

PREDICTING BLAST INJURY TO THE TORSO

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DECLARATION OF ORIGINALITY

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ABSTRACT

The improvised explosive devices (IEDs) are the most common weapon in the recent terror incidents. Energised fragments from IEDs frequently inflict severe penetrating injuries to the torso organs. The research in this thesis primarily investigated the pattern and mechanism of penetrating injuries to the torso organs and quantified the high risk of the penetrating injuries.

To clarify the pattern of the penetrating injuries, epidemiological studies in terror incidents were reviewed. This analysis suggested that the heart and liver have a very high risk of sustaining severe penetrating injuries. This research, therefore, aimed to quantify the penetrating cardiac and hepatic injuries.

Penetrating cardiac and hepatic injuries were quantified using three representative fragments of IEDs. Cadaveric lamb hearts and bovine livers were chosen as the animal specimens due to their similar material properties to the human. Tests were conducted on fresh and fresh-frozen samples using a gas-gun system in the laboratory. Perforation of the cardiac wall was primarily assessed to develop the injury-risk curves of critical injuries as a function of the striking velocity. For a penetrating hepatic injury, tissue disruption caused by a temporary wound cavity was quantified using MRI scanning so that the injury-risk curves of the liver were developed.

Finally, human tissue surrogates are beneficial for testing in any laboratory setting and so biofidelic tissue surrogates for penetrating cardiac and hepatic injury were determined in this thesis from the different concentrations of ballistic gelatine.

The outcomes in this study can be incorporated into computational models of mass casualty events which inform infrastructure design, mitigation strategies, and emergency response to reduce the risk of severe penetrating injuries.

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ABBREVIATIONS

Abbreviation	Explanation
AIS	Abbreviated injury scale
ANCOVA	Analysis of Covariance
BLI	Blast Lung Injury
CFD	Cross-Fibre Direction
CI	Confidence Interval
CN	Chisel-Nose
CT	Computerised Tomography
DMEM	Dulbecco's Modified Eagle Medium
DoP	Depth of Penetration
EFP	Explosively Formed Penetrator
FBI	Federal Bureau of Investigation
FD	Fibre Direction
fsp	Frames per second
FSP	Fragment Simulating Projectile
H&E	Hematoxylin and Eosin
HBSS	Hanks' Balanced Salt Solution
HC	Hepatic Capsule
HIP	Human Injury Predictor
HP	Hepatic Parenchyma
IED	Improvised Explosive Device
ISS	Injury Severity Score
MRI	Magnetic Resonance Imaging
NATO	North Atlantic Treaty Organisation
NISS	New Injury Severity Score
PBIED	Person-Borne Improvised Explosive Device
PWC	Permanent Wound Cavity
RC	Right-Circular
RSS	Residual sum of squares
RV	Residual Velocity
START	Study of Terrorism and Responses to Terrorism
SV	Striking Velocity
TBI	Traumatic Brain Injury
TD	Tissue Disruption
TNT	Trinitrotoluene
TWC	Temporary Wound Cavity
VBIED	Vehicle-Borne Improvised Explosive Device
VW	Ventricular Wall

CHAPTER 1

INTRODUCTION

This chapter provides a guide to this thesis. The first part of this chapter introduces blast injuries and the benefits of predicting these injuries. The research aims of this thesis are stated to predict blast injuries to the torso. The last part of this chapter describes the structure of this thesis.

1.1 Introduction

Blast injuries are the most common type of physical trauma in bombing attacks. In recent bombings, the detonation of improvised explosive devices (IED) generates energised fragments which, when reaching an individual, may inflict penetrating injuries categorised as secondary blast injuries. Of all body regions, the torso is most susceptible to penetrating injuries due to multiple vital organs residing behind the torso wall. In the torso organs, penetrating cardiac injuries are life-threatening (Campbell *et al.*, 1997) and thus there has been no record of a survivor with this injury upon arrival at medical facilities (Yasin, Nasreen and Malik, 2012). Hepatic penetrating injuries also lead to a relatively high mortality rate compared to other penetrating injuries in the abdominal organs (Turégano-Fuentes *et al.*, 2014).

The quantitative assessment of these severe penetrating injuries plays an important role in developing the prediction of mass casualties in bombing attacks. The outcome of the accurate prediction is essential for improving emergency response, medical services, and the design of large infrastructure to both minimise the number of casualties and improve their treatment alike.

For the prediction of these casualties, penetrating injuries need to be quantified using biological surrogates. Some biological surrogates have similar material properties and anatomical structure to the human and thus the resultant injury can be correlated to that in the human. In ballistic tests, the energy loss of a projectile through animal cadaveric heart and liver has been investigated (Humphrey *et al.*, 2018a, 2018b). There is, however, no study focusing on the quantitative assessment of penetrating cardiac and hepatic injuries.

Human tissue surrogates with wide availability that can be tested in any laboratory settings are of benefit. These human tissue surrogates have advantages over biological surrogates as they are tested without ethical limitations. Widely used tissue surrogates are ballistic ordnance gelatine at 10% and 20% concentration; both ballistic gelatines can replicate muscle tissue (Fackler and Malinowski, 1988; Breeze, Hunt, *et al.*, 2013). There is, however, no research investigating whether the human tissue surrogates can replicate penetrating cardiac and hepatic injuries.

1.2 Aims

The aims of individual studies in this thesis are to:

1. Clarify the occurrence and severity of the torso blast injuries in bombing attacks;
2. Review existing methodologies for quantifying penetrating injuries due to an energised fragment;
3. Quantify penetrating cardiac and hepatic injuries using biological surrogates;
4. Identify biofidelic tissue surrogates for penetrating injuries to the heart and liver.

1.3 Thesis structure

Chapter 1 provided the initial introduction and research aims of this thesis.

Chapter 2 describes the physics of explosions which directly and indirectly causes blast injuries. Based on this nature of explosions, the mechanisms of the blast injury are introduced with their general symptoms and wounds. This overview underpins the classification of the blast mechanisms related to the pattern of blast injuries.

In Chapter 3, the patterns of the blast injury are reviewed from epidemiological studies. This literature review focuses on the injury pattern of each human body and highlights blast injuries to the torso. Due to the high severity of internal torso injuries, this chapter further discusses the risk of penetrating injuries to the torso organs. The latter part of this chapter specifies the mechanisms of penetrating injuries to reveal to what degree these injuries extend across human tissue.

Chapter 4 discusses the methods of quantifying penetrating injuries to the heart and liver, which have a high risk of severe blast injury in the torso. This chapter

reviews the representative fragments in IEDs, existing experimental and computational platforms, and human surrogates to determine the appropriate method in this study.

Chapter 5 presents the quantitative assessment of penetrating cardiac injury from an energetic fragment. A cadaveric lamb heart and a gas-gun system are used to observe the response of cardiac tissue to penetration and quantify the risk of critical penetrating injuries to the heart. The findings show how a severe penetrating injury occurs depending on the striking velocity of a projectile.

Similarly, Chapter 6 explores the quantitative assessment of a penetrating hepatic injury from an energetic fragment. In this experiment, the imaging analyses of the resultant penetrating injury using fresh bovine livers are introduced. The result of each imaging analysis is compared with actual tissue damage. Ultimately, the appropriate imaging analysis is used to quantify a penetrating hepatic injury.

Chapter 7 describes the development of a more biofidelic tissue surrogate for penetrating cardiac and hepatic injuries assessed in the last two chapters. The penetration in various biofidelic tissue surrogates is compared with those in lamb hearts and bovine livers and suitable biofidelic surrogates for the heart and liver are determined.

Chapter 8 summarises this thesis and suggests future works relating to the findings of this thesis. Applications which can be developed with the outcomes of this thesis are introduced. These applications will play an important role in predicting the casualties in bombing terror incidents and reducing the risk of penetrating injuries. Finally, the overall conclusion of this thesis is described.

CHAPTER 2

BLAST INJURY

Chapter 2 reviews the fundamental physics of the blast wave and the mechanism of blast injury based on current classifications. This chapter presents the various explosive devices widely used in terror incidents.

2.1 Nature of bombing

2.1.1 Explosion

Explosion is a process which rapidly releases energy into surrounding media. This phenomenon can be seen from our daily lives to natural events: fireworks, electrical arcs and supernovae. Explosions are generally produced by chemical, electrical, or nuclear reactions. In particular, the chemical reaction of explosive materials is the most common cause of an explosion. The first explosive material, black powder, was originated in China by the 9th century and developed for weapons such as bombs and guns in the 10th century. In order to enhance the performance of black powder, Alfred Nobel invented dynamite in the 19th century. After this invention, trinitrotoluene (TNT) and composition C-4, widely known as high explosive, were developed for safer and more powerful use of explosive materials. Nowadays, these high explosives are mainly employed for military and industry purposes.

The nature of explosion involves delivering thermal and gas expansion in the surrounding atmosphere. The explosive reaction in a high explosive produces combustion with a supersonic shock front, called detonation; the velocity of this shock front reaches 6,850 m/s in TNT (Akhavan, 2004). Apart from normal combustion, the chemical reaction of high explosives is driven by the detonation, increasing the temperature to 3000-4500 K (Keshavarz, 2006). During this period, the resultant energy release forms the sudden rise of pressure, called “blast wave”, which initially propagates above the speed of sound in the air.

2.1.2 Blast wave

A blast wave involves several phases of pressure change in a few milliseconds. The actual waveform of a blast wave is complex as a blast wave reflects off the ground and interacts with incoming blast waves several times. The ideal form of a blast wave is expressed as the “Friedlander waveform” (Figure 2.1); overpressure, P of a blast wave as a function of time, t is written as

$$P(t) = P_s e^{-\frac{t}{t^*}}(1 - \frac{t}{t^*}) \quad \text{Equation 2.1}$$

where P_s is the peak pressure and t^* is the time at which pressure reaches zero after the peak.

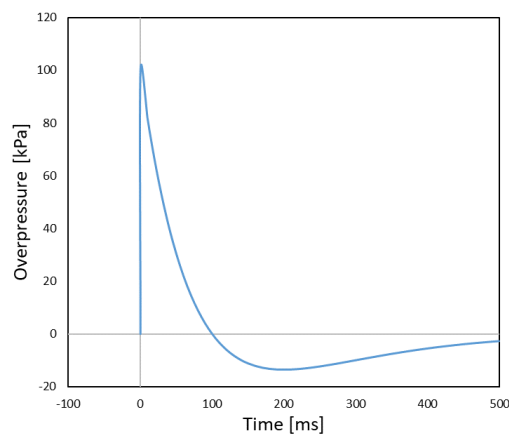


Figure 2.1 A typical Friedlander waveform representing overpressure as a function of time.

The pressure of a blast wave transfers from the positive phase to the negative phase. During the first phase of positive pressure, a discontinuous rise of pressure is known as shock front, due to similar characteristics to a shock wave. The energy of the blast wave is inversely proportional to the cube of propagation distance from the point of source and thus its peak overpressure rapidly decays to the atmospheric pressure. Subsequent to the positive phase, there is a negative pressure phase, which lasts longer than the positive phase. Meanwhile, the blast wave also acts as the energy transfer to an object in the proximity of explosion. This is governed by dynamic pressure, which represents gas movement as $\rho u^2/2$ where ρ is the gas density and u its velocity. Figure 2.2 shows the transition of wind directions due to the dynamic pressure of a blast wave. This dynamic pressure of a blast wave, called blast wind, produces strong and weak wind; both winds are capable of propelling objects forwards and backwards.

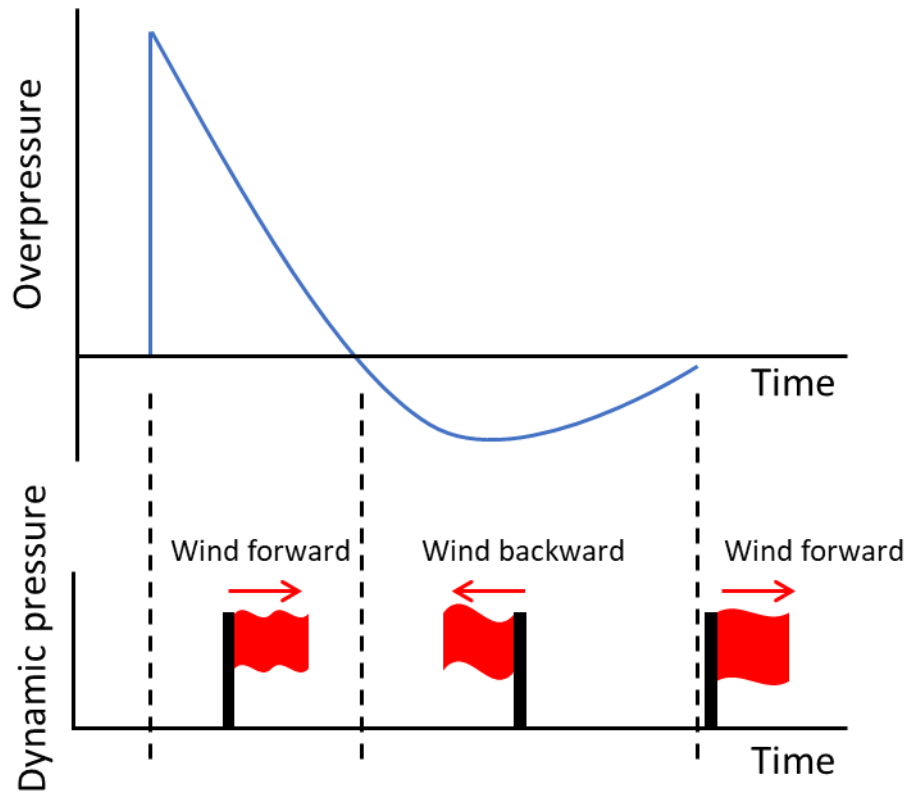


Figure 2.2 Overpressure and dynamic pressure as a function of time.

Another aspect of a blast wave is the transmission and reflection of the shock front against an object. These phenomena on the boundary of an object are governed by the acoustic impedance between two media; the acoustic impedance z is written as

$$z = \rho c \quad \text{Equation 2.2}$$

where ρ is the density of medium and c is its speed of sound in the medium. After an incident wave interacts with the boundary between medium A and medium B (Figure 2.3), it splits into a transmitted and reflected wave.

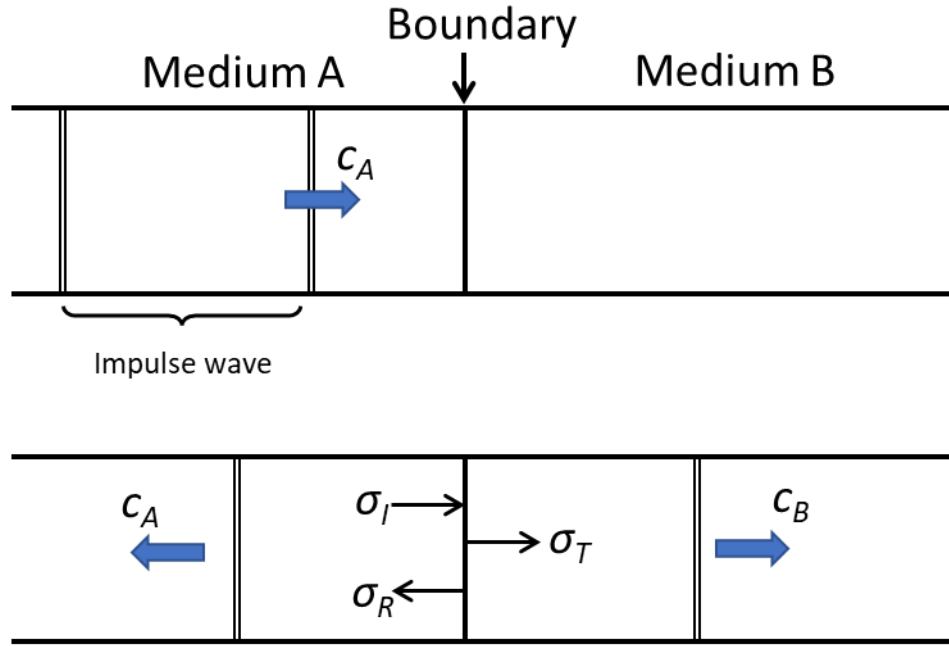


Figure 2.3 Transmission and reflection of shock front at the boundary of different acoustic impedance. Figure adapted with permission from (Meyers, 1994).

Meanwhile, the stress of incident wave σ_I , transmitted wave σ_T and reflected wave σ_R are related with the acoustic impedance in medium A, z_A and medium B, z_B as follows:

$$\frac{\sigma_T}{\sigma_I} = \frac{2 z_B}{z_B + z_A} \text{ and } \frac{\sigma_R}{\sigma_I} = \frac{z_B - z_A}{z_B + z_A} \quad \text{Equation 2.3}$$

If a shock front interacts with a free surface (Young's modulus $E_B = 0$, hence $z_B = 0$), the stress of the resultant and transmitted waves is $\sigma_T = 0$ and $\sigma_R = -\sigma_I$; therefore, the reflected wave becomes a tensile force. In contrast, the interaction of a rigid surface ($E_B = \infty$ and $z_B = \infty$) results in $\sigma_T = 2\sigma_I$ and $\sigma_R = \sigma_I$; the stress of the transmitted wave becomes double that of the incident wave.

2.2 Improvised explosive devices

Improvised explosive devices (IED) have been commonly used in bombing attacks. These attacks primarily target civilians and military personnel using various types of IED such as artillery ammunitions and handmade bombs. IEDs are defined by NATO (NATO Standardization Agency, 2019) as;

” A device placed or fabricated in an improvised manner incorporating destructive, lethal, noxious, pyrotechnic or incendiary chemicals and designed to destroy, incapacitate, harass or distract. Note: It may incorporate military stores, but is normally devised from non-military components.”

The IEDs are often manufactured with a wide range of commercial components, particularly for civilian targets due to the availability of the materials required. Figure 2.4 illustrates the IED of the Boston marathon bombings which comprised commercial components such as metal fragments and a pressure cooker as well as an explosive material.



Figure 2.4 Schematic of the IED used in the Boston marathon bombings. Figure reproduced with permission from (Singh *et al.*, 2016).

Metal fragments, such as nails, bolts and nuts, are frequently packed in IEDs to increase the lethality of the device. When the IED detonates, these fragments and the shattered casing are accelerated by the dynamic pressure of the blast wind; the initial velocity of these fragments may reach 1800 m/s, albeit rapid deacceleration

subsequently occurs due to aerodynamic drag (Bowen, T.E. and Bellamy, 1988). This energy decay of a fragment is inversely proportional to the square of the distance from the epicentre. This is slower than the energy decay of a blast wave, which is inversely proportional to the cubic distance; thus, the energised fragments are capable of retaining their kinetic energy over a longer distance than the blast wave.

Various IEDs are designed to enhance their lethality against vehicle targets, mounted or dismounted human targets. Suicide bombing attacks have consisted of the majority of bombing attacks in Israel and Pakistan (Aharonson-Daniel *et al.*, 2006; Yasin, Nasreen and Malik, 2012). A typical suicide bomb involves a person-borne IED (PBIED), which is a portable IED worn around the human body. Another common suicide bomb is a vehicle-borne IED (VBIED), which is a large IED loaded inside a vehicle. Similarly, these IEDs include steel fragments to inflict maximum harm in mass gatherings. For mounted and dismounted military personnel, artillery ammunitions attached with a detonating system are frequently used in combat fields (Nelson *et al.*, 2008). For vehicle targets in Iraq, explosively formed projectile IEDs (EFP-IEDs), which are explosive devices propelling a hypervelocity metal jet, are predominately utilised (Ramasamy *et al.*, 2008).

2.3 Classifications of blast injuries

The resultant products of a blast wave act as unique injury mechanisms which are rare in normal civilian injuries. The cause of blast-related injuries, namely blast injuries, varies from the direct effects of blast wave, such as the exposure of the human body to blast wave and high temperature gas, to the indirect effects, such as energised fragments and collapsed structures. The mechanisms of blast injury are generally classified into five categories (Horrocks, 2001). The representative mechanisms of these categories are primary, secondary and tertiary blast injuries (Figure 2.5). Primary blast injuries are caused by the direct exposure of the human body to the blast wave. Secondary blast injury is penetrating wounds due to the impacts of energised fragments. Tertiary blast injuries are blunt trauma due to the displacement of the body - caused by the

blast wind – against objects. The following subsections will specify the characteristics and main symptoms of these blast injuries including other mechanisms such as quaternary and quinary blast injury.

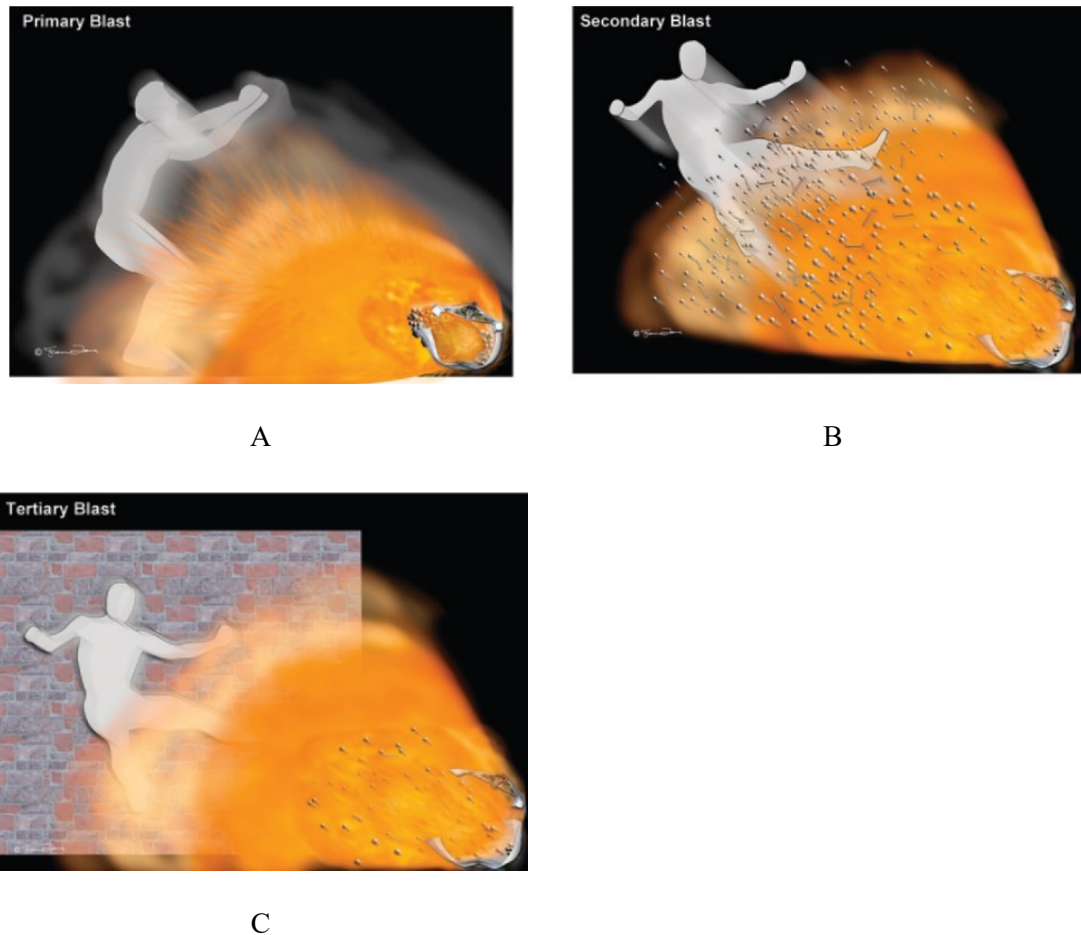


Figure 2.5 (A) The mechanism of primary, (B) secondary and (C) tertiary blast injuries. Figure reproduced with permission from (Singh *et al.*, 2016).

2.3.1 Primary blast injury

Primary blast injuries are caused by the interaction of the blast wave with the body. When the shock front interacts with the body, it transmits and reflects off the body wall based on the acoustic impedance of air and human tissue. The transmitted wave in tissue becomes stress waves which propagate at the speed of sound, splitting

into further transmitted and reflected waves if impacting on a boundary between different acoustic impedances. These stress waves inside the human body have potential for two mechanisms of primary blast injuries: 1) high stress of wave interaction at the boundary of an air-filled organ and 2) high localised pressure produced by the interaction of stress waves with their reflected waves (Cooper and Taylor, 1989).

One of the primary blast injuries is blast lung injury (BLI). BLI is caused by the exposure of the pulmonary tissue to the stress waves through the thoracic wall. Initial body reactions to BLI are related to the respiratory system such as chest pain, cough and signs of hypoxia (Elsayed and Atkins, 2010). It has the risk of parenchymal haemorrhages and the rupture of alveolar capillaries resulting in inflammation and oedema; the area of such tissue may develop to necrosis within 56h of the exposure (Gorbunov *et al.*, 2006). Another injury of the primary blast mechanism is traumatic brain injury (TBI). The cause of TBI is the exposure of brain tissue to blast waves but also reported to be an embolism due to BLI (Rosenfeld *et al.*, 2013). The repetitive exposure to even weak blast waves can cause TBI, widely known as mild TBI. These various severities of TBI result in different symptoms: anxiety, short loss of consciousness or awareness and headache for mild TBI; long loss of consciousness, brain haemorrhage and oedema for moderate and severe TBI (Rosenfeld *et al.*, 2013; Van Gils *et al.*, 2020). Primary blast injury also involves tympanic membrane rupture, which is the most common injury in the primary blast mechanism (DePalma *et al.*, 2005). Tympanic membrane ruptures occur at even low pressure (approximately 35 kPa), resulting in hearing loss and bleeding (Walker, Cervený and Alt, 1989; Horrocks, 2001). The severity of this injury is relatively minor; 49 out of 60 tympanic membrane ruptures can be cured with minor treatment (Kerr and Byrne, 1975).

2.3.2 Secondary blast injury

Secondary blast injuries are caused by the penetration of energised fragments from IEDs and from environmental debris. These fragments are propelled by the blast wind and impact the human body. The energised fragments may cause skeletal fracture or penetrate through soft tissue into the human body and may strike vital organs.

The resultant wounds of the secondary blast mechanism vary between external and internal injuries depending on the depth of penetration (DoP). External penetrating injuries include abrasion, laceration, puncture and contusion in the skin (Surani *et al.*, 2015). These external injuries in the superficial skin are typically categorised as minor (Gennarelli and Wodzin, 2008). In contrast, internal penetrating injuries are associated with bleeding from rupture of blood vessels or of organs underneath the skin. Even minor lacerations in vital organs, such as the liver and heart, are classified as moderate and serious injury, respectively (Gennarelli and Wodzin, 2008). Internal penetrating injuries may lead to further tissue damage. This is due to tissue contamination caused by bacteria and foreign materials, such as fibres of clothes that remain on the fragments (Bowyer, Cooper and Rice, 1995; Halpern *et al.*, 2003). All these factors indicate that internal penetrating injuries are more severe than external injuries.

2.3.3 Other blast injuries

Tertiary blast injury is blunt trauma from physical displacement caused by the dynamic pressure of the blast wind, tumbling to the ground and the impact of collapsed structures. The resultant injuries include concussion, lacerations, skeletal fractures, and traumatic amputation (Brismar and Bergenwald, 1982; Patel *et al.*, 2012). This injury mechanism is rare in blast injuries (Edwards *et al.*, 2016) although in confined space explosions, it has been reported that some casualties died or sustained severe injury due to collapsed structures (Brismar and Bergenwald, 1982). Quaternary blast injuries are caused by miscellaneous factors related to explosions except for the three categories: for instance, burns, inhalation and toxic injuries. Quinary blast injury is a category that was added recently; this mechanism is due to the reaction of the body to biological, radiological and chemical agents subsequent to explosions.

2.4 Summary

This chapter has focused on the fundamental physics of the blast wave and the mechanism of blast injury. Primary blast injury has unique characteristics which tend to influence specific tissue types or organs. In contrast, secondary blast injuries are

complicated; although superficial penetrating injuries are minor, internal penetrating injuries are more severe. Therefore, the widely used IEDs frequently house metal fragments to enhance their lethality as well as the direct effect of the blast wave. The next chapter will review the pattern of blast injuries seen in terrorist bombings in order to reveal the most common mechanism of blast injury and its severity.

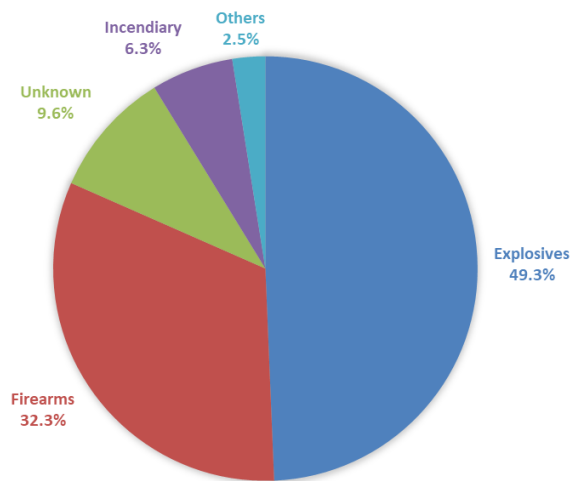
CHAPTER 3

PATTERNS OF BLAST INJURIES

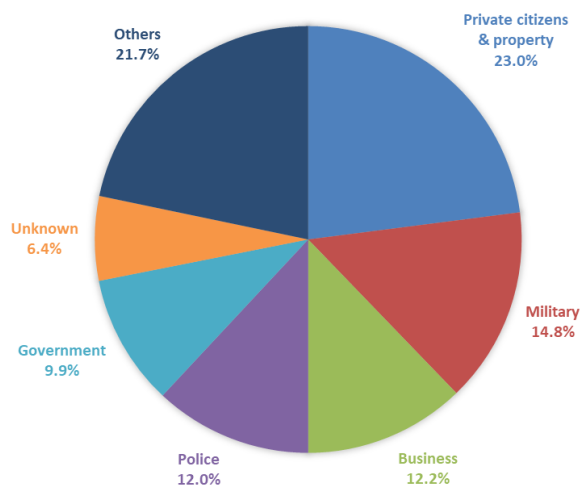
The previous chapter presented the mechanism of blast injuries and their characteristics. Chapter 3 explores the epidemiological studies of blast injuries to reveal the injury patterns resulting from explosions. Prior to the analysis of epidemiological studies, the use of injury scoring systems is described for the classification of injury severity.

3.1 Global outlook on use of explosive devices to cause harm

Bombing attacks have been the major type of weapon by terrorists. The Global Terrorism Database, an online database for terrorist events from 1970 to 2020, reports that bombing attacks account for 49.3 % (103,475 incidents) of all terrorist incidents (Figure 3.1).



A



B

Figure 3.1 (A) The weapon type of terrorist incidents and (B) the target type of bombings from 1970 to 2020. Data accessed with permission from (START, 2022).

Meanwhile, the private citizens and property (markets and streets etc.) have been the most common target group in bombing attacks, followed by the military (military personnel and platforms etc.) and the business (restaurants, cafe and petrol stations etc.) (START, 2022). This suggests that the civilians and public areas have been more frequently targeted by bombings than the military. Figure 3.2 shows the number of terrorist incidents between these military and civilian targets.

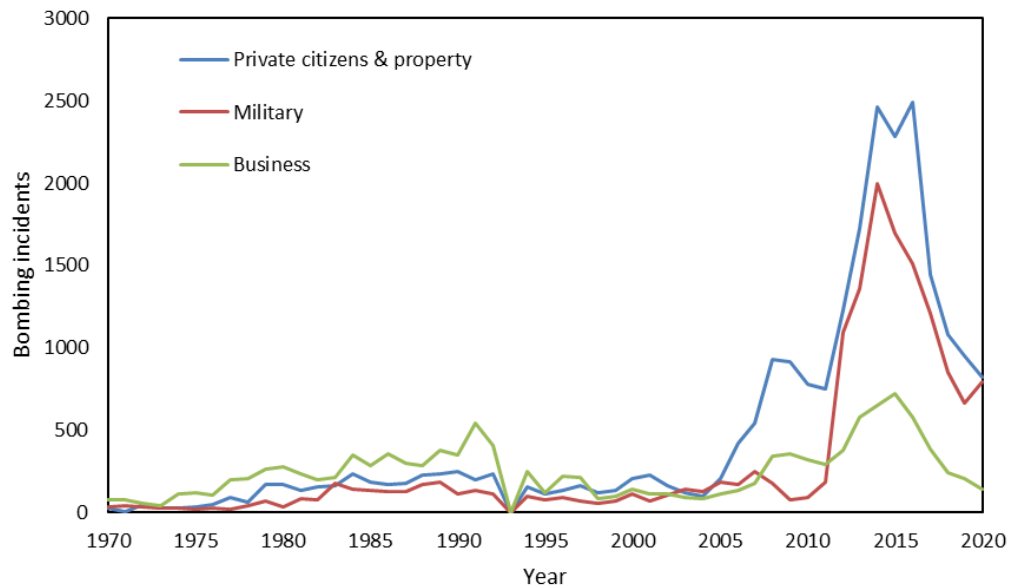


Figure 3.2 The annual terror incident of bombing attacks from 1970 to 2020. Data accessed with permission from (START, 2022).

The annual number of bombing attacks against all three groups has rapidly increased since 2005. After the peak around 2015, the number of bombing attacks decreased to less than 1,000 incidents in 2020. During this period, terror incidents against the private citizens and property; and the business occurred predominantly in the Middle East and North Africa region (43.8%), and the South Asia region (19.6%) including Iraq, Israel, Afghanistan and Pakistan (START, 2022).

3.2 Military and civilian targets

Blast injuries in a combat zone are unique; in particular, the fragmentation of large calibre ammunitions is distinct from that of IEDs against civilian targets. In World War II, Korean War and Vietnam War, penetrating wounds, mainly inflicted by the fragmentation of large calibre ammunitions, were the most common type of injury present in approximately 90% of all casualties (Bellamy, 1990). The bursting of these ammunitions mainly generates fragments from the shattering casing unlike IEDs against civilian targets where in addition to the casing, embedded metal fragments are also energised. The height of burst is also different in these situations; artillery and mortar ammunitions frequently burst in the air, albeit IEDs against civilian targets at or closer to the ground.

Another difference between attacks against civilian and military targets is the presence or not of protective equipment, which can generally mitigate the severity and the number of fatal injuries, particularly in the torso. It is obvious that protective equipment, such as bullet-proof vests and helmets, allows for reducing the frequency and severity of secondary blast injuries. Civilians and military personnel who wear no protective equipment are more likely to sustain torso injuries than the military personnel who wear body armour (Bohman *et al.*, 2005). In the Iraq conflicts, the thoracic and abdominal combat injuries accounted for 8.4% and 7.8% of all casualties in US military personnel (Dougherty *et al.*, 2009). In terror attacks, there was a high frequency of thoracic and abdominal blast injuries: 21-38.5% thoracic injuries and 15-22.6% abdominal injuries (Peleg *et al.*, 2004; Aharonson-Daniel *et al.*, 2006; Sheffy *et al.*, 2006). The protective equipment also affects the pattern of primary blast injuries. The wearer of a bullet-proof vest has reduced mortality and morbidity (Long *et al.*, 2009; Wood *et al.*, 2012; Sekine *et al.*, 2021). An adverse effect was also reported that five of six sheep wearing soft armour died due to the exposure to a blast wave at a peak pressure of 420 kPa, whereas only two of six sheep wearing no soft armour died at the same peak pressure of a blast wave (Phillips *et al.*, 1988). All these aspects can influence the pattern of blast injuries. Therefore, these groups of casualties should be distinguished for epidemiological analysis.

