Data subsets found (Tukey's HSD)	
	Clothing state	Viewing plane	Group 1	Group 2
NL	$F_{2, 18} = 1.24$, p = NS	$F_{1, 18} = 0.07$, p = NS	No subgroups identified	
D2	$F_{2, 18} = 0.04$, p = NS	$F_{1, 18} = 0.40$, p = NS	No subgroups identified	
H2	$F_{2, 18} = 2.38$, p = NS	$F_{1, 18} = 1.20$, p = NS	No subgroups identified	
E1	$F_{2, 18} = 1.30$, p = NS	$F_{1, 18} = 0.06$, p = NS	No subgroups identified	
EA	$F_{2, 8} = 1.22$, p = NS	N/A	No subgroups identified	

No significant differences were found among clothing states for each series of measurements taken.

6.5 Discussion

Whilst previous work has demonstrated the significant effect of clothing with projectiles striking an extremity wound model [9,10], the serendipitous findings from these experiments allude to how important a factor projectile yaw is with regard to the resulting wounding pattern.

In contrast to these previous studies, the presence of clothing did not appear to further influence the severity of wounding seen from the damage inflicted upon the model with projectiles already yawing prior to striking their targets.

From a clinical perspective, the smaller and narrower the wound channel, and the less evidence of significant cavitation found, then the less invasive the level of surgical management is required [5,33,34]. These results clearly demonstrate wounding patterns which are still substantial and as such would require relatively invasive surgical management compared to more simple through and through soft tissue wounds [9,10,35,36]. The size of temporary cavity formation relative to the yaw of the projectile, though not measured within this study, is clearly increased proportionally to the contact surface area of the projectile with tissues and as such the damage recorded is a reflection of this. The use of the 5.45 mm projectile has previously been demonstrated to yaw early within target penetration and despite no evidence of external deformation or fragmentation, has been found to have internally deformation of the lead tip found above the steel core [17,19].

The findings from this paper, coupled with other recent studies [9,10], provide a more realistic expectation of injury patterns that may be expected on the battlefield, where typical engagements with the enemy will be of varied distances, and therefore varied projectile velocity and symmetry.

6.5.1 Limitations

There were several limitations to consider. The main limitation was the control of yaw. Use of a larger barrel to fire projectiles from ensures an increased precession and nutation as the projectile exits the barrel, however with no literature pertinent to deliberately inducing yaw of this ammunition type, measuring and reproducing the accuracy of yaw in degrees was neither achieved within this experiment, nor comparable to existing data elsewhere.

Clothing was a limited to being representative of that worn by UK troops on current operations only, however this is building into an increasing amount of data being gathered within this field for future comparison [9,10]. This could be useful to look at other nations' military clothing or civilian agency clothing such as police, when examining GSW patterns in future studies.

Ammunition was limited to one type. It would be beneficial to test multiple types pertinent to the threat expected by modern troops in combat.

6.6 Conclusion

Clothing state does not influence damage within an extremity GSW model where projectiles yaw before striking the target. Projectile yaw is therefore a key variable with regard to causation of damage within this extremity wound model.

6.7 Acknowledgements

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7 DISCUSSION

7.1 Introduction

The work presented in the previous chapters details the epidemiology behind UK military GSW from the last decade, and also the models developed and used to test the effect of MTP clothing on GSW patterns. The findings of the clinical burden justify a need for ballistic research to further characterise wounding patterns, in particular to the extremities, and ultimately to search for treatment strategies towards mitigating this burden in lieu of inevitable future conflict. That military clothing has not previously been examined with respect to the effect it confers towards extremity GSW patterns offered a foundation from which to build this thesis. This discussion will now address two parts. The first part will summarise the research findings to demonstrate the knowledge uncovered and address where that knowledge sits in relation to the bigger picture. The second part will address the scientific rigour behind the data gathering and experimental design for all models used in this work.

7.2 Summary and relevance of research findings

Each chapter’s findings will now be summarised, with key points and new knowledge discussed

7.2.1 The clinical burden

Chapter 2 detailed the clinical burden of GSW to the UK military over twelve years of recent combat operations in Iraq and Afghanistan [1]. Key statistics are summarised as follows: 24% of all British casualties within the study period were due to GSW, of which over half suffered injury to the extremity. Of a total of 723 GSW casualties, 546 survived and 177 died. Of the survivors, 69% suffered extremity wounding. Three quarters of all GSW casualties underwent a total of 2,357 surgical procedures which were carried out over a total of 1,455 surgical episodes (median of 3 surgical procedures carried out over a median of 2 surgical episodes per casualty undergoing treatment). Mean time per surgical procedure was 122 minutes. As a testament to the tenacity and experienced gained from clinicians working throughout such prolonged conflicts, casualties undergoing surgical procedures during the treatment period examined were also found to have had a survival probability of 96%. Finally, casualties accumulated 25 years LoS across medical treatment facilities.

A key consideration of this work was that it was the first study to present UK GSW epidemiological data from the complete conflict time periods in Iraq and Afghanistan, and as such captures the extent of resource use not previously known. These statistics therefore provide a useful reference towards planning clinical and medical logistic support for future UK military operations.

With the substantial burden of extremity GSW found amongst survivors, this work provides contextual and comparable data to recent studies examining UK military casualty extremity injuries from multiple traumatic mechanisms [2-5]. The statistics from chapter 2 also provide a point of comparison to US military casualty data from a similar time period within the same conflicts [6-12], as well as to historical US military casualty data from the conflict in Vietnam [13-17]. This comparison shows where GSW proportionally sits as a mechanism of injury and what anatomical regions suffered the most in conflicts both past and present. Interestingly, it is clear that whatever different PPE states have been worn throughout decades of conflicts by soldiers, extremities are often left relatively exposed. That 96% of the UK GSW casualties whom received surgical treatment survived their injuries also highlights the importance of remembering that the clinical burden is not just measured upon the initial management of injuries as they are sustained. The burden should also include the longer term work required for out-of-hospital rehabilitation and any subsequent re-admission to hospital due to complication or further clinical need. This latter is extremely difficult to capture and to date has not been adequately explored with respect to UK military GSW casualties [1,2,18]. As such, the reported clinical burden within this thesis only represents a proportion of the sheer magnitude of clinical resources needed to try and recover these patients back to an acceptable quality of life and function within society.

Financial cost estimation of GSW treatment of those military casualties identified in Chapter 2 was not easy to ascertain. Gross estimates provided by the QEHB put approximated costs over the time period examined in excess of £26m [19]. Considering the numbers of casualties treated, these costs represent a substantial economic burden to the UK taxpayer, especially where it does not include costs for rehabilitation, mental health treatment, or logistic use external to the hospital infrastructure (such as military transport, ambulance transport or police escorts) so is likely underestimated. By comparison, civilian USA data describes annual costs as high as $174 billion for firearm-related injuries (including deaths, medical care, insurance costs, public health costs, mental health costs, decreased quality of life costs and loss of earnings) though for a much greater number of casualties [20].

7.2.2 Clothing effects on gunshot wounding

7.2.2.1 Synthetic modelling

With the clinical burden identified, the next stage was to use an already validated synthetic wound ballistic model to test the effect of UK military clothing (chapter 3) [21].

Of the 36 gelatine blocks shot, half were by each of the two ammunition types of interest (7.62 x 39 mm and 5.45 x 39 mm). Six blocks were shot in each clothing state (C_{nil}, C_{min} or C_{max}) by each ammunition type, with wounding patterns measured by HSV and physical dissection. In all measurements apart from H2 it was demonstrated that the clothing state of C_{max} led to significantly different measurements when compared to C_{nil}. In the cases of NL and D1 measurements, C_{max} also led to significantly different measurements when compared to C_{min}.

No previous study exists within the literature that examines the effect of UK military clothing on GSW patterns. The key point taken from this study was demonstrated in the comparison of the wounding pattern within the gelatine block to an anatomical overlay (Figure 3.7). This demonstrated that a projectile which might have otherwise passed through a limb before yawing significantly, would yaw sooner within that limb due to the presence of C_{max}. With maximal temporary cavitation therefore occurring earlier, a greater amount of KE would be imparted to the tissues and thus subjecting them to greater deformative stress. Crucially, this observation would likely necessitate a more extensive level of surgical management and therefore contribute more substantially towards the resultant clinical burden.

This finding corroborates findings from other studies which have examined the effect of intermediate layers on GSW patterns in gelatine models and found the damage to be worse [22-25]. It also highlights the importance of clinicians, in both the civilian and military context, considering what casualties were wearing when they sustained their injuries.

7.2.2.2 Cadaveric animal modelling

Even though validated for study, the homogenous density of gelatine in the model used in chapter 3 necessitated the requirement for testing a more anatomically biofidelic model. Once the appropriate animal model was identified, the challenges associated with how to analyse the samples, which were opaque unlike gelatine, led to testing several different techniques as detailed in chapter 4 [26].

With the method of contrast CT scanning found to yield reproducible data measurements, the effect on GSW patterns from the different clothing states were tested on a cadaveric deer hind limb model (chapter 5) [27,28].

Of the 24 deer limbs shot, half were by each ammunition type, as used in chapter 3. Four limbs were shot in each clothing state (again, C_{nil}, C_{min} or C_{max}, as in chapter 3) for each ammunition type. In this model NL was not affected by clothing state for either ammunition type. However, the presence of C_{max} did significantly affect the maximum height of the permanent cavity (H2) in limbs shot by both ammunition types by increasing it, as well as significantly increasing the distance to that maximum height (D2) where 5.45 mm projectiles were used. It was also found that the presence of C_{max} led to significantly larger entrance wounds for both ammunition types, with entrance wounds caused by 7.62 mm projectiles being significantly larger than those caused by 5.45 mm projectiles.

Once again, no previous study appears within the literature that examines the effects of UK military clothing on GSW patterns within a cadaveric deer limb model or by using the method of contrast CT scanning to analyse the wounding patterns. The key finding of this study was that having a significantly greater H2 found within the GSW pattern in the presence of C_{max} meant an overall larger wound was sustained (Figure 5.7). This finding would be consistent with a greater delivery of KE to the tissues to have caused such an increase in damage, and the resulting tissue injury would no doubt require an increased level of surgical intervention. This observation would further demonstrate how these GSW patterns would markedly contribute towards the subsequent clinical burden, and corroborate findings from chapter 3.

That C_{max} has been demonstrated to cause worse wounds within two extremity GSW models from chapters 3 and 5 raises the question about general clothing effects. High velocity GSW from military firearms have become sadly more prevalent throughout the developed world with several notable incidents of mass shootings of civilians, including the recent Las Vegas shooting in October 2017 which resulted in 58 dead and around 500 wounded [29,30]. Whilst it is important to note that the spread of injuries sustained will not be comparable to that of a military population wearing a configuration of body armour and personal protective equipment (PPE), it should be acknowledged that with the more vital structures at risk within the torso that higher rates of fatality may be observed. This would again suggest a higher proportion of survivors suffering extremity injuries and once more a substantial clinical burden required to treat and rehabilitate their injuries.

GSW injuries amongst civilian populations vary across the globe. Countries where society has a prevalence of guns available to either law enforcement or ordinary citizens, such as the USA, often see handgun injuries either from accidents, criminal activity, or from suspects wounded by police [30-32]. Wider application of the findings from this thesis therefore raise the question of a requirement to test clothing worn by civil service personnel exposed to GSW in the line of duty, such as those within law enforcement, and ensure that their potential for injury is not worsened by the uniforms and apparel that they wear. Work by Mabbott in 2015 has already been conducted with regard to UK police body armour, which found that wounds in a gelatine and porcine model were worse when firing 5.56 mm and 9 mm projectiles through torso soft body armour due to projectiles ricocheting off the rear armour back into the model [24]. Whilst the permutations of clothing worn by a general civilian population are far too variable to test individually against GSW, clothing effects on wounding patterns should be at least considered when encountering these wounds from a clinical or forensic perspective.

Among military populations, the demonstrable worsening effect of C_{max} towards GSW patterns from projectiles travelling symmetrically at muzzle velocity broaches the concept of varying the clothing state according to the threat. If the threat to be mitigated is greatest from a different mechanism, i.e. explosive, then the PPE worn should quite rightly mitigate against that threat. If the greater threat becomes GSW, then it is at this point that it should be considered to change the current PPE stance and alter the clothing state accordingly, or provide a catalyst for development of PPE which specifically mitigates against the threat of extremity GSW. Examples where GSW may provide a greater threat include, but are not limited to, close-quarters fighting e.g. building clearance, compound clearance, urban warfare, or Special Forces operations.