3.3 Injury scoring system

The severity of blast injuries can be categorised with injury scoring systems. These injury scoring systems are clinical criteria to classify casualties based on their injury severity. These systems help to perform triage and to predict the mortality and morbidity of the resultant injuries. This section introduces the injury scoring systems widely used for the casualties of blast injuries.

The Abbreviated Injury Scale (AIS) was established to classify crush injuries in automotive accidents and has been widely used for blast-injury patients. The concept of the AIS is to categorise the severity of a single injury (1 - minor to 6 - untreatable) in each body area (head, neck, face, thorax, abdomen, extremities) (Baker *et al.*, 1974). This evaluation system has been developed to adapt to a wide range of injury types whereby its current version (AIS 2015) contains a total of 2,006 injury codes (Loftis, Price and Gillich, 2018). The AIS scores are not proportional to mortality rates but can be linked to them. In the 1990-1998 version of the AIS, survival rate was estimated from 181,707 patients who sustained a single injury: the average survival rates were 0.99 for AIS 1, 0.99 for AIS 2, 0.97 for AIS 3, 0.85 for AIS 4, 0.60 for AIS 5 and 0.21 for AIS 6 (Gennarelli and Wodzin, 2006).

The Injury Severity Score (ISS) is an indicator of multiple injuries to assess the severity of injury at patient level. It is calculated from the AIS scores of the three most severely injured body regions (Baker *et al.*, 1974). The calculation of the ISS is to sum the square of these three AIS scores:

$$ISS = AIS_a^2 + AIS_b^2 + AIS_c^2 \quad \text{Equation 3.1}$$

The value of ISS ranges from 1 to 75. The patient who has AIS 5 injuries in three body regions is diagnosed as the maximum score injury (ISS 75), although the patient with AIS 6 in any body region is automatically diagnosed as ISS 75. Regarding the severity of ISS, the National Trauma Data Bank in the U.S. classified ISS 1-9 as “minor”, ISS 10-15 as “moderate”, ISS 16-24 as “severe”, and over ISS 25 as “very severe” (Fildes,

2006). This classification of the ISS is more predictable for the overall severity of multiple injuries than the AIS, whereas multiple localised injuries in the same body region may be underestimated (Copes *et al.*, 1990). For instance, for a casualty that has several organ injuries in the abdominal part, only the highest AIS score will be chosen of this body area in the calculation of the ISS. Even if another injury in this body area is more severe than injuries in other body areas, such injury is ignored for the ISS classification. In order to improve this limitation, the New Injury Severity Score (NISS) is used to sum the square of the three highest AIS scores regardless of the body area (Osler, Baker and Long, 1997).

3.4 Review of epidemiological studies in bombings

This section introduces current epidemiological studies of civilian blast injuries to reveal the injury patterns based on their mechanisms and commonly injured body areas. To explore the overall pattern of blast injuries, this section investigates various terrorist attacks such as different surrounding environments and different types of IED. In this review, epidemiological studies on military personnel were excluded because wearing body armour and the energised fragments from large calibre ammunitions discussed in Section 3.2 are different scenarios from civilian blast injuries.

3.4.1 Mechanisms of blast injury

This subsection reveals the occurrence of blast injury in each mechanism mentioned in section 2.3. Through this review, the most common mechanism of blast injury in civilian casualties is identified.

The occurrence of primary and secondary blast injuries predominates in civilian casualties. From 1970 to 2014 terrorist bombing attacks, primary and secondary blast injuries made up 21.5% and 50.5% of all blast injuries, respectively (Edwards *et al.*, 2016). This dominance of secondary blast injury is attributed to multiple energised fragments from an IED with 40.9% of patients presenting

penetrating injuries in three or more body regions (Sheffy *et al.*, 2006). Moreover, due to the low dissipation of fragment energy, the area of the mortality and morbidity caused by secondary blast injuries is widespread (Figure 3.3).

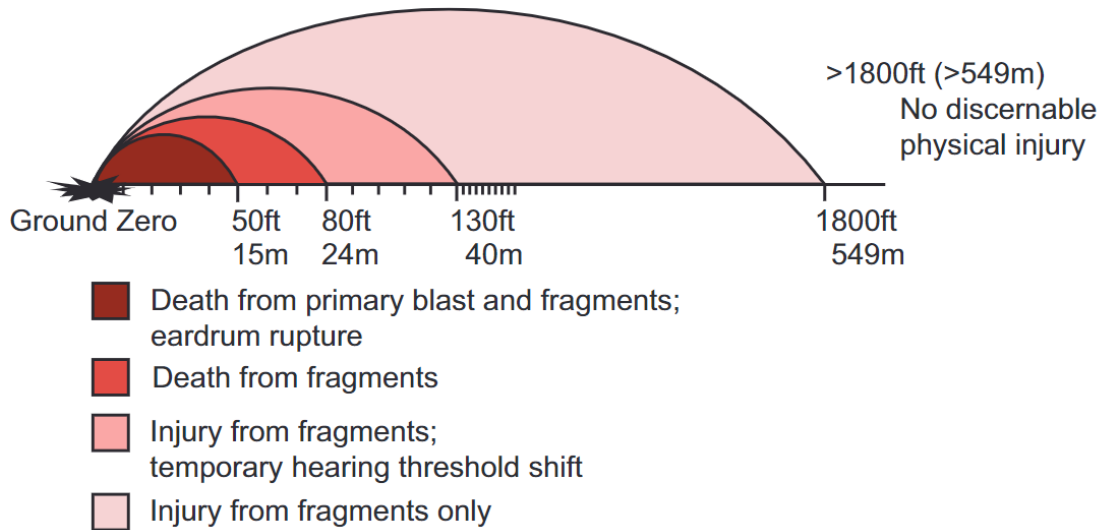


Figure 3.3 The morbidity and mortality of primary and secondary blast injuries associated with distance from the open-air explosion of a 155-mm shell. Figure reproduced with permission from (Champion, Holcomb and Young, 2009).

Tertiary and quaternary blast injuries are less common with approximately 12.7% and 15.2% injuries of all blast mechanisms, respectively (Edwards *et al.*, 2016). Collapse of buildings, whose causative injuries are categorised as tertiary blast injuries, is a rare scenario of terrorist bombings. This scenario, however, caused a large number of casualties in a confined-space explosion (Brismar and Bergenwald, 1982; Arnold *et al.*, 2004). In the quaternary blast mechanism, burns are frequently seen (Mathews and Koyfman, 2015). The mortality rate of the quaternary blast injury varies in epidemiological studies reporting 2.7% of initial survivors and 42% of casualties with burns (Frykberg and Tepas, 1988; Almogy, 2005).

3.4.2 Body areas

This subsection clarifies commonly injured body areas and the injury severity. In order to compare such body area in each bombing attack, the same definition of the body area should be used in all epidemiological studies reviewed here. Therefore, this review chose epidemiological studies which investigated the entire human body divided into the anatomical areas of AIS system; thus, the studies on injury patterns of only few body areas and the different definition of body area from the AIS system were excluded from this review. In addition to the injury patterns, mortality and injury severity in each body area are discussed here to reveal which body area leads to the most severe injury.

Table 3.1 summarises the epidemiological studies on civilian blast injuries investigating injury patterns in body areas classified with the AIS.

Author	Record of patients			Number of patients (% of total casualties)					Total casualties
	Location	Setting	Year	Extremities	Torso		Face	Head	
					Thorax	Abdomen			
Brismar et al.	Bologna, Italy	Railway station	1980	20 and 18* (19%) and (17%)*	20 (19%)	7 (7%)	22 (21%)	43 (40%)	107
Peleg et al.	Patients in 9 trauma centres, Israel	NM	2000-2002	242 and 234* (39%) and (38%)*	135 (22%)	75 (12%)	NM	115** (18%)	623
Aschkenasy-Steuer et al.	Patients in a Jerusalem trauma centre, Israel	Buses, restaurants and city centres etc.	2000-2004	39 and 46* (39%) and (46%)*	51 (50%)	32 (32%)	56 (55%)	44 (44%)	101
Turégano-Fuentes et al.	Madrid, Spain	Trains	2004	71 (14%)	199 (39%)	28 (5%)	291 (57%)	49† (10%)	512
Yasin et al.	Rawalpindi and Islamabad, Pakistan	Suicide bombings in vehicle, restaurant and mass gathering area etc.	2007-2009	868† (67%)	428 (33%)	544 (42%)	428‡ (33%)	143 (11%)	1296

NM not mentioned in the paper * upper and lower extremity injuries, respectively. ** only traumatic brain injuries. † only the skeletal injuries of lower limb long bones. ‡ only hearing loss.

Table 3.1 The injury locations of admitted patients in bombing terrorist attacks: the data derived from the epidemiological studies (Brismar and Bergenwald, 1982; Peleg *et al.*, 2004; Aschkenasy-Steuer *et al.*, 2005; Turégano-Fuentes *et al.*, 2008; Yasin, Nasreen and Malik, 2012). One patient has injuries in one or more body areas.

The extremities are the most common body region injured by the secondary blast mechanism. The extremity injuries predominated in all incidents except in the Madrid train bombings, which inflicted only 14% of extremity injuries. This is because all explosions took place inside the trains (confined-space explosion), so it is hypothesised that the kinetic energy of the energised fragments significantly decreased due to impacts on objects such as train seats. In the Pakistan bombings, predominant injuries to lower limb long bones were reported as combined injuries such as open fracture and contamination (Yasin, Nasreen and Malik, 2012). Weil *et al.* reported that the long bone fracture due to energised fragments was diagnosed as severe injury (ISS 20.0 ± 12.8); however, only 3 of these patients died (Weil *et al.*, 2007). In suicide bombings, approximately two-thirds of extremity injuries were diagnosed as minor or moderate severity (AIS 1-2) (Aharonson-Daniel *et al.*, 2006).

The overall occurrence of thoracic blast injuries was also high, particularly in confined-space bombings. In the Jerusalem bombings, all 51 casualties presenting with thoracic injuries sustained acute lung injuries; in the Madrid train bombings, 58 and 43 patients had lung contusion and BLI, respectively (Aschkenasy-Steuer *et al.*, 2005; Turégano-Fuentes *et al.*, 2008). These findings suggest that the lung is the most susceptible organ to blast injuries in the torso. In contrast, the occurrence of abdominal injuries was minor except for in the Pakistan suicide bombings.

The severity of these torso blast injuries has been classified most frequently as critical. Over half of thoracic and abdominal blast injuries were diagnosed as an AIS 3 or more in suicide bombings (Aharonson-Daniel *et al.*, 2006). In the Madrid train bombings, 89% critically ill patients had sustained thoracic injuries (Peral-Gutierrez de Ceballos *et al.*, 2005). It is reported that when casualties had internal injuries in both thorax and abdomen, 86.4% of those were diagnosed as very severe injuries (ISS 25 or more) (Peleg *et al.*, 2004). The high injury severity in these body regions is likely related to injuries to the vital organs behind the thoracic and abdominal wall.

Facial injuries are also frequently observed in blast injuries but commonly classified as minor. These facial injuries were reported to be 428 cases of hearing loss in the Pakistan suicide bombings (Table 3.1). In the Madrid train bombings, 240 out of 291 facial injuries were a tympanic membrane rupture (Turégano-Fuentes *et al.*,

2008). These ear injuries are frequently caused by the primary blast mechanism; even low-pressure blast wave at 35 kPa is capable of perforating the tympanic membrane (Horrocks, 2001; Walker et al., 1989). Therefore, the occurrence of this injury is expected to be high in confined or semi-confined explosions; indeed, 46.29% and 40.96% casualties sustained this injury in trains (confined space) and semi-confined spaces (Magnus, Khan and Proud, 2018). The tympanic membrane rupture, however, is categorised as minor (AIS 1) (Gennarelli and Wodzin, 2008). Another common facial injury was ocular injury; 95 and 7 casualties had this injury in the Madrid train bombings and the Bologna bombing, respectively (Brismar and Bergenwald, 1982; Turégano-Fuentes *et al.*, 2008). The majority of ocular injuries are also categorised as minor (AIS 1) (Gennarelli and Wodzin, 2008).

Head injuries were common in the Bologna bombing and patients of a Jerusalem trauma centre. In the Bologna bombing, it was reported that the building partially collapsed, so this tertiary blast mechanism would explain the high occurrence of head injuries (Brismar and Bergenwald, 1982). In the Jerusalem trauma centre, the mechanism was not specified but patients sustained oedema and bleeding in the brain (Aschkenasy-Steuer *et al.*, 2005). In the patients of 9 Israel trauma centres, 115 casualties sustained TBI, caused by the primary blast mechanism. These epidemiological studies indicate that head injuries mainly result from the primary and tertiary blast mechanisms. The severity of these head injuries is high. In suicide bombings, two-third of head injuries were severe (AIS 3 or more) (Aharonson-Daniel *et al.*, 2006). According to the epidemiological study of TBI in Israel, mild and moderate TBI constituted 20.8% and 27.1% of all patients with head injuries, respectively (Savitsky *et al.*, 2016). Only 6.2% of the patients sustained severe TBI; however, the mortality rate in the patients of this severity group was 31.6% (Savitsky *et al.*, 2016).

3.4.3 Torso organs

The previous subsection described injury patterns across body areas and alluded to very severe internal injuries in the torso. This subsection focuses on blast injuries to the torso organs to reveal common and severe injuries. In this review, the common organs in the clinical observation of epidemiological studies are considered;

for instance, the stomach was excluded due to it being less commonly featured in the epidemiological studies of blast injuries. Injury to the lung was divided into specific symptoms such as BLI, pneumothorax and haemothorax so that such symptoms can be further reviewed to distinguish the primary blast injury from the other mechanisms in epidemiological studies. Moreover, mortality and injury severity in each organ were also specified here to determine the torso organ presenting the highest mortality.

The overall torso organ injuries were less common except for Pakistan suicide bombings where the number of patients varied between 6% and 28% of total casualties (Table 3.2). It is evident that PBIEDs accounted for 71% of all bombing attacks in the Pakistan bombings (Yasin, Nasreen and Malik, 2012). The PBIEDs, which are worn around the torso, caused the different occurrence of blast injuries from conventional IEDs (Yazgan and Aksu, 2016).

Author	Bombing attacks			Number of patients (% of total casualties)							Total casualties
	Location	Setting	Year	Lung (BLI)	Lung (Pneumothorax)	Lung (Haemothorax)	Small bowel	Liver	Spleen	Kidney	
Katz et al.	Jerusalem, Israel	Bus	NM	11 (38%)	2 (7%)	2 (7%)	1 (3%)	0 (0%)	0 (0%)	0 (0%)	29
Turégano-Fuentes et al.	Madrid, Spain	Trains	2004	43 (8%)	31 (6%)	13 (3%)	3 (1%)	9 (2%)	10 (2%)	3 (1%)	512
Aylwin et al.	London, UK	Trains	2005	NM	1 (4%)	2 (7%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	27
Yasin et al.	Rawalpindi and Islamabad, Pakistan	Suicide bombings in vehicle, restaurant and mass gathering area etc.	2007-2009	142 (11%)	167 (13%)	368 (28%)	337 (26%)	147 (11%)	103 (8%)	76 (6%)	1296
Parlak et al.	Ankara, Turkey	Railway station	2015	NM	3 (4%)	3 (4%)	7* (9%)	2 (3%)	0 (0%)	2 (3%)	77

NM not mentioned in the paper * including large bowel

Table 3.2 Blast injuries to the torso organs in the admitted patients of bombing terrorist attacks, derived from epidemiological studies (Aylwin *et al.*, 2006; Turégano-Fuentes *et al.*, 2008; Yasin, Nasreen and Malik, 2012; Parlak and Beşler, 2020)

The lung is the most common blast-injured organ in the torso. Particularly, in the Jerusalem bus bombings and the Madrid train bombings, BLI was frequently found in this body area so that these findings support that BLI frequently occurs in closed and semi-closed space explosions (Magnus, Khan and Proud, 2018). Another study also suggests that 83% patients had sustained BLI due to a closed-space explosion from 1983 to 2004 in Jerusalem (Avidan *et al.*, 2005). The clinical signs of BLI involve pneumothorax and haemothorax (Hare *et al.*, 2007) while in the Ankara bombing, this pneumothorax and haemothorax were caused by the secondary blast mechanism (Parlak and Beşler, 2020). Other studies did not specify the blast mechanism of these lung injuries (Aylwin *et al.*, 2006; Turégano-Fuentes *et al.*, 2008; Yasin, Nasreen and Malik, 2012); these patients would sustain both or one of primary or secondary blast mechanisms. The severity of these lung injuries is considerably high; BLI injuries were classified as very severe (average ISS: 52.6) (Smith, 2011). The mortality rate of patients with BLI is high; severe BLI was found in 11% of victims in the Royal Victoria Hospital, Belfast (Stein and Hirshberg, 1999). The severity of the lung pneumothorax and haemothorax depends on the degree of wounds, ranging between moderate (AIS 2) and critical injuries (AIS 5) (Gennarelli and Wodzin, 2008).

Small bowel injuries were minor except for in the Pakistan suicide bombings. It is thought that small bowel injuries were caused by primary blast effects in the Madrid train bombings, whereas in the Ankara station bombings, the mechanism of all these injuries was considered to be secondary blast (Turégano-Fuentes *et al.*, 2008; Parlak and Beşler, 2020). In the Pakistan bombings, the mechanism of small bowel injuries was not specified despite it being the most common injury among the abdominal organs. The resultant injuries due to primary blast in the small bowel are regarded as immediate rupture and delayed perforation; the former is mainly caused by the direct effect of primary blast and is rare in casualties, whereas the latter is a delayed injury due to ischemia (DePalma *et al.*, 2005). The severity of rupture and perforation depends on the amount of tissue loss, ranging between AIS 3 and AIS 4 (Gennarelli and Wodzin, 2008).

Liver injuries were dominant in the Pakistan suicide bombings. It is noted that all liver injuries in Pakistan suicide bombings were diagnosed as a laceration (Yasin,

Nasreen and Malik, 2012); these were potentially caused by secondary or tertiary blast. Another study reports that 6 of 28 patients with abdominal organ injury suffered from secondary blast injuries to the liver (Turégano-Fuentes *et al.*, 2014). The severity of liver injury depends on the loss of tissue; for instance, a liver laceration varies between moderate (AIS 2) and maximum (AIS 6) (Gennarelli and Wodzin, 2008). There is no epidemiological research estimating the mortality rate of hepatic blast injuries from a large amount of patient data. One study reports a 23% mortality of liver blast injuries; 3 out of 13 casualties died after hospital admission (Turégano-Fuentes *et al.*, 2014).

Injury to the spleen and kidneys was uncommon in the bombing attacks reviewed. It is reported in the Madrid train bombings and in the Israel bombings that 6 spleen and 3 kidney injuries were observed among 28 patients with abdominal organ injuries; only one victim who had a spleen and liver injury died after admission (Turégano-Fuentes *et al.*, 2014).

Cardiac penetrating injuries were the most common cause of immediate death in terrorist bombings. In the Pakistan suicide bombings, it is noted that there was no survivor with cardiac penetrating injury before arrival to hospital (Yasin, Nasreen and Malik, 2012). There is no report, however, on the mortality rate of cardiac injuries due to terrorist bombings; this is because most of the epidemiological studies reviewed estimate the mortality rate from admitted patients excluding immediate death before arrival at hospital. Moreover, it is difficult to conduct a post-mortem examination and to access these records due to legal, cultural and religious restrictions (Stein and Hirshberg, 1999; Turégano-Fuentes *et al.*, 2008). These limitations, as well as the lack of epidemiological data, inhibit the estimation of the mortality rate of cardiac penetrating injuries in bombings. The overall mortality rate of cardiac penetrating injuries including stab wounds, gunshot wounds and secondary blast injuries was estimated at 94% before arrival at hospital and 50% in admitted patients (Campbell *et al.*, 1997). Therefore, it is assumed that cardiac penetrating injuries in civilian blast injuries have considerably high mortality rates.

3.4.4 Conclusion for reviewing torso blast injuries

Internal penetrating injuries reaching the torso organs are very severe. Hepatic penetrating injuries lead to a relative high mortality rate compared to other penetrating injuries in the torso organs. It is also thought that cardiac penetrating injury results in the highest mortality rate in the torso organs. Quantifying these penetrating hepatic and cardiac injuries can help to improve blast injury prediction and hence prevention and care. This thesis therefore concentrates in secondary blast injuries to liver and heart.

3.5 Specific mechanisms of secondary blast injury

In this section, the specific mechanisms of secondary blast injury are clarified. Clinical observations suggest that a portion of surrounding tissue of a penetrating wound is also permanently damaged (Fackler *et al.*, 1984). There is, however, no previous study to have looked into this in the liver and heart; this further damage is a key factor for the accurate prediction of the severity penetrating injury.

3.5.1 Wound cavity

Penetration of a projectile into soft tissue is thought to create a temporary cavity before this settles to a permanent cavity (Figure 3.4).

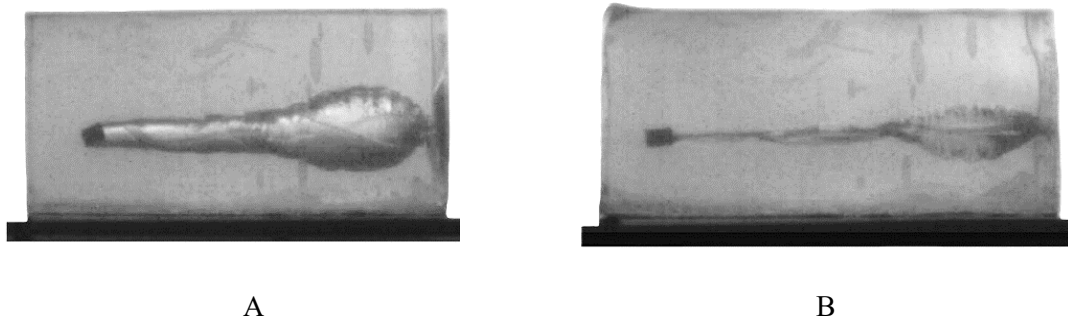


Figure 3.4 (A) Development of a temporary cavity and (B) permanent cavity behind a chisel-nose fragment in a gelatine soft-tissue surrogate. Figure reproduced with permission from (Breeze *et al.*, 2014).

A temporary wound cavity is thought to be caused by a contracting and expanding passage behind a fragment, lasting a few milliseconds after a fragment strikes the tissue (Figure 3.4 A). A permanent wound cavity is the passage that remains after a fragment comes to rest (Figure 3.4 B). The maximum volume of the tissue expansion has been reported to occur in 2-3 ms (Cooper and Ryan, 1990), reaching 12.5 times the diameter of a 6 mm steel sphere shot at around 1,000 m/s (Fackler, 1987). These wound cavities are observations in gelatine blocks, which are commonly used as human soft-tissue surrogates, and thought to occur in human soft tissue too. There, however, is no real-time and non-invasive observation of both wound cavities in biological tissue.

The temporary wound cavity can create tissue damage around the permanent wound cavity. During the temporary wound cavity, the lateral wall of the passage repeatedly compresses the surrounding tissue. This behaviour has been shown to cause microscopic change in the surrounding tissue (Oehmichen, Meissner and König, 2000; Breeze *et al.*, 2014) which may develop into irreversible damage such as necrosis (Wang *et al.*, 1988; Korać, Crnica and Božo, 2006). The area of this irreversible tissue damage can be determined on the basis of the level of tissue disruption seen by the surgeon operating on it (Figure 3.5) (Tsokos, Sperhake and Paulsen, 2005).

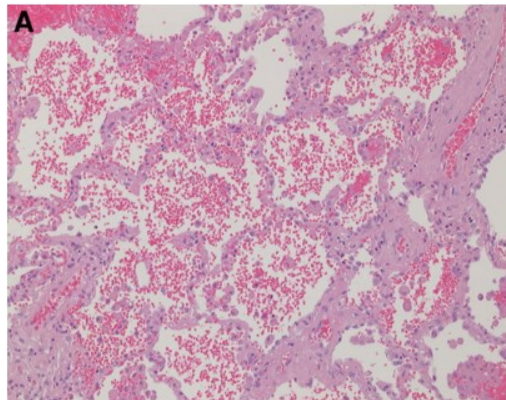


Figure 3.5 Pulmonary tissue disruption surrounding the permanent wound cavity of a gunshot wound. Figure reproduced with permission from (Tsokos, Sperhake and Paulsen, 2005).

Some studies recommended that the area of this tissue damage is surgically removed to prevent further development of necrosis (Bowyer, Cooper and Rice, 1995; Halpern *et al.*, 2003). Therefore, actual tissue loss should be regarded as the combination of the surrounding tissue with irreversible damage and the permanent wound cavity.

3.5.2 Stress wave

Another factor of tissue damage is believed to be the interaction of stress waves produced by the impact of a fragment. It is thought that the propagation of stress waves reaches distant tissue from their impact point; this may lead to further tissue damage (Suneson, Hansson and Seeman, 1990; Courtney and Courtney, 2009; Petit and Mercier, 2011). The mechanism of these injuries would be similar to the primary blast injury discussed in subsection 2.3.1. The resultant injuries are mainly caused by 1) high stress of wave interaction at the boundary of organs and 2) high localised pressure due to the interactions of these stress waves. When a projectile was shot into the porcine thigh, peak average pressures of 125 kPa and 270 kPa were recorded in the brain and abdominal cavity (Suneson, Hansson and Seeman, 1987). When dorsal root ganglion cells were exposed to stress waves, an 84% reduction in oxygen consumption was observed before and after the exposure; it implied mitochondria damage due to the interaction of stress waves (Suneson *et al.*, 1990). Clinical evidence has also supported the resultant injury from shock waves produced by a shock wave lithotripter (Willis *et al.*, 2006; McAteer and Evan, 2008; Connors *et al.*, 2014). Shock wave lithotripter with maximum 2,000 shock waves at 24 kV produced lesion at approximately 5% of renal volume (Willis *et al.*, 2006). This treatment exposes the organ to repeated shock waves; the single or fewer exposures, like in blast injury, might cause no damage or less severe damage. In contrast, Oehmichen *et al.* investigated tissue disruption in gunshot wounds around the permanent wound cavity in the brain, suggesting that it is reasonable to attribute this tissue disruption to the temporary wound cavity (Oehmichen, Meissner and König, 2000). These findings cannot prove whether or how much the stress wave damages the surrounding tissue, but the resultant tissue disruption may be distinguished between reversible and irreversible tissue damage regardless of whether the mechanism that caused it was the temporary wound cavity or the stress wave.

3.6 Summary

Primary and secondary blast injuries are predominant in civilian blast injuries. In particular, half of all blast injuries in civilian casualties are caused by the secondary blast mechanism. The injury pattern depends on type of IED and the surrounding environment; in particular, the PBIED is capable of propelling its fragments towards the torso so casualties who wear no protective equipment are highly likely to sustain serious penetrating injuries to vital organs behind the torso wall.

In these secondary blast injuries in the torso organs, the liver and the heart have the high risk of severe penetrating injury. The temporary wound cavity causes the tissue disruption around the permanent wound cavity; this tissue disruption may become irreversible tissue damage. Actual tissue loss should involve both irreversible damage and permanent wound cavity. The quantitative assessment of this actual tissue loss has the potential to enable more accurate prediction of blast casualties.

The next chapter presents the feasibility of existing laboratory platforms to propel representative fragments in IEDs. The human surrogates available for ballistic tests are also discussed for quantifying penetrating hepatic and cardiac injuries.

CHAPTER 4

EXPERIMENTAL PLATFORMS AND HUMAN

SURROGATES

The previous chapter found that penetrating injuries to the liver and heart have the high mortality among the torso organs. To predict their probability, this study needs to consider how these penetrating injuries in the liver and heart can be replicated experimentally or computationally. Chapter 4 reviews the development of the experimental surrogates for quantifying penetrating cardiac and hepatic injury. This chapter also discusses a suitable platform and representative fragments to replicate penetrating injuries caused by IEDs. The last section specifies how the risk of penetrating injuries is quantified using a suitable human surrogate.

4.1 Representative fragments

Inside IEDs, various shapes and mass of metal fragments are housed to enhance their lethality. The parameters of the fragments generally alter an injury pattern and severity as influencing the retardation in tissue (Woodcock *et al.*, 2006). To replicate penetrating injuries caused by conventional IEDs, the representative fragments need to be used in this study.

Spherical and cylindrical fragments were frequently found in casualties (Breeze, Leason, *et al.*, 2013; Singh *et al.*, 2014; Yazgan and Aksu, 2016). The dimensions and shape of retained fragments inside the body can be identified using radiography. When such fragment is excised from the body, their material is also identifiable. There were, however, only a few studies that reported the parameters of the retained fragments. Approximately 4-mm and 5-mm-diameter metallic ball bearings were found in the casualties of the Boston marathon bombing (Eikermann *et al.*, 2014; Singh, Sodickson and Abujudeh, 2016). Breeze *et al.* investigated the shape of fragments retained inside the neck of UK soldiers and estimated their mean mass assumed to be C22 carbon steel (Breeze, Leason, *et al.*, 2013). Their findings revealed a right-circular (RC) cylinder with mean mass of 0.78 g was most frequently found in the soldier's neck. Following the RC cylinder, a sphere with mean mass of 0.44 g was the next most common fragment in the neck (Breeze, Leason, *et al.*, 2013). Despite no report on chisel-nose (CN) cylinder-shaped fragments retained in the body of casualties, this shape is accepted in ballistic tests because NATO defines it as the fragment simulating projectile (FSP) for testing ballistic protection (NATO Standardization Office, 2015). In particular, 1.1-g-CN cylinders have been widely used to evaluate the performance of protective equipment (Iremonger and Went, 1996; Naebe *et al.*, 2013; Rubio *et al.*, 2019); hence, testing with this FSP allows for comparing the results produced here with existing data. Furthermore, the outcome of this projectile will be utilised to predict the severity of a penetrating injury when the projectile perforates protective equipment.

The photographs and the parameters of the FSPs chosen in this study are shown in Figure 4.1 and Table 4.1. There is no description of length and diameter for the 0.78-g-RC cylinder in the literature (Breeze, Leason, *et al.*, 2013). These

parameters of the RC cylinder were determined from the mass versus diameter relationship of recommended RC cylinders in the NATO standard (NATO Standardization Office, 2015). From 7 cylinders ranging from 0.16 to 4.15 g of mass, the diameter and length of 0.78-g cylinder were estimated to be 4.5 and 6.3 mm, respectively (NATO Standardization Office, 2015).



A

B

C

Figure 4.1 (A) Photographs of a 5-mm sphere, (B) 0.78-g-right-circular (RC) cylinder and (C) 1.1-g-chisel-nose (CN) cylinder.

Shape	Material	Mass [g]	Diameter [mm]	Length [mm]
Sphere	Carbon steel	0.51	5	-
RC cylinder	Carbon steel	0.78	4.5	6.3
CN cylinder	Carbon steel	1.1	5.4	6.4

Table 4.1 The parameters of the sphere, right-circular (RC) cylinder and chisel-nose (CN) cylinder.

4.2 Experimental and computational platforms to replicate penetrating injuries

This study requires an experimental or computational platform to replicate penetrating injuries using the representative fragments of IEDs. The mass, geometry and striking velocity of a projectile generally affect the depth of penetration into

human tissue (Breeze, James and Hepper, 2013); hence, these parameters influence the severity of the penetrating injury. In the previous section, the mass and geometry of the projectile in this study were determined based on the clinical data of terror incidents and NATO standardisation. The next subsections primarily focus on the capability of experimental platforms to accelerate a projectile towards a target. The range of the resultant injury needs to cover both minor and critical severity to extensively quantify the risk of penetrating injuries. It is believed that a fragment impact at less than 600 m/s enables patients to survive their penetrating injuries (Bowen, T.E. and Bellamy, 1988). This range of velocity would be enough for this study to observe a direct impact on the heart and liver. To quantify the risk of the injury accurately, the reproducibility of impacts on the sample is also indispensable for this study.

4.2.1 Gas gun

A gas gun is an experimental apparatus to launch a projectile at a desired velocity using a high-pressure gas. The various types of gas gun exist for experimental use to accelerate a projectile at a wide range of velocity. A light-gas gun system is employed for hypervelocity physics such as the re-entry of spacecraft and a high-speed impact (Berggren, 1965; Burchell *et al.*, 1999; Lexow *et al.*, 2013). The mechanism of a light-gas gun typically divides into two stages; a piston is accelerated by gunpowder at the first stage and then the piston compresses light gas at the second stage. This compressed light gas such as hydrogen propels a projectile at approximately 10 km/s (Lexow *et al.*, 2013). Such destructive energy of a high-speed impact would not be suitable for replicating the penetrating injury caused by the energised fragments of IEDs. Conventional gas guns are capable of propelling a projectile up to approximately 1,500 m/s by simply expanding compressed gas (Fowles *et al.*, 1970; Bourne, 2003), and thus more appropriate for replicating the penetrating injury assessed here.

Figure 4.2 shows the 32-mm-bore gas-gun system housed in Imperial College London. A projectile is fixed with vacuum grease on a hollow polycarbonate sabot. The prime and reservoir section are sealed with Mylar diaphragms. The prime section is filled with compressed gas at half of the burst pressure of the diaphragm, and the

reservoir is filled with compressed gas at just above the burst pressure. The diaphragms are ruptured when the gas in the prime section is vented to atmospheric pressure. The compressed gas in the reservoir then expands through the breech and propels the sabot. After the sabot accelerates through the long barrel, the projectile is detached from the sabot by the sabot stripper and strikes the sample. The compressed gas in the reservoir then expands through the breech and propels the sabot. After the sabot accelerates through the long barrel, the projectile is detached from the sabot by the sabot stripper and strikes the sample.

The maximum gas pressure in the reservoir and prime section of the gas gun is considerably lower than the gas expansion of gunpowder; hence, the gas gun needs a long barrel to deliver enough energy to a projectile. Conversely, the striking velocity at the sample can be readily changed by the burst pressure of the Mylar diaphragm used, gas pressure and type of gas filled in the prime and reservoir section. The performance of the 32-mm-bore gas gun in Imperial College London is satisfactory for this study as it is capable of propelling a projectile between 20 and 600 m/s (Nguyen *et al.*, 2020).

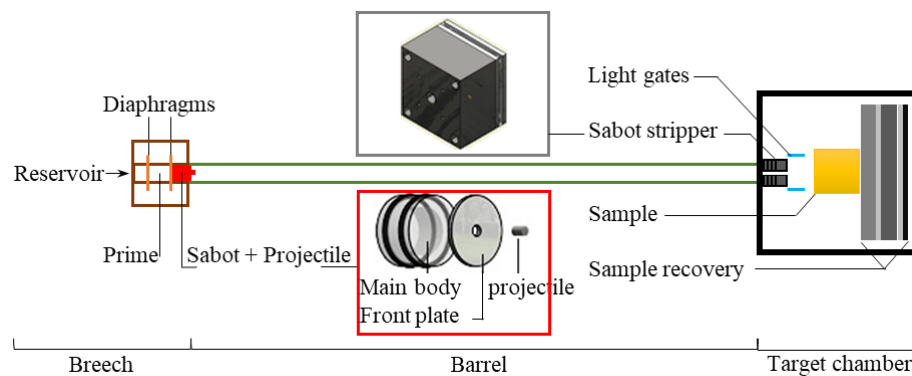


Figure 4.2 Gas-gun system for experiments on projectile penetration to gelatine. Figure adapted with permission from (Nguyen *et al.*, 2019).

4.2.2 Gunpowder launcher

Another experimental apparatus is a launcher which propels a projectile with gunpowder (Figure 4.3). Such system is almost similar to a rifle; a projectile is placed near or in a gunpowder-loaded cartridge instead of a bullet. The projectile is accelerated in a barrel by the gas expansion of gunpowder. This experimental

apparatus is capable of propelling a projectile from low to supersonic speeds; striking velocities at a target were reported to be between 50 and 1,600 m/s (Breeze, Hunt, *et al.*, 2013; Breeze *et al.*, 2015; Humphrey *et al.*, 2018a). The structure of the gunpowder launcher is simple and compact; it mainly consists of a barrel and a cartridge chamber. The resultant velocity of a projectile using this platform, however, is very sensitive to the condition of the loaded gunpowder. The residue of gunpowder in the barrel and high recoil force may increase the variance of the resultant velocity (Fowles *et al.*, 1970); therefore, it is less appropriate for adjusting the striking velocity of a projectile.

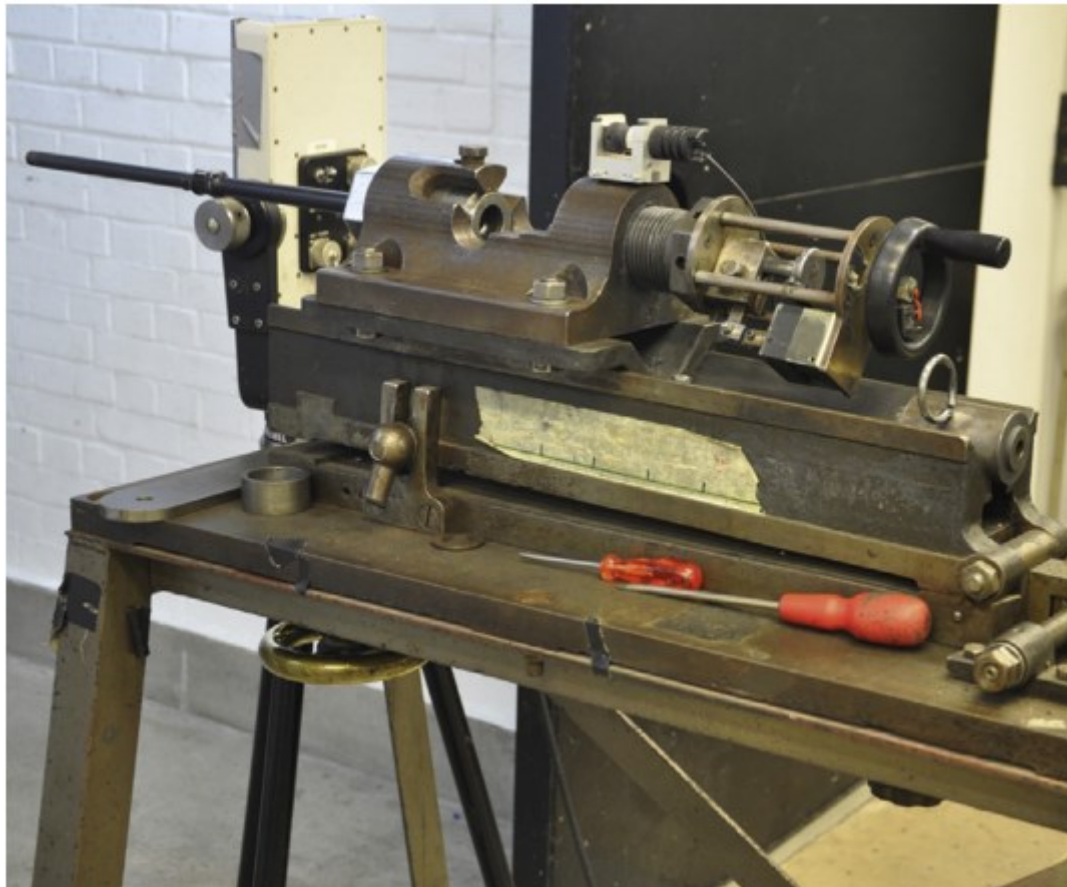


Figure 4.3 Gunpowder launcher with a 7.62-mm barrel. Figure reproduced with permission from (Breeze *et al.*, 2015).

4.2.3 Free-field test

Free-field testing can mimic a realistic blast wave and energised fragments using a full-scale IED model. This method allows for choosing any size of human surrogate and IED model due to a large area available on a test ground. Sielicki *et al.* measured the velocities and trajectories of energised fragments from a PBIED model (Figure 4.4) (Sielicki *et al.*, 2021). The initial velocities of these fragments extensively ranged between 69 and 577 m/s and their initial vertical angles varied from -43° to 50° (Sielicki *et al.*, 2021). Although the velocity range by this experimental model is satisfactory for this study, the variation of the fragment velocities and initial angles from the PBIED model were significantly inconsistent.

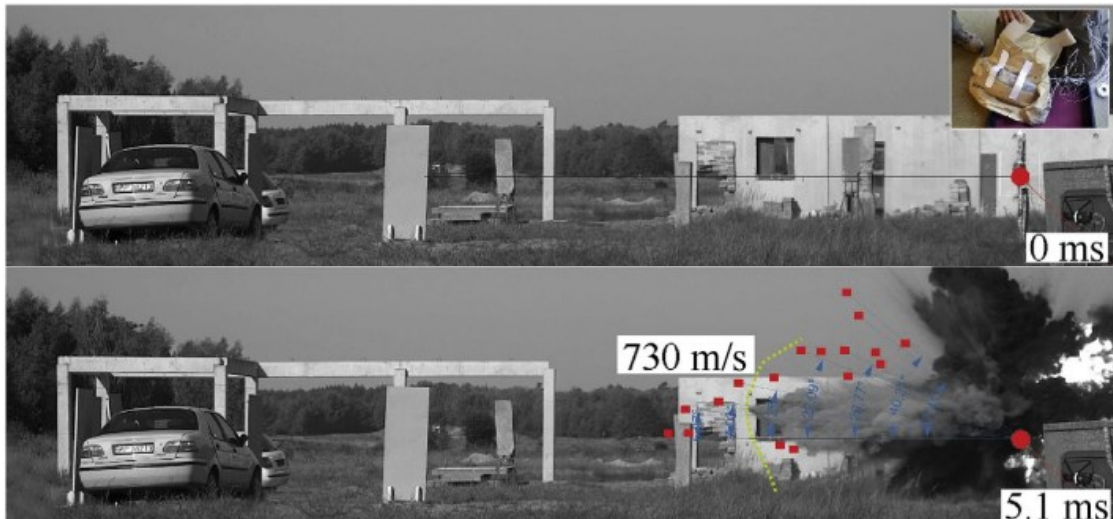


Figure 4.4 Free-field test using a PBIED model (red circle); red squares and yellow dots show the trajectories of the energised fragments and the blast wave, respectively. Figure reproduced with permission from (Sielicki *et al.*, 2021).

4.2.4 Computational tools

Computer simulation is also an available tool for replicating the penetrating injuries. In this method, human organ models are computationally impacted by a projectile to quantify penetrating injury. The simulation model for the human organ is

generally created with viscoelastic or hyperplastic material models (J C Roberts *et al.*, 2007; Umale *et al.*, 2013). Soft tissue has strain-rate dependence, which is the change of material properties during deformation depending on the rate of strain. The strain rate of blast loading is considerably high, ranging between 100 and 3000 /s (Pervin, Chen and Weerasooriya, 2011; Gu *et al.*, 2012) so their material models need to be developed with several material tests at low to high strain rates. The material properties of human organs with anisotropy such as muscle tissue are altered based on the compression and elongation of the fibre and of cross-fibre direction. The material testing in each direction is required to build these simulation models. If a human organ during elastic-plastic behaviour due to extremely high pressure acts like a fluid, hydrodynamic effects should be considered (Nagayama *et al.*, 2006). In this case, an equation of state such as the Shock-Hugoniot needs to be established from further material testing. Moreover, the geometry of this simulation model is established based on the human body (J C Roberts *et al.*, 2007). Such high-fidelity model leads to the accurate estimation of penetrating injury. For the development of the injury model, the simulation, however, results in a high computational cost and needs to be repeated to quantify penetrating injury in a wide range of striking velocities.

In contrast, a low fidelity model does not have medium and small anatomical structures such as blood vessels and some organs to reduce the computational complexity. This simulation model cannot quantify penetrating injuries to the human organs, but can predict blast injuries in mass gatherings, and so is suitable for injury predictions in terror incidents. Simulation tools for terror incidents have been developed for civilian and military settings (Stanley and Brown, 1978; Pope, 2011). After the London terror attacks in 2005, UK government agencies developed the Human Injury Predictor (HIP) code, which allows for quick-running simulations to predict the severity and the number of primary and secondary blast injuries in bombing attacks (Pope, 2011). This code is capable of performing statistical analysis in large groups of individuals, so the human model of this simulation was assumed to be a cylinder divided into five regions (Figure 4.5) (Pope, 2011). The injury prediction of this model is simplified for both primary and secondary blast injuries. For primary blast injuries, the injury severity is estimated from the peak pressure and impulse of a blast wave on the human body (Pope, 2011). For secondary blast injuries, the injury severity is assessed from the DoP in cylindrical body parts modelled as gelatine

without any anatomical structure (Pope, 2011). The estimated DoP is calculated with the equation of motion

$$-m \frac{dv}{dt} = \alpha v^2 + \beta v + \gamma \quad \text{Equation 4.1}$$

, where m is mass of a fragment, v is velocity of a fragment and t is time. The α , β and γ are coefficient values obtained from experimental data (Pope, 2011).

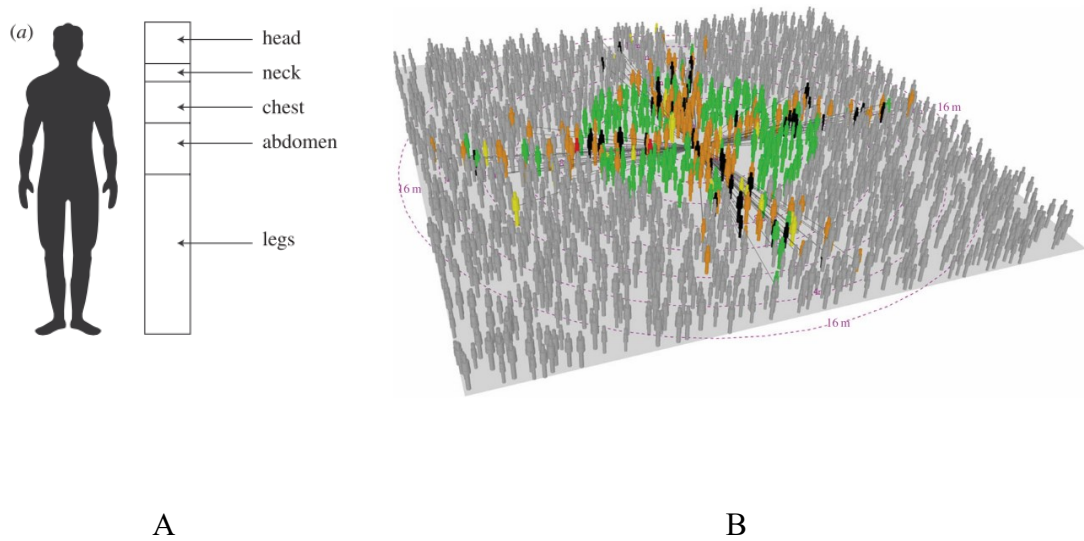


Figure 4.5 The injury prediction of HIP code for an explosive device simulation model of HIP code; (A) a cylindrical human model and (B) simulation results in an open-air explosion (the colour of the human model demonstrates triage levels). Figure reproduced with permission from (Pope, 2011).

The US military also developed an injury prediction tool, called ComputerMan. The anatomical model of this tool has higher fidelity than that of HIP code. The model of ComputerMan involves the precise geometry and various tissue components of human anatomy; for instance, the male model divides into 108 horizontal slices and 5-mm square cells in each sliced section (Stanley and Brown, 1978). These square cells can represent 296 different types of the tissues (Bourget, Dumas and Bouamoul, 2012). This simulation, however, was designed for military

missions. Unlike the HIP code, ComputerMan is used to estimate the probability of incapacitation for an individual military mission (Eisler *et al.*, 2001).

The concept of the HIP code is appropriate for the prediction of penetrating injuries in mass gatherings. The injury prediction requires an injury model, which is a mathematical function relating the physical response of the human model to the probability of resultant injury. The human model in the HIP code needs to be developed by incorporating the injury model of the organs such as the heart and liver.

4.2.5 Summary for experimental and computational platforms

This study aims to quantify the risk of penetrating injuries to the heart and liver using the three projectiles discussed in Section 4.1. In this study, experimental platforms are required to propel the projectiles up to the striking velocity of 600 m/s with high reproducibility. All three experimental platforms are capable of accelerating a projectile up to this velocity, although the free-field test with an IED model has low reproducibility of fragment velocities and their initial vertical angles. Due to these factors and availability in our laboratory, gas-gun system is most suitable for this study.

The computational tools with high fidelity models are available for quantifying the risk of penetrating injury although require the material properties of the organs. The simulation for the development of the injury model needs to be repeated in a wide range of projectile velocities despite a large computational cost due to high fidelity. Alternatively, the injury model derived from experimental results can be also incorporated into the simulation model. Hence, the computational tools are not suitable for the quantitative assessment of penetrating hepatic and cardiac injuries in this study.

4.3 Human surrogates

This section explores human surrogates which are feasible for replicating penetrating injuries from blast fragments. For ballistic tests, the similar size of the surrogate to the human anatomical structure is preferred due to the interpretation of resultant penetrating injuries without any scaling law. Therefore, the following subsections review the characteristics of large human surrogates. This literature review includes studies on a gunshot wound as the injury mechanisms of this wound are also associated with the permanent and temporary wound cavity (Fackler, 1987).

4.3.1 Human cadaver

A human cadaver in ballistic tests takes advantage of the injury prediction over other surrogates because of the same geometry and cadaveric response to the living human. It is also advantageous that, although a cadaver undergoes post-mortem changes, the material properties of fresh human cadavers would be closest to those of living human tissue in cadaveric surrogates.

Post-mortem degradation occurs depending on tissue type and storage time. Early post-mortem degradation appears the relaxation and contraction of muscle tissue, known as rigor mortis, in 1 or 2 hours of the death (Shedge *et al.*, 2021). In the next 12 hours, the rigor mortis reaches the peak of the stiffening and is then kept for another 12 hours (Shedge *et al.*, 2021). Such post-mortem degradation in the cadaver can be minimised by freeze storage; therefore, in ballistic test, freshly cadaveric samples are generally frozen at the time of acquisition and thawed prior to the day of testing. Previous studies have shown that this process affects the material properties of some cadaveric organs: the change of ultimate force and strain at failure in muscle tendons (Leitschuh *et al.*, 1996; Giannini *et al.*, 2008), tensile strength in 13 torso organs (Maiden and Byard, 2016) and the Young's modulus in arteries (Venkatasubramanian *et al.*, 2006). This change of material properties is attributed to dehydration and tissue disruption during a freeze-thaw cycle (Venkatasubramanian *et al.*, 2010). In contrast, it is also reported that a freeze-thaw cycle does not affect

material properties: stress-strain curves, tensile strength and ultimate strain in ligaments (Woo *et al.*, 1986).

Despite its advantages, a human cadaver has difficulty in accumulating experimental data. Ballistic tests with a human cadaver become less popular due to ethical issues. Furthermore, testing with a human cadaver is subject to acquisition by a body donation programme where a human cadaver is typically acquired. These factors prevent researchers from obtaining a large number of samples although the quantitative assessment in this study requires a large number of ballistic tests in a wide range of striking velocities.

4.3.2 Animal

Both living and cadaveric animals have been utilised in ballistic tests (Fackler *et al.*, 1984; Janzon and Seeman, 1985; Breeze, Hunt, *et al.*, 2013; Breeze, James and Hepper, 2013; Humphrey *et al.*, 2018a; Nguyen, Breeze and Masouros, 2022). Both animal surrogates can replicate the mechanical behaviour of human tissue, whereas only living animal surrogates are available to observe the pathophysiological behaviour. For living animal tests, small animals such as rodents have been widely used, but scaling the results to humans has not been straightforward and remains to be validated. Therefore, most ballistic studies prefer large animals such as pigs, goats and cattle (Fackler *et al.*, 1984; Janzon and Seeman, 1985; Breeze, Hunt, *et al.*, 2013; Breeze, James and Hepper, 2013; Humphrey *et al.*, 2018a; Nguyen, Breeze and Masouros, 2022).

There are some limitations in using both living and cadaveric large animals in laboratory settings. It is difficult to conduct living large animal tests in laboratory settings due to ethical limitations. Such test is required to follow the additional steps of test protocols such as anaesthesia, so facilities for testing of large animals need to be equipped appropriately. Alternatively, large animal cadavers can be used in conventional laboratory settings but undergo post-mortem degradation in the same manner as a human cadaver. To minimise post-mortem degradation, animal cadavers are also frozen at the time of slaughter, although this freeze-thaw cycle has been reported to alter the material properties of some animal tissues. It has been reported

that a freeze-thaw cycle alters the failure values in the porcine spleen and bovine liver (Lu, Kemper and Untaroiu, 2014; Duong *et al.*, 2015), but that it does not affect the failure values in the porcine liver (Duong *et al.*, 2015).

4.3.3 Ballistic ordnance gelatine

Another experimental surrogate used in a laboratory setting is ballistic ordnance gelatine. The ballistic gelatine at 10% and 20% concentration is accepted as a human tissue surrogate, in which the permanent wound cavity in living porcine muscle (Fackler and Malinowski, 1988) and in porcine leg and neck muscle can be replicated (Breeze, Hunt, *et al.*, 2013). Unlike human cadavers and animal surrogates, the ballistic gelatine allows researchers to accumulate experimental data, such as the DoP and the energy loss of a projectile, without ethical issues. In ballistic tests with gelatine blocks, the DoP is roughly related to the severity of penetrating injuries. It is reported that the minimum distances to the liver and heart are 17 mm and 18 mm from the skin, respectively (Breeze, Lewis and Mahoney, 2020). The DoP in the gelatine compared with the distances to these vital organs may be a practical way of estimating roughly, but not precisely, penetrating injury.

4.3.4 Summary for human surrogates

This study quantifies the risk of the penetrating injury in samples commensurate with human injury to the liver and heart. To quantify a wide range of risk of penetrating injuries, a large number of samples is necessary in this study. Human cadavers are not suitable for this surrogate because their cadavers are not constantly acquired from the donation programme. Cadaveric or living small animals are not enough for evaluating penetrating injury as the dimensions of the samples are considerably smaller to the human. Living large animals have similar dimensions to the human but testing with these samples is limited due to ethical consideration. These arguments suggest that the cadaveric liver and heart of large animals are the most suitable surrogate in this study.

The ballistic ordnance gelatine is beneficial for testing in any laboratory settings. These ballistic gelatines can replicate penetrating injury in muscle tissue

although there is no study suggesting that the penetration responses of these gelatines are similar to the heart and liver. Therefore, these gelatines cannot be used for quantifying the risk of penetrating injuries. These gelatines, however, have advantages over any biological surrogates because they are available in a non-biological laboratory and without ethical consideration. In addition to the cadaveric animal heart and liver, the ballistic gelatines are also chosen as samples. In this study, the penetration responses of the ballistic gelatines in the several concentrations are compared with those of the cadaveric animal heart and liver to determine a more biofidelic surrogate.

4.4 Material properties for cadaveric animal liver and heart

In this section, the dimensions and material properties of the cadaveric animal liver and heart are compared with the human ones to determine suitable animal surrogates for the purposes of this study.

4.4.1 Heart

Figure 4.6 illustrates the cross section of the human heart. The human heart consists of two upper chambers (left and right atrium) and two lower chambers (left and right ventricle). The cardiac tissue mainly contains muscle fibres, thus having anisotropy depending on the fibre direction. Therefore, the cardiac surrogate cannot be sectioned into the small size and needs to be chosen based on the similar anatomical parameters to the human heart as well as material properties. The mass of a whole heart and the thickness of the ventricular wall in the human and large animals are shown in Table 4.2. The mass of the ovine heart is closest to the human heart in the three animals. The thickness of the porcine and ovine ventricle is closer to the human. In Table 4.2, the sheep under the age of 12 months is generally categorised as lamb, so the lamb heart has the most similar anatomical structure and parameters to the human heart out of the three animals.

Figure 4.7 shows the material properties of the human, porcine, bovine and ovine ventricle in a fibre and cross-fibre direction. The overall stress-strain curves of

the bovine ventricle are closest to those of the human ventricle in the three animals. The stress-strain curve of the ovine ventricle in the cross-fibre direction is also closer to that of the human ventricle, albeit there is a difference with the fibre direction of the human ventricle. Although the bovine heart has similar material properties to the human, the overall comparisons including the anatomical parameters suggest that the ovine heart is the most suitable surrogate in this study.

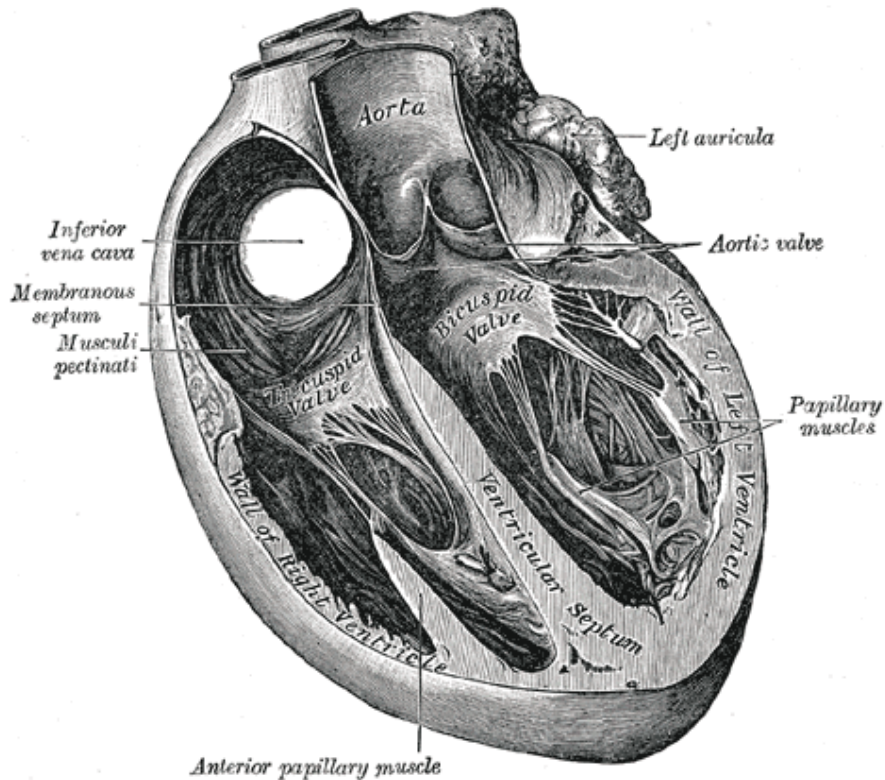


Figure 4.6 The cross section of the human heart (Gray , Lewis, Warren H., 1918).

	Human	Swine	Cow	Sheep *
Mass of a whole heart [g]	123-306	370.41 ± 45.83	2,470 ± 270	165.1 ± 13.0
Thickness of left ventricle [mm]	12-15	7.2 ± 1.5 **	34.0 ± 3.5	17.8 ± 0.7 **
Thickness of right ventricle [mm]	3-5 **	3.8 ± 1.5 **	13.5 ± 3.2	8.8 ± 1.7 **

Table 4.2 Anatomical parameters of the heart. The values show a range or mean ± one standard deviation. * Under the age of 12 months (categorised as lamb), ** Thickness during the relaxation period measured using radiography or ultrasonography. All values are derived from the existing studies (Foale *et al.*, 1987; Olivetti *et al.*, 1991; Ho, 2009; Noci *et al.*, 2012; Acorda and Pajas, 2015; Zurbrigg *et al.*, 2018; Lock *et al.*, 2019; Omann *et al.*, 2019).

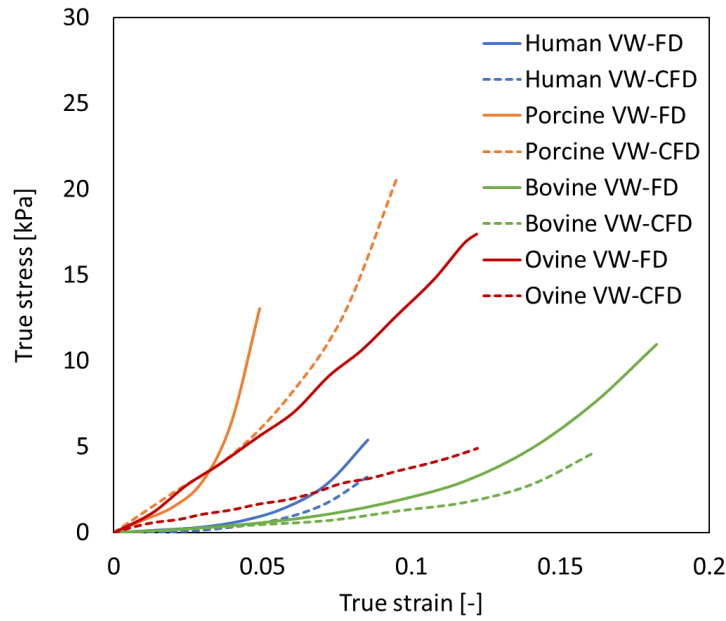


Figure 4.7 Equibiaxial test of the ventricular wall (VW) in a fibre direction (FD) and cross-fibre direction (CFD) (Ghaemi, Behdinin and Spence, 2009; Wang *et al.*, 2010; Sommer *et al.*, 2015; Javani, Gordon and Azadani, 2016).

4.4.2 Liver

Figure 4.8 shows a schematic of the human liver. The human liver consists of two large lobes (left and right lobe) and two small lobes (caudate and quadrate lobe); each lobe has a thin membrane covered on the outer surface, called capsule, and main tissue underneath the capsule, called parenchyma. The mean size of the human liver is 7 and 10.5 cm for women and men, respectively (Wolf, 1990). The liver is a soft and solid organ and reported to be isotropic (Pervin, Chen and Weerasooriya, 2011).

Figure 4.9 shows the material properties of the human, porcine and bovine liver obtained from uniaxial compression and tensile tests between strain rates of 0.005 and 1.0 s^{-1} (Tamura *et al.*, 2002; Kemper *et al.*, 2010, 2013; Pervin, Chen and Weerasooriya, 2011; Lu, Kemper and Untaroiu, 2014; Duong *et al.*, 2015). Table 4.3 represents the average failure stress and strain of the human, porcine and bovine livers. The bovine liver has similar material properties to the human liver. In contrast, the

material properties of the porcine liver are stiffer than the other two. In particular, whereas the values of failure strain for all livers are similar, the failure stress of the porcine liver is considerably higher than that of the human and bovine livers. These different material properties are attributed to cellular structures inside the liver. Specifically, the connective tissue in the cellular structure of the porcine liver is thicker than that in the human and bovine livers (Kemper *et al.*, 2010).

Consequently, the cadaveric bovine liver is the most suitable surrogate in readily available large animals due to isotropy and the similar material properties to the human liver. The dimensions of the bovine liver are larger than those of the human liver. Due to isotropy, a whole liver surrogate can be sectioned into small blocks with the similar dimensions of the human liver. To satisfy the same boundary condition in this sectioned liver, the capsule needs to be maintained on the striking surface.

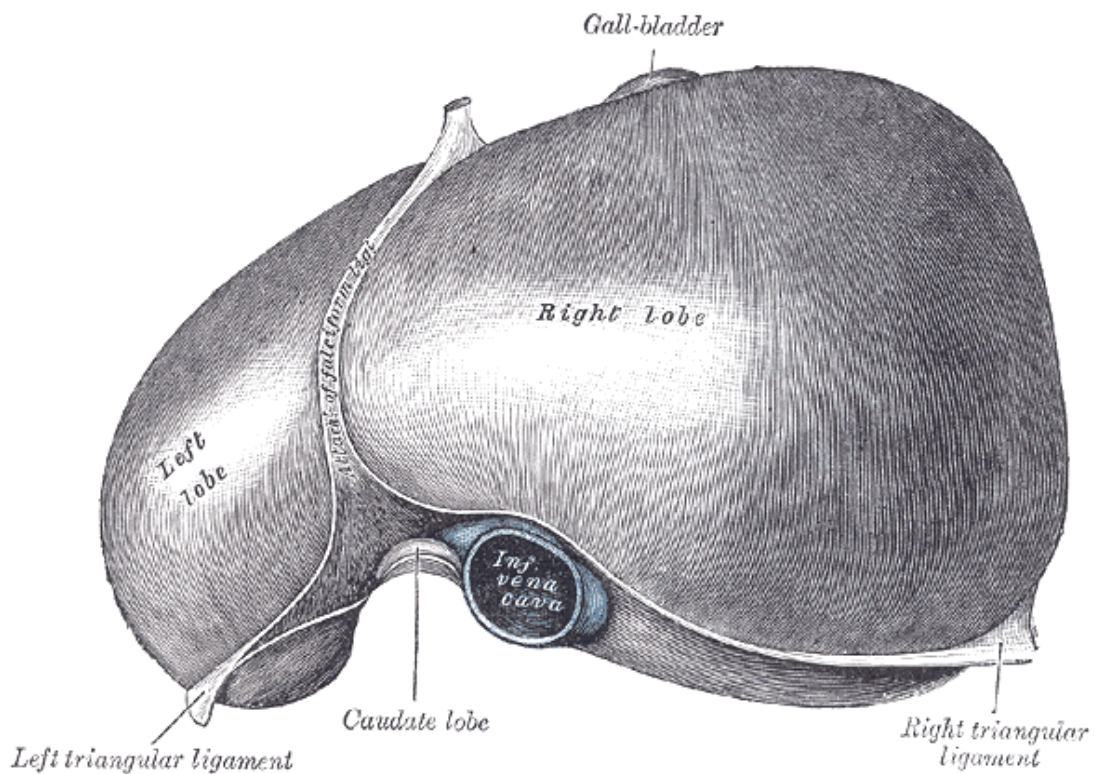
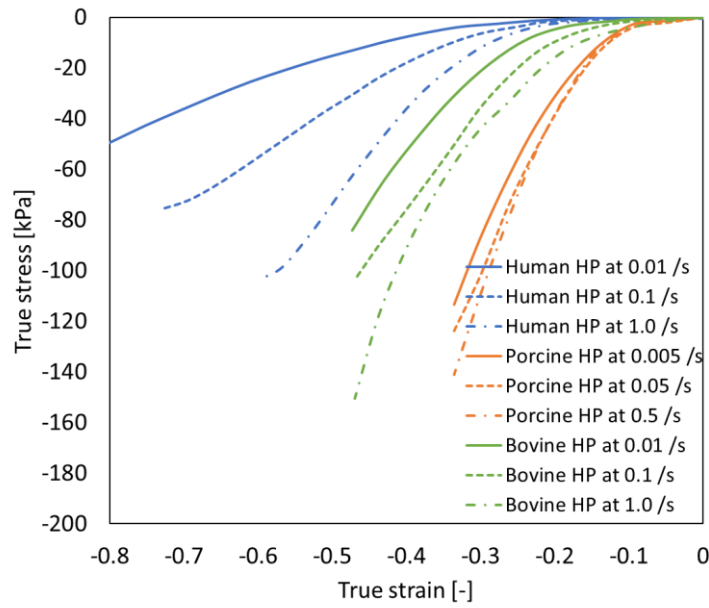
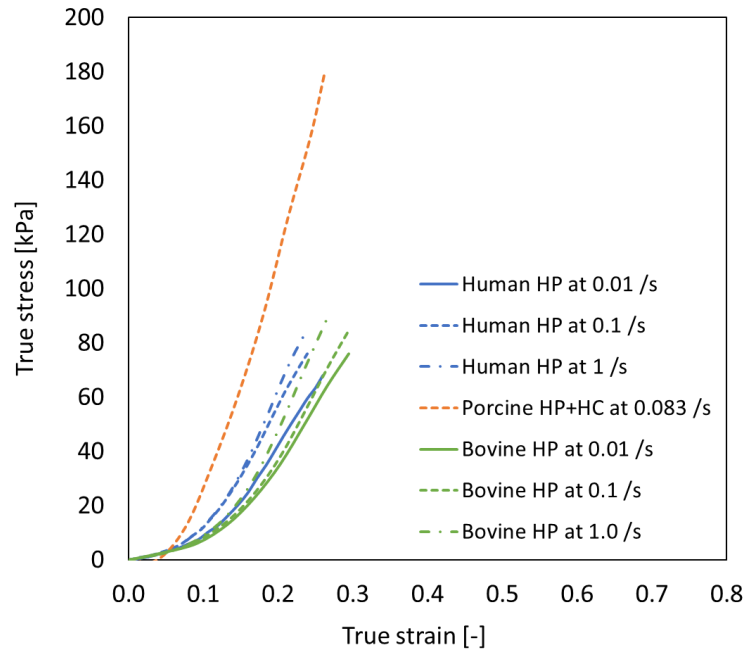


Figure 4.8 The schematic view of the human liver (Gray , Lewis, Warren H., 1918).



A



B

Figure 4.9 (A) Material properties of the hepatic parenchyma (HP) and hepatic capsule (HC) in uniaxial compression tests (Tamura *et al.*, 2002; Pervin, Chen and Weerasooriya, 2011; Kemper *et al.*, 2013) and (B) in uniaxial tensile tests (Kemper *et al.*, 2010; Lu, Kemper and Untaroiu, 2014; Duong *et al.*, 2015).

	Human liver	Porcine liver	Bovine liver
Strain rate [1/s]	0.089	0.083	0.1
Average failure stress [kPa]	76.71	182	54.68
Average failure strain [-]	0.25	0.26	0.19

Table 4.3 Average failure stress and strain of the human, porcine and bovine liver (Kemper *et al.*, 2010; Duong *et al.*, 2015; Dunford, LeRoith and Kemper, 2018).

4.5 Injury-risk curve

In this study, the cadaveric bovine liver and ovine heart are used to quantify the risk of penetrating injuries to hepatic and cardiac tissue, respectively. For the quantitative assessment of injury, injury-risk curves are commonly used to predict the probability of injury to the human body due to a physical insult (Figure 4.10) (North Atlantic Treaty Organization, 2007). The injury-risk curve represents the injury probability of a certain severity associated with a parameter of the physical response such as the deformation or force at a location within the human body. The severity of the injury is evaluated with injury scoring systems such as the AIS shown in Figure 4.10. To develop the injury-risk curves, clinical data or experimental data are commonly used (North Atlantic Treaty Organization, 2007).

In order to create the injury-risk curves, the clinical or experimental data are categorised as zero and one probability based on whether the resultant injury occurs at the parameter of a physical response (Figure 4.10). The transition between these binary data is statistically evaluated based on a maximum likelihood function and plotted as a S-shaped curve. This curve is generally accompanied with an upper and lower confidence interval so that the variability in the probability of injury can be predicted. This injury-risk curve, therefore, represents the quantitative assessment of injury and thus chosen to quantify a penetrating cardiac and hepatic injury in this study.