7.2.3 The importance of projectile yaw

With the significant effect of C_{max} on GSW patterns demonstrated in chapters 3 and 5, it was important to consider what the key factor influencing the wound was: the clothing or the projectile. This led to the describing of preliminary yaw effects in chapter 6 [33].

In chapter 6, 12 deer limbs were shot by 5.45 x 39 mm ammunition where several degrees of yaw were induced serendipitously for each shot. Clothing states as used in Chapters 3 and 5 were again utilised. The key finding of this work was that the damage sustained by the deer limbs was severe, irrespective of the clothing state.

This finding reiterated that a projectile causes wounding relative to the transfer of KE through the contact surface area it has with its target (in conjunction with its mass, velocity, and amount of time spent within the target, i.e. the rate of deceleration and drag coefficient) [34]. This suggests that if a projectile strikes a target symmetrically and is travelling fast enough (and the target is small enough) that the projectile can pass through the target without any significant KE transfer, and leave a more simple wound profile behind [35-38]. But as soon as yaw of the same fast-moving projectile is incurred before striking or whilst within the target, either by presence of intermediate layers or due to the loss of symmetry of flight, then the KE transfer is greatly increased and the wounding potential more clinically significant [21,22,39,40].

7.3 Scientific rigour

The data gathered and the experiments conducted provide the narrative to this thesis. The aim of testing the effects of MTP clothing on GSW first required the use of a validated model (gelatine block testing, chapter 3) in order to provide some element of control and known outcomes to test the clothing. The outcomes of MTP effects, once established, could then be applied to a different model. The decision to develop a cadaveric animal limb model was made in order to reproduce a higher level of biofidelity towards wounding that might be seen within real casualties. As such, the opacity of the model meant the need to develop an appropriate method of wounding pattern visualisation. Once these methods had been individually attempted and compared, the resultant method of contrast CT scanning provided a useful way of visualising wounding patterns in such a way as to provide measurable parameters of damage comparable to the gelatine model.

7.3.1 Ammunition and clothing

Ammunition selected for this work was batch controlled to try and limit the variability in physical properties that can be seen within ammunition of the same type [41]. Appendices D and E summarise the consistency of the batches of ammunition used through microhardness testing and elemental analysis and proved acceptable consistency.

The clothing selected for this work was UK standard issue MTP military clothing. Fabric analysis found in appendix F determined consistency amongst samples selected which might be expected amongst a factory produced standard issue clothing set. With the constant development of new and improved materials for use as PPE for UK military personnel [42], and indeed other multinational military organisations, the different available clothing should be considered for ballistic testing where GSW is the subject of study. The historic lack of clothing in ballistic testing does not invalidate previous research, but future researchers should consider the interaction of intermediate layers between the projectile and its target when researching wound ballistics, especially in light of the findings from this work.

7.3.2 Gelatine and animal tissue

The gelatine used in this work came from the same batch of GELITA® ballistic gelatine and was manufactured according to a developed protocol within the Impact and Armour Group at Cranfield University. This process is described in appendix C along with the calibration of the gelatine blocks during experiments based on previous work by Jussila [43]. This calibration process consisted of firing a 5.5 mm steel ball-bearing (BB) into each gelatine block with a depth of penetration (DoP) recorded against the impact velocity in m/s of the BB. The calibration data was then plotted on a graph containing pooled calibration data from several studies from the same institution, using the same method, to demonstrate consistency and can be seen at Figure 3.5 [21,24,44]. Whilst the size of the gelatine block is substantially larger than that of a human limb, this allowed visualisation of the complete wounding pattern within the block for subsequent analysis and comment throughout the experiments conducted.

The selection of fallow deer was based on two key concepts: i) the morphology of deer femurs being comparable to that of human femurs [45]; ii) the mass of the hind limb was comparable to that of a human thigh [46,47]. The dense skeletal muscle and lack of subcutaneous fat seemed a more reasonable comparison to that of a fit and healthy young soldier compared to other commonly used animal tissues, i.e. pig, where skin and subcutaneous tissues are noted to be thicker

[48]. Disadvantages included variation in sex and age of the deer limbs acquired due to their method of acquisition and seasonal availability.

7.3.3 Wounding patterns

The wounding patterns seen throughout these experiments demonstrate substantial variation even within controlled states. This is frequently the case within ballistic study [49,50]. With the demonstrable effect of clothing as an intermediate layer and its subsequent effects on the wounding patterns within these experiments, the crucial factor was actually the projectile. The wounding was a result of the projectile imparting KE to the target tissues, and as such was determined by the contact surface area of the projectile with the tissues and the time taken for the projectile to traverse those tissues [34,51]. The greater the contact surface area, and the longer the time taken to travel over a fixed distance, the greater the amount of KE can be imparted over that distance. Typically, the contact surface area is increased when the projectile either fragments, deforms or yaws [34,52,53]. Fragmentation may be determined by factors such as the composition of the projectile, i.e. lead core projectiles are more likely to fragment than projectiles with a mild steel core [21]. Yaw will occur when flight stability of the projectile is lost (or was never achieved). When this stability is removed by intermediate layers such as clothing, then increased damage was seen in the experiments presented here. However when the projectile yawed prior to striking the target, increased damage was again seen but irrespective of the intermediate layers. KE values cannot be typically calculated by clinicians faced with GSW casualties which is why these values were not measured during these experiments. However understanding the physical process of how wounding from projectiles occurs is fundamental towards subsequent clinical management and therefore understanding the effects of KE transfer to the tissues [36,38,40].

When considering the exposure of troops to the varying conditions or environments of combat, engagement distances may differ greatly. As such, troops may be exposed to projectiles travelling symmetrically and asymmetrically. Therefore the resultant variation in wounding patterns is immense. This in part can be corroborated by the Length of Stay (LoS) data from Chapter 2 showing an

IQR of 4-16 days [1]. Clearly the more simple wounds require a shorter LoS and vice versa.

Challenges associated with variable control in GSW modelling help illustrate this point where even under the most tightly controlled studies, there will still be variations in the wounding patterns seen [21,30,54,55]. As such, with troops in combat or civilians under fire both at risk of exponentially greater variation, it cannot be realistic to predict every type of wounding pattern for every combat or shooting situation. However, it is a reasonable starting point to detail those wounding patterns seen under the circumstances described within this thesis and take them in conjunction with other wounding patterns from military firearms or other weapon systems described within the literature [24,25,44,56,57].

7.3.4 Biofidelity

It is paramount towards the content of this thesis to acknowledge that the models used do not offer any indication as to the viability of tissues within the GSW zone of injury. Assumption as to the clinical state of tissues is not unreasonable with the knowledge of ballistic injury as it currently stands, however this is not a substitute for live tissue study and as such necessitates consideration of such work. With the ability of skeletal muscle to tolerate the deformation of temporary cavitation to a reasonable degree when compared to other tissue types of a greater specific gravity, i.e. bone [35], soft tissue modelling allows reasonable control for ballistic wound modelling. This should not lead researchers to shy away from the development of complex wound modelling, as injuries seen following bone strike can range from relatively simple to catastrophic and require anything from minimal to a substantial amount of clinical resources and skill towards treatment [38,58]. Whilst models such as gelatine offer reasonable methods to visualise GSW patterns and are validated against live swine thigh muscle tissue [49,52,59], the homogenous density cannot reasonably substitute the biofidelity of real anatomy when considering the potential effects of tissues arranged within fascial compartments around bone and neurovascular structures. All of these multi-faceted organic components are at risk of injury from gunshot and each requires careful consideration towards the most appropriate clinical management, often requiring specialists from different surgical disciplines in order to reach an acceptable clinical outcome [40,60-63].

Whilst the use of synthetic and animal tissue in these experiments provided a reasonable assumption of ballistic wounding patterns in real human casualties, it would be beneficial to collect prospective wounding data during future conflicts to help provide a comparison to wound ballistic data for such models as used here, and to thus aid development of models of improving biofidelity in future ballistic study.

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8 CONCLUSIONS

Conclusions for all studies and experiments are presented at the end of each relevant chapter. This section contains the conclusions for the thesis as a whole.

This thesis has highlighted the clinical burden of GSW to the UK military following recent conflicts and has described the methods developed to identify soft tissue extremity wounding patterns following GSW within a synthetic and a cadaveric animal model, and has tested the effects of UK military clothing in the minimal and maximal states as worn by front-line service personnel at this time.

Therefore it may be concluded that GSW to the UK military during the Iraq and Afghanistan conflicts caused a substantial clinical burden in terms of casualty numbers, injuries sustained and length of stay within medical treatment facilities. Also that the presence of the maximal clothing state as worn by service personnel on the front line leads to greater damage within the two extremity models used in this thesis from two known ammunition types at a known engagement distance. This implies a greater level of surgical intervention required to manage these injuries in the clinical context, however this observation would require live tissue study to validate. The reality of treating GSW is that the heterogeneity of wounds seen is such that it becomes extremely challenging to predict the injuries sustained within an ever-evolving military operational theatre. The models presented within this work offer a foundation from which to further examine this problem.

Future work is considered within the next section.

9 FUTURE WORK

This can be considered in two parts: further work using the models developed within this thesis; and future development of new models.

9.1 Further work

Altering individual variables controlled within the modelling for this PhD invites areas for study to build a greater series of wound pattern analysis and understanding for the wider wound ballistic research community. Several variables from this thesis will be discussed separately below, but should be considered together.

9.1.1 Clothing

With a baseline for testing UK military clothing provided by the work in chapters 3, 5 and 6, the next step would be to test different permutations of the clothing layers used, and to introduce different clothing layers as worn by other aspects of the UK military, such as RNPCS. Comparison to military clothing worn by different nations' militaries would also be of value, and also comparison to clothing worn by civil authorities, such as the police, ambulance service and fire service, whom may be at risk of ballistic injury in the advent of a terrorist attack.

9.1.2 Ammunition

It should be considered to vary the ammunition types used for testing. Other ammunition types for military firearms are relevant due to ongoing conflicts worldwide [1], but should also reflect those available within civilian settings, such as for weapons systems used by police or by criminal elements.

9.1.3 Engagement distance

Whilst this work tested targets at 10 m from the end of the gun barrel, it can be acknowledged that the heterogeneity of combat means that GSW will likely be sustained from varying distances even in a single engagement. As such, these distances should be altered to reflect battlefield conditions or the conditions that may be encountered by those at risk of sustaining GSW.

9.2 Future model development

The idea of future model development falls into two categories: building upon these existing models, or developing entirely new models

9.2.1 Building upon existing models

The use of gelatine as a synthetic medium to represent extremity soft tissues for wound ballistics research has a proven track record [2-7]. This could be further developed to model other anatomical configurations, such as two limbs side by side, i.e. a double-limb strike. This would further build an understanding of wound profiling for all possible eventualities following extremity GSW. Adding synthetic bone or neurovascular components, as well as skin, subcutaneous and fascial tissue surrogates may all also provide greater biofidelity towards honing this model and negating the need for cadaveric or live tissue modelling in the future.

The same could be considered for the deer limb model with respect to the double limb strike, or to try projectile strikes using other regions of the existing cadaveric anatomy for further study.

9.2.2 New model development

The final aspect of future work would be to consider entirely new models. To date, a valid computer model for penetrating wound ballistic trauma does not exist within the available literature and would undoubtedly be of benefit. However the development of computer modelling in something with so many variables would be both expensive and complex.

There are other synthetic limb models in existence which have been developed for different purposes [8-10], however the development of a cheap, biofidelic, synthetic extremity model for ballistic testing would be advantageous.

One key feature which could not be explored within the work of this PhD was the ability to examine the zone of injury following GSW in live tissue for viability study. Whilst the use of live tissue study is expensive and requires appropriate ethical considerations, the value of applying the testing conditions from this work with clothing layers to a live tissue model would be substantial when addressing research into the surgical requirements towards treating these wounds.

9.3 Future work summary

Future work should look to build upon understanding of extremity GSW patterns using existing models by altering individual variables such as clothing, ammunition type and engagement distance, and develop new models to test knowledge gained from this PhD further, such as biofidelic synthetic models, computer modelling and live tissue study.