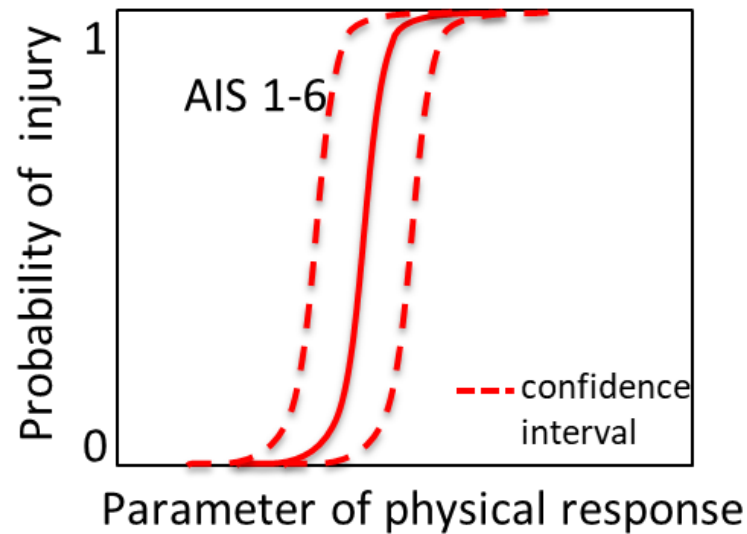


Figure 4.10 The example of an injury-risk curve; the curve represents the degree of injury severity using injury scoring systems such as AIS 1 (minor) – 6 (maximal).

4.6 Summary

This chapter has described a suitable platform and surrogate that can be used to achieve the aims of this study. The gas-gun system is suitable and will be used to propel the representative fragments of IEDs: 5-mm sphere, 0.78-g-RC cylinder and 1.1-g-CN cylinder to the target samples. The cadaveric bovine liver and ovine heart are chosen to establish injury-risk curves that can associate the severity of injury to the tissue with a physical parameter of the insult, such as speed at an impact of the fragment.

For the accumulation of experimental data in a non-biological laboratory and for testing protective equipment, the ballistic ordnance gelatine is a potential candidate for a human tissue surrogate of hepatic and cardiac response against blast fragments. In this study, the penetration responses of various concentrations of ballistic gelatine are compared with those of the cadaveric bovine liver and ovine heart to identify relevant biofidelic surrogates.

The next three chapters describe the quantitative assessment of a penetrating cardiac and hepatic injury, and the development of a more biofidelic tissue surrogate for hepatic and cardiac tissue.

CHAPTER 5

PENETRATING CARDIAC INJURY

Chapter 4 determined the appropriate platform and the cadaveric animal heart for studying penetrating cardiac injury. In this chapter, the three representative fragments in IEDs are shot into cadaveric lamb hearts to investigate the relationship between the penetration behaviour of the lamb heart and the striking velocity of the projectile. Ultimately, injury-risk curves are developed for each projectile, allowing for the quantitative assessment of a penetrating cardiac injury.

Parts of this chapter have been published:
Hirotaka Tsukada, Thuy-Tien N. Nguyen, John Breeze and Spyros D. Masouros,
The risk of fragment penetrating injury to the heart, *Journal of the Mechanical Behavior of Biomedical Materials*.

5.1 Introduction

Penetrating cardiac injury is a highly lethal event; the mortality rate - including stab wounds, gunshot wounds and secondary blast injuries - has been estimated at 94% before arrival at hospital and 50% in admitted patients (Campbell *et al.*, 1997). Energy loss of spherical projectiles through the porcine heart at striking velocities between 200 and 900 m/s has been reported before (Humphrey *et al.*, 2018a, 2018b), but it is unclear how these relate to the probability of human penetrating cardiac injury.

Historically, the assumption in injury models is that penetration anywhere near the heart is unsurvivable, which is an over-simplification. Newer models with higher fidelity incorporate individual anatomical structures, such as the heart, using human 3D geometries (Eisler *et al.*, 2006; J C Roberts *et al.*, 2007). These simulation models for the heart can be developed with the material properties of each organ, so the resultant injuries are predictable from the outcomes of the simulation. There, however, is no quantitative injury model such as an injury-risk curve in these models. Quantitative assessment of cardiac injuries can be conducted using a clinical scoring system such as the Abbreviated injury scale (AIS). In the AIS, cardiac laceration without perforation and perforation through the cardiac wall attain a score of 3 (serious) and 5 (critical), respectively (Gennarelli and Wodzin, 2008).

This study aimed to quantify the risk of a cardiac penetrating injury from a variety of relevant energised projectiles. Cardiac injury-risk curves were developed by accelerating fragments to a range of striking velocities upon fresh and freshly frozen lamb hearts.

5.2 Materials and methods

5.2.1 Sample preparation

Fresh lamb hearts were obtained from a local abattoir at the time of slaughter. The pericardium was removed from these samples where the veins and arteries were also dissected at a local abattoir. During transport, each sample was placed in a plastic

bag filled with cell culture solution, Dulbecco's Modified Eagle Medium (DMEM), and stored in an insulated bag with ice. Upon arrival at the laboratory, each sample was stored in the refrigerator and kept at 4 °C in DMEM until testing. All fresh lamb hearts were tested within 48 h of slaughter to minimise degradation of the tissue. Fresh-frozen lamb hearts were also used in this study. These samples without the pericardium were frozen at the time of slaughter; these were thawed fully at room temperature prior to testing.

5.2.2 Method

A 32-mm bore gas-gun system was used to propel a fragment simulating projectile (FSP) towards the target in Chapter 4 (Figure 5.1). The FSP was carried by the sabot and accelerated using compressed air. The FSP was detached from the sabot at the sabot stripper and impacted the sample. The striking velocity of the FSP was calculated from the footage of a high-speed camera with the recording resolution of 256×120 pixels and the sample rate of approximately 150k fps (Phantom VEO 710, Vision Research, United States).

The sample, in a thin plastic bag, was clamped onto the mounting apparatus as shown in Figure 5.1. The polycarbonate mounting apparatus had holes cut out at entrance and exit to allow the flight of the FSP through the tissue. To investigate the effect of the plastic bag, tests were performed on plastic bags filled at the bottom with 200 g of water, which was of similar mass to that of a lamb heart. The velocities of the 5-mm sphere before and after passing through the bag showed that the kinetic energy absorbed by the plastic bag was negligible for the tested range of striking velocities between 33 and 124 m/s (Table 5.1).

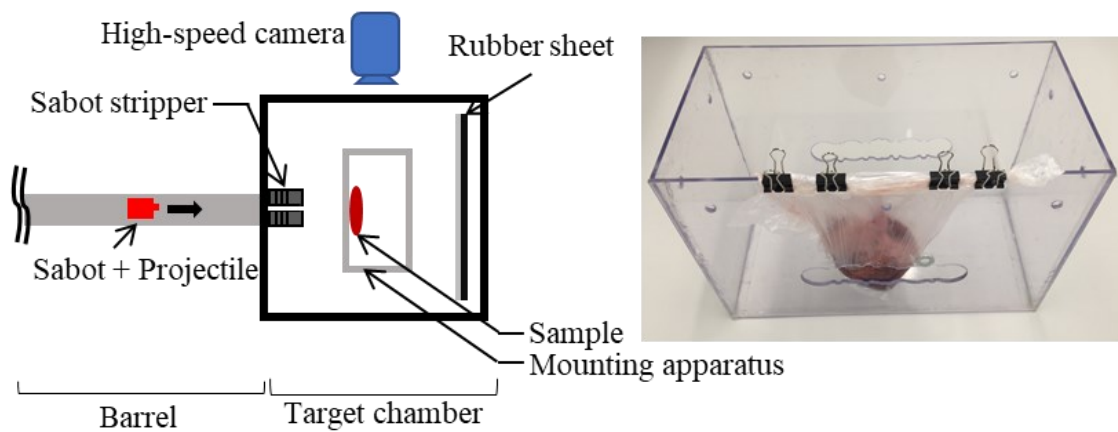


Figure 5.1 (left) A schematic of the 32-mm bore gas-gun system and (right) a photograph of mounting apparatus at the target chamber; the heart is placed in a plastic bag which is suspended with clips from a polycarbonate container.

Projectile		Striking velocity	Escape velocity	Energy loss
Shape	Mass [g]	[m/s]	[m/s]	[mJ]
Sphere	0.51	37.39	34.45	2.21
		92.49	90.87	0.66
		119.79	119.79	0

Table 5.1 Energy loss of the 5-mm sphere before and after passing through the plastic bag filled at the bottom with 200 g of water.

The FSPs were shot into the left and right side of the two cardiac walls, at ventricular and atrial locations (Figure 5.2 A). The tests were classified as no penetration, penetration into (commensurate with an AIS 3 injury), and perforation through the cardiac wall (commensurate with an AIS 5+ injury) (Figure 5.2 B-D). To optimise the use of samples, when considerably shallow penetration or no penetration was observed, an additional FSP was shot into the intact tissue away from the previous impact in the same cardiac wall.

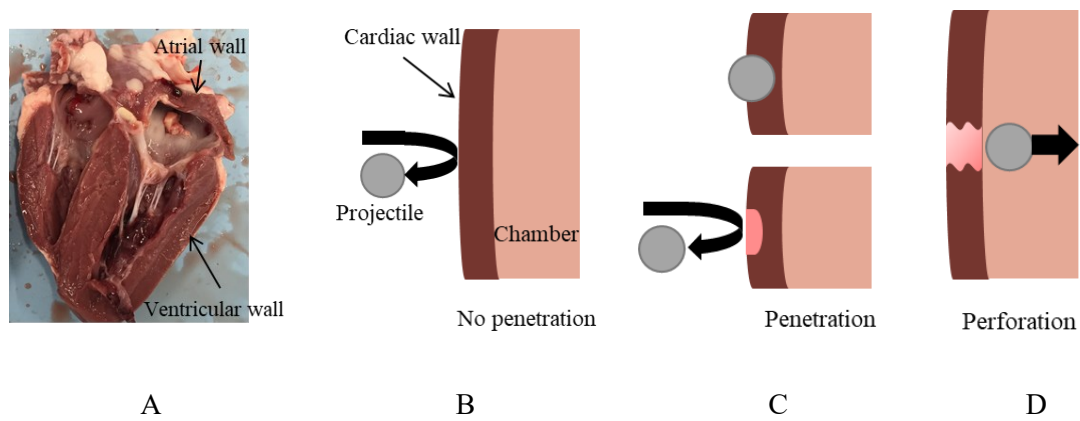


Figure 5.2 (A) Section through the lamb heart denoting the locations of atrial and ventricular walls. Test outcomes were classified as: (B) no penetration, when the projectile bounces off the cardiac wall without causing damage; (C) penetration, when the projectile penetrates the cardiac wall but does not come out the other end or when it bounces off the wall causing a shallow wound; and (D) perforation, when the projectile penetrates into and escapes from the cardiac wall into the chamber.

DoP was measured using radiography (Fluoroscanner InSight FD, Hologic Inc., United States). When the projectile perforated the cardiac wall and remained inside the sample (Figure 5.2 D), a small steel marker was placed at the entrance of the penetrating wound, and the sample was scanned on the top, side and front surface. In each scan, an X-ray beam with divergence is emitted towards the image receptor; consequently, the sample is magnified on the scanned image. The measurement of DoP in each orthogonal view was calibrated based on a known dimension such as the diameter of the steel marker or the retained projectile.

DoP was calculated from the distances between the entrance hole (x_1, y_1, z_1) and the furthest end of the retained projectile (x_2, y_2, z_2) obtained from the three orthogonal scans shown in the 3D coordinate (Figure 5.3).

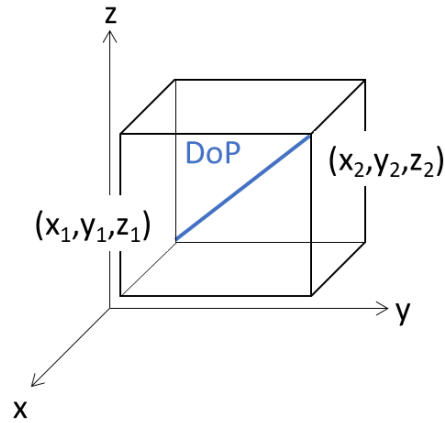


Figure 5.3 The DoP of the sample presented as the 3D coordinate system.

From these three orthogonal scans, the distances of 2D plane d_{xy} , d_{yz} and d_{xz} are written as

$$d_{xy} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

$$d_{xz} = \sqrt{(x_2 - x_1)^2 + (z_2 - z_1)^2} \text{ and} \quad \text{Equation 5.1}$$

$$d_{yz} = \sqrt{(y_2 - y_1)^2 + (z_2 - z_1)^2}$$

DoP in the 3D coordinate is shown as the following formula:

$$DoP = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad \text{Equation 5.2}$$

Each distance squared of 2D plane (Equation 5.1) is added and replaced with the DoP in the 3D coordinate (Equation 5.2):

$$d_{xy}^2 + d_{xz}^2 + d_{yz}^2 = 2\{(x_2-x_1)^2 + (y_2-y_1)^2 + (z_2-z_1)^2\} \quad \text{Equation 5.3}$$

$$d_{xy}^2 + d_{xz}^2 + d_{yz}^2 = 2DoP^2 \quad \text{Equation 5.4}$$

$$DoP = \sqrt{\frac{d_{xy}^2 + d_{xz}^2 + d_{yz}^2}{2}} \quad \text{Equation 5.5}$$

In this study, DoP in the 3D coordinate system was calculated from the distances of 2D plane d_{xy} , d_{xz} and d_{yz} (Equation 5.5) derived from the radiography.

In order to statistically compare DoP in each experimental condition, DoP as a function of the striking velocity was fitted with a linear regression:

$$DoP = \alpha SV + \beta \quad \text{Equation 5.6}$$

where DoP is penetration depth [mm], SV is the striking velocity of a projectile [m/s], and α and β are the slope coefficient and the y-intercept of the linear regression, respectively. For the comparison of the three projectiles assessed here, energy loss during the penetration normalised with the projectile mass m was defined as energy loss density ELD ;

$$ELD = \frac{m (SV^2 - RV^2)}{2 m} = \frac{SV^2 - RV^2}{2} \quad \text{Equation 5.7}$$

where RV shows residual velocity. The residual velocity becomes zero when the projectile penetrated into the sample but did not escape from the whole sample. In order to ascertain the effect of a freeze-thaw cycle and of impact locations on penetration behaviour, 5-mm spheres were shot into different locations of both fresh and frozen-thawed lamb hearts. The linear regressions of the DoP over striking velocities were compared using the statistical software SPSS (version 28, IBM, United States). An analysis of covariance (ANCOVA) was performed using the general linear model univariate procedure to obtain the p-values of their slopes and y-intercepts.

Survival analysis was carried out using the statistical software NCSS (v11, NCSS, United States) to establish injury-risk curves representing the injury probability as a function of the striking velocity. Prior to the survival analysis, a best fit analysis was performed with all experimental data to determine the statistical model of the injury-risk curves based on maximum likelihood values. The normal distribution was identified as the most suitable model for the survival analysis. The corridor of the injury-risk curve was estimated using the 95% confidence interval (CI); when the 95% CI could not be calculated from the survival analysis due to no overlapping data points between striking velocities resulting in tissue perforation and not, the corridor was estimated with the standard deviation using the method suggested in the AEP-2920 NATO standard (NATO Standardization Office, 2015). To compare statistically tissue resistance to perforation between the different locations on the cardiac wall and between storage conditions, the striking velocities at 50% probability of perforation through the cardiac wall (V_{50}) were used and the independent Student's t-test was performed from the arithmetic mean according to the AEP-2920 NATO standard (NATO Standardization Office, 2015). To ascertain whether injury-risk curves of all impact scenarios can be combined in each projectile group, the z-test was performed on striking velocities in the range between 1% and 99% probability of an AIS 5+ injury. The parameters of the z-test such as population mean and 95% CI were obtained from the outcome of the survival analysis.

5.3 Results

Fifty-five lamb hearts were used to conduct 159, 56 and 53 impact tests using the 5-mm sphere, the 0.78-g-RC cylinder and the 1.1-g-CN cylinders, respectively (Table 5.2). The left and right of each cardiac wall were targeted in this test; the average thickness of each cardiac wall is shown in Table 5.3.

Sample storage	Projectile	Number of tests			
		Left ventricle	Right ventricle	Left atrium	Right atrium
Fresh	Sphere	33	42	16	12
	Sphere	15	14	14	13
Freeze/thaw	RC cylinder	13	14	13	16
	CN cylinder	13	17	15	8

Table 5.2 Number of impact test conducted per storage condition, fragment used, and target location. RC: right-circular, CN: chisel-nosed

Sample	Thickness			
	Ventricular wall [mm]		Atrial wall [mm]	
	Left	Right	Left	Right
Lamb heart	14.05 ± 2.94	8.50 ± 1.70	4.43 ± 1.98	2.91 ± 1.38
Human heart	12.46 ± 3.84*	4 ± 1*	2.4 ± 0.7*	2.7 ± 0.7*

Table 5.3 The thickness of ventricular and atrial walls (mean ± one standard deviation).

* The thickness of the human ventricular wall was obtained from existing studies (Foale *et al.*, 1987; Sommer *et al.*, 2015; Varela *et al.*, 2017).

5.3.1 Effect of storage and impact conditions

DoP as a function of the striking velocity was measured for the shots whereby the projectile perforated the cardiac wall and came to rest inside the heart. Figure 5.4 represents DoP as a function of the striking velocity and cardiac wall perforation V_{50} values using the 5-mm sphere shot into the left and right cardiac walls of the fresh samples. There were no significant differences ($p \geq 0.05$) between the two slopes, intercepts, and V_{50} values of the left and right cardiac walls.

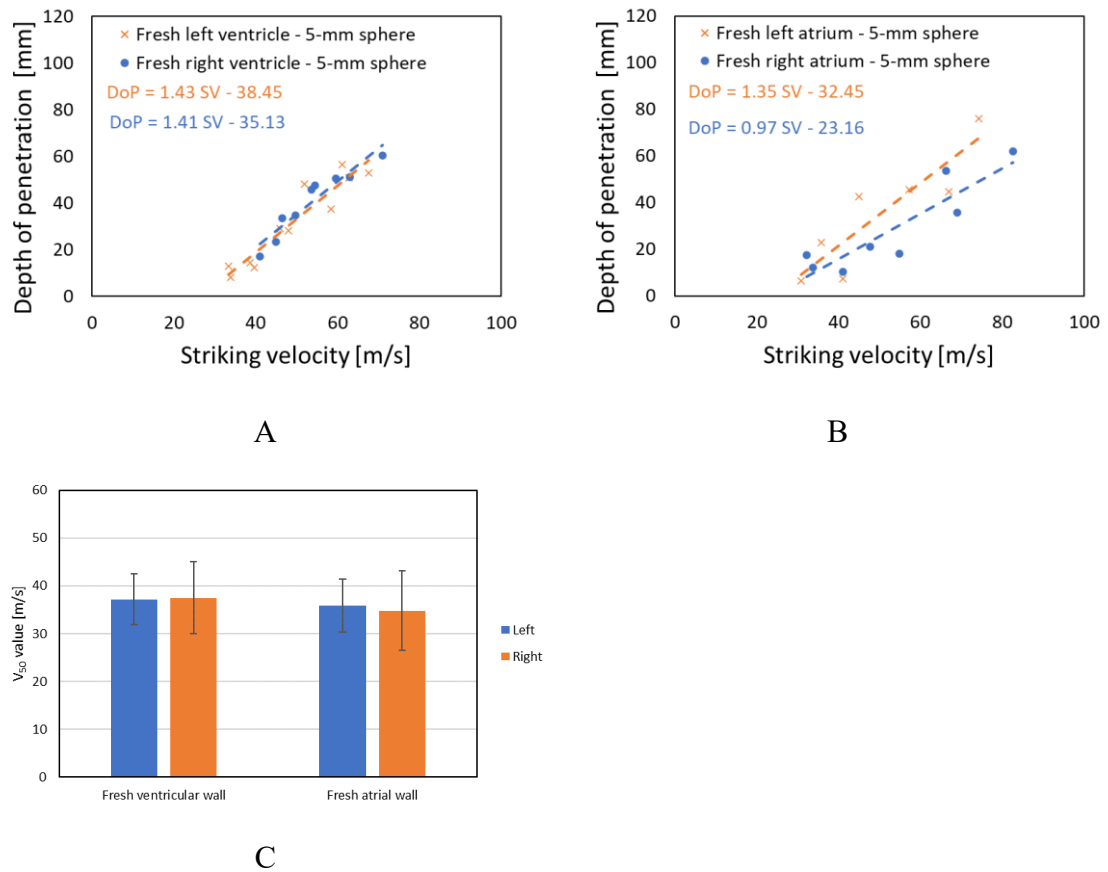


Figure 5.4 (A) The DoP using the 5-mm spheres shot into the left and right ventricle of the fresh heart, and (B) the left and right atrium of the fresh heart; (C) shows V_{50} values for cardiac wall perforation by the 5-mm spheres impacting different locations of the fresh heart, with one standard deviation (error bars) as obtained from the method suggested in the AEP-2920 NATO standard (NATO Standardization Office, 2015).

Table 5.4 shows the comparison of the slopes of DoP over FSP-striking velocity and their y-intercepts using the 5-mm spheres for different locations (ventricle and atrium) and storage conditions (fresh and frozen-thawed). There were no significant differences between any pairs of data sets.

Storage and impact location		Fresh		Freeze and thaw	
		Ventricle	Atrium	Ventricle	Atrium
Fresh	Ventricle		0.14/0.28	0.77/0.58	0.80/0.44
	Atrium	0.14/0.28		0.66/0.84	0.52/0.27
Freeze and thaw	Ventricle	0.77/0.58	0.66/0.84		0.98/0.44
	Atrium	0.80/0.44	0.52/0.27	0.98/0.44	
No significance $p \geq 0.05$					

Table 5.4 Tests of statistical significance under the two storage conditions using the 5-mm sphere projectiles; p-values for slope and y-intercept of linear regression derived from the DoP versus striking velocity graphs are shown in this table, respectively.

Figure 5.5 shows the injury-risk curves for an AIS 5+ injury for the 5-mm sphere between the fresh ventricle and fresh atrium; the frozen-thawed ventricle and frozen-thawed atrium; and the fresh and frozen-thawed sample for both impact locations. In Figure 5.5 A and C, these striking velocities between 1% and 99% probability of an AIS 5+ injury were statistically compared using the z-test estimated from the 95% CI. There were no significant differences ($p \geq 0.05$) between these velocity values suggesting that there was no difference between the risk curves for the fresh ventricular and atrial walls, and for the fresh and frozen-thawed conditions. In Figure 5.5 B, the 95% CI of the frozen-thawed atrium could not be evaluated due to no overlap data between 0 and 1 probability of an AIS5+ injury. Therefore, these corridors were not statistically comparable despite achieving no significance between the V_{50} values of the frozen-thawed ventricle and atrium.

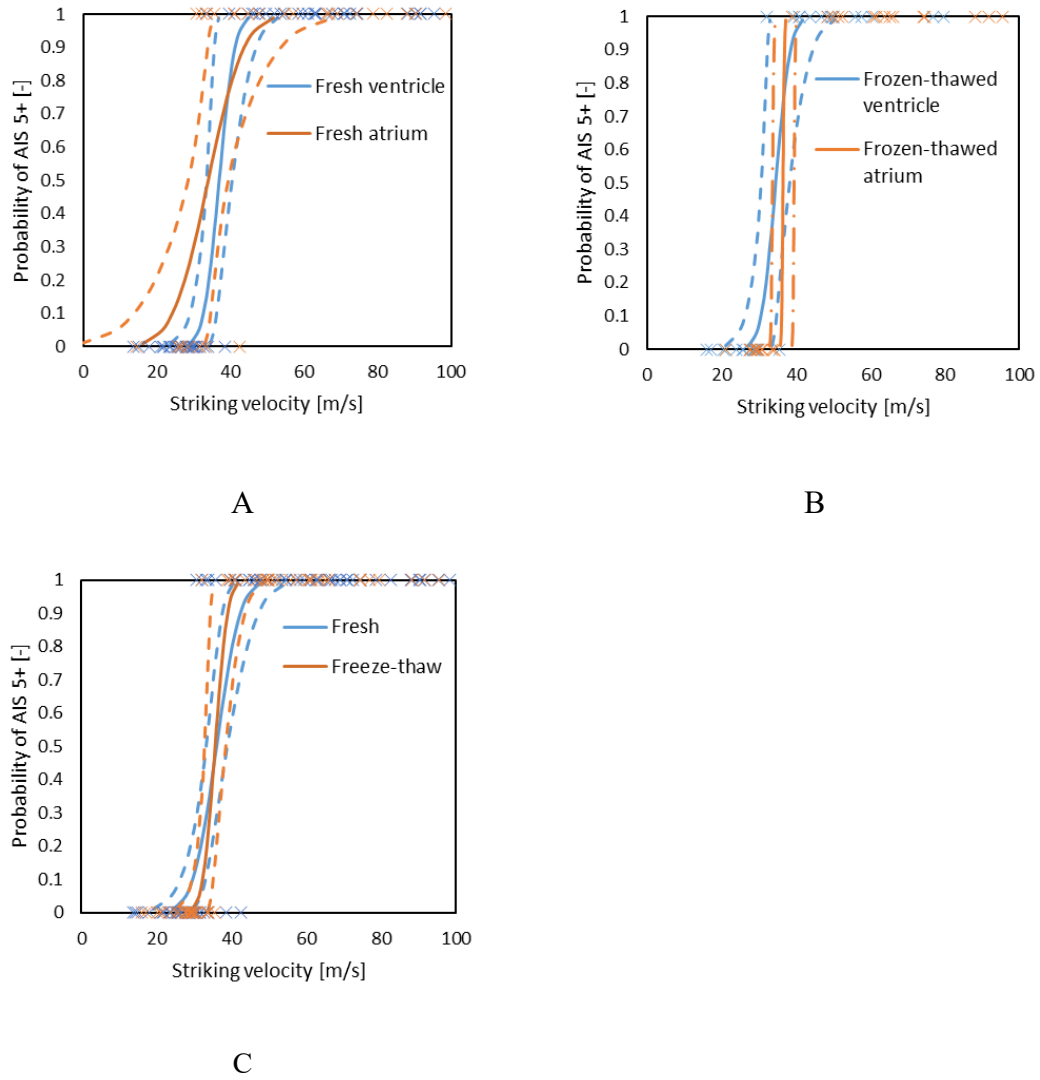


Figure 5.5 (A) The injury-risk curves of AIS 5+ for the 5-mm sphere into the fresh ventricle and fresh atrium, (B) into the frozen-thawed ventricle and frozen-thawed atrium and (C) into the overall fresh and overall frozen-thawed sample whereby ‘overall’ indicates the combined data for both impact locations; the 95% confidence interval and standard deviation corridor of each injury-risk curve are shown with dashed lines and dash-dotted lines, respectively. Cross marks at zero and one represent no perforation and perforation of the cardiac wall obtained from the experiments, respectively.

5.3.2 Overall ballistic response of cardiac tissue

Figure 5.6 shows the combined DoP of the overall ventricle and atrium impacts as a function of the striking velocity for each FSP. The slopes and y-intercepts obtained from tests on ventricular and on atrial walls had no statistical differences ($p \geq 0.05$) for each FSP. Therefore, the linear regression of each graph was estimated from the combined data set of both impact locations. In order to compare the three projectiles, DoP as a function of the energy loss density is shown in Figure 5.7. In this graph, the same datapoints of Figure 5.6 were used so all residual velocities became zero in Equation 5.7.

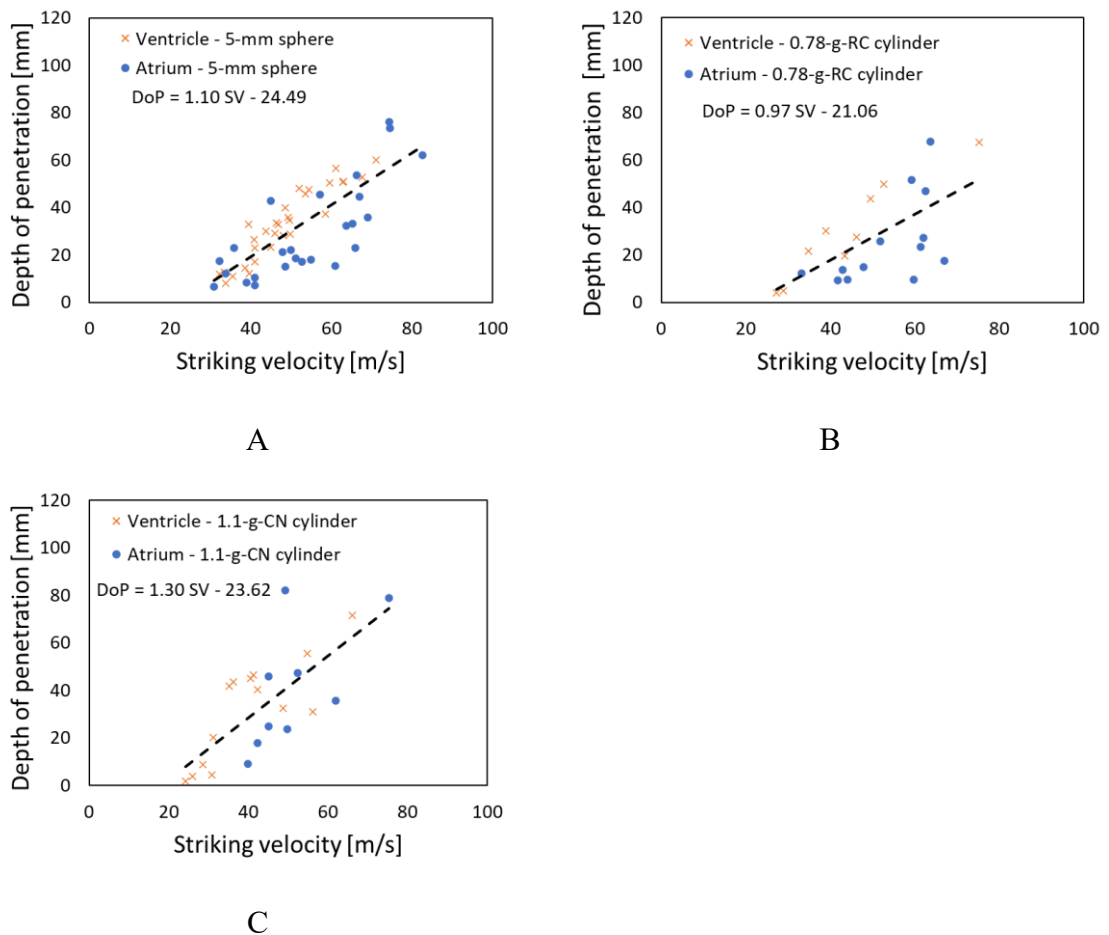


Figure 5.6 (A) The DoP into both the fresh and frozen-thawed heart samples using the 5-mm spheres, (B) the frozen-thawed heart samples using the 0.78-g RC cylinders, and (C) the frozen-thawed heart samples using the 1.1-g CN cylinders. Linear regressions were produced from data of both impact locations

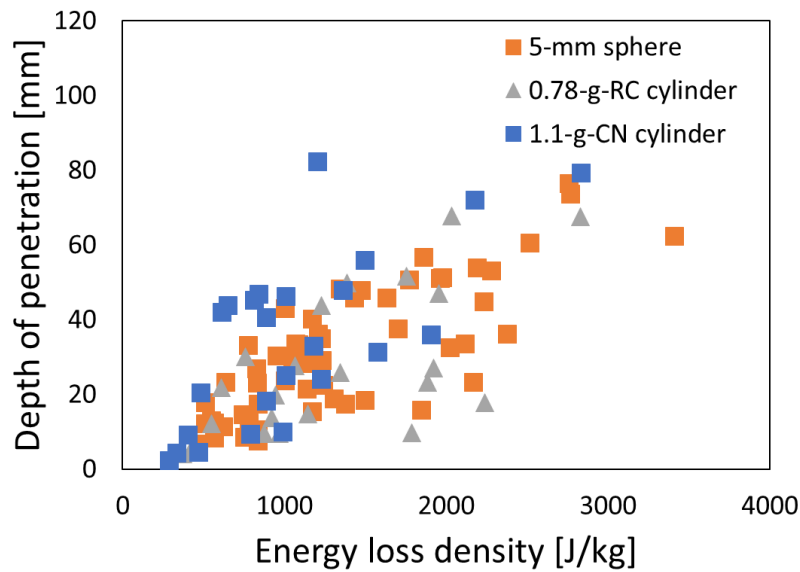


Figure 5.7 The DoP as a function of the energy loss density.

The injury risk curves for the 5-mm sphere were compared between AIS 3+ and AIS 5+ injury (Figure 5.8). In the range of 1 to 99% probability of injury, the striking velocities for penetration into (AIS 3+) and perforation through the cardiac wall (AIS 5+) for the 5-mm sphere were not statistically different (z-test, $p \geq 0.05$).

Figure 5.9 and Figure 5.10 show the injury-risk curves of each cardiac wall and of the overall cardiac wall for an AIS 5+ injury, respectively. The V_{50} values (mean $\pm$ standard deviation) of the overall cardiac wall (Figure 5.10) were 36.1 ± 4.2 m/s for the 5-mm sphere, 33.9 ± 4.8 m/s for the 0.78-g-RC cylinder, and 31.1 ± 3.9 m/s for the 1.1-g-CN cylinder.

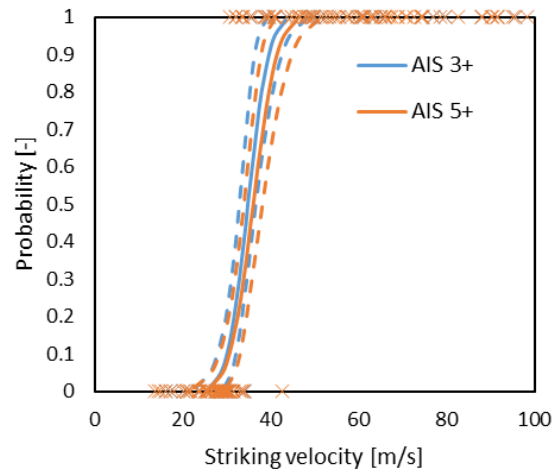
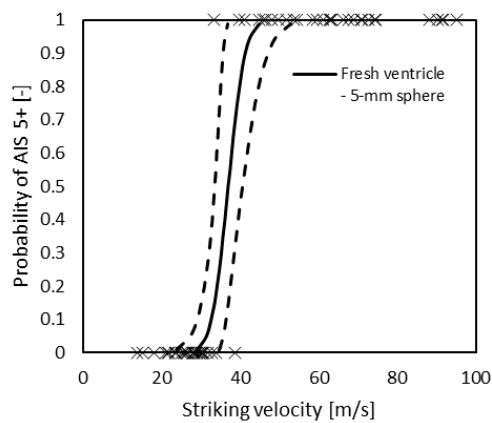
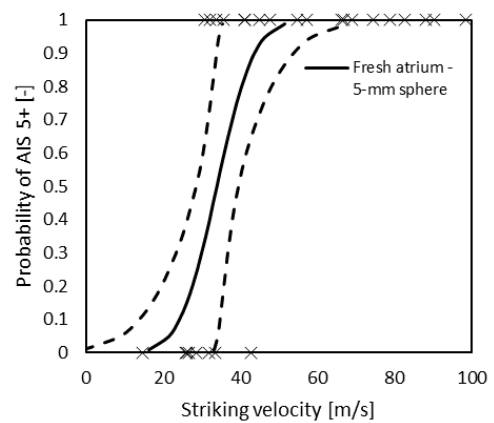


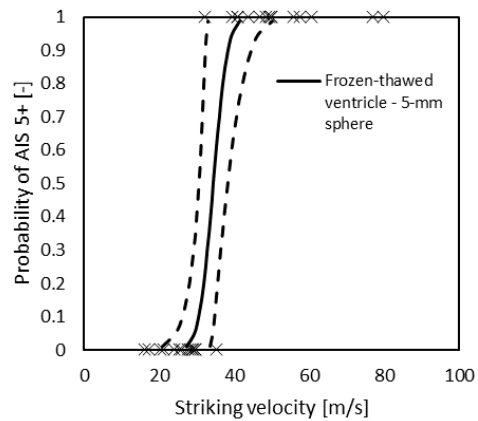
Figure 5.8 The injury-risk curves of AIS 3+ and AIS 5+ for the 5-mm sphere into the overall fresh sample; the 95% confidence interval corridor of each injury-risk curve is shown with dashed lines. Cross marks represent no perforation at zero and perforation at one.