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APPENDICES

Appendix A – CURES approval

CURES Submission: Approved

REPLY REPLY ALL FORWARD

donotreply@infonetica.net
Tue 17/10/2017 12:37

Mark as unread

To: Stevenson, Tom;
Cc: Carr, Debra;

Dear Tom

Reference: CURES/3579/2017
Title: Ballistic extremity wounding: Quantifying tissue damage associated with military firearms

Your proposed research activity has been reviewed by CURES and you can now proceed with the research activities you have sought approval for.

Please remember that CURES occasionally conducts audits of projects. We may therefore contact you during or following execution of your fieldwork. Guidance on good practice is available on the research ethics intranet pages.

If you have any queries, please contact cures-support@cranfield.ac.uk

We wish you every success with your project.

Regards

CURES Team

May we remind you of the importance of addressing health and safety issues in your research. Templates and further guidance are available here.

Figure A.1 CURES approval for experimental work

CURES Submission: Approved

DELETE REPLY REPLY ALL FORWARD ...

donotreply@infonetica.net

Mon 24/10/2016 14:20

Mark as unread

To: Stevenson, Tom;

Cc: Carr, Debra;

Dear Tom

Reference: CURES/2076/2016
Title: Joint Theatre Trauma Registry Search

Your proposed research activity has been reviewed by CURES and you can now proceed with the research activities you have sought approval for.

Please remember that CURES occasionally conducts audits of projects. We may therefore contact you during or following execution of your fieldwork. Guidance on good practice is available on the research ethics intranet pages.

If you have any queries, please contact cures-support@cranfield.ac.uk

We wish you every success with your project.

Regards

CURES Team

May we remind you of the importance of addressing health and safety issues in your research. Templates and further guidance are available here.

Figure A.2 CURES approval for JTTR search

Appendix B – JTTR analysis data

B.1 Injury locations and numbers

Table B.1 Injury locations by number of casualties

Injury Location	Total no. of casualties (%Total)	Survivors (%) (%T)	Fatalities (%) (%T)
Abdomen	49 (6.8)	35 (6.42) (4.8)	14 (7.9) (1.93)
External	1 (0.1)	1 (0.18) (0.14)	0 (0) (0)
Face	26 (3.6)	25 (4.58) (3.5)	1 (0.14) (0.56)
Head	115 (15.9)	30 (5.5) (4)	85 (48.0) (11.8)
Lower Extremity	237 (32.8)	235 (43.04) (32.5)	2 (1.12) (0.28)
Neck	23 (3.2)	10 (1.83) (1.4)	13 (7.3) (1.8)
Other Trauma	3 (0.4)	0 (0) (0)	3 (1.69) (0.41)
Spine	18 (2.5)	11 (2.01) (1.52)	7 (3.95) (0.97)
Thorax	106 (14.7)	58 (10.62) (8.0)	48 (27.1) (6.6)
Upper Extremity	142 (19.6)	141 (25.82) (19.5)	1 (0.56) (0.14)
Uncoded	3 (0.4)	0 (0) (0)	3 (1.69)
Total Extremities	379 (52.4)	376 (69.0) (52.0)	3 (1.69) (0.41)

Table B.2 Isolated versus multiple injury locations by survivor casualties only

Injury Location	Multiple GSW by region	Isolated GSW by region
Abdomen	24	10
External	1	1
Face	18	6
Head	78	16
Lower Extremity	210	118
Neck	12	5
Other Trauma	2	1
Spine	2	1
Thorax	72	14
Upper Extremity	120	117
Uncoded	-	-
Total Extremities	330	185

185 casualties have isolated extremity wound (26% of total casualties; 34% of total survivors) 330 casualties have multiple injuries but only to extremities (46% of total casualties; 60% of total survivors)

Table B.3 Injury locations by number of injuries

Injury Location	Number of injuries	Percentage of injury total
Abdomen	292	10.3
External	18	0.6
Face	184	6.5
Head	506	17.9
Lower Extremity	540	19.2
Neck	140	5.0
Other Trauma	10	0.3
Spine	157	5.6
Thorax	612	21.6
Upper Extremity	368	13.0
Total Extremities	908	32.1

B.2 Gunshot wound casualty classifications

Table B.4 Gunshot wound casualty classifications

Classification	**Iraq**	**Afghanistan**	**Total**
Total	120	603	723
Died	**49**	**128**	**177**
Survived	**71**	**475**	**546**
Killed by enemy (KIA and DOW)	39	122	161
Died of Wounds only (all from enemy action)	11	13	24
Wounded by enemy (WIA)	56	428	484
Killed non-enemy action (KNEA)	10	6	16
Wounded non-enemy action (WNEA)	15	47	62
Killed by Negligent Discharge (ND)	6	3	9
Wounded by ND	12	40	52
Killed by accident	4	3	7
Wounded by accident	3	7	10
Total non-enemy action killed and wounded	25	53	78

Appendix C – Gelatine block preparation

Gelatine block preparation and calibration is summarised in chapter 3 [1]. This appendix provides a standardised complete method required to manufacture 32 kg 10% by mass gelatine blocks measuring 250 (w) x 250 (h) x 500 (l) mm.

C.1 Manufacturing process

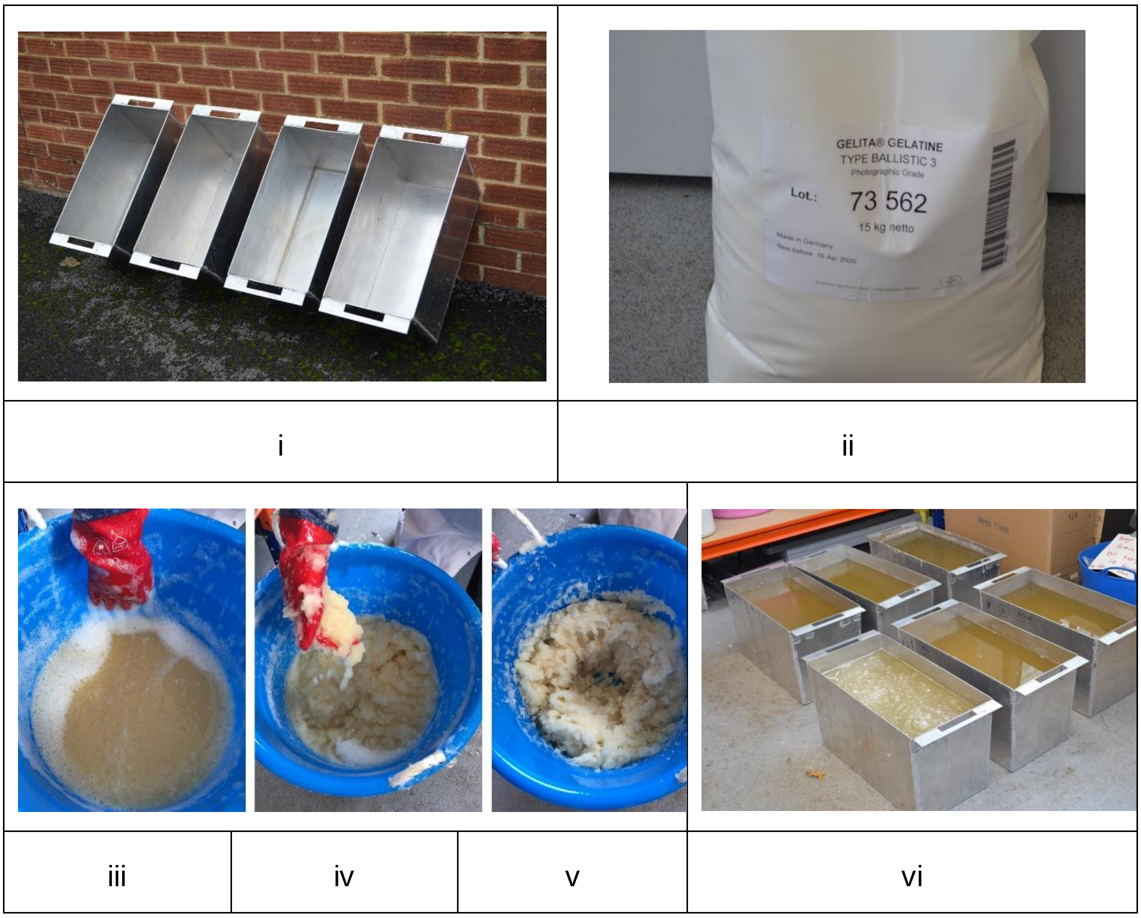


Figure C.1 Gelatine block manufacturing process

Spray all moulding tins with mould release spray and allow to dry (i).

Weigh out 9.6kg cold water (<20 degrees) and add to mixing bucket.

Weigh out 3.2kg batch controlled gelatine powder (ii) and add half to mixing bucket

Stir the mixture, then add remaining half of cold water; aim to get the consistency of “cous-cous” whilst stirring and ensure large clumps are broken up by hand (iii), then when consistency becomes more like “mashed potato” (iv), create a hole in the centre (v).

Weigh out 9.6kg hot water (aim for around 62-65 degrees) and add to mixing bucket by pouring into the hole made above (keep stirring and break up any clumps by hand).

Weigh out final 9.6kg hot water (same as above) then add to mixing bucket whilst stirring.

Decant approximately half the gelatine mix into a mould, then stir the mixing bucket once more by hand, and add remaining contents to the mould.

Add 10 drops of cinnamon oil to clear the froth and air bubbles from within the mix and stir thoroughly to prevent the oil sinking to the bottom.

Repeat for as many blocks as desired – skim frothy top layer off if required and allow to set (vi).

Once set, condition at 4 ^{o}C for 24 hours.

C.2 Calibration process

	
i	ii

Figure C.2 Gelatine block calibration process

Calibration technique is similar to that conducted within other work [2-4].

5.5 mm steel ball-bearings (BB) loaded into sabots and cases with propellant added.

BB fired into gelatine block (i). BB visible within dotted white circle, having entered from left side of the image.

Depth of penetration (DoP) measured (ii) and compared with calibration data from previous work from the same institution (Chapter 3, Figure 3.5)

C.3 References

1. Stevenson T, Carr DJ, Stapley SA (2018) The effect of military clothing on gunshot wounds in gelatine. Int J Leg Med:1-11. doi:doi.org/10.1007/s00414-018-1972-8

2. Jussila J (2004) Preparing ballistic gelatine--review and proposal for a standard method. Forensic science international 141 (2-3):91-98. doi:10.1016/j.forsciint.2003.11.036

3. Mabbott A (2015) The overmatching of UK Police body armour. Cranfield University,

4. Mahoney PF (2018) Development of a synthetic bone and tissue model to simulate overmatch military ballistic head injury. Cranfield University

Appendix D – Projectile microhardness analysis

Microhardness analysis was conducted to characterise ammunition physical properties and ensure reproducible quality was found within the respective batches of 7.62 x 39 mm and 5.45 x 39 mm ammunition used throughout this PhD.

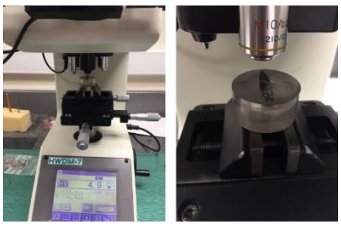
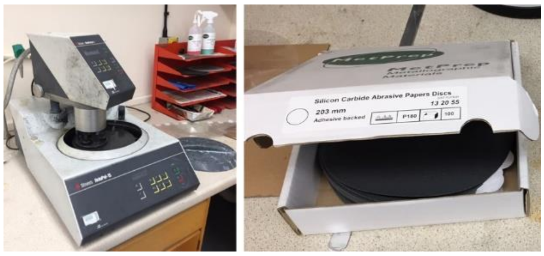
	
i 7.62 mm (*left*) 5.45 mm (*right*)	ii
	
iv	iii

Figure D.1 Microhardness analysis, clockwise from top left

Sample projectiles were “pulled” from their cartridge cases (i), mounted within an epoxy resin (ii) and sectioned and polished using a Struers Rotopol 15 to polish the sample projectiles (iii), and an Indentec Highwood microscope with diamond tipped load point to measure hardness (iv), as summarised in chapter 3.

Sample test points were taken as shown in Figure D.2.