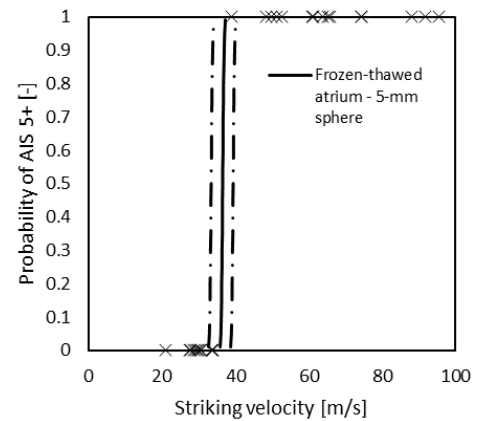
A



B



C



D

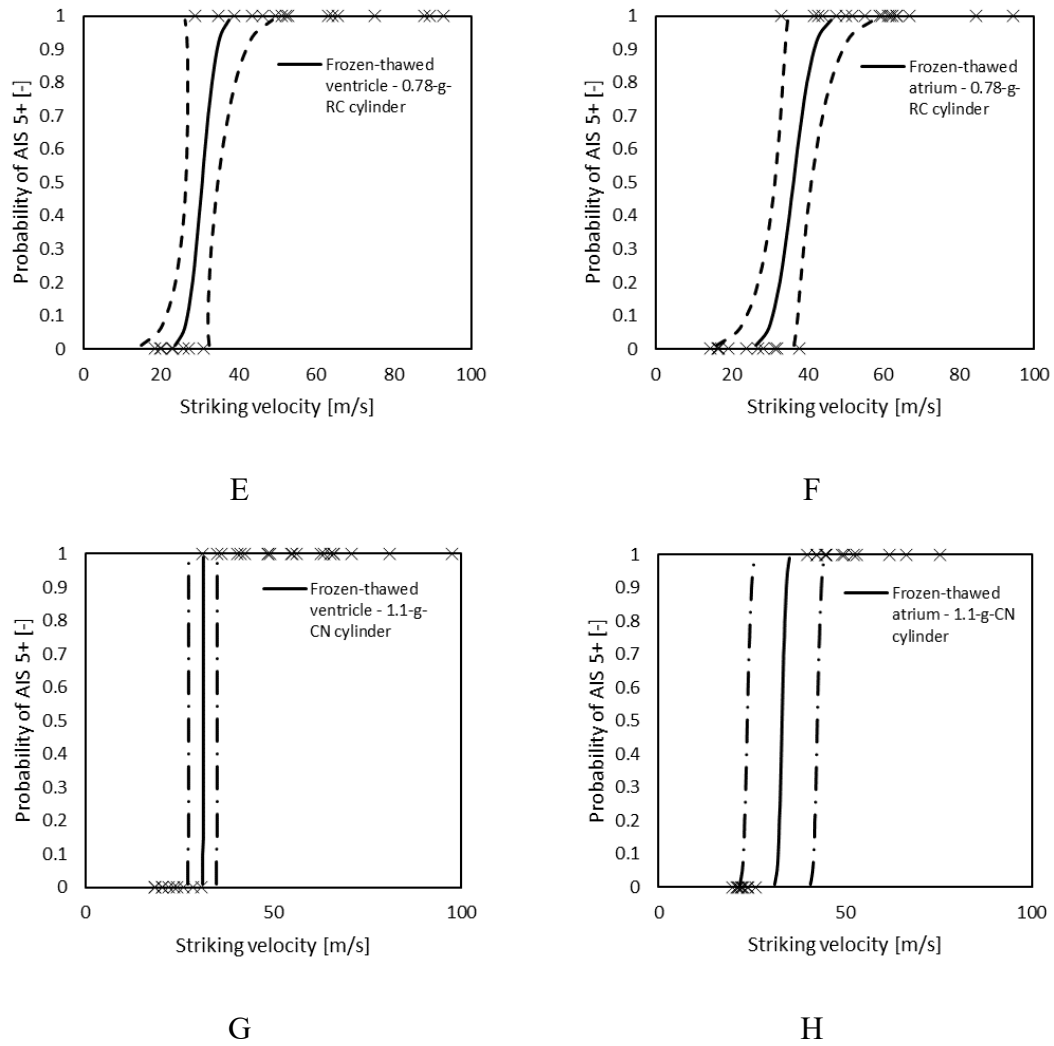


Figure 5.9 (A) The injury-risk curves of an AIS 5+ injury for the 5-mm sphere into the fresh ventricle and (B) the fresh atrium; (C) for the 5-mm sphere into the frozen-thawed ventricle and (D) the frozen-thawed atrium; (E) for the 0.78-g-RC cylinder into the frozen-thawed ventricle and (F) the frozen-thawed atrium; and (G) for the 1.1-g-CN cylinder into the frozen-thawed ventricle and (H) the frozen-thawed atrium. The corridor of the injury-risk curve shown with the dashed lines and dash-dotted lines indicates the 95% confidence interval and the standard deviation, respectively. Cross marks represent no perforation at zero and perforation at one.

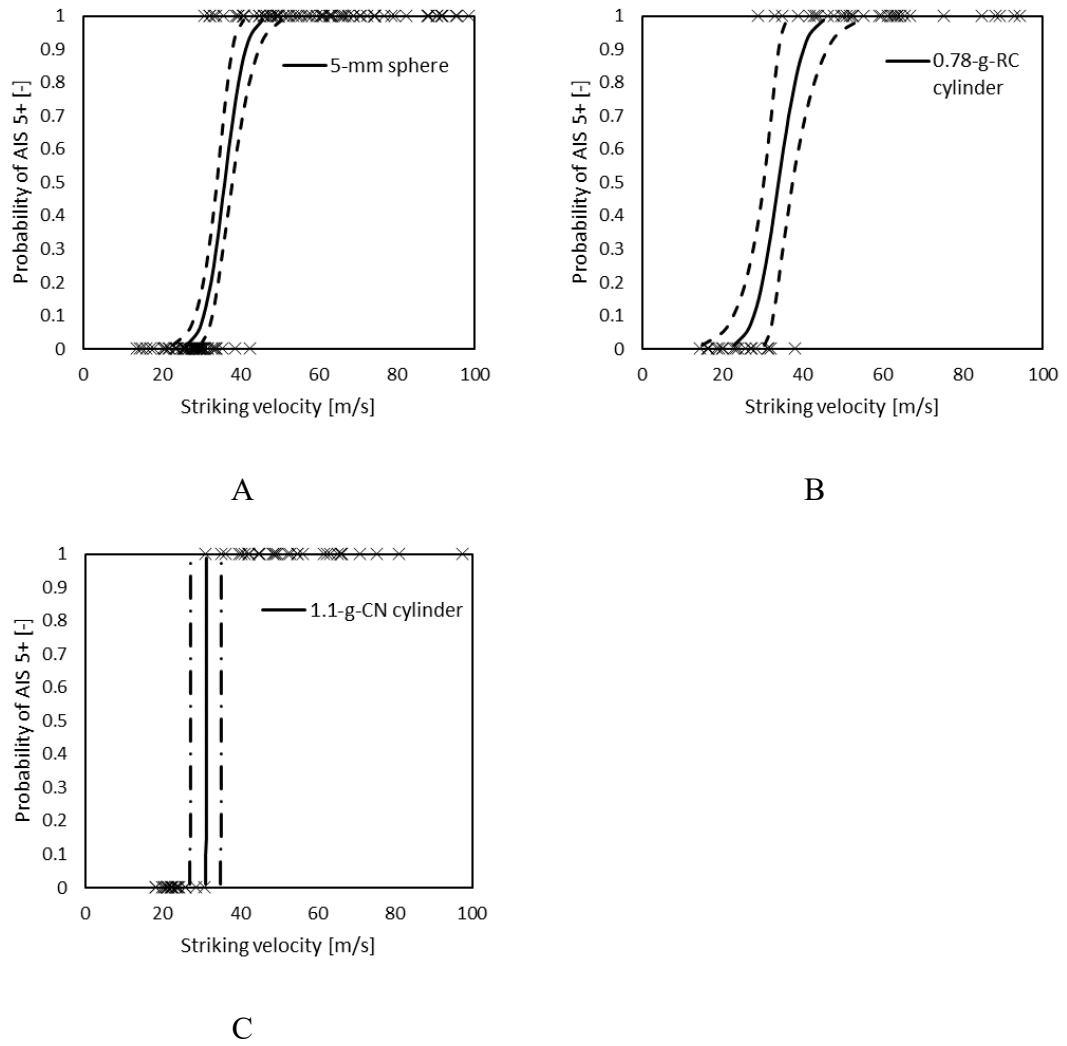


Figure 5.10 The injury-risk curves of an AIS 5+ injury (A) for the 5-mm sphere into both the fresh and frozen-thawed heart, (B) for the 0.78-g-RC cylinder into the frozen-thawed heart, and (C) for the 1.1-g-CN cylinder into the frozen-thawed heart. The corridor of each injury-risk curve is denoted with dashed lines and dash-dotted lines representing the 95% confidence interval and the standard deviation. Cross marks represent no perforation at zero and perforation at one.

5.4 Discussion

This study is the first to quantify the risk of penetrating injury into cardiac tissue using 3 types of FSP. The results show that relatively low striking velocities can cause perforation through the cardiac wall commensurate with an injury which is likely to be critical; the V_{50} value of perforation through the cardiac wall into the chamber was approximately half that into the intercostal muscles against the 0.78-g-RC cylinder (33.9 vs. 66 m/s) (Nguyen, Breeze and Masouros, 2022). The striking velocity of projectiles was calculated from the footage of the high-speed camera. The camera setting was determined as the maximum sampling rate (approximately 150k fps) at the recording resolution of 256×120 pixels. In this camera setting, the measurement error of the striking velocity mostly depends on the recording resolution; thus, it is approximately 2 m/s.

The retardation of the projectile was found to be similar when the projectile impacted ventricular or atrial walls (Figure 5.4 and Table 5.4). Even though the trajectory of the projectile post perforation was dependent on impact location, no significant differences were found in the slopes of DoP against striking velocity and their y-intercepts between all impact locations. These findings support that the data sets of both ventricle and atrium impacts, for both left and right sides, can be combined into a single linear regression (Figure 5.6). Some projectiles struck the atrium at the dense connective tissue of the cardiac valve adjacent to the atrial wall. This likely lead to the larger variances of the slopes of the DoP against striking velocity in the atrium impacts, compared to those in the ventricle impacts. The large variance in the DoP of a cylindrical projectile is likely due to the change of the projectile's yaw angle post impact and subsequent tumbling during tissue penetration (Bellamy, 1990).

Cardiac laceration with no perforation – classified as an AIS 3 injury (Gennarelli and Wodzin, 2008) – was seen infrequently in this study suggesting that it is an unlikely injury pattern to occur in this mechanism. There were no significant differences between the striking velocities for penetration into (AIS 3+) and perforation through the cardiac wall (AIS 5+) for the 5-mm sphere (Figure 5.8). This suggests that the projectile is highly likely to perforate the cardiac wall if it manages to

cut through the surface. Similarly, despite the different thicknesses of ventricular and atrial walls (Table 5.3), there were no significant differences between the striking velocities at various risks of perforation through ventricular and atrial walls (Figure 5.5). This suggests that resistance to perforation through the cardiac wall is similar irrespective of impact location. Therefore, it was possible to combine these data sets to establish a single injury-risk curve for each projectile regardless of the impact location.

Some studies report that the material properties of soft tissue are influenced by a freeze-thaw cycle partly due to the expansion of the water inside the tissue damaging its structure during freezing (Santago *et al.*, 2009; Duong *et al.*, 2015). Others have found that the material properties of leg ligament and the energy absorption of projectile penetration into the muscle tissue are unaffected by a freeze-thaw cycle (Woo *et al.*, 1986; Breeze *et al.*, 2015). The results in this study show that the slopes and y-intercepts of DoP against striking velocity and the risk of perforation had no statistical differences across storage conditions. Therefore, one freeze-thaw cycle in this study did not affect the penetration and perforation behaviour into cardiac tissue, which agrees with the findings of the previous study on penetration through muscle tissue (Woo *et al.*, 1986; Breeze *et al.*, 2015).

The lamb heart in this study was inserted inside a plastic bag and clamped onto the mounting apparatus without backing material behind the sample (Figure 5.1 right). We deemed this mounting to be acceptable in its ability to simulate the *in situ* condition during fragment penetration, as the posterior surface of the heart lies against the aortic arch and spine and so would be loosely supported by these organs in a case of a posterior displacement. The high-speed camera footage of the experiment indeed showed consistently negligible displacement of the heart for the duration of the projectile's motion (that is, till it came to rest in the cardiac wall, within the heart after perforation, or till it bounced off the cardiac wall), thus confirming that the exclusion of a backing material in our setup did not affect the penetration behaviour.

Mass and geometry of FSPs are parameters shown to affect levels of tissue damage (Breeze, James and Hepper, 2013) and thus were expected to influence the V_{50} values and the injury-risk curves. Therefore, extensive testing incorporating FSPs spanning relevant mass and geometry envelopes would be required to develop relevant

injury-risk curves. Alternatively, the energy loss density in Figure 5.7 might be used to roughly predict the DoP of another projectile which has similar mass and shape to the three projectiles assessed in this study. The choice of FSPs in this study was based on field data and standard practice in the assessment of armour. In the Boston Marathon bombing, 17 fragments were found in the body of casualties and 5 ball bearings were estimated at approximately 5-mm of diameter using CT scans (Singh, Sodickson and Abujudeh, 2016). During UK military operations in Afghanistan, 16 fragments were excised from the neck of soldiers and 8 fragments were identified as cylinders with a mean mass of 0.78 g (Breeze, Leason, *et al.*, 2013). Accordingly, the 5-mm steel sphere and 0.78-g-RC steel cylinder were considered representative of fragments to study penetrating injuries. Although less relevant to data from recent explosive events, the 1.1-g-CN steel cylinder is widely used in ballistic tests and recommended in the AEP-2920 NATO standard (NATO Standardization Office, 2015). Hence, it was also included in this study to allow for comparisons within the defence community with existing, albeit commercially sensitive, data from test houses.

IED fragments would be expected to reach a casualty and the curved boundaries of the heart across a range of yaw angles. A low yaw angle at impact would be retarded during penetration less than a high yaw angle, thus leading to greater DoPs and lower V_{50} values. This study focused on the worst-case scenario, which is associated with low yaw angles. The orientation of the projectile at the sample was observed using a high-speed camera. Impacts by the cylindrical projectile at high yaw angles ($> 60^\circ$) were therefore removed from the experimental data here, also due to the high probability of them tumbling during penetration.

Use of a cadaveric animal model to infer behaviour of living human tissue is a limitation of the study. The lamb heart was chosen because the thickness of its ventricular wall and material properties are closer to those of the human heart compared to other animals (Foale *et al.*, 1987; Karimi, Moghaddam and Rezazadeh, 2008; Ghaemi, Behdinin and Spence, 2009; Wang *et al.*, 2010; Sommer *et al.*, 2015; Javani, Gordon and Azadani, 2016; Omann *et al.*, 2019). The use of fresh and fresh-frozen cadaveric tissue intended to limit any tissue degradation. The muscle tissue in the heart stiffens immediately after death (Shedge *et al.*, 2021) so even the fresh cardiac muscle does not replicate behaviour of living muscle tissue. Therefore, it is

likely that the V_{50} values calculated here were slightly underestimated based on this change in material properties. Lower striking velocities than this study may cause blunt injury to the heart. Existing studies suggest that the blunt cardiac injury caused bruise and ischaemia; the most severe condition is the cardiac arrest leading to sudden death (Kunz *et al.*, 2011; Link, 2012). These resultant injuries are associated with a biological reaction, which can not be observed in the cadaveric heart.

Furthermore, in the cadaveric animal model there was air instead of blood inside the cardiac chambers; the difference in density of the two fluids could have affected the observed DoP. The effect of the presence of blood on the projectile is estimated from the equation of motion and the drag force:

$$m \frac{dv}{dt} = -\frac{1}{2} C_D A \rho v^2 \quad \text{Equation 5.8}$$

where m , v and A are projectile mass, velocity and the cross-section of a projectile. C_D and ρ are drag coefficient (0.47 for sphere) and the density of the blood (1025 kg/m³). From this equation of motion for the 5-mm sphere with an initial velocity of 50 m/s, the estimated DoP of the blood-filled chamber was 5 mm less than that of the air-filled chamber; hence, the DoP of this study was likely slightly overestimated. Approximately 120 ml of blood exist in each ventricle at the end of the diastole (Hall *et al.*, 2021). The periodical change of the overall mass of the heart in itself we estimate would have a minimal effect on the penetration resistance values because of the negligible displacement of the heart that we saw in the high-speed video footage during projectile penetration. During the systolic and diastolic cycles, the periodical change of the cardiac wall stress, observed to be between 4 and 17 kPa in the left ventricle (Alter *et al.*, 2016), would likely affect the V_{50} values; specifically, we estimate that tension in the wall would result in a lower V_{50} value. Indeed, investigating how such an increase in cardiac wall stress affects the V_{50} value should be considered in future research.

In this test, the pericardium was removed from the samples. The human pericardium is made of muscle tissue but is only 0.55 mm thick; hence, this thickness

is within the one standard deviation of the lamb cardiac wall thickness and approximately 5% and 15% of the lamb ventricular and atrial wall thickness (Table 5.3), respectively. Moreover, the material properties of the human pericardium were approximately close to those of the ventricular wall shown in Figure 4.7 (Lee *et al.*, 1987). Therefore, the effect of the pericardium was expected to be negligible, but further study will be needed to quantify penetrating cardiac injuries more accurately.

5.5 Conclusion

The study presented in this chapter is the first quantitative assessment of cardiac penetrating injuries from energised fragments. A 50% probability of DoP commensurate with a critical injury to the heart was found to occur with fragment striking velocities of only 31 to 36 m/s. Striking location was shown to not affect the probability of injury. The data from this study can be implemented directly into computational models of injury prediction for mass-casualty events and so inform the design of infrastructure, of protocols for emergency responses, and for personal protective equipment. In the next chapter, penetrating hepatic injuries are quantified using cadaveric bovine livers.

CHAPTER 6

PENETRATING HEPATIC INJURY

In chapter 3, the liver and heart were found to be at a high risk of severe penetrating injury among torso organs. Chapter 4 investigated the material properties and dimensions of the liver in large animals available for testing in the laboratory. The bovine liver was chosen as the specimen in this study due to the similar material properties to the human liver. In this chapter, the DoP and V_{50} values in bovine liver blocks - similar in dimensions to those of the human liver – were obtained to develop injury-risk curves using a similar experimental method to that in Chapter 5 for quantifying a penetrating cardiac injury.

6.1 Introduction

Liver tissue disruption extends through the surrounding tissue of the permanent wound cavity (Fackler *et al.*, 1984). The mechanism by which this extended tissue disruption occurs is thought to be the expanding and contracting movements of the temporary wound cavity. There is no study quantifying how this mechanism affects hepatic tissue, but Fackler *et al.* reported a bullet impact at 905 m/s into the abdomen of a living swine caused larger tissue disruption in the liver (approximately 13 cm in diameter) than in muscle, bowel wall and lung (Fackler *et al.*, 1984).

The irreversible tissue damage in fresh muscle can be analysed at a microscopic level. The aforementioned tissue disruption was macroscopic and observable in a cadaveric organ (Fackler *et al.*, 1984; Fackler, Bellamy and Malinowski, 1988). Few studies conducted histology to identify the microscopic tissue disruption around the permanent wound cavity in fresh porcine legs within 30 minutes of slaughter (Korać, Crnica and Božo, 2006) and the muscle tissue of living swine (Li *et al.*, 2015). Confocal microscopy on the other hand can identify cellular changes with live and dead fluorescent stains. For instance, propidium iodide stain cannot penetrate live cells and binds to dead cells. As mentioned in Chapter 3, the level of these microscopic tissue changes could indicate irreversible tissue damage.

The quantitative assessment of a penetrating hepatic injury plays a key role in the accurate prediction of injury. The AIS system categorises the hepatic laceration of more than 3 cm as score 3 (serious); and 25-75% tissue loss in a hepatic lobe as score 4 (severe) (Moore *et al.*, 1989; Gennarelli and Wodzin, 2008). For the assessment of tissue loss in muscle tissue, Janzon and Seeman shot a bullet and spherical projectile into living swine and measured the mass of debridement in muscle tissue (Janzon and Seeman, 1985). For the hepatic tissue, only the energy loss of the 6.35-mm-steel sphere in the porcine liver has been investigated at striking velocities between 200 and 900 m/s (Humphrey *et al.*, 2018a, 2018b) and between 400 and 1,200 m/s (Eason, Pryor Jr and Adams, 1975). The penetrating hepatic injury has not, however, been quantified based on tissue loss.

This study aims to (1) find the appropriate method of imaging analysis to identify tissue disruption around the permanent wound cavity and (2) establish the injury-risk curves of a penetrating hepatic injury. For the imaging analysis, MRI, histological analysis and confocal microscopy were performed to examine tissue disruption around the permanent wound cavity. The suitable imaging analysis was used to estimate the volume of tissue loss associated with AIS 4.

6.2 Materials and methods

6.2.1 Sample preparation

In this study, fresh bovine livers were chosen as the samples because a freeze-thaw cycle reduced the ultimate strain of the bovine liver (Lu, Kemper and Untaroiu, 2014). The fresh bovine livers were obtained from a local abattoir at the time of slaughter. During transport, the bovine livers were immersed in cell-culture media, Dulbecco's Modified Eagles Medium (DMEM), sealed in a plastic bag, and ice was placed on the plastic bag. This process can minimise post-mortem decomposition (Dunford, LeRoith and Kemper, 2018). Upon arrival at the laboratory, the bovine livers were cut into small blocks whilst ensuring that the thin outer membrane (capsule) on the impact face remained intact. The dimensions of the liver block were approximately $100 \times 100 \times 50$ mm. Until those blocks were tested, they were soaked in DMEM and stored at 4.0 °C. All experiments were performed within 48h of slaughter to minimise postmortem decomposition of the bovine liver (Dunford, LeRoith and Kemper, 2018).

6.2.2 Method

The gas-gun system shown in chapter 4 and 5 was used to accelerate the three representative projectiles (5-mm sphere, 0.78-g-right-circular (RC) cylinder and 1.1-g-chisel-nose (CN) cylinder). The experiment with the gas-gun was conducted by the

same method described in chapter 5. In this study, the projectiles were shot in the range of the striking velocities between 15 and 330 m/s. In the target chamber of the gas-gun system, a polycarbonate mounting apparatus was placed to hold the block of the bovine liver on a plastic sheet (Figure 6.1). The front and back face of the mounting apparatus have a 30 mm hole where the projectile passed through.

After each shot, the DoP inside the liver block was scanned using radiography (Fluoroscanner InSight FD, Hologic Inc., United States). As specified in Chapter 5, the DoP was measured as the distance between small steel markers at the entrance and exit hole or to a retained projectile from the three orthogonal scans.

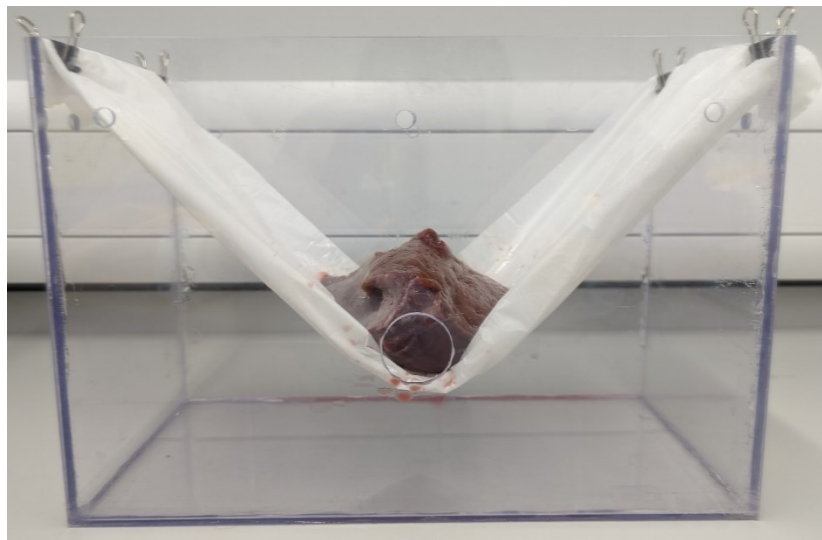


Figure 6.1 Mounting apparatus for the block of the bovine liver.

6.2.3 Imaging analysis: MRI

In order to find tissue disruption, three imaging analyses were conducted in this study. After a series of shots, the liver sample was sectioned into a small block (approximately $70 \times 50 \times 50$ mm) to be fitted in the MRI scanner. Some liver blocks with more than 70 mm of DoP were further sectioned into half blocks to be scanned separately. When the projectile remained inside the bovine liver, the liver was gradually sliced from the opposite side of the entrance hole to extract the retained

projectile. The liver block was inserted into a plastic bottle and held by a polystyrene foam block (Figure 6.2). This foam block has a small chamber to trap the air during MRI scanning because the air is shown as a dark dot on MRI. To minimise post-mortem decomposition, the liver block in the plastic bottle was immersed in DMEM and kept at 4 °C until MRI scanning. The liver block was imaged on a 9.4T MRI scanner (BioSpec 94/20, Bruker, Germany) using 3D T1 weighted FLASH (spatial resolution $300 \times 300 \times 300 \mu\text{m}^3$) and T2 weighted multi-slice RARE (spatial resolution $300 \times 300 \times 800 \mu\text{m}^3$) sequences.

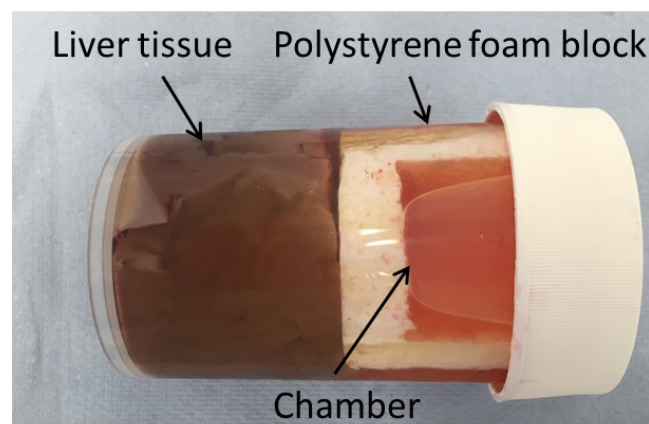


Figure 6.2 Sample holder for MRI scanning.

6.2.4 Tissue analysis: histology

The histological analysis was conducted to examine cell state around a permanent wound cavity. After the 5-mm sphere was shot into the bovine liver, the transverse section of the liver was sliced at 30 mm from an entrance hole and from an exit hole (Figure 6.3). The sliced liver adjacent to the permanent wound cavity was cut into a small block with dimensions: 25 mm $\times$ 30 mm $\times$ 5 mm. For fixation, the liver block inserted in a histology cassette was soaked in 10% formalin for 5h and then in 70% ethanol for 24h. After the fixation process, the samples were transported to histologists who performed an embedding and staining process. The liver block was embedded with wax and cut into thin slices. The slice was stained using haematoxylin and eosin (H&E). The state of the hepatic tissue was assessed by a skilled pathologist.

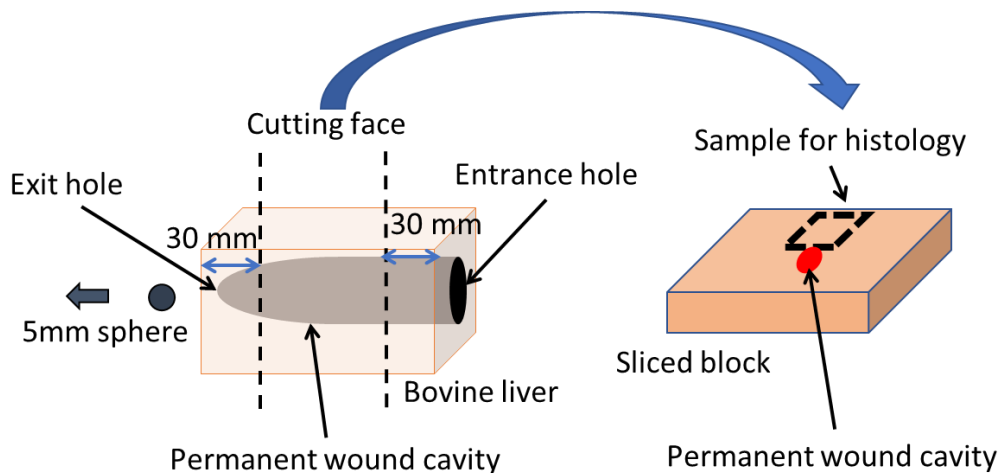


Figure 6.3 The preparation of a hepatic sample for histological analysis.

6.2.5 Imaging analysis: confocal microscopy

Confocal microscopy was performed to examine cell viability in hepatic tissue. Upon the arrival at the laboratory, the liver sample was prepared for confocal microscopy and then incubation started at approximately 19h of slaughter. Prior to the incubation, sample storage in DMEM at 4 °C enables liver cells to minimise the activity of metabolism, resulting in the prevention of post-mortem decomposition. To restore metabolism, incubation at 37 °C and 95% air, 5% CO₂ was performed. The control sample was observed at 0h, 3h and 24h incubation to ascertain how the post-mortem decomposition developed during this active metabolism. No further samples were used for confocal microscopy because no viability was observed in the control samples after 3 and 24h incubation (these results shown in Subsection 6.3.1 and Figure 6.13). The detailed procedure is described as:

Sample preparation

- 1 Excise a thin sheet with 3 cm thickness
- 2 Core the liver sheet using an 8-mm-diameter biopsy punch
- 3 Make 4% agarose solution at 37 °C and pour it into a well plate
- 4 Place the liver cores into the well plates

- 5 Store the well plates at 4 °C for 5min to solidify the agarose solution
- 6 Remove the agarose block from the well plate and trim the excessive agarose block around the embedded liver core (Figure 6.4)

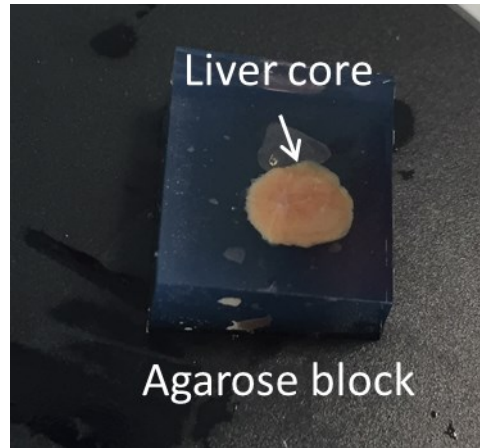


Figure 6.4 A liver core embedded in a 4% agarose block.

Sample slice with a vibratome (VT1000S, Leica)

- 7 Set a blade (double edge, Personna platinum) in the vibratome
- 8 Pour Hank's balanced salt solution (HBSS) into the buffer tray of the vibratome and place ice cubes in the cooling bath (Figure 6.5)
- 9 Attach the liver-embedded agarose block to the bottom of the buffer tray using superglue
- 10 Slice the liver core using the vibratome (Figure 6.5): thickness 300 μm , cutting speed 3 (0.125 mm/s) and frequency 9 (90 Hz)
- 11 Remove the remaining agarose from the liver slice using a tweezer
- 12 Wash the liver slice twice with HBSS and transfer them into a well plate filled with HBSS
- 13 Incubate the liver slice at 37 °C and 95% air, 5% CO₂ for 3 and 24 hours



Figure 6.5 The set-up of the vibratome.

Examination with the confocal microscope (SP8, Leica)

- 14 Replace old HBSS with new one in the well plate and add live/dead fluorescent stains: 1 μ l Hoechst 33342 and 1 μ l propidium iodide solution per 1 mL HBSS
- 15 Place the well plate on ice and incubate liver slices in the stain solution for 30 min
- 16 Rinse the liver slices with HBSS
- 17 Place the liver slice inside an O-ring (1 mm diameter) in a glass slide
- 18 Pour cold HBSS droplets in the O-ring and place a coverslip onto the O-ring (Figure 6.6)
- 19 Examine the liver slice using the confocal microscope (excitation/emission maximum: 360/460 nm for Hoechst stain and 535/617 nm for propidium iodide stain)

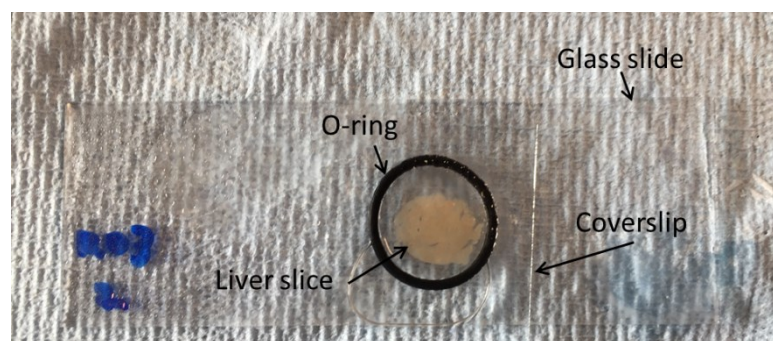


Figure 6.6 The mounting of the liver slice on a glass slide.

6.2.6 Measurement of tissue disruption area

To estimate the degree of injury severity, the 5-mm spheres were shot at the range of the striking velocity between 60 and 330 m/s. Tissue disruption was identified with the imaging analysis. It is reported that the radius of the tissue disruption caused by a sphere was divergent from an entrance hole and convergent to an exit hole (Fackler, Bellamy and Malinowski, 1988). In this study, the shape of the tissue disruption was assumed to be simplified as two truncated cones (entry-side and exit-side portion) before and after a maximum radius r_{max} (Figure 6.7).

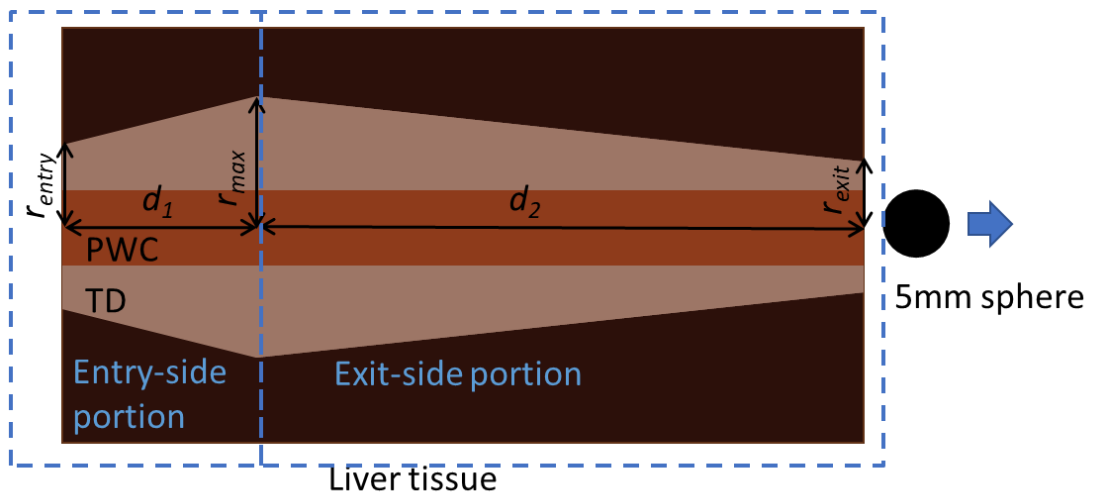


Figure 6.7 The simplified shape of the tissue disruption (TD) caused by the temporary wound cavity around the permanent wound cavity (PWC).

The volume of the tissue disruption V was calculated with the formula of a truncated cone:

$$V = \frac{\pi d_1}{3} (r_{entry}^2 + r_{entry}r_{max} + r_{max}^2) + \frac{\pi d_2}{3} (r_{max}^2 + r_{max}r_{exit} + r_{exit}^2)$$

Equation 6.1

where r_{entry} and r_{exit} are the radius of the tissue disruption at the entrance hole and at the exit hole, respectively. The r_{max} is the maximum radius of the tissue disruption.

The origin of these radii is the centre of the permanent wound cavity, regardless of the shape of the tissue disruption. The d_1 and d_2 are the depth between the entrance hole and the maximum radius of the tissue disruption, and between the maximum radius of the tissue disruption and the exit hole, respectively.

6.2.7 Statistical analysis

The AIS 4 of a penetrating hepatic injury represents 25-75% tissue loss in a lobe (Moore *et al.*, 1989; Gennarelli and Wodzin, 2008). In order to calculate the ratio of this tissue loss, the volumes of the right and left lobe (997 and 493 cm³, respectively) were used here (Abdalla *et al.*, 2004). In this study, the volume of the tissue loss identified using the imaging analysis was estimated with Equation 6.1. The r_{entry} , r_{exit} and r_{max} were derived from empirical data. The volume of the tissue loss was commensurate with the human liver; therefore, the d_1 and d_2 in Equation 6.1 were determined based on the dimensions of a 3D liver model. Ultimately, the injury-risk curves were calculated based on following assumptions:

- The tissue loss is calculated from the cross-section of three layers from a male 3D model (Complete Anatomy, 3D4Medical) in Figure 6.8.
- The dimensions of the liver in the 3D model are estimated from the chest depth of a 50th percentile US male (23.32 cm) (Gupta, 2018)
- A projectile strikes the liver at 0, 45, 90 and 135° and moves straight through the centre of mass (blue and orange lines shown as the potential length of a tract in Figure 6.8 (A)) in the cross-section of each lobe.

The potential lengths of a tract mentioned above were measured in the liver of the male 3D model and shown in Table 6.1.

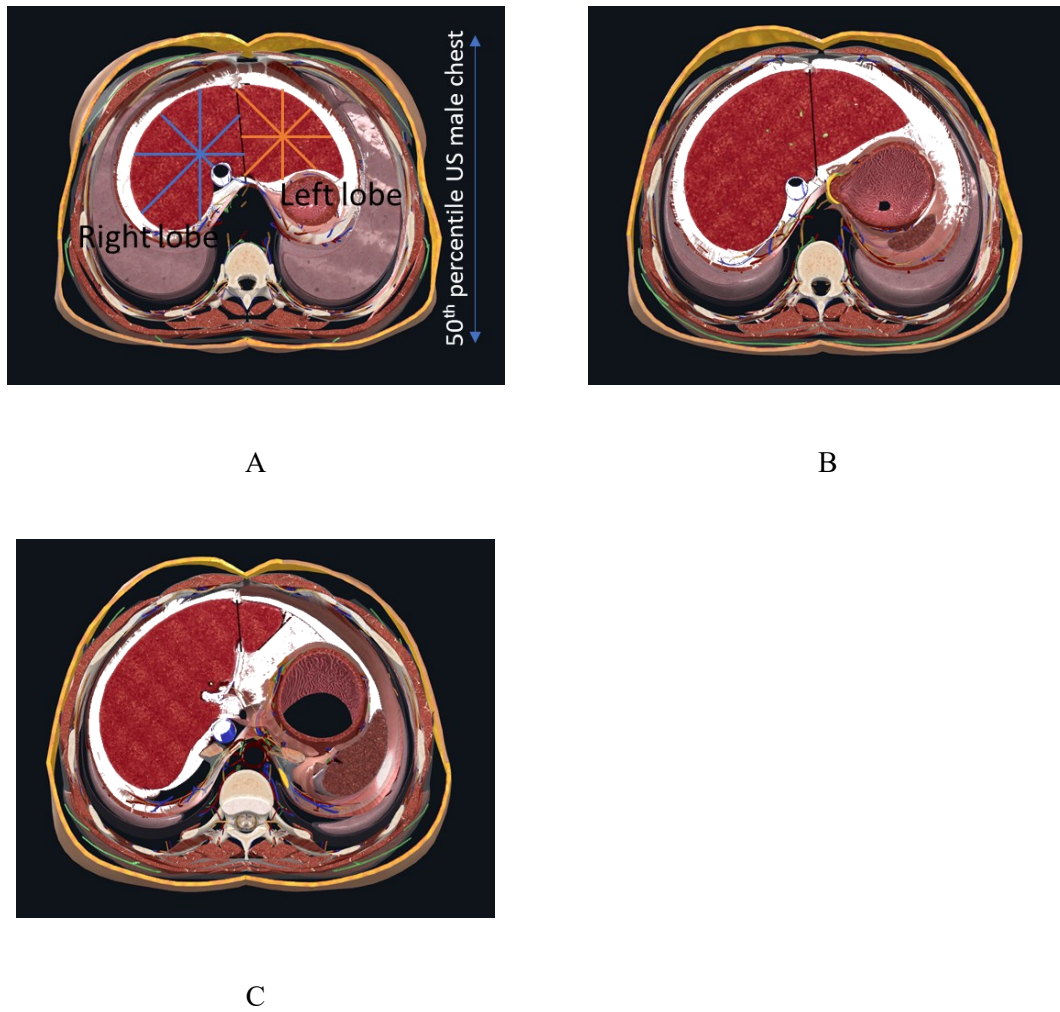


Figure 6.8 (A) The cross-section of the top area, (B) middle area and (C) bottom area in the liver of a 3D male model. Blue and orange lines in (A) show the potential length of a tract through the right lobe and left lobe, respectively. Figure reproduced with permission from a male 3D model (Complete Anatomy, 3D4Medical).

Cross-section of the liver		Length at each angle of projectile impact [mm]			
		0°	45°	90°	135°
Right lobe	Top	83.7	110.3	104.8	67.8
	Middle	98.6	129.9	126.4	82.7
	Bottom	84.1	142.3	128.4	85.5
Left lobe	Top	69.4	70.4	67.4	89.3
	Middle	70.1	65.4	60.6	68.0
	Bottom	32.2	36.7	37.2	36.1

Table 6.1 The potential length of a tract from each lobe of the male 3D model.

Survival analysis was performed using the statistical software NCSS (v11, NCSS, United States) to establish injury-risk curves from all estimated volumes of the tissue disruption obtained from the three layers in each lobe. In this survival analysis, a best fit analysis was conducted with all experimental data. The normal distribution was determined to create the injury-risk curves. The corridor of the injury-risk curve was chosen as the 95% confidence interval (CI) or the standard deviation calculated based on the AEP-2920 NATO standard mentioned in Chapter 5 (NATO Standardization Office, 2015). In the same method in chapter 5, the V_{50} values of AIS score were obtained from either the result of the survival analysis or the AEP-2920 NATO standard (NATO Standardization Office, 2015).

6.3 Results

Total 70 bovine liver blocks from 8 whole livers were used for DoP measurements and the development of the injury-risk curves. After the DoP measurements, 11 out of these 70 blocks were scanned with MRI. Two blocks were independently obtained from another whole liver; each block was used for only histology and confocal microscopy. The average mass of the liver blocks (mean $\pm$ one standard deviation) was 501 ± 152 g. The average width, depth and height were 103 ± 25 mm, 109 ± 28 mm and 53 ± 14 mm, respectively.

6.3.1 Imaging analysis

For MRI scanning, a total of 11 liver blocks were used to examine tissue disruption. The striking velocity, exit velocity and DoP for the MRI samples are shown in Table 6.2.

Liver	Projectile	Striking velocity [m/s]	Exit velocity [m/s]	DoP [mm]
S1	5-mm sphere	62.4	-	50.6**
S2 *		105.9	40.5	106.4
S3		140.0	57.2	114.3
S4		305.8	217.8	58.9
S5 *		334.2	185.0	101.8
R1	0.78-g-RC cylinder	58.5	-	96.3**
R2		101.5	44.9	99.7
R3		140.0	70.0	91.1
C1	1.1-g-CN cylinder	57.4	27.3	75.1
C2		107.8	61.4	91.0
C3		138.4	60.3	106.9

Table 6.2 Liver blocks for MRI scanning; * shows that the liver sample was split into two half blocks and scanned separately and ** shows that DoP was a distance between an entrance hole and retained projectile.

After MRI scanning, samples S4 and S5 were sectioned to compare the tissue disruption and a permanent wound cavity with those of MRI. Figure 6.9 shows MR images of a slice in the coronal plane and a photograph of the cross-section for sample S5. In the sectioned liver block, the boundary between intact tissue and tissue disruption was plotted with dashed lines (Figure 6.9 C), although this boundary was blurred. In the T2 sequence, the permanent wound cavity was clear because DMEM filled cavities which became bright in MRI scanning (Figure 6.9 B). In the T1 sequence, the DMEM was shown as moderate brightness, so the air bubbles trapped inside the sample (black dots in Figure 6.9 A) were clearer than in the T2 sequence.

The calculated volume from the distribution of these bubbles was closer to the actual tissue disruption measured in the cross-section of the sample (Figure 6.9 C).

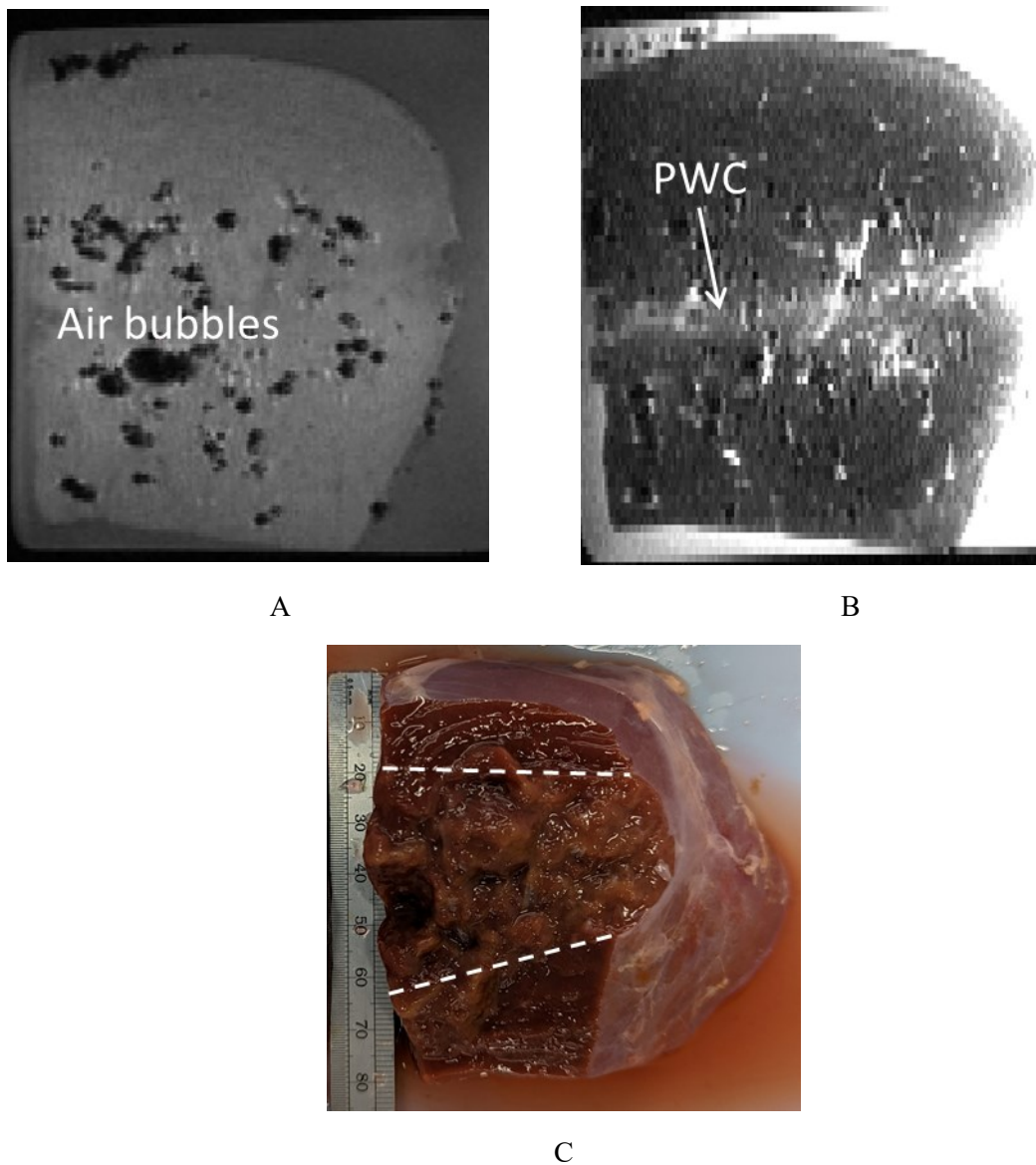


Figure 6.9 (A) The coronal plane of the liver sample S5 obtained from 3D multi-slice T1 sequence, (B) from 2D multi-slice T2 sequence and (C) the coronal cross-section of the liver sample S5; PWC indicates the permanent wound cavity and dashed lines denote the boundary of tissue disruption.

A slice in the axial plane of the liver sample S5 obtained from the T1 sequence and T2 sequence is shown in Figure 6.10. The air bubbles shown as black dots in T1 sequence were manually checked in the MR slice images. In some axial planes of MRI scans, the area of the air bubbles existed only on one side from the permanent wound

cavity (The dashed circle of Figure 6.10 A). Additionally, the area of both the air bubbles and the permanent wound cavity was elliptical in shape and not axisymmetric.

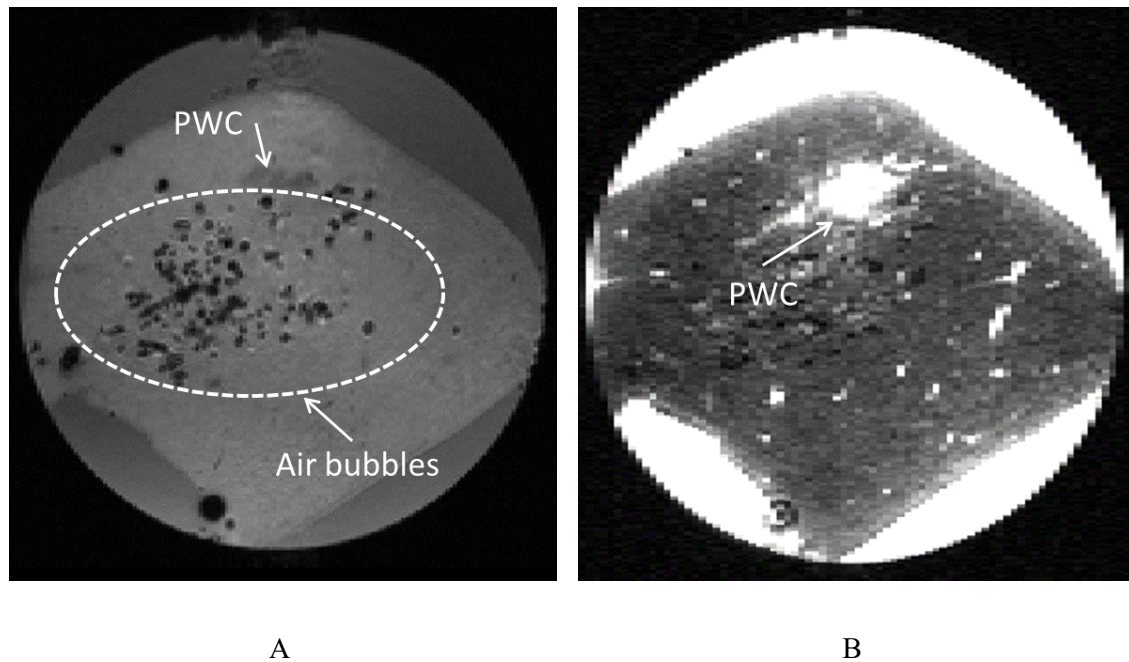
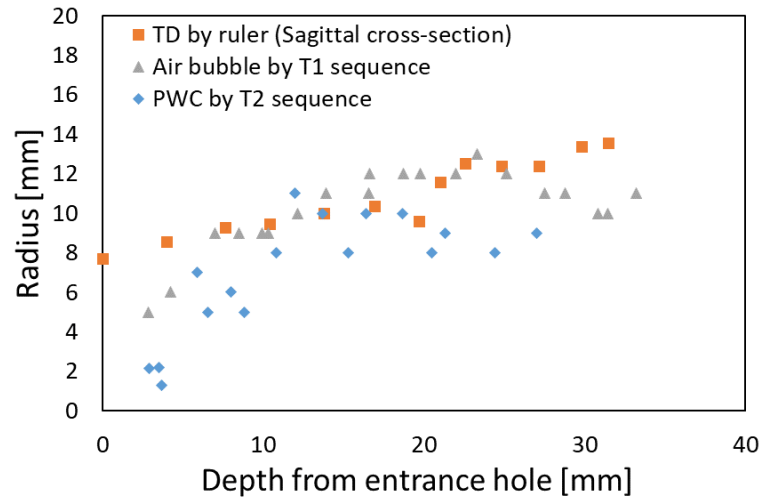
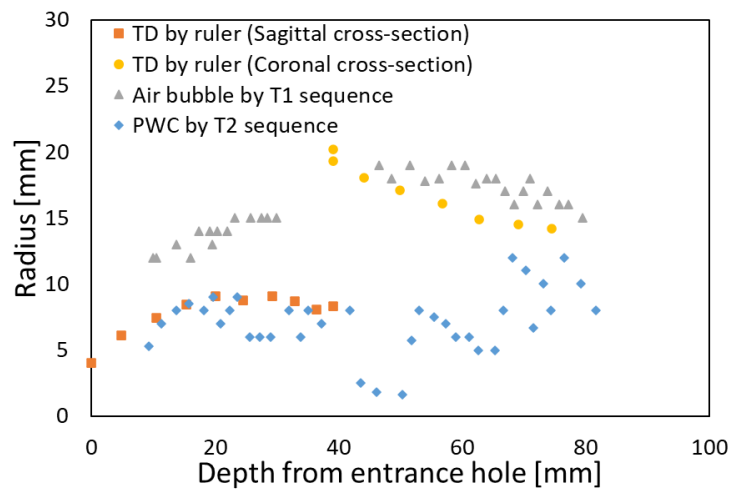


Figure 6.10 (A) The axial plane of the liver sample S5 in 3D multi-slice T1 sequence and (B) in 2D multi-slice T2 sequence. PWC represents the permanent wound cavity. A dashed circle shows the area of the air bubbles trapped inside the sample.

The furthest sides of the air bubble and permanent wound cavity from their centre were estimated as the maximum radii which were derived from the T1 and T2 sequence to be comparable with the actual tissue disruption directly measured in the samples S4 and S5 using a ruler (Figure 6.11). From this radius and depth in the axial planes of MRI scans, the volume was roughly calculated. In sample S4, the volumes of these air bubbles and permanent wound cavity were 4% and 54% different from the direct measurement using a ruler, respectively. In sample S5, the volumes of the air bubbles and permanent wound cavity were 327% and 26% different from the direct measurement of the sagittal cross-section in the first half of this sample; and 12% and 81% difference from that of the coronal cross-section in its second half, respectively.



A



B

Figure 6.11 (A) The radius of the tissue disruption (TD), air bubbles and permanent wound cavity (PWC) in the sample S4 and (B) in the sample S5.

For histological examination, a sample was shot with the 5-mm sphere at the striking velocity of 181.3 m/s. Figure 6.12 shows the hepatic cells adjacent to a permanent wound cavity in the entrance side and exit side, and a control sample. No histological changes were observed in the cells near adjacent to the permanent wound cavity.

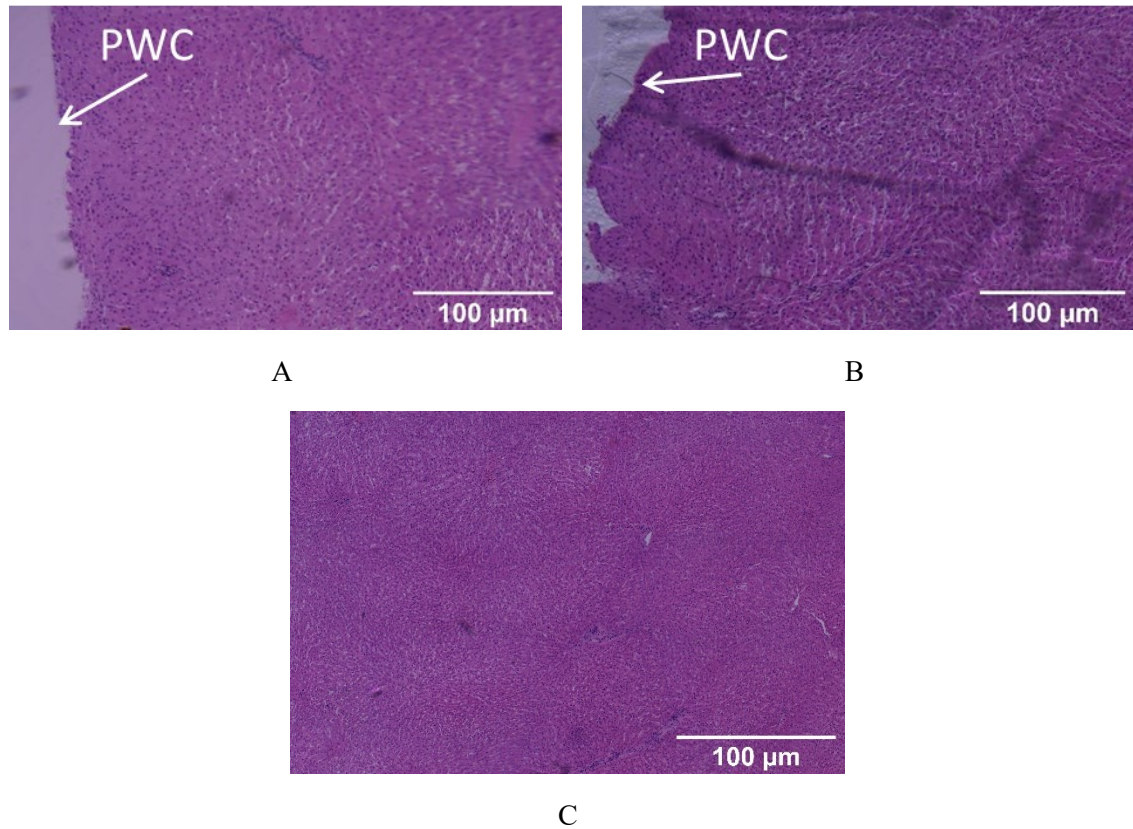


Figure 6.12 Histological examination of hepatic cells adjacent to the permanent wound cavity (PWC) by H&E stain (10x magnification): (A) the sample excised at 30mm depth from the entrance side and (B) at 30 mm depth from the exit side, and (C) the control sample.

For confocal microscopy, the control samples were transported from a local abattoir to the laboratory within 3 hours of the slaughter. After approximately 16h of sample preparation, the slices from the control sample were incubated at 0h, 3h and 24h (Figure 6.13). The viability of the hepatic cells at 3h and 24h reached 0% compared to the control sample at 0h incubation.

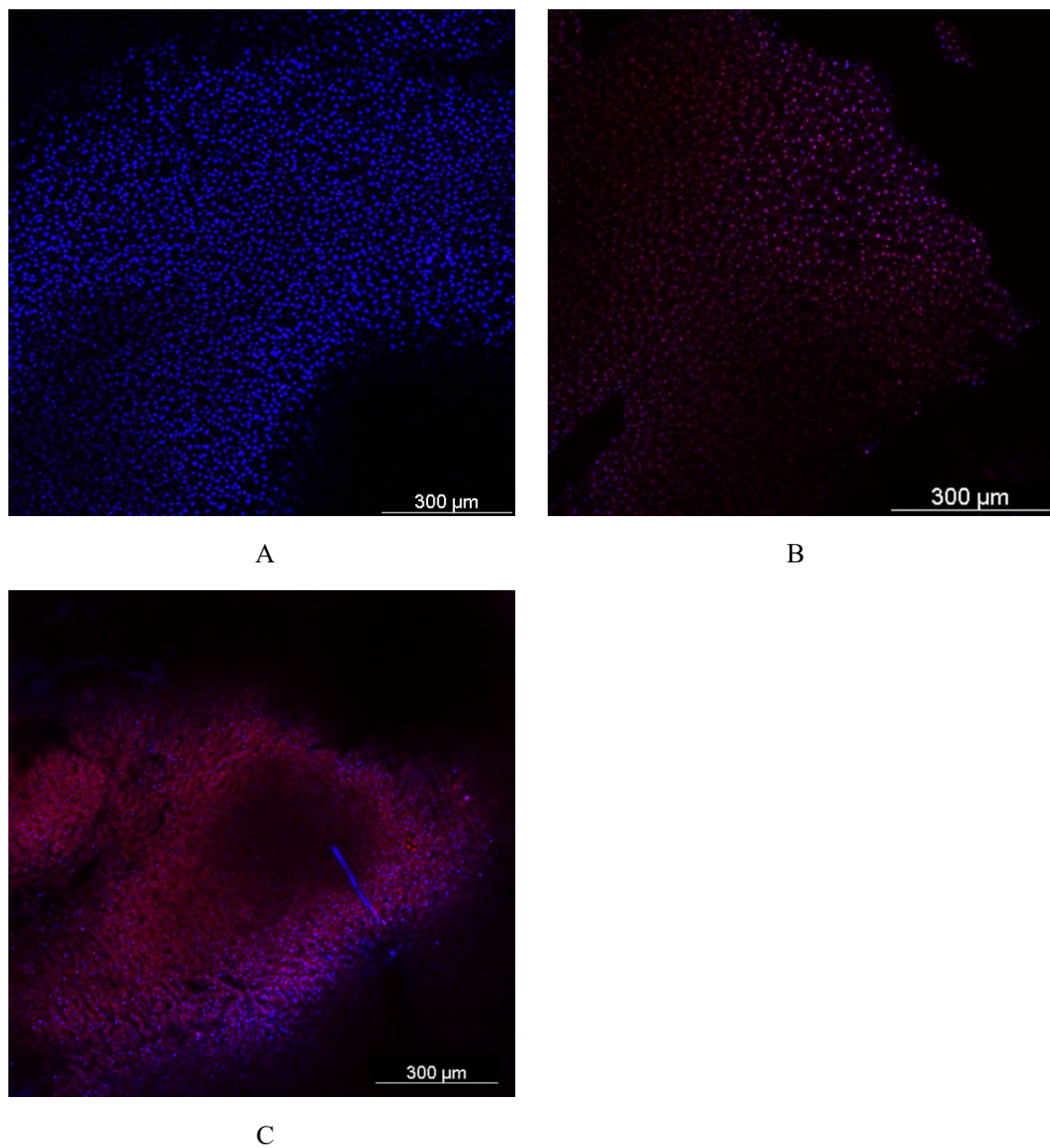


Figure 6.13 Examination of hepatic cells by confocal microscopy: control sample at (A) 0h, (B) 3h and (C) 24h incubation (37 °C and 95% air, 5% CO₂). Hoechst 33342 (blue) binds all cells and propidium iodide (red) binds only dead cells.

6.3.2 Depth of penetration

DoP and residual velocity as a function of striking velocity are shown in Figure 6.14. The data points in each graph are approximated with a linear regression. Figure 6.15 represents the DoP as a function of the energy loss density in the three projectiles assessed in this study.

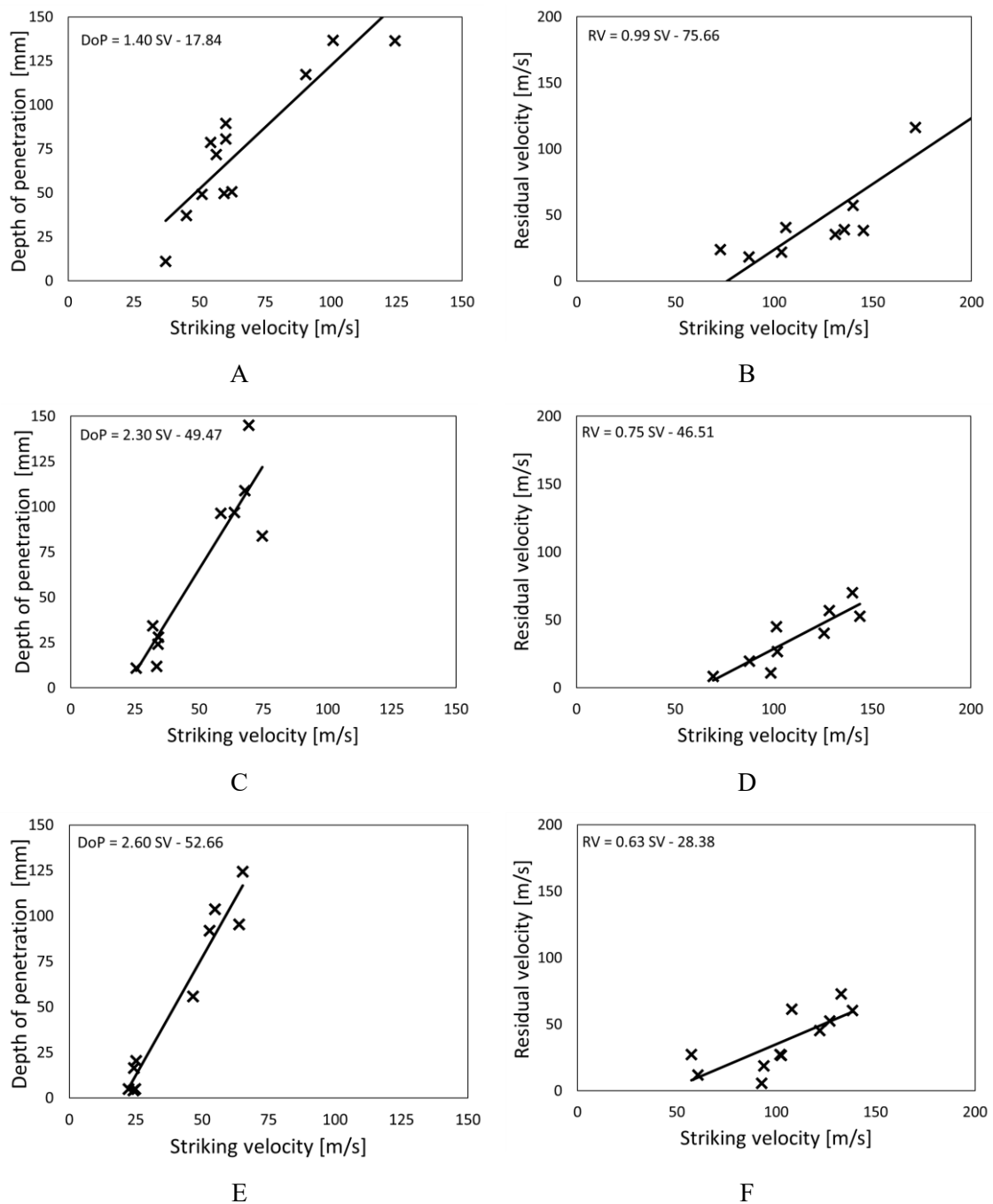


Figure 6.14 (A) DoP and (B) residual velocity (RV) as a function of striking velocity (SV) for the 5-mm sphere, (C and D) for the 0.78-g-RC cylinder and (E and F) for the 1.1-g-CN cylinder.

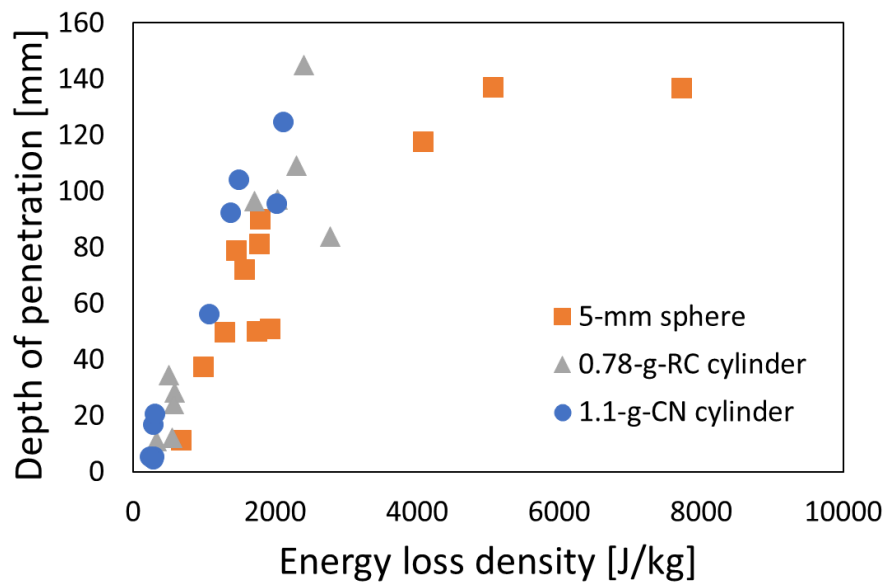
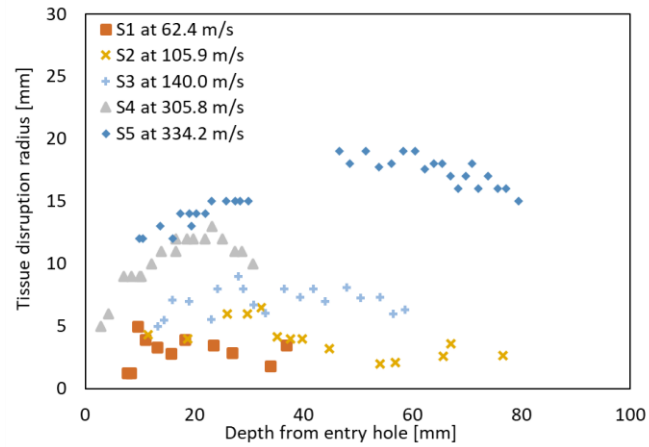


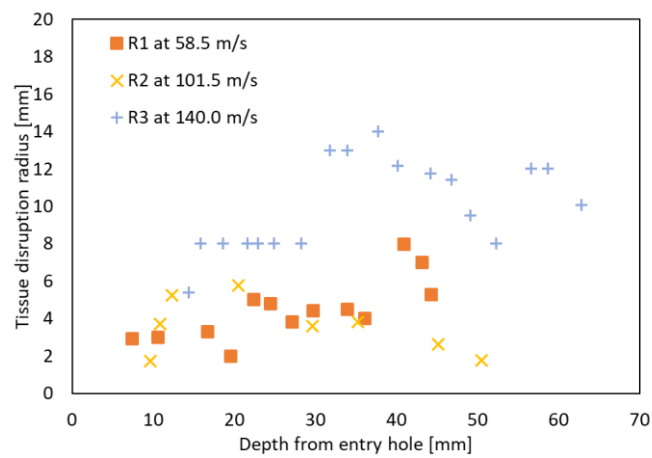
Figure 6.15 The DoP as a function of the energy loss density.