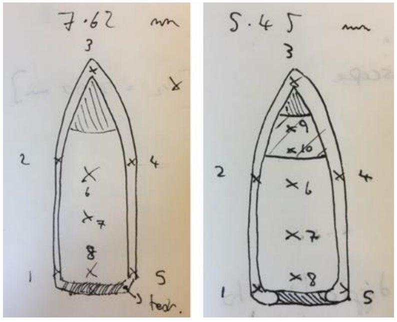
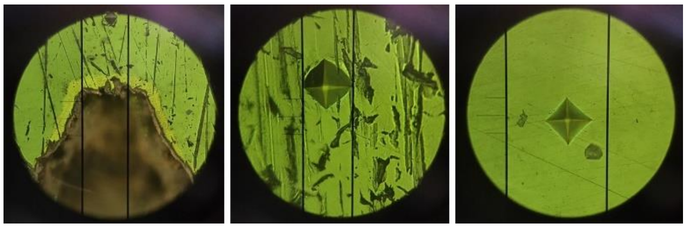
	
Testing schematic	Microscopic images of testing

Figure D.2 Sample testing schematic with example images

D.1 – Microhardness results: 7.62 mm projectiles

Table D.1 7.62 mm jacket microhardness analysis

		1	**2**	**3**
Area	**test point**	**Hardness (Hv)**		
jacket	1	178.8	179.6	174.4
	2	177.6	186.2	180.8
	3	186.0	204.4	198.7
	4	193.6	172.1	198.1
	5	184.4	179.6	174.2
	Mean	184.1	184.4	185.2
	SD	6.4	12.3	12.3
	CV	3.5	6.6	6.6

Table D.2 7.62 mm core microhardness analysis

		1	**2**	**3**
area	**test point**	**Hardness (Hv)**		
core	6	6.7	8.4	8.7
	7	7.5	7.5	5.9
	8	6.8	7.4	7.6
	Mean	7.0	7.8	7.4
	SD	0.4	0.6	1.4
	CV	6.2	7.1	19.1

D.2 – Microhardness results: 5.45 mm projectiles

Table D.3 5.45 mm jacket microhardness analysis

		1	2	3
area	**test point**	**Hardness (Hv)**		
jacket	1	186.0	186.5	176.1
	2	209.6	208.7	202.3
	3	203.5	183.6	156.9
	4	186.0	198.1	200.2
	5	175.9	167.0	192.5
	Mean	192.2	188.8	185.6
	SD	13.9	15.7	19.1
	CV	7.2	8.3	10.3

Table D.4 5.45 mm core microhardness analysis

		1	2	3
area	**test point**	**Hardness (Hv)**		
core	6	828.6	816.4	800.8
	7	848.8	799.7	809.2
	8	827.4	828.6	828.6
	Mean	834.9	814.9	812.9
	SD	12.0	14.5	14.3
	CV	1.4	1.8	1.8

Table D.5 5.45 mm tip microhardness analysis

		1	2	3
area	**test point**	**Hardness (Hv)**		
tip	9	4.9	2.7	4.6
	10	5.9	4.5	4.9
	Mean	5.4	3.6	4.8
	SD	0.7	1.3	0.2
	CV	13.1	35.4	4.5

Appendix E – Projectile elemental analysis

In order to ensure the elemental composition was consistent for both ammunition types used throughout this PhD, the projectiles taken for microhardness in appendix F were then analysed using a Hitachi SU3500 scanning electron microscope (SEM) with EDAX analysis and TEAM software, as summarised in chapter 3.

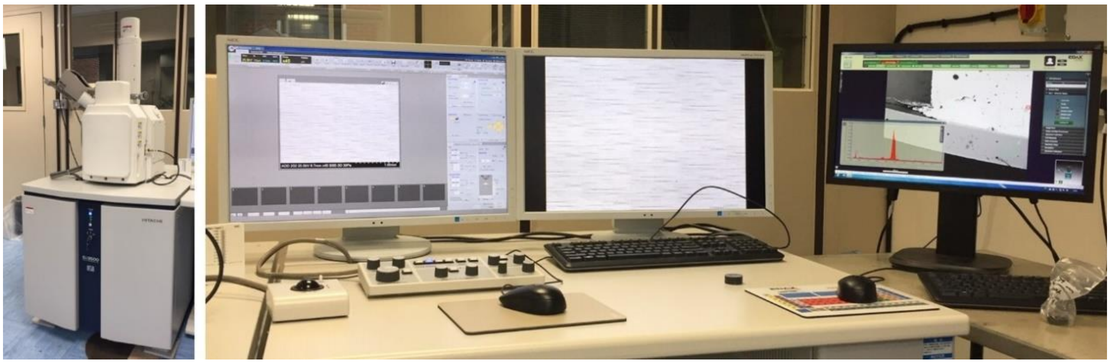


Figure E.1 SEM use for projectile elemental analysis

E.1 – Elemental analysis results: 7.62 mm projectiles

E.1.1 Projectile core

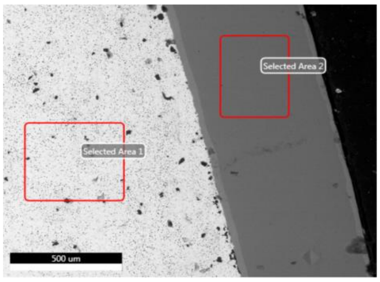
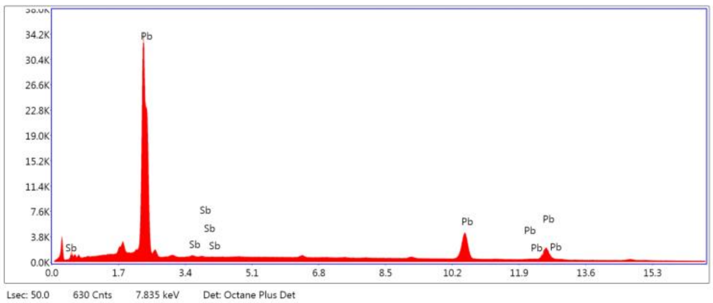
	
Selected area: Area 1 (*left*)	X-ray spectrum

Figure E.2 Elemental analysis: 7.62mm core, Area 1, 500µm

E.1.2 Projectile jacket

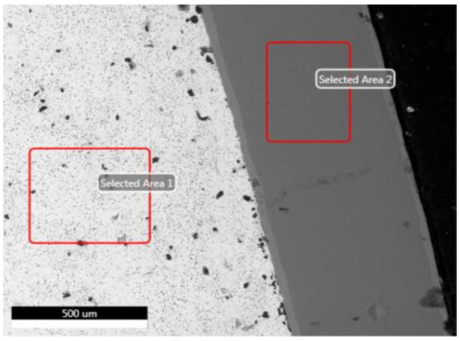
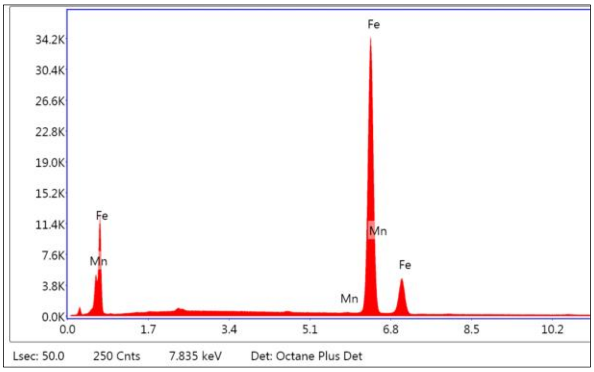
	
Selected area: Area 2 (*right*)	X-ray spectrum

Figure E.3 Elemental analysis: 7.62mm jacket, Area 2, 500µm

E.1.3 Projectile jacket coating

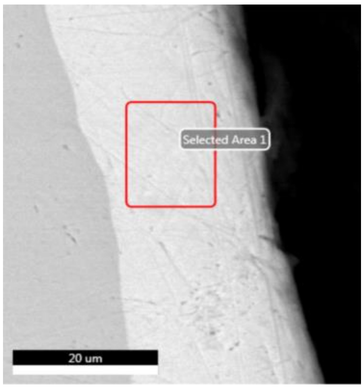
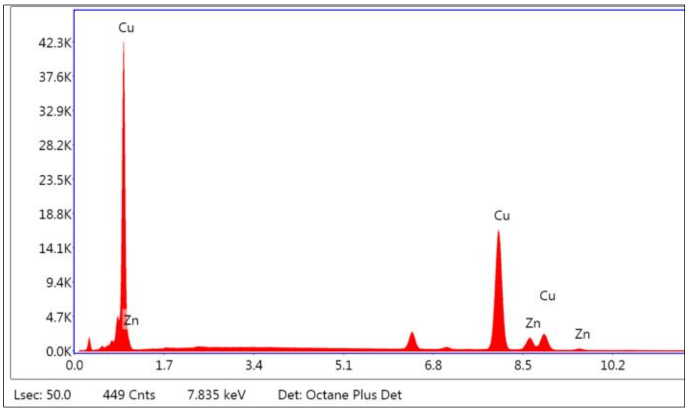
	
Selected area: Area 1	X-ray spectrum

Figure E.4 Elemental analysis: 7.62mm jacket coating, Area 1, 20µm

E.2 – Elemental analysis results: 5.45 mm projectiles

E.2.1 Projectile main core

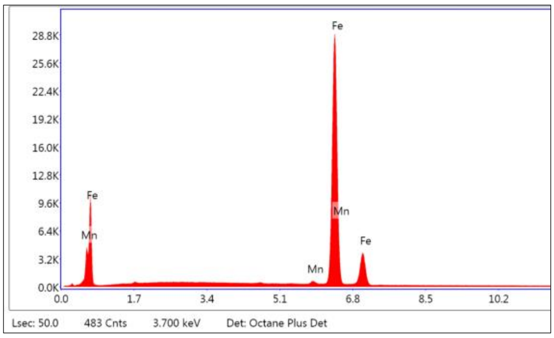
<table>
<tr><td>
</td><td>
</td></tr>
<tr><td>Selected area: Area 1</td><td>X-ray spectrum</td></tr>
</table>

Figure E.5 Elemental analysis: 5.45mm main core, Area 1, 500µm

E.2.2 Projectile core tip

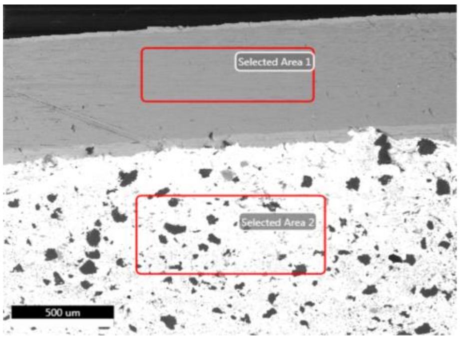
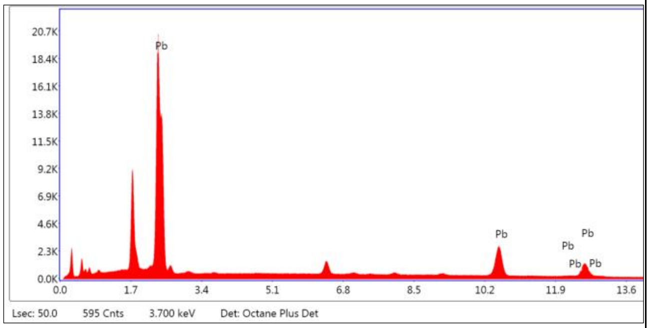
<table>
<tr><td>
</td><td>
</td></tr>
<tr><td>Selected area: Area 2 (bottom)</td><td>X-ray spectrum</td></tr>
</table>

Figure E.6 Elemental analysis: 5.45mm core tip, Area 2, 500µm

E.2.3 Projectile jacket

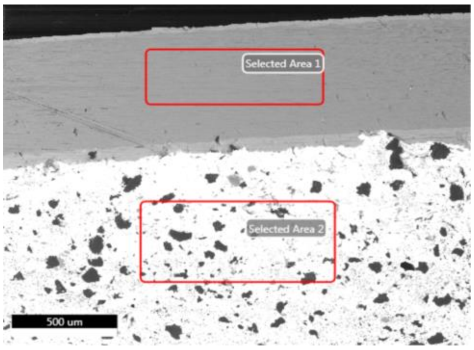
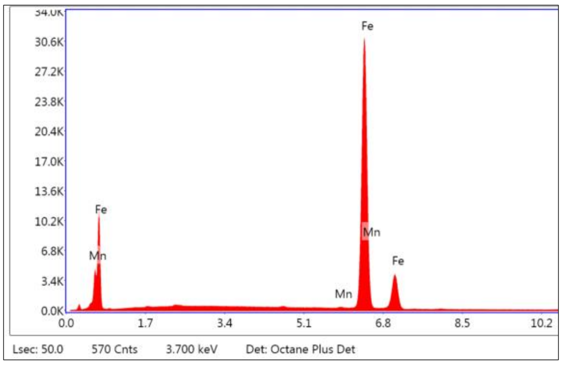
	
Selected area: Area 1 (*top*)	X-ray spectrum

Figure E.7 Elemental analysis: 5.45mm jacket, Area 1, 500µm

E.2.4 Projectile jacket coating

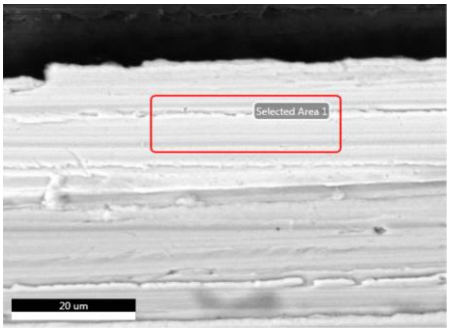
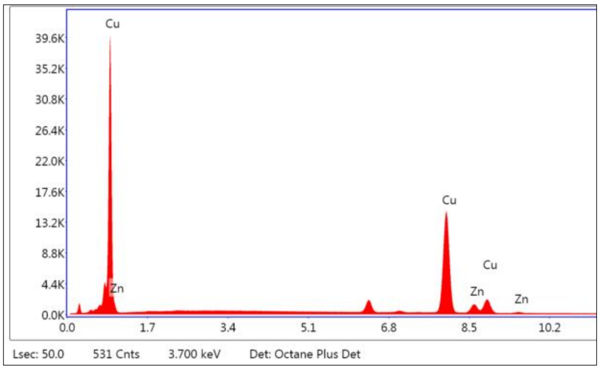
	
Selected area: Area 1	X-ray spectrum

Figure E.8 Elemental analysis: 5.45mm jacket coating, Area 1, 20µm

Appendix F – Fabric analysis

Fabric analysis was undertaken in order to ensure the clothing types used throughout these experiments were consistent for use throughout this PhD. This process is summarised in chapter 3 and required individual clothing samples from each layer as used in the clothing states C_{min} and C_{max} during experiments.

i

ii

iii

Figure F.1 Fabric layers for all clothing states

Fabric samples for MTP trousers (used in C_{min}) were cut to measure 250 x 250 mm (i). Fabric samples for C_{max} layers, i.e. the t-shirt (ii – bottom right), UBACS (ii – middle top) and smock (ii – top right) were cut in relation to the upper sleeve pocket size on the UBACS and Smocks, measuring 200 x 150 mm. The arm brassard samples (ii – far left) were checked for presence of the filler (iii).

Mass per unit area and thickness of the samples were measured, using Oxford A2204 scales to measure mass and a Mitutoyo C1012MB thickness gauge to measure thickness of the MTP trouser samples, and the individual samples of the t-shirt, UBACS and Smock. The arm brassard alone and then all combined layers for C_{max} were measured using Mettler PE16 scales for mass and a Shirley Thickness Gauge (Shirley Developments Ltd., 87137) for thickness.

Table F.1 MTP trousers analysis

Trouser Samples	Mass per unit area g/m2	Thickness mm
1	191	0.42
2	191	0.46
3	191	0.42
4	189	0.43
5	194	0.44
SD	2	0.017
Mean	191	0.43

Table F.2 T-shirt analysis

T-shirt Samples	Mass per unit area g/m2	Thickness mm
1	176	0.52
2	179	0.54
3	181	0.54
4	180	0.54
5	178	0.53
SD	2	0.0089
Mean	179	0.53

Table F.3 UBACS analysis

UBACS Samples	Mass per unit area g/m2	Thickness mm
1	1303	1.38
2	1368	1.49
3	1362	1.25
4	1333	1.15
5	1326	1.21
SD	27	0.14
Mean	1338	1.30

Table F.4 Smock analysis

Smock Samples	Mass per unit area g/m2	Thickness mm
1	1426	6.41
2	1384	7.58
3	1363	6.3
4	1335	5.71
5	1495	6.29
SD	62	0.68
Mean	1401	6.46

Table F.5 Brassard analysis

Brassard Samples	Mass per unit area g/m2	Thickness mm
1	4867	11.61
2	4796	11.96
3	4867	11.59
4	4742	11.65
5	4813	11.37
SD	53	0.21
Mean	4817	11.64

Table F.6 Combined clothing analysis

Combined C_{max} Samples	Mass per unit area g/m2	Thickness mm
1	7772	31.2
2	7727	31.5
3	7773	32.2
4	7591	32.8
5	7813	33.6
SD	86	0.97
Mean	7735	32.26

Appendix G – Experimental shooting raw data

Raw data from all experiments as details from chapters 3-6 are included below. Mean, SD and CV data are all presented within the relevant chapters and are not duplicated here.

Table G.1 Gelatine block shoot raw data (for chapter 3)

Block number	Projectile used	Clothing state	NL (mm)	D1 (mm)	H1 (mm)	D2 (mm)	H2 (mm)	Calibration BB velocity (m/s)	BB DoP (mm)	Projectile impact velocity (m/s)	Block temperature post shoot (ºC)
1	7.62 x 39 mm	Nil	95	237	188	255	86	747	381	655	6.6
2	7.62 x 39 mm	Nil	36	162	163	151	120	737	359	642	6.6
3	7.62 x 39 mm	Nil	50	172	166	170	115	744	356	655	4.3
4	7.62 x 39 mm	Nil	140	230	223	282	155	764	356	648	4.4
5	7.62 x 39 mm	Nil	82	188	189	172	162	702	352	651	7.4
6	7.62 x 39 mm	Nil	32	183	179	168	158	726	356	652	6.5
1	7.62 x 39 mm	Min	83	210	179	213	97	750	364	643	7.6
2	7.62 x 39 mm	Min	49	159	200	175	157	723	345	650	4.2
3	7.62 x 39 mm	Min	187	311	213	297	100	696	366	668	8.8
4	7.62 x 39 mm	Min	42	146	181	119	145	731	357	640	7.8
5	7.62 x 39 mm	Min	26	146	200	107	166	722	348	643	4.4
6	7.62 x 39 mm	Min	60	174	184	157	134	726	362	657	7.8
1	7.62 x 39 mm	Max	34	174	236	137	139	759	380	644	7.8
2	7.62 x 39 mm	Max	61	201	233	195	125	747	380	639	8.7
3	7.62 x 39 mm	Max	5	119	176	116	107	749	378	636	8.5
4	7.62 x 39 mm	Max	30	151	222	97	129	720	372	644	7.7

Block number	Projectile used	Clothing state	NL (mm)	D1 (mm)	H1 (mm)	D2 (mm)	H2 (mm)	Calibration BB velocity (m/s)	BB DoP (mm)	Projectile impact velocity (m/s)	Block temperature post shoot (ºC)
5	7.62 x 39 mm	Max	28	146	181	104	136	754	368	641	5.3
6	7.62 x 39 mm	Max	0	128	181	164	95	774	372	648	5.2
1	5.45 x 39 mm	Nil	66	165	177	152	130	668	349	871	7.7
2	5.45 x 39 mm	Nil	46	146	213	125	135	696	355	888	9
3	5.45 x 39 mm	Nil	70	182	206	154	108	747	371	877	8.8
4	5.45 x 39 mm	Nil	118	224	230	200	134	n/a	n/a	878	7.4
5	5.45 x 39 mm	Nil	52	169	212	152	174	714	346	914	5
6	5.45 x 39 mm	Nil	31	148	227	106	140	721	357	870	4.9
1	5.45 x 39 mm	Min	19	135	205	109	135	680	354	874	7.7
2	5.45 x 39 mm	Min	58	175	190	158	125	717	356	864	6.8
3	5.45 x 39 mm	Min	37	168	182	121	120	706	362	883	7.8
4	5.45 x 39 mm	Min	36	151	204	120	138	696	354	879	8.7
5	5.45 x 39 mm	Min	58	203	173	210	135	714	343	871	4
6	5.45 x 39 mm	Min	35	159	203	121	148	698	344	872	5.6
1	5.45 x 39 mm	Max	15	127	178	114	135	710	368	887	8.4
2	5.45 x 39 mm	Max	10	119	162	80	112	707	358	880	7.1
3	5.45 x 39 mm	Max	0	99	170	139	135	n/a	370	890	8.4
4	5.45 x 39 mm	Max	13	124	174	86	122	732	365	909	8
5	5.45 x 39 mm	Max	0	112	168	121	130	714	355	882	5.5
6	5.45 x 39 mm	Max	20	114	183	107	135	769	373	908	5.3

Table G.2 Deer limb shoot raw data (for chapter 5)

			NL (mm)		H2 (mm)		D2 (mm)		TT (mm)		Impact velocity (m/s)	E1		E2	
Deer limb number	Projectile	Clothing state	Axial	Coronal	Axial	Coronal	Axial	Coronal	Axial	Coronal		Axial	Coronal	Axial	Coronal
1	7.62x39mm	Nil	48.7	76	28.2	48.8	91.8	82.8	105	108	633	4.5	6.3	10.4	15.1
2	7.62x39mm	Nil	28.5	32.4	10.7	21	80.6	80.9	88.4	86	635	5	5	7.7	8.4
3	7.62x39mm	Nil	26.1	42.8	14.9	16	81.8	75.7	108	109	645	5.2	4.9	4.8	9.4
4	7.62x39mm	Nil	51.9	46.1	15.9	14.8	78.2	81.1	97.1	96.6	647	5.9	6	10.2	12.7
5	7.62x39mm	Min	10.4	54	16.4	14.7	56.3	56	97	97.6	659	4.3	3.4	13.8	11.2
6	7.62x39mm	Min	46.5	41.5	13.7	12	57.9	47.7	85.5	85.2	653	4.7	4.1	11.3	5.7
7	7.62x39mm	Min	27.3	14.4	12	14.3	60.4	34.6	96.8	98.7	647	5.3	5.4	6.3	13.5
8	7.62x39mm	Min	19.3	35.9	17.2	17	45	41.8	93.2	93.6	647	4.1	5.3	11	14.7
9	7.62x39mm	Max	52.5	46.2	22.3	53.5	87.2	79.5	87.2	87.7	650	4.4	5.5	22.3	80
10	7.62x39mm	Max	35.3	18.4	n/a	12	n/a	31.5	n/a	95.8	643	6.5	6.8	14.8	n/a
11	7.62x39mm	Max	33.7	33.6	18.5	19.2	48.2	49.2	91.5	86.2	634	3.4	5.2	8.7	5.6
12	7.62x39mm	Max	36.3	30.6	30.3	30.6	90.5	91.4	90.5	91.4	649	5.2	4.9	12.6	27.9
1	5.45x39mm	Nil	26.9	28.7	24	28.1	54.9	81.3	86.8	88.5	923	4	2.6	23.1	20.4
2	5.45x39mm	Nil	21.7	82.6	19.2	24.9	45	55.1	83.6	82.6	923	3.3	2	11.3	21.5
3	5.45x39mm	Nil	11	24.2	23.3	25.6	42.5	52.3	83.9	81.4	919	4.3	4.6	23.7	22.1
4	5.45x39mm	Nil	35.9	36.7	17.5	27.8	51.1	71	78	75.2	922	3.5	4	4	26.8
5	5.45x39mm	Min	89.8	88.9	6.5	10.3	n/a	88.9	89.8	92.4	888	4.5	4.7	13.6	15.7
6	5.45x39mm	Min	10.3	37.8	15	20.2	22.7	49.2	81.6	82.9	888	2.6	2.3	10.1	20.7
7	5.45x39mm	Min	0	0	22.3	21.2	32.6	29.6	90.6	88.7	859	2.2	2	n/a	n/a
8	5.45x39mm	Min	14.4	16.7	19.8	20.7	35.1	31.9	82.6	83	878	3.1	2.2	8.3	20
9	5.45x39mm	Max	0	0	28.5	23	84.4	81.5	8.4.4	84.4	912	7.3	6.3	30	30.8