6.3.3 Volume of tissue loss

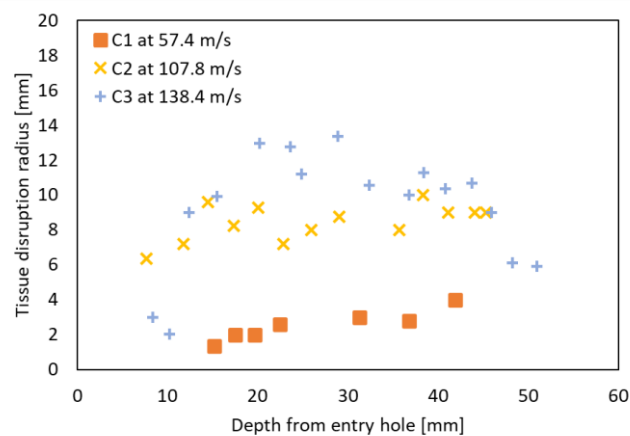
In order to calculate the volume of tissue loss, the tissue disruption estimated from the air bubbles in the T1 sequence was assumed to be tissue loss. The radius of the tissue disruption in various striking velocities is shown in Figure 6.16.



A



B



C

Figure 6.16 (A) The radius of tissue disruption produced by the 5-mm sphere, (B) 0.78-g-RC cylinder and (C) 1.1-g-CN cylinder.

In this study, only the 5-mm spheres were shot into the bovine liver in a wide range of striking velocity to reveal the relationship between the striking velocity and

the volume of tissue disruption. A depth at the maximum radius of the tissue disruption d_l and the maximum radius of the tissue disruption r_{max} were compared in each striking velocity and approximated with linear regression (Figure 6.17).

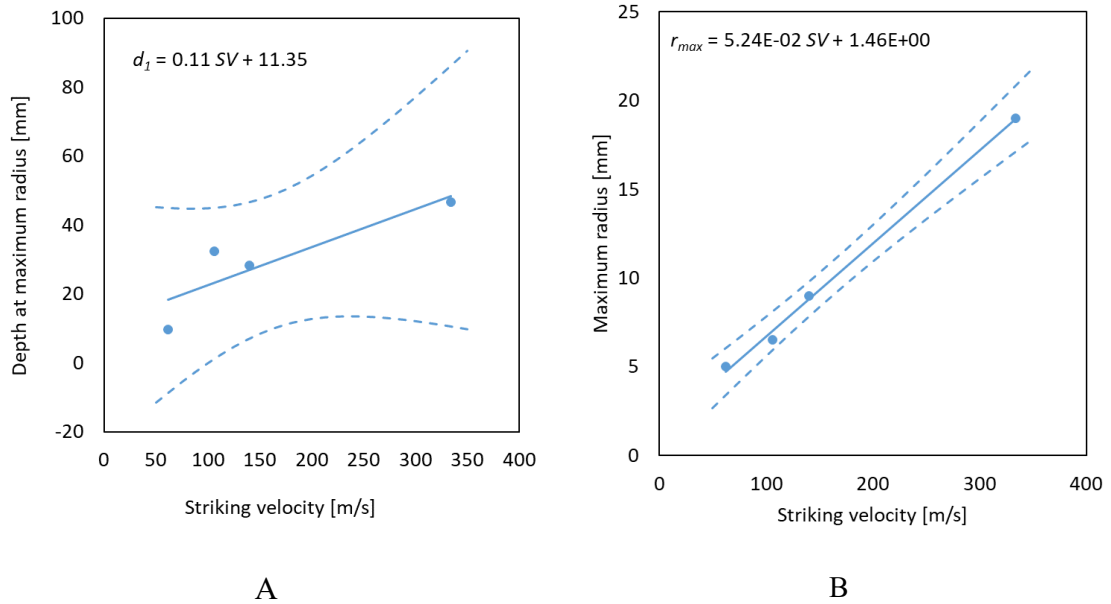


Figure 6.17 (A) Depth at maximum radius d_l and (B) maximum radius r_{max} of the tissue disruption as a function of the striking velocity. The dashed line shows 95% CI.

From the linear regressions in Figure 6.17, depth at the maximum radius of the tissue disruption d_l [mm] and the maximum radius of the tissue disruption r_{max} [mm] linearly proportional to the striking velocity SV [m/s] are written as

$$d_l = 0.11 SV + 11.35 \quad \text{Equation 6.2}$$

$$r_{max} = 5.24 \times 10^{-2} SV + 1.46 \quad \text{Equation 6.3}$$

To obtain the radius of the tissue disruption at an entry hole r_{entry} , the radius of the tissue disruption in the entry-side portion was compared between samples in various striking velocities (Figure 6.18). The data points derived from the sample S1 were removed from this graph because only few data points were measured in this dataset. Each slope and y-intercept of the linear regressions were plotted as a function of the striking velocity in Figure 6.18 B and C.

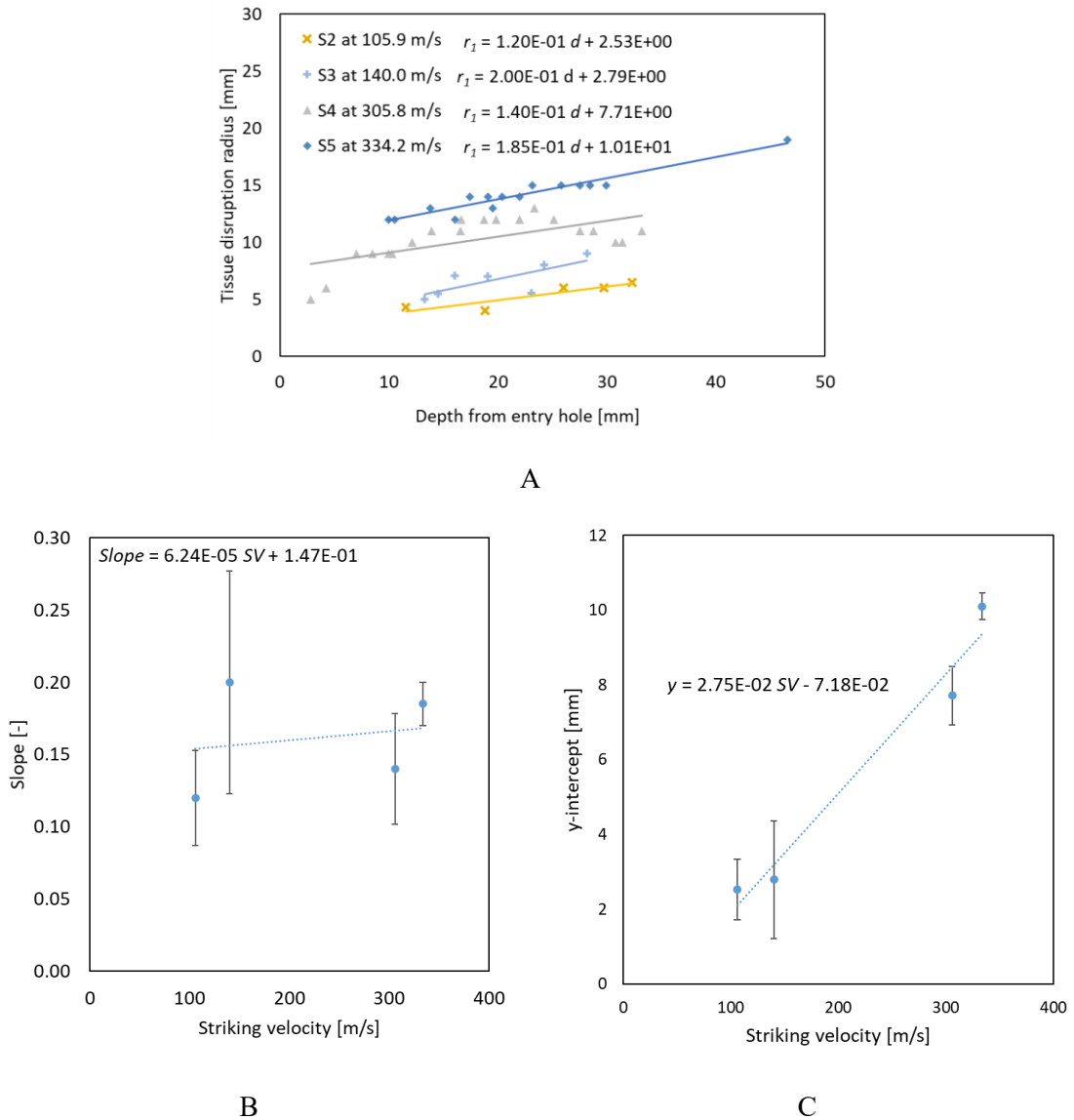


Figure 6.18 (A) The radius of the tissue disruption as depth from an entry hole in the entry-side portion; (B) the slope and (C) y-intercept of the linear regressions as a function of the striking velocity. Error bars denote one standard error.

From the linear regressions in Figure 6.18 B and C, the radius of the tissue disruption in the entry-side portion r_1 [mm] is shown as

$$r_1 = [6.24 \times 10^{-5} SV + 1.47 \times 10^{-1}] d + [2.75 \times 10^{-2} SV - 7.18 \times 10^{-2}]$$

Equation 6.4

where d represents a depth from an entry hole [mm]. The radius of the tissue disruption at an entry hole r_{entry} [mm] is expressed as

$$r_{\text{entry}} = 2.75 \times 10^{-2} SV - 7.18 \times 10^{-2} \quad \text{Equation 6.5}$$

Likewise, the radius of the tissue disruption in the exit-side portion was compared between samples (Figure 6.19). The data points from the sample S4 were removed due to only few data points in this graph. Figure 6.19 B and C show the slope and intercept as a function of the striking velocity.

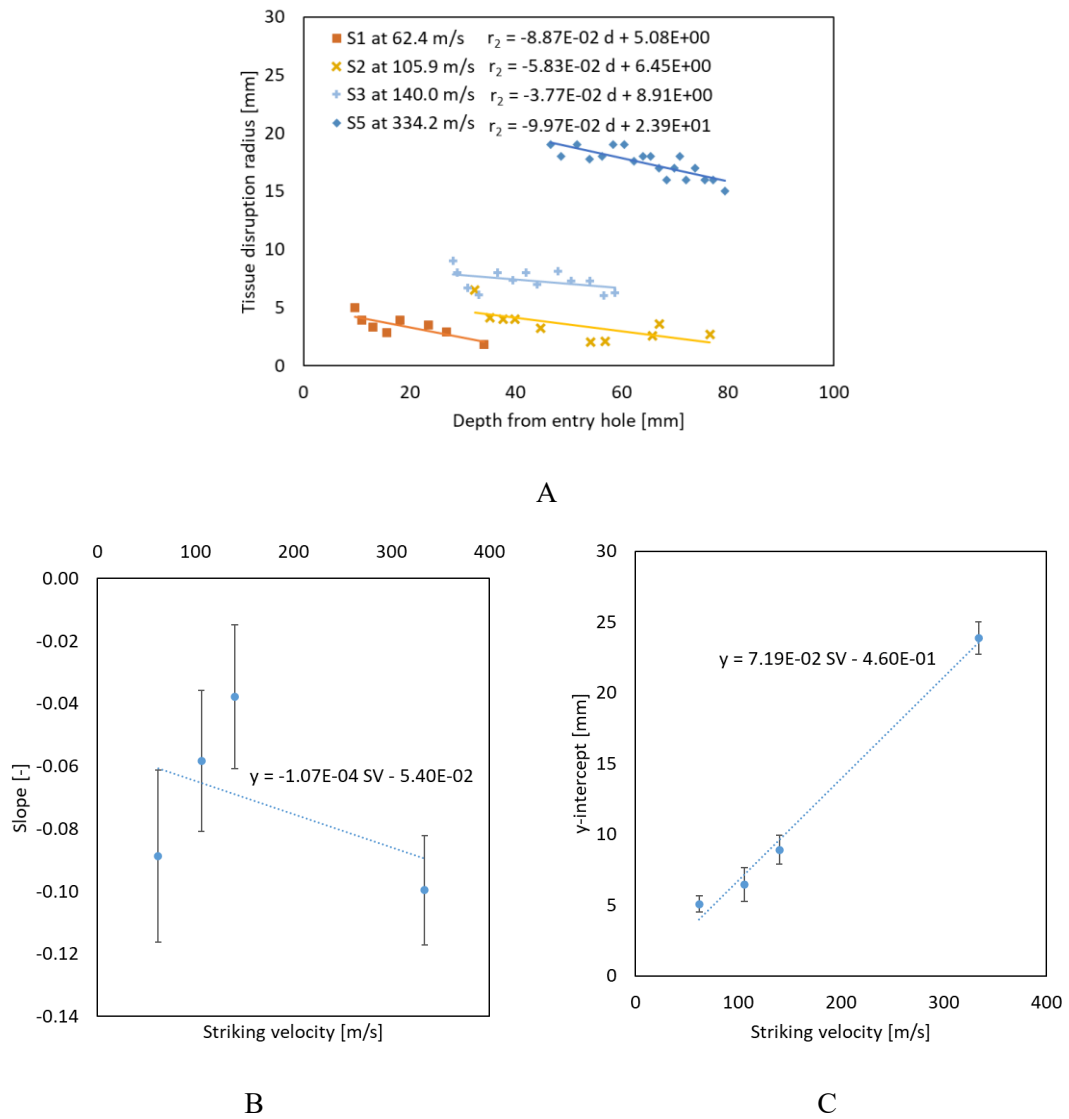


Figure 6.19 (A) The radius of the tissue disruption as depth from an entry hole in the exit-side portion; (B) the slope and (C) y-intercept of the linear regressions as a function of the striking velocity. Error bars indicate one standard error.

From Figure 6.19 B and C, the radius of the tissue disruption in the exit-side portion r_2 [mm] and the radius of the tissue disruption at an exit hole r_{exit} [mm] are described as

$$r_2 = -[1.07 \times 10^{-4} SV + 5.40 \times 10^{-2}] d + [7.19 \times 10^{-2} SV - 4.60 \times 10^{-1}]$$

Equation 6.6

$$r_{exit} = -[1.07 \times 10^{-4} SV + 5.40 \times 10^{-2}] DoP + [7.19 \times 10^{-2} SV - 4.60 \times 10^{-1}]$$

Equation 6.7

where DoP [mm] is the depth from an entry hole to an exit hole or a remained projectile. The DoP is shown as

$$DoP = d_1 + d_2$$

Equation 6.8

6.3.4 Injury-risk curves

The injury-risk curves for AIS 3+ (laceration of more than 3 cm) are shown for each projectile (Figure 6.20). The V_{50} values for AIS 3+ (mean $\pm$ standard deviation) were 56.3 ± 26.1 m/s for the 5-mm sphere, 39.0 ± 7.1 m/s for the 0.78-g-RC cylinder and 38.7 ± 14.5 m/s for the 1.1-g-CN cylinder. The V_{50} value for the 1.1-g-CN cylinder was calculated based on the AEP-2920 NATO standard (NATO Standardization Office, 2015).

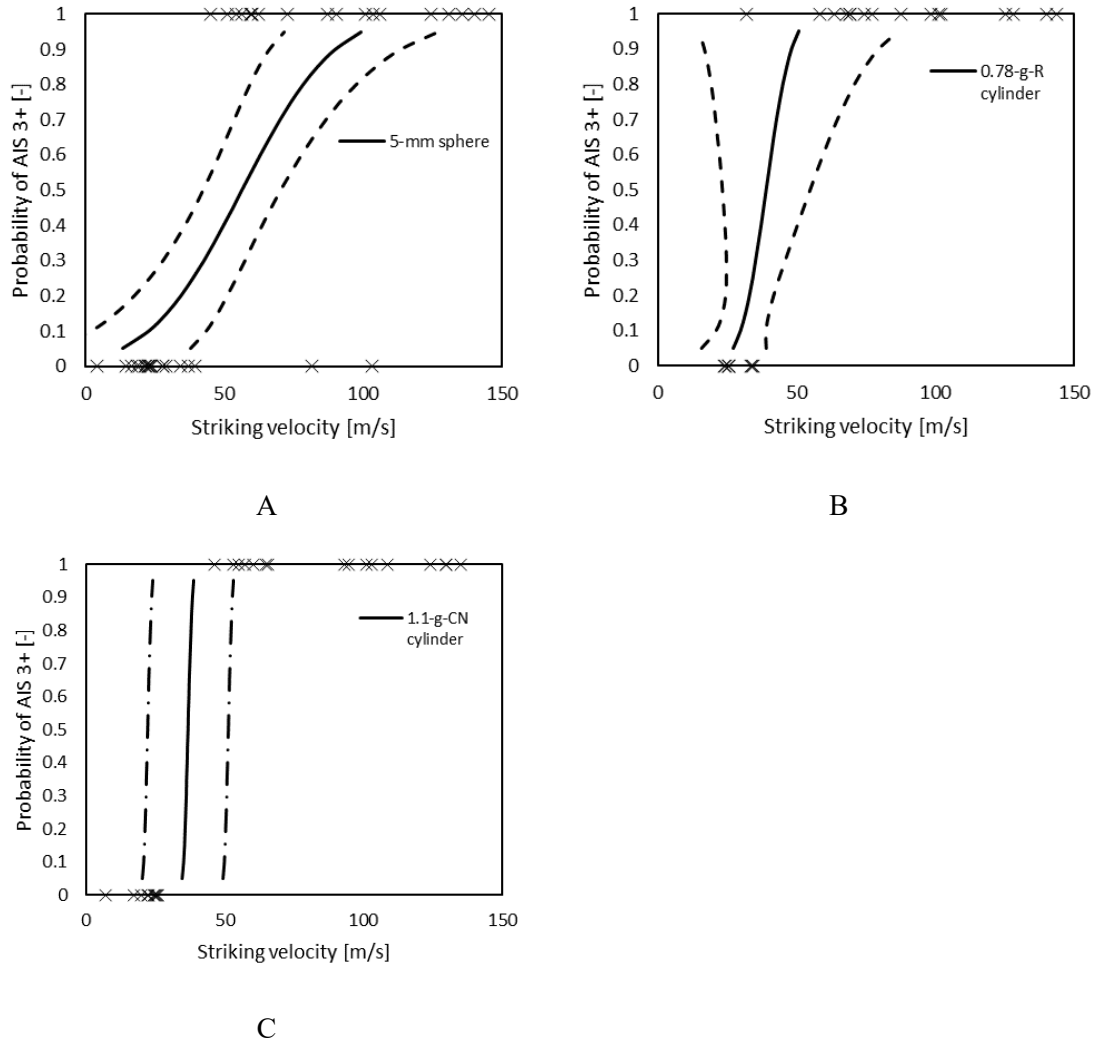


Figure 6.20 The injury-risk curve for AIS 3+ for the (A) 5-mm sphere, (B) 0.78-g-RC cylinder and (C) 1.1-g-CN cylinder into the liver; the corridor of the injury-risk curve (dashed lines and dash-dotted lines) indicates the 95% confidence interval and the standard deviation.

The volume of the tissue loss was calculated using Equation 6.1- 6.3, 6.5, 6.7 and 6.8. The variable of DoP in these equations was determined from the potential length of a tract in Figure 6.8 and Table 6.1. In order to estimate the tissue disruption in a wide range of striking velocity, the variable of striking velocity SV in each equation was inserted from 100 m/s to 1,000 m/s. The volume of tissue disruption was derived from the following steps:

1. Calculate r_{entry} , r_{max} and r_{exit} from Equation 6.3, 6.5 and 6.7
2. Obtain d_1 and d_2 from Equation 6.2 and 6.8
3. Estimate the volume of tissue disruption V from Equation 6.1

AIS 4 occurs when the volume of tissue disruption exceeds 25% of total volume in each lobe. Due to different volumes in each lobe, the injury-risk curve was separately established in the left and right lobe. Figure 6.21 shows the injury-risk curve for AIS 4+ using the 5-mm sphere into the right and left lobe. These data were categorised as AIS 4+ injury (one) or no AIS 4+ injury (zero) for the calculation of injury-risk curves. The V_{50} values for AIS 4+ (mean $\pm$ standard deviation) were 676.3 ± 101.3 m/s for the right lobe and 541.2 ± 42.3 m/s for the left lobe.

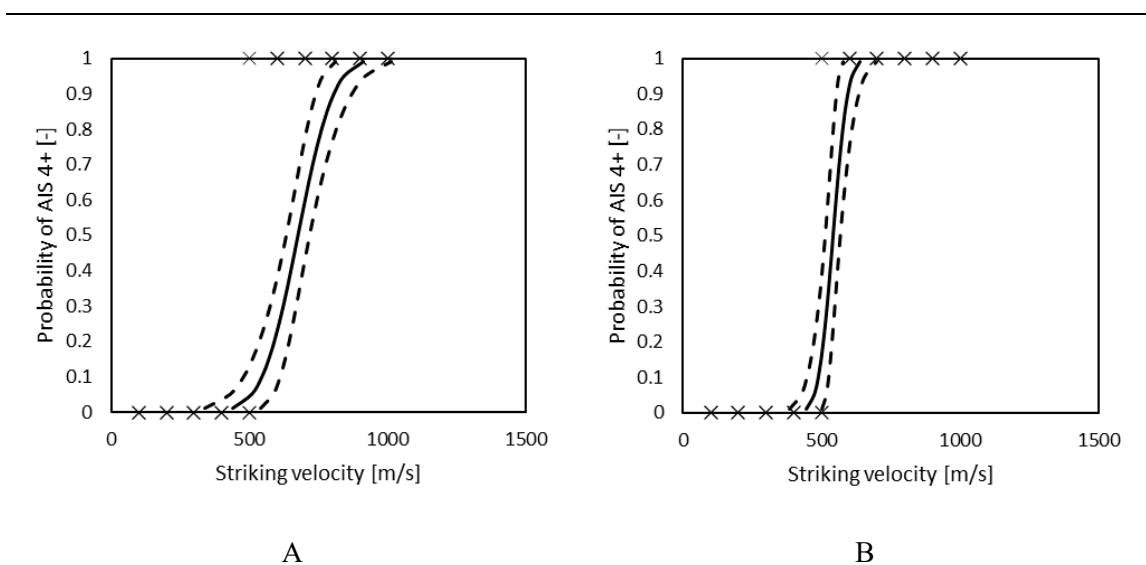


Figure 6.21 (A) The injury-risk curve for AIS 4+ for the 5-mm sphere into the right lobe and (B) left lobe; the 95% confidence interval corridor of each injury-risk curve is shown with dashed lines.

6.4 Discussion

This study in Chapter 6 was the first to estimate the tissue disruption area in the liver and to establish injury-risk curves. The V_{50} values for an AIS 4+ injury were considerably higher than those for an AIS 5+ in the heart (Chapter 5). This indicates that for the same projectile impact, the injury to the liver is less severe than an injury in the heart, but the liver is more likely to be struck by multiple projectiles due to the larger surface area of the liver over the heart.

MRI scanning was found to be the most suitable imaging modality for estimating the volume of tissue disruption among the three imaging analyses in this study. As air bubbles were trapped in areas of tissue disruption, the distribution of the air bubbles was visible in the 3D T1 weighted FLASH sequence. Inside the liver sample, the air bubbles were trapped in the middle of the tissue disruption despite few bubbles near the entry and exit hole where the air bubbles escaped from the sample. To calculate the entire volume of tissue disruption, the radius of the tissue disruption near the entrance and exit hole was extrapolated with Equation 6.4 and Equation 6.6. The volume estimation of the tissue disruption, therefore, was not affected much by a small number of air bubbles. The tissue disruption on the cross-section was not axisymmetric in some axial planes of MRI scans (Figure 6.10). Moreover, their radius measured by a ruler was different depending on the cutting plane of the sample (Figure 6.11 B); therefore, the measurement of tissue disruption using a ruler would not be suitable.

The shape of the tissue disruption assumed here was based on the large block of the gelatine. Fackler et al. investigated the tissue disruption area in the gelatine block of 25 cm × 25 cm × 50 cm dimensions where a resultant temporary cavity was significantly smaller than the dimensions of the gelatine block (Fackler, Bellamy and Malinowski, 1988). In this study, the size of the liver block was smaller than their gelatine block. Air bubbles reached the proximity of the surface of the sample when the projectile struck at approximately 300 m/s; hence, the air bubbles existed in the one side from the permanent wound cavity (Figure 6.10). This suggests that the boundary condition would affect the distribution of the air bubbles. Even in this case, the radius of the tissue disruption was measured from the centre of the permanent wound cavity to furthest side of the air bubble. The volume of the tissue disruption was estimated in the worst-case scenario when a projectile passes through the middle of the liver. In this study, the size of the liver block, however, was similar to the left or right lobe of the human liver, so it was pragmatic for the injury prediction of each lobe and including any effect of the boundary condition.

The irreversible tissue damage due to the temporary wound cavity could not be observed by the histology and confocal microscopy of the liver samples. In the histological analysis, the adjacent tissue to the permanent wound cavity was intact.

This intact tissue would be attributed to the limited activity of the metabolism as this liver sample was cooled at 4°C after testing. In the confocal microscopy, the control samples were incubated at 3h and 24h to clarify the effect of the metabolism on the sample. Consequently, most of the hepatic cells died even at 3h incubation, suggesting that the samples in this study rapidly developed ischemia under the incubation condition.

The injury-risk curve for AIS 4+ assessed in the 3D liver model highly depends on the potential length of a tract. The 95% CI of the AIS 4+ in the liver was considerably large. This large 95% CI was associated with the survival analysis using a wide range of the tracts assumed in the 3D male liver (Figure 6.8), suggesting that these injury-risk curves are used for rough estimation of a penetrating injury when the DoP inside the liver is unknown. When the DoP is known, the occurrence of the AIS 4 injury can be precisely evaluated depending on whether the volume of tissue disruption per lobe exceeds 25% (Moore *et al.*, 1989; Gennarelli and Wodzin, 2008).

A wide range of the experimental data leads to a more accurate estimation of tissue disruption. In this study, the five impacts of the 5-mm sphere in the range of striking velocity up to 330 m/s were used to create the injury-risk curves of the AIS 4+. The projectile impact around 400 m/s caused tissue disruption over the outer surface of the sample, resulting in a large rupture instead of the permanent wound cavity inside the sample. In this sample, the permanent wound cavity did not retain its shape so the volume of tissue disruption could not be measured. For the injury-risk curves of AIS 4+ (Figure 6.21), the volume of tissue disruption, therefore, was extrapolated from 400 to 1,000 m/s with Equation 6.1. There is no comparable data for this volume estimation of tissue disruption in such a high velocity. In the porcine muscle, the depth at the maximum radius of the tissue disruption was approximately 100 mm when a 6-mm sphere was shot into porcine muscle at 1,031 m/s (Fackler, Bellamy and Malinowski, 1988). This value was 25% smaller than the estimation of the liver with Equation 6.2 at the same velocity because the muscle tissue is more resistant to the stretch of the temporary wound cavity (Fackler, 1987). This suggests that the volume estimation of the tissue disruption in Equation 6.1 would be acceptable in a higher striking velocity but the accurate prediction requires further experimental

data up to 1000 m/s in order to improve the coefficients of Equation 6.2, 6.3, 6.5, 6.7 and 6.8.

Additional datapoints in Figure 6.17 - 6.19 also improve a linear regression to accurately predict the volume of the tissue disruption. In this study, only four datapoints were assumed to be approximated with a linear regression because DoP as a function of striking velocity in a ballistic gelatine has been found to be a linear relationship in low striking velocity (up to 200 m/s) (Jussila, 2004; Swain *et al.*, 2014; Pullen, Kieser and Hooper, 2020). The material properties of both gelatine and liver blocks are isotropic and thus a linear regression was chosen here in Figure 6.17 - 6.19. This approximation with few datapoints, however, would lead to the large deviation of each slope and y-intercept value.

A non-invasive technique was considered to offer the most accurate means for DoP measurement in the liver. The opaque and elastic property of such soft organ inhibit the direct measurement of DoP. The exact location of the cavity is roughly identifiable from the several scanned images of fluoroscopy and thus the precise sectioning of the sample along the DoP would be impractical through these fluoroscopic images. Another way of direct measurement, such as inserting a rod from the entrance to the retained projectile, may cause the projectile to move deeper than the original position due to tissue elasticity, resulting in an error of DoP measurement. In this study, the sample housed in the mounting apparatus was scanned after each shot and the DoP was calculated from the three orthogonal images. The X-ray tube and receptor faced the box of the mounting apparatus; hence, the measurement error of each orthogonal angle was minimal.

The retained projectile can be used as an indicator of the depth of the permanent wound cavity. In this study, the furthest side of the projectile was used for the DoP measurement. In the soft tissue, a projectile may bounce back from the furthest side of the cavity before coming to rest, but there was no visible cavity ahead of the projectile in the X-ray images. Moreover, the sample observed in the high-speed video footage did not move backwards after reaching the maximum DoP. This observation suggests that these measurement and mounting methods enable us to observe DoP accurately in the liver block.

6.5 Conclusion

This chapter quantified penetrating hepatic injuries using energised fragments. In particular, severe penetrating injury (AIS 4+) into the liver was evaluated using the 5-mm sphere. The air bubbles trapped inside the liver sample were used to measure the volume of tissue disruption by the 3D T1 weighted FLASH sequence of the MRI. Liver injury-risk curves of AIS 4+ were established based on the liver of a 50th percentile US male.

In the next chapter, the penetration in various concentrations of ballistic gelatine is investigated and compared with the penetrating cardiac and hepatic injury in order for the appropriate concentration of gelatine to be determined.

CHAPTER 7

BIOFIDELIC TISSUE SURROGATE

Chapters 5 and 6 revealed relationships between the striking velocity and DoP, and established injury-risk curves for a penetrating cardiac and hepatic injury. This chapter examines whether widely used soft-tissue simulants can represent a penetrating cardiac and hepatic injury; specifically, penetration into several concentrations of gelatine is compared with that in the lamb heart and bovine liver. Ultimately, the concentrations of gelatine for which the DoP most closely correlates with that into heart and liver are proposed.

7.1 Introduction

Human tissue surrogates for penetrating injuries have been used over the years to observe penetrating reactions. Human cadavers and animals are not always ideal for ballistic tests due to the ethical limitation and alternations in material properties. Some substitutions of these surrogates for penetrating injuries are commonly made of ballistic gelatine, ballistic soap and synthetic polymer (Fackler, 1987; Nicholas and Welsch, 2004; Moy *et al.*, 2006); they are highly preferred in laboratory settings due to no ethical limitation. Furthermore, there are some requirements and experimental advantages in the gelatine and synthetic polymer surrogates; they generally involve high reproducibility, homogeneity, high transparency, and similar response to penetration into human tissue (Jussila, 2004; Humphrey and Kumaratilake, 2016). These surrogates therefore are available to observe the development of both a permanent and a temporary wound cavity using a high-speed camera.

The human tissue surrogates for vital organs have a potential to predict severe injury accurately. Such biofidelic surrogates are available for the experimental use and commonly designed to replicate the deformation behaviour of the organ. There are some tissue surrogates for the blunt trauma of the torso organs (Jonsson, Arvebo and Schantz, 1988; Roberts *et al.*, 2005; J. C. Roberts *et al.*, 2007). A lung surrogate made of plastic foam was developed for behind armour blunt trauma (Jonsson, Arvebo and Schantz, 1988). A whole torso surrogate including the heart, lung, liver and stomach made of silicone rubber was established based on the same geometry of a 5th percentile male (Roberts *et al.*, 2005; J. C. Roberts *et al.*, 2007). There, however, is no human tissue surrogate for penetrating injuries to torso organs. In particular, as discussed in Chapter 3, penetrating cardiac and hepatic injuries have been observed with relatively high mortality in the torso organs (Campbell *et al.*, 1997; Turégano-Fuentes *et al.*, 2014).

Among the human tissue surrogates, the ordnance ballistic gelatine at 10% and 20% concentrations is the most commonly used in ballistic tests. Historically, the FBI and NATO have used the 10% gelatine cooled at 4 °C and 20% gelatine at 10 °C, respectively (Fackler *et al.*, 1984; Nicholas and Welsch, 2004). These concentrations of gelatine have been shown to replicate retardation force and DoP in porcine muscle

(Fackler and Malinowski, 1988; Breeze, Hunt, *et al.*, 2013). Consequently, these gelatine surrogates are widely accepted for quantifying injury severity in soft tissue and so used to evaluate the performance of personnel protective equipment. There has, however, been no evidence whether these concentrations of ballistic gelatine can represent a penetrating cardiac or hepatic injury.

This study aims to find a biofidelic surrogate that can be used to quantify a penetrating cardiac and hepatic injury. Gelatine at various concentrations was chosen as the potential surrogate. The DoP and V_{50} values in each concentration of gelatine were measured and compared with the data from the experiments on lamb heart and bovine liver presented in Chapter 5 and 6.

7.2 Materials and methods

7.2.1 Sample preparation

Ballistic gelatine blocks between 5% and 30% concentration were prepared. The gelatine was produced with the method described by Breeze et al. (Breeze, James and Hepper, 2013):

- 1 Add gelatine powder (porcine gelatine 300 bloom) gradually into heated-distilled water at $70\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$ while the water is stirred to dissolve slowly.
- 2 Stir the gelatine mixture for 5 minutes and leave to rest for 5 minutes.
- 3 Stir the gelatine mixture for an additional 5 minutes and then leave to rest for 45 minutes.
- 4 Remove the excess foams off the gelatine and pour the gelatine mixture into a mould.
- 5 Cool the gelatine in the refrigerator at $10\text{ }^{\circ}\text{C}$ overnight until complete solidification.

In order to calibrate the gelatine block, DoP in the first shot of each series of tests was compared with that of previous test. This calibration ensured that the resultant DoP was within 10% tolerance of the previous DoP in the same concentration of the gelatine.

7.2.2 Experimental protocol

The dimensions of gelatine blocks were $250 \times 145 \times 50$ mm and determined based on the size of the target chamber in the gas gun. The striking velocity of the projectile was calculated from the footage of a high-speed camera. In this test, the three projectiles (5-mm sphere, 0.78-g-RC cylinder and 1.1-g-CN cylinder) were shot at up to 150 m/s of striking velocity in the same range of velocity as the previous tests with the heart and liver. Approximately 20 projectiles were fired into each gelatine block (Figure 7.1); impact points on the gelatine were distant from adjacent permanent cavities. Each temporary cavity and projectile were observed in the footage of a high-speed camera and did not interact with other permanent cavities and projectiles of previous shots.