			NL (mm)		H2 (mm)		D2 (mm)		TT (mm)		Impact velocity (m/s)	E1		E2	
Deer limb number	Projectile	Clothing state	Axial	Coronal	Axial	Coronal	Axial	Coronal	Axial	Coronal		Axial	Coronal	Axial	Coronal
10	5.45x39mm	Max	49.7	61.6	19.1	28.6	83.6	82	104.5	107.5	904	4.7	4	27.3	28.2
11	5.45x39mm	Max	37.7	59.4	30.7	42.3	48.1	83.4	86.6	83.4	926	5.1	3.1	6.8	16.3
12	5.45x39mm	Max	44.3	44.8	41.8	36.2	77.4	100	102	105	948	4.9	4	16.5	27.1

Table G.3 Deer limb yaw shoot raw data (for chapter 6)

			NL (mm)		H2 (mm)		D2 (mm)		TT (mm)		Impact velocity (m/s)	E1		E2	
Deer limb number	Projectile	Clothing state	Axial	Coronal	Axial	Coronal	Axial	Coronal	Axial	Coronal		Axial	Coronal	Axial	Coronal
1	5.45x39mm	Nil	21.7	30.5	16.9	16.3	70.9	82.7	97.5	96.2	907	4.1	6.5	22.2	34.9
2	5.45x39mm	Nil	54.7	57.1	20	23.4	80.9	78	101	99.8	908	6.1	4.7	15.5	20.3
3	5.45x39mm	Nil	70.8	63.7	19.9	25.3	85.6	89.9	91.4	89.9	911	5.6	2.9	22	29
4	5.45x39mm	Nil	30.4	21.6	12.1	14.2	41.4	36.8	98.9	98.7	911	4.5	4.3	16	20.7
5	5.45x39mm	Min	66.8	64	22.3	21.9	83.9	85.4	87.5	89.1	911	8	12.6	17.4	25
6	5.45x39mm	Min	9.3	9.8	16.5	21.8	35.8	35.4	108	109	910	3.6	2.5	9.3	9.3
7	5.45x39mm	Min	0	0	13.5	18	77.6	84.1	88.9	88.9	910	11.4	11.4	22.7	9.7
8	5.45x39mm	Min	49.6	53.2	14.2	17.6	76.9	87.4	107	115	911	3.6	5.2	13	38
9	5.45x39mm	Max	0	0	28.5	23	84.4	81.5	8.4.4	84.4	912	7.3	6.3	30	30.8
10	5.45x39mm	Max	49.7	61.6	19.1	28.6	83.6	82	104.5	107.5	904	4.7	4	27.3	28.2
11	5.45x39mm	Max	14.2	31.9	11.8	18.8	28.3	46.2	102	100	896	5.6	8.1	13	12.6
12	5.45x39mm	Max	11.1	19	31.3	24.9	53.6	84	102	104	897	14.1	n/a	n/a	16.7

Appendix H – Other academic works

H.1 A NOVEL METHOD FOR IMAGING SOFT TISSUE GUNSHOT WOUNDS IN A CADAVERIC ANIMAL MODEL

Curry C, Stevenson T, Carr DJ, Stapley SA, Gibb IE

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H.1.1 Abstract

Introduction: Computed-Tomography (CT) in examining gunshot wounds (GSW) has previously been utilised for forensic study. Whilst CT is used within the acute clinical setting for GSW, there is currently no available literature examining the use of CT for mapping GSW patterns in ballistic research. This paper aims to present a novel method of imaging soft tissue GSW in a cadaveric limb model with direct percutaneous infiltration of contrast into wound tracks. Methods: Eighteen shaved cadaveric fallow deer hind limbs underwent GSW with 7.62 x 39 mm and 5.45 x 39 mm ammunition. Each limb was shot once by a projectile fired on an indoor range by a number 3 proof housing. Each limb then went on to undergo non-contrast and contrast (using 10-20 mls of omnipaque 300) CT scanning using a dual source Siemens SOMATOM Definition Multi-Slice CT (MSCT) scanner, with 1.0 mm slice soft tissue and bone reconstructions and 3D reconstruction. Multiplanar image reconstruction was created using Syngo CT2012B software. Results: Axial and coronal images in the bone algorithm provided the most useful images, with contrast injection allowing for precise mapping of GSW tracks for further dimensional measurements as required. Conclusion: Using contrast enhanced images and 3D reconstructions, damage representative of the permanent wound track can be visualised along with the trajectory that the projectile takes.

Keywords: Gunshot, Wound, Limb, CT, Contrast

H.1.2 Introduction

The use of Computed Tomography (CT) in scanning gunshot wounds (GSW) has been widely employed in forensic examinations for over 40 years, with the first CT assessment of a head GSW taking place in 1977 [1]. Several publications have since been released extolling the usefulness of these services to the forensic pathologist as a helpful adjunct to post-mortem examination, e.g. [2-9].

To determine what information is required about GSW patterns from imaging techniques such as CT, it is paramount to understand that GSW patterns are hugely variable and that there are many different parameters of damage that can be measured [10]. Damage has previously been measured in different models, both synthetic and organic. Examples of damage measurements include the use of surgical debridement and calculating the mass of debrided tissues [11-13], the use of microscopy and staining to identify tissue damage within the zone of injury from GSW [14,15], measuring the depth of penetration within the targets [16,17], and by calculating dimensions and volumes of the wounding patterns seen [18-21]. The use of CT in ballistic modelling has previously been identified as a valuable research tool warranting further investigation [22,23].

Typically, CT scans have been used to determine such information as the number of GSWs sustained by a patient, the location of the projectiles within tissues (if no exit wound), and the trajectory of the wound track left by the projectile passing through tissue [4]. Importantly, CT scans have proven superior to standard X-rays during post-mortem examinations as they are able to create a true 3D representation of the area under examination, thereby facilitating spatial awareness, rather than being limited to reducing the body to a 2D image, as per the latter [4,24]. Specific examples of GSW studies using CT include articles by Usui [5] and Maiese [6] which extol the benefits of CT in autopsy examinations. Although both articles use small sample sizes to justify their conclusions (3 and 2 cases respectively), they are clear as to the potential benefits of using CT to ascertain relevant information without the need for more traditional, destructive autopsy methods. In particular, both articles detail the usefulness of CT in cases of GSW, and accurately describe how CT can be used to find projectiles embedded within the body and the type of damage seen. Puentes [7] describes a case where, using CT, a GSW was precisely imaged but again, the article refers to a single case. Thali [8] used both CT and Magnetic Resonance Imaging (MRI) to show the extent of GSWs in eight human cadavers, and successfully explains the benefits of both modalities, but accurately highlights the advantages of CT over MRI (for example quicker scan time, less artefact, superior cortical bone injury visualisation) but also acknowledges that MRI excels at soft tissue contrast and is able to best delineate the wound track. With this advent of improved imaging in ballistic injuries described within forensic literature, it can be acknowledged that the use of CT scanning in wound ballistics has also provided a method to identify GSW and their characteristics within the civilian clinical setting [25-28], as well as within the deployed military setting of recent conflicts [29]. Image reconstruction within injured patients is typically described as using IV contrast arteriography to identify vascular injury and identify the wound track by visualisation of damaged tissue in clinical correlation with the trajectory of the projectile (if known), or the presence of air pockets within tissues helping to delineate the presence of the track.

A summary of projectile effects within tissues can be found at [30] and a more comprehensive text on wound ballistics as a complete topic at [31].

The aim of this paper is to present a novel method of imaging soft tissue GSW in a cadaveric limb model to illustrate the benefits of CT imaging with direct percutaneous infiltration of contrast into ballistic wound tracks as a research tool.

H.1.3 Scanning protocol

Study ethical approval was granted was granted through CURES (CURES/3579/2017).

The cadaveric material used in this work was fallow deer (*Dama dama*) hind limbs, where the morphology of a deer femur has previously been shown to be comparable to a human femur [32], and the typical mass of fallow deer limbs is comparable to the mass of human thighs when measured against human anthropometric data [33-35]. Eighteen hind limbs[1] were used, with limb mass ranging between 9.5-13 kg and measuring approximately 280 mm x 700 mm x 100 mm (width x height x thickness). Limbs were used both as fresh targets (within 72 hours of culling) and also stored by freezing and subsequently defrosted over a 72 hour period for use, due to differences in availability of range or CT facilities and the acquisition of limbs. Differences in ballistic effects to fresh versus frozen cadaveric tissue can be considered negligible [36]. Each limb was shaved on the lateral surface and suspended upside down from a metal hook and sustained a single gunshot wound per limb, using batch controlled 7.62 x 39 mm projectiles and 5.45 x 39 mm projectiles. Shots were placed to traverse soft tissues of the posterior muscle compartment of the hind limb, travelling from lateral to medial. These ammunition types were chosen to provide a representation of small arms projectiles used within recent conflicts [21,37,38]. Projectiles were fired from an Enfield number 3 proof housing, with limb targets set at 10 m from the end of the barrel to control projectile flight stability whilst travelling at muzzle velocity. For the purposes of reproducing this protocol, the ammunition type used does not have to be limited to the examples listed above, nor does the tissue model have to be limited to fallow deer limb tissue only.

Following shooting, on arrival at the CT scanning unit, the limbs were individually and completely wrapped in cling-film, with a small opening created over the entrance wound (Figure H.1). Limbs were then orientated such that the exit wound (medial hind limb) was face down and the entrance wound (lateral hind limb) was face up (Figure H.2). The limbs were scanned using a dual source (2 x 64 slice) Siemens SOMATOM Definition Multi-Slice CT scanner (System SOMATOM Definition AS, 64622, Siemens AG, Wittelsbacherplatz, DE – 80333 Munchen, Germany). Each limb was scanned twice, using a standard adult pelvis protocol (exposure figures were 120 kV and 25-32 mAs) with 1.0 mm slice soft tissue and bony reconstructions in the axial, sagittal and coronal planes (Figure H.3). Scanning times for each limb were less than 1 minute per scan. The first

[1] All deer providing limbs were culled for entry into the human food chain, not specifically for this research

scan provided non-contrast images and were viewed best within multi-planar reconstruction (MPR) as part of the Syngo CT2012B software package provided with the CT scanner.

Figure H.1 Cling-film wrapped cadaveric limb material with exposed entrance wound

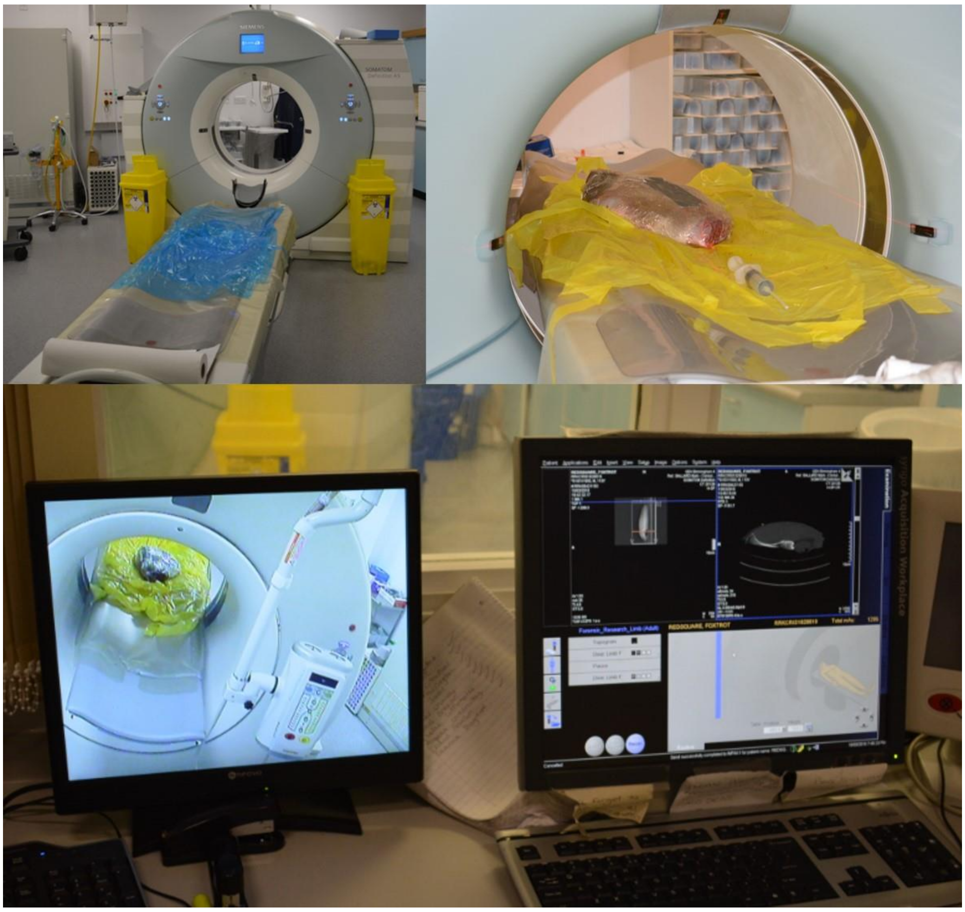

Figure H.2 Clockwise from top left – CT scanner; cling-film wrapped cadaveric limb in position for scanning; scanning room view and image reconstruction within CT control room

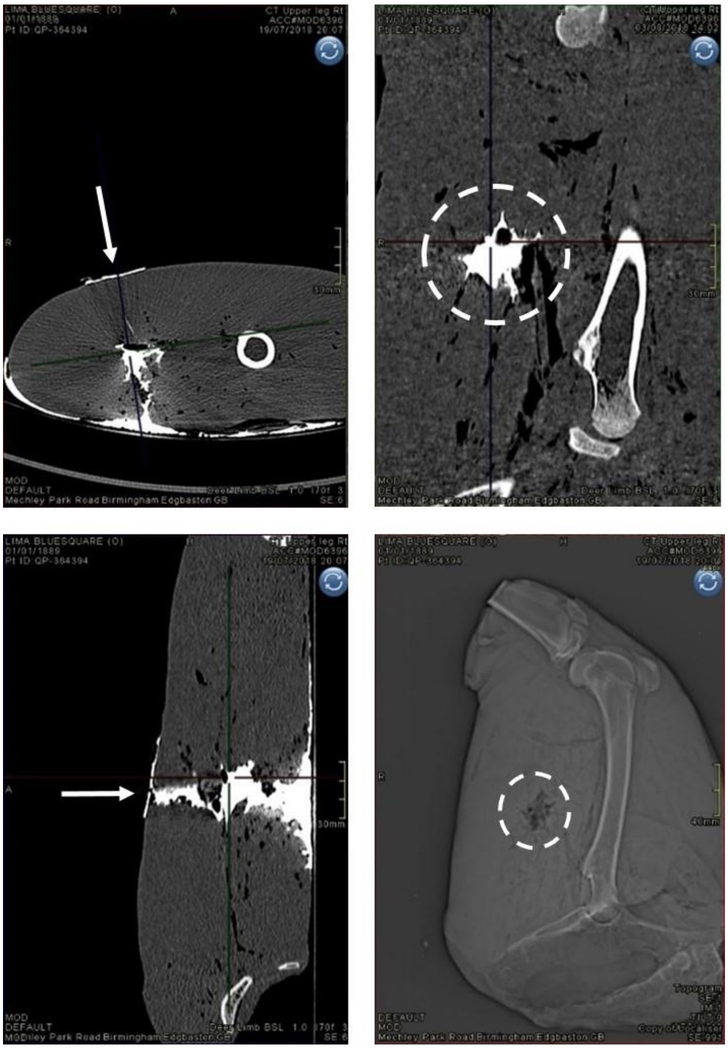

Figure H.3 Arrows indicate projectile direction of travel, dotted circles indicate coronal section view of GSW track – Clockwise from top left – Contrast image, axial plane; contrast image, sagittal plane; X-ray scout view, sagittal plane; contrast image, coronal plane

Prior to the second scan, in order to better delineate the GSW track, approximately 10-20 mls of Omnipaque 300 (OMNI300, GE Healthcare) intravenous contrast media was then introduced into the GSW track by manually injecting whilst simultaneously probing the track with a 5” mixing tube connected to a 50 ml Omnifix Luer Lock Solo syringe (Figure H.4), taking care not to cause any tissue damage. Once the contrast media was seen at the entrance to the GSW the injection was ceased and duct tape used to cover the entrance hole, thereby minimising any leakage of the contrast media. The limbs then each underwent the second scan using the same protocol as before.

Figure H.4 Contrast being injected into GSW track

H.1.4 Imaging

Dimensions of interest for this study for measurement from the permanent cavity within shot limbs were as follows: the neck length (NL) which is the initial narrow wounding channel seen; the maximum height of the permanent cavity (H1); the distance from entry to the maximum height of the permanent cavity (D1); and finally, the total track length (TT).

Following the first scan, the non-contrast limb images could be viewed in the required planes to attempt identify the GSW track (Figure H.5). Following the second scan, the contrast limb images were reconstructed in a bony algorithm and could be viewed in the required planes with the GSW track evident (Figure H.3). The non-contrast images were initially reconstructed in a soft tissue algorithm for subsequent comparison to the contrast images (Figure H.6), but as the study progressed, it was found that the bone algorithm provided clearer images overall and was used preferentially for non-contrast scans as well (Figure H.7).

Figure H.5 Non-contrast images in soft tissue algorithm, arrows indicate projectile direction of travel - Top: axial view; Bottom: coronal view

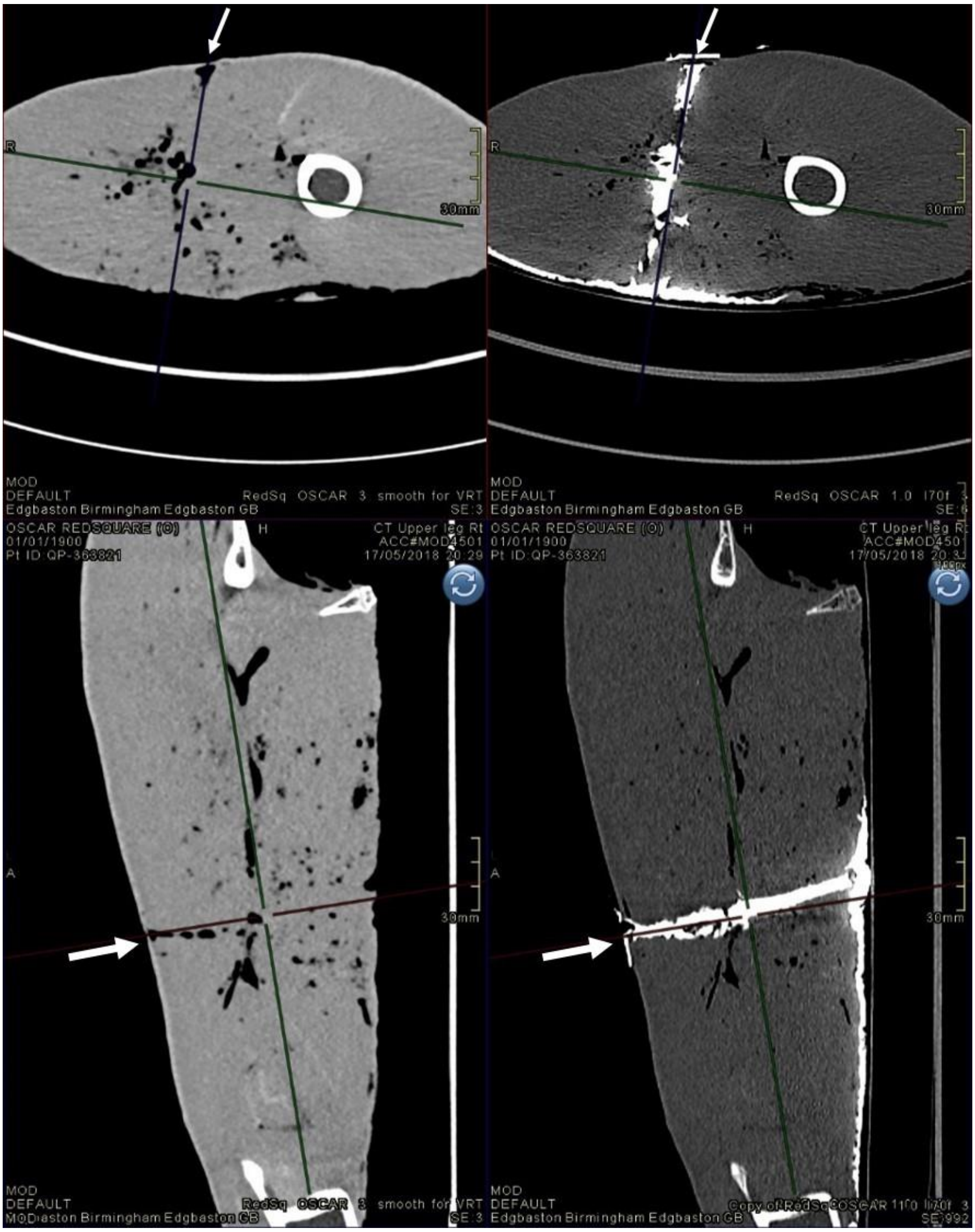

Figure H.6 Arrows indicate projectile direction of travel – Axial and coronal view comparison of non-contrast imaging in soft tissue algorithm (left: top and bottom) with contrast imaging in bone algorithm (right: top and bottom) of the same specimen in the same position, demonstrating the GSW track

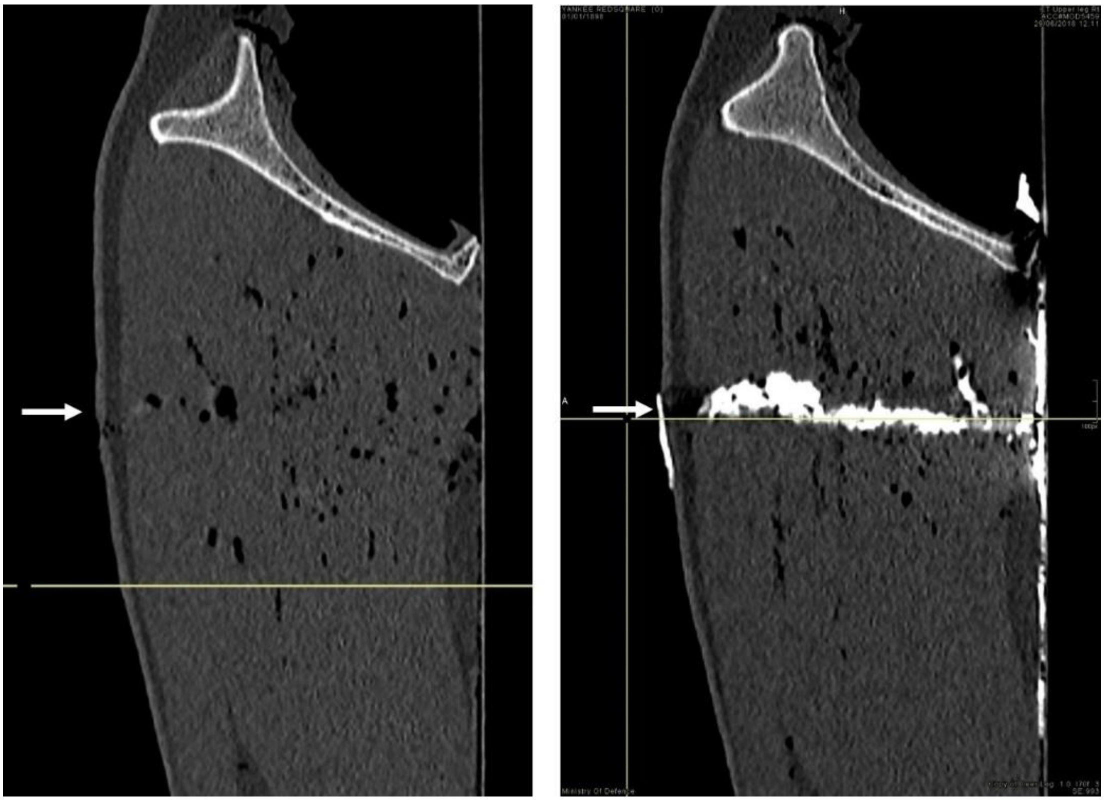

Figure H.7 Arrows indicate projectile direction of travel – Left: non-contrast axial view of specimen in bone algorithm; Right: contrast axial view of same specimen in bone algorithm, highlighting GSW track

Once scanning was complete, further 3D reconstruction from the soft tissue algorithm images using Agfa Healthcare Enterprise Imaging (IMPAX agility), v8.1.1 SP6 software (Septestraat 27 B-2640 Morstel, Belgium) was used to produce images with digital subtraction of soft tissues to demonstrate the contrast-filled GSW track in relation to the femur. This process also allowed the GSW track to be visualised in greater detail by removing much of the artefact and peripheral tissue (Figure H.8).

All 18 limbs were successfully scanned using both plain and contrast enhanced methods. The contrast allowed for the clear representation of the internal damage to the limbs and facilitated measurement of the GSW track dimensions of interest. All measurements were taken in two planes of image viewing, axial and coronal, with the mean, standard deviation (SD) and coefficient of variation (CV) of raw data measurements for each dimension recorded in Table H.1.

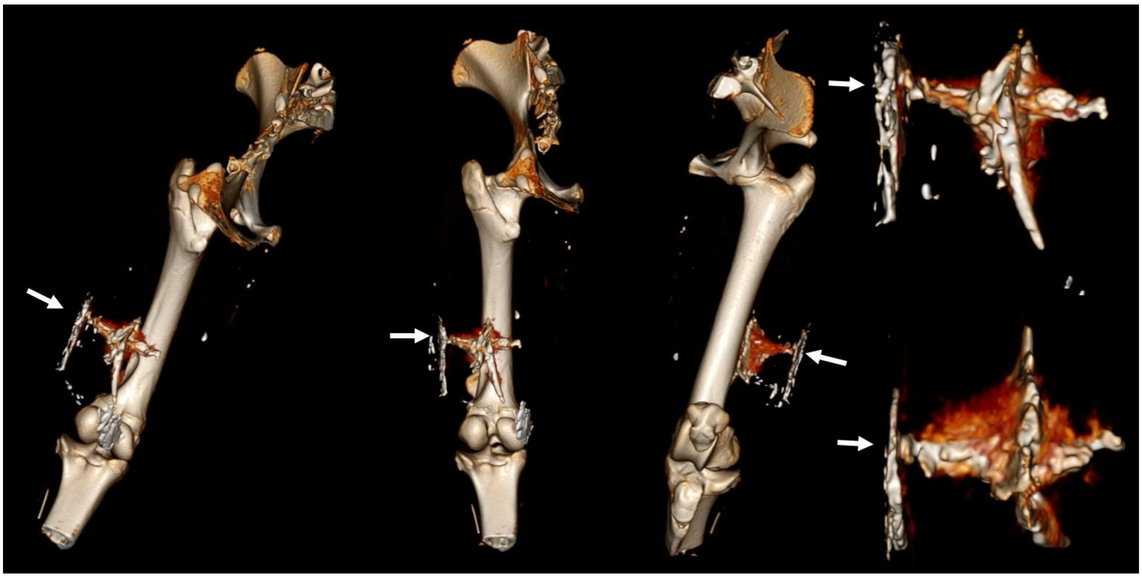

Figure H.8 3D reconstruction of GSW track in relation to femur with digital subtraction of soft tissues, arrows indicate projectile direction of travel – Far left: GSW offset from femur, posterior oblique view; middle left: GSW overlying femur, posterior view; middle: Femur overlying GSW, anterior oblique view; top right: GSW track with all other tissues digitally subtracted, posterior view; bottom right: GSW track, inferior view

H.1.5 Results

The 7.62mm projectiles had a mean velocity of 696 m/s (SD = 49 m/s) at the time of impact, and the 5.45mm projectiles had a mean velocity of 915 m/s (SD = 7 m/s). All 18 limbs were perforated by projectiles. No projectile fragments were found to be retained within any limb scans. Ammunition characteristics are described in other work conducted by part of this research group [21].

Dimensional measurements taken from contrast CT imaging of limbs are collated in Table H.1 below:

Table H.1 Mean, SD and CV for dimensions measured on CT imaging of deer limbs post shooting

		NL			H2			D2			TT		
Projectile	**CT view**	**Mean (mm)**	**SD (mm)**	**CV (%)**	**Mean (mm)**	**SD (mm)**	**CV (%)**	**Mean (mm)**	**SD (mm)**	**CV (%)**	**Mean (mm)**	**SD (mm)**	**CV (%)**
7.62 mm (n = 10)	Axial	33.4	13.6	40.7	16.2	5.9	36.5	71.4	21.0	29.5	95.2	7.3	7.7
	Coronal	42.1	25.6	60.9	26.1	14.3	54.8	64.8	23.0	35.5	96.1	9.1	9.5
5.45 mm (n = 8)	Axial	34.1	19.6	57.3	19.1	3.8	19.7	59.0	17.7	29.9	90.1	8.4	9.3
	Coronal	43.1	22.1	51.1	23.2	5.2	22.3	68.4	18.4	26.9	89.0	8.9	10.0

Larger CVs were noted within the NL, H2 and D2 measurements, as would be expected. Measurements could not be reliably taken from non-contrast images as wound tracks were not consistently visible during image analysis.

H.1.6 Discussion

There is a shortage of literature pertaining to the CT scanning of cadaveric animal parts following GSW. A substantial portion of the literature reviewed related to forensic imaging, particularly with regards to the use of CT scanning for autopsy purposes in the case of human deaths e.g. [2-8]. However, whilst several of these studies describe the use of imaging techniques to visualise the GSW track or to locate projectiles embedded within tissues, none of them specifically detail the characteristics of GSW tracks [7,8]. The clinical cases reported within the examined literature frequently describe the trajectory of wound tracks as well as the clinical structures traversed and injured [25-27]. The development of this method to visualise GSW tracks in cadaveric material following the percutaneous infiltration of contrast medium with CT scanning has provided increased ease in identifying the wound tracks including measuring key dimensions and size and shape.

The current work confirmed that the extent of damage within the permanent cavity caused due to the ballistic injury could be precisely detailed using the described method; in particular it was possible to clearly delineate the wound track in multiple viewing planes and also in 3D. It should be noted that remote injury secondary to the effects of temporary cavitation was not examined in this work, beyond noting the presence of air pockets on images remote to the wound tracks in several limb scans. Non-contrast imaging was extremely challenging in the majority of cases to facilitate precise interpretation as to the dimensions and course of the track until compared with contrast images directly (Figure H.7). The use of contrast and 3D reconstruction allowed for specific characteristics of the wound tracks to be gained, namely NL, H1, D1 and TT, comparable to damage parameters measured within other studies [18-21]. It is essential to understand these wound track characteristics as they are directly relevant to the degree of damage sustained through the transfer of kinetic energy (KE) to the tissues and the effects of temporary cavity formation [30]. This is particularly pertinent with regards to potentially increased internal damage caused by an inherently unstable projectile that may yaw or fragment on passing through different tissue types [10,17]. An initial small entry and / or exit wound in the clinical setting may provide a clinician with a misleading idea of the injury's extent without consideration of these important factors [9,30,31]. Ultimately, the ability to capture precise imaging of a GSW track within a specimen under study gives researchers greater freedom in choosing which parameters of damage they wish to measure, adding substantial versatility to their chosen model plus the capacity to electronically store the images should reassessment ever be required.

Cadaveric tissue modelling in the study generating this work has allowed development of a CT scanning protocol which can be extrapolated into other research models as a reproducible technique to both view GSW patterns and measure the required parameters of damage.

H.1.7 Limitations

As with any novel technique development, there were several limitations encountered that should be considered. Time, cost and availability of a CT scanner may preclude some researchers from being able to benefit from the use of this protocol. Limitations discovered during this protocol specifically included anatomical orientation, contrast penetration within the wound, limb decomposition within images, software handling for reconstructing images. Image distortion was not an issue within this study, however should be considered. Should metallic fragments have been retained within a limb, there would undoubtedly have been some distortion artefact seen within the image reconstruction. Anatomical orientation was best managed macroscopically with an understanding of the rudimentary anatomy of the cadaveric animal limb being used. With consistency on placement of the limb on the scan tray, images could then be easily manipulated to the appropriate plane for analysis. Contrast penetration with the GSW track proved challenging in just one limb, with the initial contrast scan found to have incomplete contrast penetration, and necessitated re-scanning following repeat injection. This was likely due to the tortuous nature of the wound track and was subsequently overcome without difficulty. Several images demonstrated large amounts of free air within the cadaveric material, suggesting that decomposition had accelerated beyond what was expected compared to other limb samples. This can be mitigated with knowledge of the limb material's history through its relevant supplier. Whilst the dimensions of the GSW pattern can be ascertained, a further limitation is that no comment can be passed as to the tissues' viability, as this model was cadaveric. Finally, from a clinician's perspective, the software used to re-create imaging and allow analysis was cumbersome and challenging to use without training. In this instance, several of the authors were familiar with the software, however other researchers may find this to be an obstacle. Another limitation that warrants discussion is that this model examined GSW of the soft tissue only. Even with the level of variable control exercised for this testing, there is still substantial variability seen within GSW characteristics across the different limbs, reflected by the CVs of measurements taken (Table H.1), and represents one of the challenges regularly faced by wound ballistic researchers [10,17]. Bone and neurovascular injuries bring an increasing complexity to ballistic modelling, and where the method in this study has not previously been described, it was felt that it would be more appropriate to begin with modelling that controlled as many variables as possible. This would lead on to the potential for future modelling studies to include testing and examining these other wounding characteristics.

H.1.8 Conclusion

Using CT scanning to identify GSW tracks in cadaveric animal limbs has proven to be an effective method, with precise and reproducible images and measurements gained that clearly demonstrate the degree of tissue damage caused by projectiles as they enter and pass through the limbs. Using contrast enhanced images and 3D reconstructions, damage representative of the permanent wound track can be visualised, along with the trajectory that the projectile takes.

H.1.9 Acknowledgements

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- Sgt David Muchena
- Imaging Department, Queen Elizabeth Hospital Birmingham (QEHB)

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H.2 Other relevant publications

- Chandler H, Macleod K, Penn-Barwell JG, Bennett PM, Fries CA, Kendrew JM, Midwinter M, Bishop J, Rickard RF, Sargeant ID, Porter K, Rowland T, Mountain A, Kay A, Mortiboy D, Stevenson T, Myatt RM (2017) Extremity injuries sustained by the UK military in the Iraq and Afghanistan conflicts: 2003 – 2014. Injury 48(7):1439-43. doi:http://dx.doi.org/10.1016/j.injury.2017.05.022

This paper characterises extremity injuries suffered by UK service personnel from all trauma mechanisms throughout the Iraq and Afghanistan conflicts from 2003-14. Particular focus was on numbers of surgical procedures required, amputation rate, and length of stay in a medical treatment facility.

- Penn-Barwell J, Stevenson T (2017) The effect of projectiles on tissues. In: Breeze J, Penn-Barwell J, Keene D, O'Reilly D, Jeyanathan J, Mahoney P (eds) Ballistic Trauma: A Practical Guide. 4th edn. Springer International Publishing, pp 35-46. doi:10.1007/978-3-319-61364-2_5

This book chapter examines the process of injury caused by projectiles in human tissues. Specific focus is on elements of both projectile properties such as yaw, deformation and fragmentation, and tissue properties such as density (e.g. muscle tissue, bone tissue etc.) that influence the variability of injuries seen by clinicians.

- Carr DJ, Stevenson T, Mahoney P (2018) The use of gelatine in wound ballistics research. Int J Leg Med 132(6):1659-64. doi:10.1007/s00414-0181831-7

This paper provides a commentary on the use of gelatine blocks in wound ballistic studies, discussing areas of importance including the need to calibrate gelatine blocks, important considerations of projectiles to be used, what damage measurements to consider, and what effect intermediate layers such as clothing can have.

H.3 Prizes awarded for PhD work

Epidemiological data from chapter 2 was presented at several forums and won the following prize:

- Best e-poster for “Trauma & Military Surgery” – Association of Surgeons in Great Britain and Ireland Annual Conference, Glasgow, UK, May 2017

Experimental findings of chapter 3 were presented at several forums, earning several accolades as listed below:

- Student award for best poster in “Vulnerability and Survivability” – 30th International Symposium on Ballistics, Long Beach, California, USA, September 2017
- Philip Fulford Prize for “Best Research Presentation” – Combined Services Orthopaedic Society Annual Meeting, Birmingham, UK, May 2018
- Colt Foundation Prize for “Best Research Presentation” – Colt Foundation Meeting, Royal Society of Medicine, London, UK, December 2018