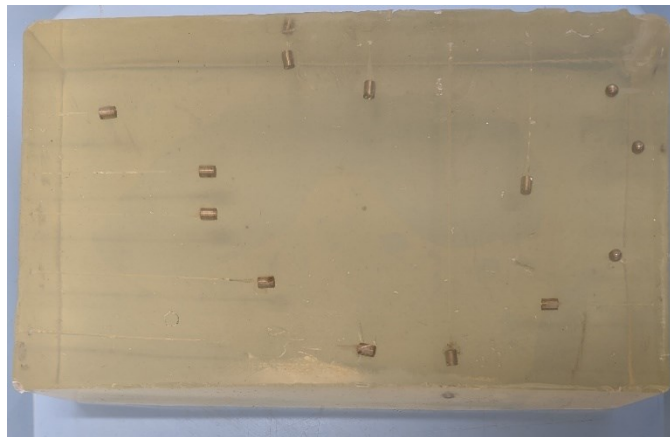


Figure 7.1 A gelatine block struck by 5-mm spheres and 0.78-g-RC cylinders.

After a series of shots, the gelatine block was cut along each permanent cavity. The DoP in the gelatine blocks was then measured with a ruler which was directly placed on the permanent cavity. In this study, DoP is the distance between the entrance hole and the furthest side of the permanent cavity regardless of the projectile location; this is because the projectile frequently reversed from the furthest point travelled before coming to rest inside the gelatine.

7.2.3 Statistical analysis for the liver and heart

The slopes and intercepts of the linear regressions (Equation 5.6) were compared with the bovine liver and lamb heart experimental results using the statistical software SPSS (version 28, IBM, United States). An analysis of covariance (ANCOVA) with the general linear model univariate procedure was used to obtain the p-values for slopes and y-intercepts. When there was no significant difference attained in the slope, but significant difference attained in the y-intercept, the value of the y-intercept in the gelatine was changed based on the best fit linear regression compared to data points obtained in the cadaveric lamb heart or bovine liver (Figure 7.2).

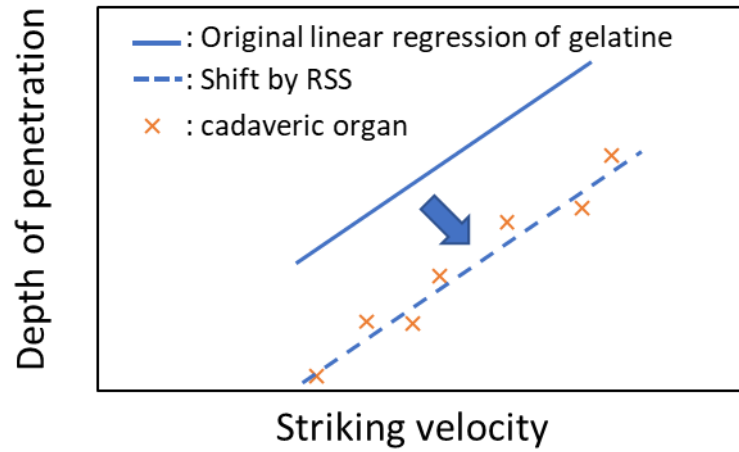


Figure 7.2 The y-intercept shift of gelatine to cadaveric organ data by the residual sum of squares (RSS).

Specifically, the new y-intercept of the gelatine was calculated by minimising the residual sum of squares (RSS):

$$RSS = \sum_{i=1}^n (Organ\ DoP_i - f(SV_i))^2 \quad \text{Equation 7.1}$$

where *Organ DoP* is depth of penetration in the lamb heart or bovine liver [mm] and $f(SV)$ is the predicted value of *DoP* [mm] obtained from Equation 5.6 using the slope α and a new y-intercept β of the gelatine.

The V_{50} values of penetration were calculated from the arithmetic mean of the three highest velocities of non-penetration and the three lowest velocities of penetration as specified in the AEP-2920 NATO standard (NATO Standardization Office, 2015). These V_{50} values obtained from the gelatine blocks were statistically compared with the data for cardiac wall (ventricular and atrial wall) and liver using the independent Student's t-test.

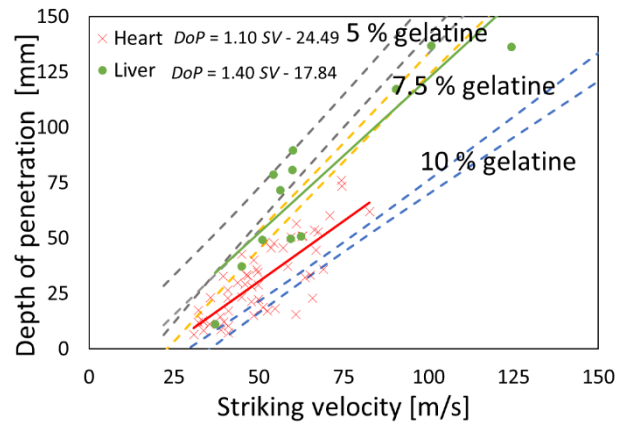
7.3 Results

The gelatine blocks between 5% and 30% concentrations were utilised to carry out 81, 77 and 59 shots using the 5-mm sphere, 0.78-g-RC cylinder and 1.1-g-CN cylinder, respectively.

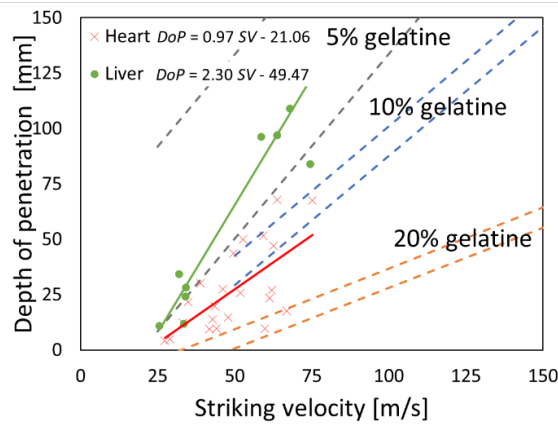
7.3.1 Depth of penetration

DoP as a function of the striking velocity in the gelatine was compared with the lamb heart and bovine liver results obtained in Chapters 5 and 6 (Figure 7.3). Linear regression was also used to fit the DoP versus striking velocity graph of the heart and liver tests. The slope and y-intercept of the linear regression in each concentration of the gelatine are presented in Table 7.1. Figure 7.4 shows the slope and y-intercept as a function of the gelatine concentration approximated with a linear regression. In order to find which the gelatine concentration has the closest DoP to that of the heart and liver in each projectile, the slope and y-intercept were statistically compared between the gelatine concentrations and the lamb heart or bovine liver (Table 7.2). No significant differences ($p \geq 0.05$) in both slope and y-intercept were observed between the heart and the 10% gelatine for all three projectiles; and between the liver and the 5 to 7.5% gelatine only in the 5-mm sphere. Despite no significant differences between the slope of the liver and the 5% gelatine in the 0.78-g-RC and

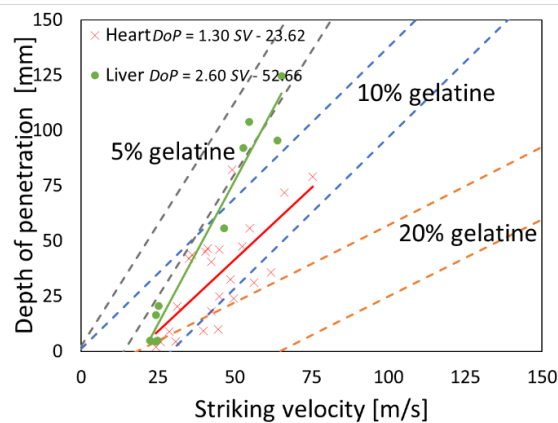
1.1-g-CN cylinder, there were significant differences between the y-intercept of these data sets.



A



B



C

Figure 7.3 (A) DoP as a function of the striking velocity in the gelatine, lamb heart and bovine liver using the 5-mm sphere, (B) the 0.78-g-RC cylinder and (C) 1.1-g-CN cylinder. Dashed lines show the 95% confidence interval of gelatine.

Slope coefficient and y-intercept in each projectile		Gelatine concentration			
		5%	7.5%	10%	20%
5-mm Sphere	α	1.70	1.59	1.08	-
	β	-19.98	-30.44	-35.48	-
0.78-g-RC cylinder	α	1.67	-	1.17	0.55
	β	8.20	-	-22.57	-22.22
1.1-g-CN cylinder	α	2.22	-	1.37	0.70
	β	-14.35	-	-19.53	-29.32

Table 7.1 The slope and y-intercept of the linear regression (Equation 5.6) from the graphs presented in Figure 7.3.

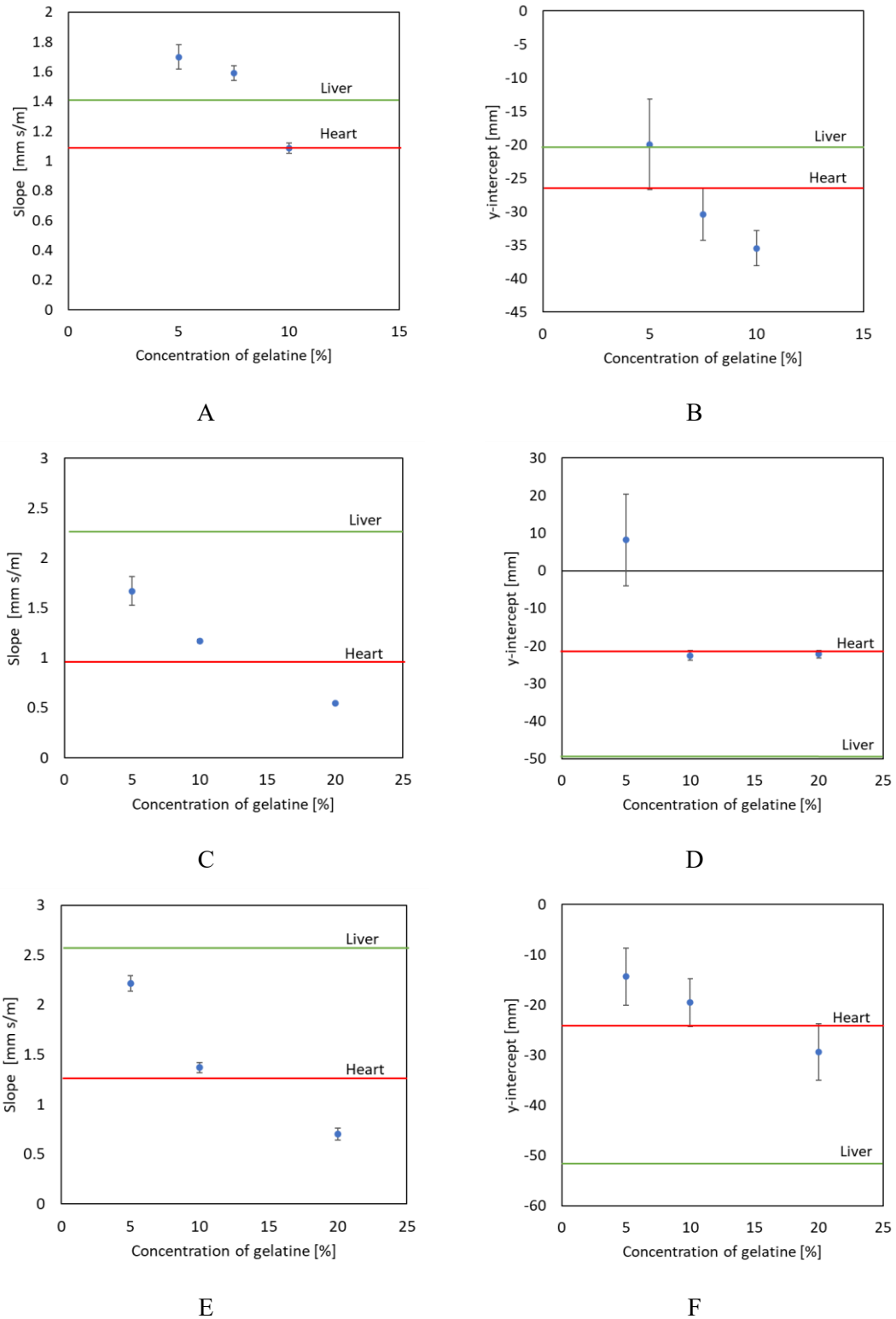


Figure 7.4 Comparisons of the slope and y-intercept derived from the DoP versus the striking velocity graph in each concentration of gelatine struck by (A) and (B) the 5-mm sphere, (C) and (D) the 0.78-g-RC cylinder, and (E) and (F) the 1.1-g-CN cylinder. The red and green bar show the value of heart and liver, respectively. The error bars show the standard error.

Projectile and sample		Gelatine concentration			
		5%	7.5%	10%	20%
5-mm sphere	Heart	<0.001/0.605	<0.001/0.452	0.934/0.199	-
	Liver	0.156/0.887	0.286/0.325	0.082/0.178	-
0.78-g-RC cylinder	Heart	0.026/0.105	-	0.305/0.885	0.034/0.914
	Liver	0.103/0.016	-	<0.001/.024	<0.001/.026
1.1-g-CN cylinder	Heart	0.04/0.579	-	0.793/0.756	0.029/0.715
	Liver	0.076/0.002	-	<0.001/.002	<0.001/.033

No significance $p \geq 0.05$

Table 7.2 Statistical comparisons of the slope and y-intercept between gelatine concentrations and heart and liver data. Values show the p-value for the slope / y-intercept, respectively.

In the 0.78-g-RC and 1.1-g-CN cylinder, the best fit linear regression was performed for the 5% gelatine. The new y-intercept, β was calculated based on the minimum RSS (Equation 7.1). The slopes and new y-intercepts are shown in Figure 7.5. There were no significant differences between the y-intercept in the liver and the new y-intercept in the 0.78-g-RC and 1.1-g-CN cylinder. The differences between the new and the original y-intercept of the 5% gelatine were 26.52 mm for the 0.78-g-RC cylinder and 23.03 mm for the 1.1-g-CN cylinder.

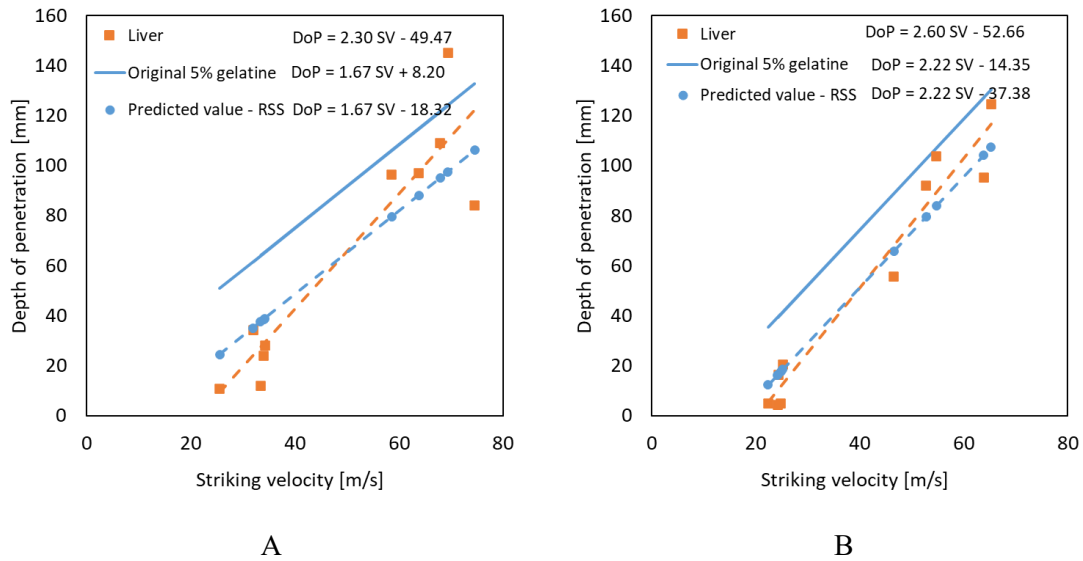
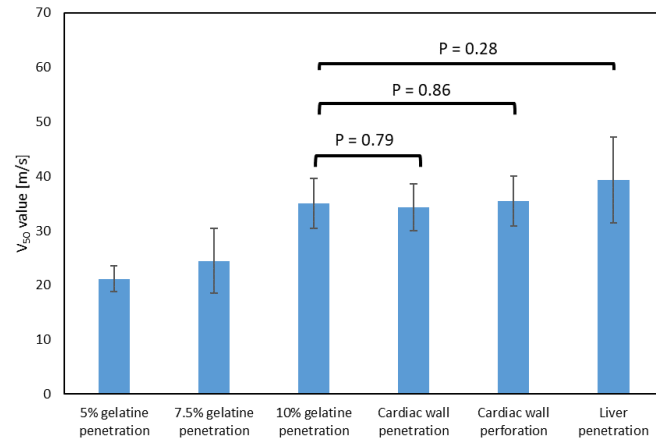


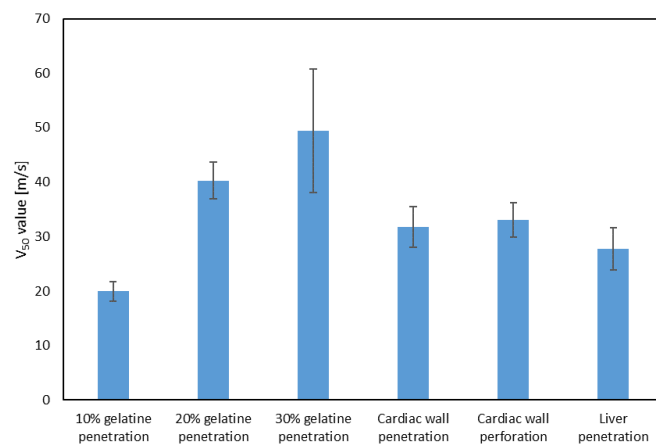
Figure 7.5 The best fit analysis with the residual sum of squares (Equation 7.1) derived from the DoP as a function of the striking velocity in the 5% gelatine struck (A) by the 0.78-g-RC cylinder and (B) by the 1.1-g-CN cylinder.

7.3.2 V_{50} values

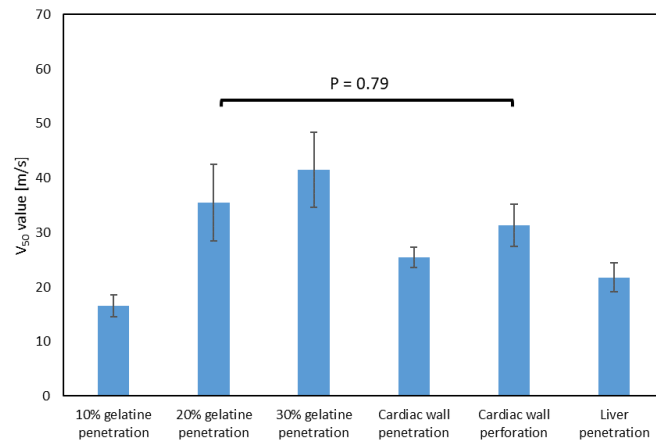
V_{50} values of penetration in each concentration of gelatine were compared with those of penetration and perforation into the cardiac wall, and of penetration into the liver (Figure 7.6). There were no significant differences between the V_{50} values of all cadaveric organs assessed here and the 10% gelatine in the 5-mm sphere; and between the perforation of the cardiac wall and the 20% gelatine in the 1.1-g-CN cylinder. In contrast, significant differences were observed in the V_{50} values of the two cadaveric animal organs and any concentration of gelatine in the 0.78-g-RC cylinder.



A



B



C

Figure 7.6 Comparison of V_{50} values for (A) the 5-mm sphere, (B) the 0.78-g-RC cylinder and (C) the 1.1-g-CN cylinder. The error bars show one standard deviation and the p-value when there is no statistical significance between the gelatine and the cadaveric animal organ ($p \geq 0.05$).

In order to compare these V_{50} values as a function of gelatine concentrations, Table 7.3 shows the mean and one standard deviation of the V_{50} value in each concentration of gelatine. Figure 7.7 shows the V_{50} values as a function of the gelatine concentration compared with the cardiac wall and liver. The appropriate concentration of gelatine for the 0.78-g-RC cylinder was qualitatively evaluated from only three datapoints. Its linear regression in Figure 7.7 B was interpolated at the V_{50} value of cardiac wall perforation for the 0.78-g-RC cylinder (33.06 ± 3.12 m/s). Consequently, 18% concentration would be suitable for estimating the perforation of the cardiac wall in the 0.78-g-RC cylinder.

Projectile	Gelatine concentration				
	5%	7.5%	10%	20%	30%
5-mm sphere	21.17 ± 2.33	24.46 ± 5.96	35.00 ± 4.63	-	-
0.78-g-RC cylinder	-	-	20.00 ± 1.79	40.30 ± 3.33	49.47 ± 11.34
1.1-g-CN cylinder	-	-	16.58 ± 2.05	35.47 ± 7.00	41.51 ± 6.83

Table 7.3 The V_{50} values of penetration in each concentration of the gelatine; values show mean and one standard deviation.

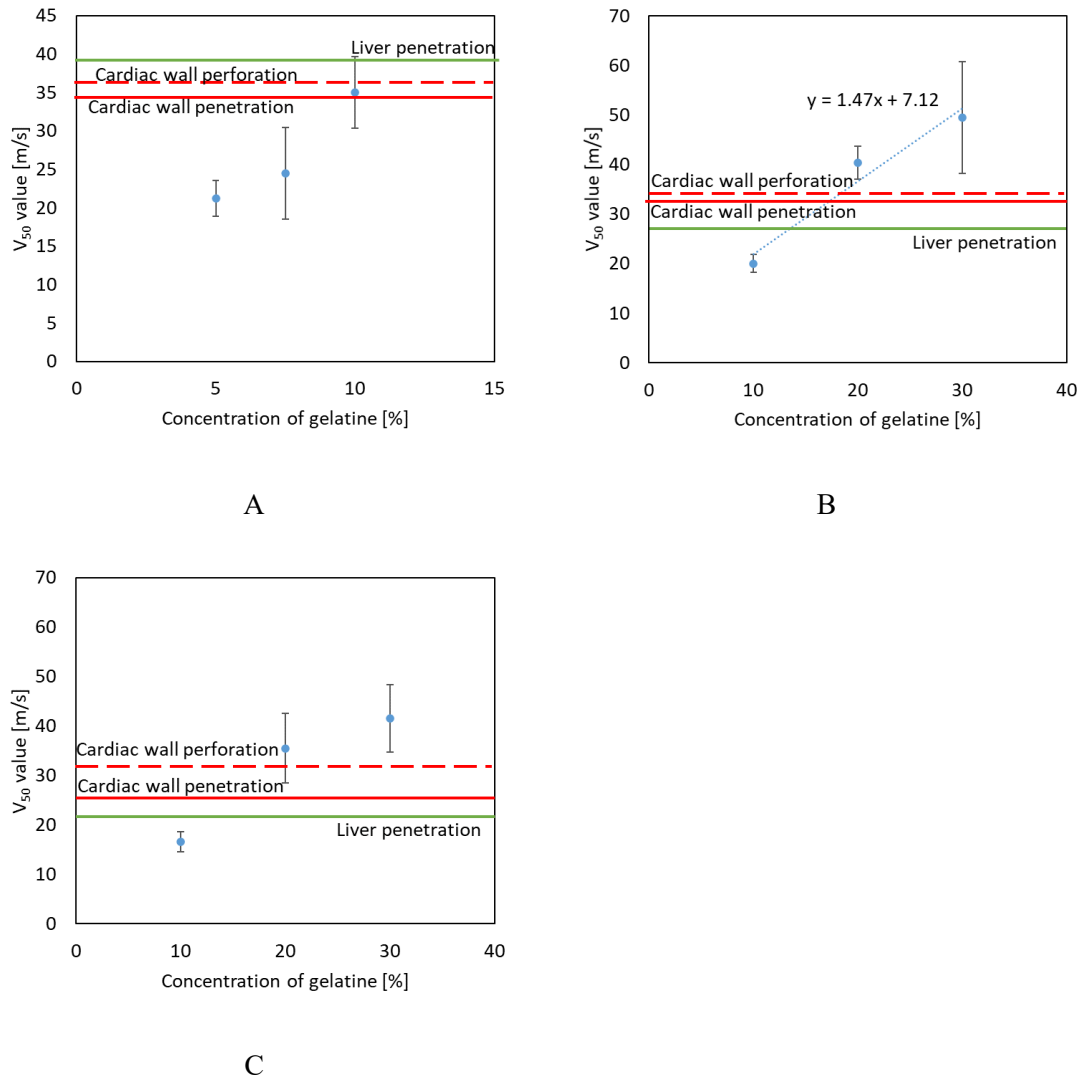


Figure 7.7 Comparisons of V_{50} values in each concentration of the gelatine struck by (A) the 5-mm sphere, (B) the 0.78-g-RC cylinder, and (C) the 1.1-g-CN cylinder. The green and red lines show penetration of the liver and of the cardiac wall, respectively. The red dashed line shows the perforation of the cardiac wall. Error bars show one standard deviation.

7.3.3 Biofidelic surrogate

Table 7.4 summarises the concentrations of gelatine that were found to estimate best DoP in the liver and heart, and the V_{50} for perforation through the cardiac wall. As discussed in Chapter 5, the perforation of the cardiac wall represents a severe injury (AIS 5) (Gennarelli and Wodzin, 2006).

Projectile	DoP		V ₅₀ value
	Heart	Liver	Cardiac wall perforation
5-mm sphere	10%	7.5%	10% (penetration)
0.78-g-RC cylinder	10%	5% *	18% (penetration)
1.1-g-CN cylinder	10%	5% **	20% (penetration)

Table 7.4 Most suitable concentrations of gelatine for estimation of DoP and V₅₀ values for perforation through the cardiac wall. * and ** indicate that it is required to subtract 26.52 mm and 23.03 mm from the DoP measured in the 5% gelatine, respectively for RC and CN cylinder penetration into the liver.

7.4 Discussion

This study intended to find a biofidelic surrogate for quantifying penetrating cardiac and hepatic injury. Gelatine blocks between 5% and 30% concentration were used to measure DoP and V₅₀ values of penetration for striking velocities from 14 to 150 m/s across 3 types of fragments. DoP produced by these fragments is associated with retardation force and kinetic energy. If tumbling is negligible, a small cross-section and heavy projectile (namely, a large length to diameter (L/D) ratio) creates a large DoP at the same velocity. Hence, DoP in the cylindrical projectiles was larger than that in the sphere (steeper slopes shown in Table 7.1).

For DoP estimation in the heart, the 10% gelatine is the most biofidelic surrogate for all projectiles used here. The slopes of the DoP versus striking velocity graphs for 10% gelatine were closest to those of the experiments with lamb hearts; in addition, there were no significance differences between the 10% gelatine and the heart data sets for both slope and y-intercept in all three projectiles.

AIS 5 injury in the heart can be assessed using gelatine of concentration between 10% and 20%. Perforation of the cardiac wall is classified as AIS 5 (Gennarelli and

Wodzin, 2008). In this study, there were no significant differences between the perforation of the cardiac wall and the penetration of the 10% gelatine for the 5-mm sphere; and the 20% gelatine for the 1.1-g-CN cylinder (Figure 7.6). For the 0.78-g-RC cylinder, 18 % gelatine would be a suitable surrogate for the estimation of an AIS 5 injury.

For DoP estimation in the liver, the 7.5% gelatine for the 5-mm sphere; and 5% gelatine for 0.78-g-RC cylinder and 1.1-g-CN cylinder are the most biofidelic surrogates. The slope values derived from the tests in these gelatine blocks were closest to those of the tests on liver (Figure 7.4). Moreover, there were no significant differences between the slope derived from the tests on liver and those from gelatine blocks for all three projectiles (Table 7.2), although no significant difference was found only between the y-intercept of the liver and of 7.5% gelatine in the 5-mm sphere. The gelatine block at concentration of less than 5% may have a similar slope and y-intercept to that of the liver tests for the 0.78-g-RC and 1.1-g-CN cylinder. A low concentration gelatine is extremely fragile and so is not practical for experimental use. Alternatively, the proposition is that the DoP of hepatic tissue for the 0.78-g-RC and 1.1-g-CN cylinder can be estimated by subtracting 26.52 mm and 23.03 mm from the DoP in the 5% gelatine, respectively. For injury prediction, DoP in the liver is associated with moderate and serious injury (AIS 2 and 3), which represent less or equal to a 3 cm laceration and more than 3 cm laceration in depth, respectively (Gennarelli and Wodzin, 2008). The 7.5% gelatine for the 5-mm sphere and 5% gelatine for the 0.78-g-RC cylinder and 1.1-g-CN cylinder, therefore, are available to predict AIS 2 and 3 when the estimated DoP to the liver exceeds these thresholds.

The prediction of severe penetrating injuries to the liver requires estimated tissue loss in the gelatine. An AIS 4 injury of the liver is categorised as 25% tissue loss of a hepatic lobe. Chapter 6 revealed that the V_{50} values of AIS 4 (mean $\pm$ one standard deviation) were 676.3 ± 101.3 m/s and 541.2 ± 42.3 m/s for the right lobe and left lobe, respectively. This tissue loss area extended over the permanent wound cavity in the radial direction so is thought to be caused by the temporary wound cavity (Fackler *et al.*, 1984). The maximum radius of the temporary cavity, however, depends on the size of a gelatine block and constraint condition around it so these parameters may prevent the resultant disruption associated with tissue loss from developing in the

gelatine (James, 2020). In order to find a surrogate for the estimation of an AIS 4 injury of the liver, further tests should be conducted using a gelatine block of similar size to the liver.

The size of the gelatine block was determined based on the target chamber size of the gas gun instead of the heart and liver; in particular, the depth of the gelatine was larger than the heart and liver. This enables us to measure the larger DoP produced by the permanent cavity, resulting in a wide range of DoP available in this study. Only the formation of the temporary cavity would be affected by the different sample size. In this study, the permanent cavities, however, were primarily compared with those in the heart and liver and thus these results have the negligible effect on the sample size.

7.5 Summary

This chapter demonstrated that cardiac and hepatic penetrating injury due to the three projectiles assessed here can be predicted with acceptable accuracy using ballistic gelatine. A biofidelic cardiac tissue surrogate was shown to be gelatine at 10% concentration for DoP estimation and gelatine at 10% to 20% concentration for the prediction of an AIS 5 injury. Biofidelic hepatic tissue surrogates were shown to be the 7.5% gelatine for penetration by a 5-mm sphere; and the 5% gelatine for penetration by a 0.78-g-RC and 1.1-g-CN cylinders. These hepatic tissue surrogates were shown to be appropriate for both DoP estimation and for prediction of an AIS 2-3 injury to the liver. Ballistic tests with the three projectiles proposed here offer a pragmatic and practical method to accumulate the experimental data of the surrogates for DoP and injury prediction in any laboratory setting, thus allowing for the accurate prediction of these penetrating cardiac and hepatic injuries.

CHAPTER 8

SUMMARY, DISCUSSION, AND FUTURE WORK

Chapter 8 summarises this thesis and highlights main findings. As an overall summary, brief reviews and some key points in the previous chapters are provided. A discussion on the research is presented, including limitations of the research and further development of this work is proposed. Potential applications using the outcomes in this thesis are also discussed.

8.1 Overall summary

Explosive devices are the most frequently used weapon in battlefields and terror incidents. Penetrating injuries due to energised fragments from explosions are the main cause of blast injuries. Due to the vital organs behind the torso wall, penetrating injuries to the torso lead to a high mortality rate. This thesis investigated the pattern of the penetrating injuries to the torso organs and quantified the risk of penetrating cardiac and hepatic injuries.

At the beginning of this thesis, the patterns of torso blast injuries were reviewed relating to their injury mechanisms in Chapter 2 and 3. Chapter 2 introduced the overview of the blast injuries and characteristics of various IEDs. Chapter 3 moved on to the literature review of injury patterns in current terror bombings. These chapters revealed the relationships among the mechanism of the blast injury, injury pattern and IED type. Of all the blast injuries, injuries to the heart and the liver have the high risk of severe penetrating injury due to the energised fragments. The risk of these organ injuries has not, however, been quantified. Nevertheless, such quantitative assessment plays an important role in developing simulation model which allows for the accurate prediction of the casualties in bombing attacks.

In Chapter 4, the experimental methods were chosen to quantify a penetrating cardiac and hepatic injury. The three projectiles (5-mm sphere, 0.78-g-RC cylinder and 1.1-g-CN cylinder) used in this study were determined based on the representative fragments seen in IED attacks and are recommended in the NATO standard. A gas-gun system was deemed suitable to conduct tests due to the high reproducibility of the striking velocity. The cadaveric lamb heart and bovine liver were used as appropriate animal models in this study due to the similar material properties to the human. As human tissue surrogates are beneficial in any laboratory settings, ballistic gelatine, a widely used human tissue surrogate, was also chosen as the basis to find a biofidelic surrogate for laboratory, standardised tests of penetrating cardiac and hepatic injuries.

In the following two chapters, the quantitative assessment of a penetrating cardiac and hepatic injury was investigated. In Chapter 5, frozen-thawed lamb hearts were used as the samples due to no significant difference found between DoP in fresh

and frozen-thawed lamb hearts. The perforation of the cardiac wall categorised as AIS 5 injury (characterised as critical) was primarily assessed to establish injury-risk curves. This finding suggests that a relatively low striking velocity (approximately 35 m/s in the three projectiles) into the heart caused an AIS 5 or more severe injury. In Chapter 6, fresh bovine livers were chosen as the samples. The tissue disruption extending around a permanent wound cavity was identified using MRI scanning. An AIS 4 injury (characterised as severe) of the liver, which represents 25-75% tissue loss in a hepatic lobe, was evaluated based on the volume of the tissue disruption. This finding shows that this severe hepatic injury due to the 5-mm sphere occurred at the impact velocity of 676 and 541 m/s for the right lobe and the left lobe, respectively.

In Chapter 7, biofidelic tissue surrogates for the heart and liver were determined from different concentrations of ballistic gelatine. Gelatine was tested at various concentrations, and the results compared with those of the lamb heart and bovine liver obtained in Chapter 5 and 6. Ballistic gelatine of 10% was found to be a biofidelic tissue surrogate for the DoP estimation of the heart in the three projectiles. A biofidelic surrogate for the DoP estimation of the liver was shown as 5% gelatine for the 5-mm sphere and 7.5% gelatine for the 0.78-g-RC cylinder and 1.1-g-CN cylinder.

This thesis is the first to quantify penetrating cardiac and hepatic injuries. This quantitative injury assessment could be incorporated into, and improve upon the accuracy of, predictive computational models of casualties in the aftermath of terror incidents. Such simulation results will allow for improving the protocol of the emergency service and the design of large infrastructure to reduce the risk of the penetrating injuries.

8.2 Discussion and future work

The quantitative assessment of penetrating injury to heart and liver can be used to develop new injury models. As discussed in Chapter 4, existing simulation models for blast-injury prediction have a low or moderate fidelity of the anatomical geometry and links the physical response of the model to the resultant injury. The geometry of the organs can be developed based on the 3D human data and the injury-risk curves in

Figure 5.9, 6.20 and 6.21 can be incorporated into each organ model. Moreover, the injury criterion of the AIS 4+ in Equation 6.1 can be also used to evaluate whether the tissue loss per hepatic lobe exceeds 25% (AIS 4).

The risk of penetrating cardiac and hepatic injuries was correlated here with the velocities striking each organ. Current computational models of injury calculate the striking velocity reaching the torso and use it to predict probability of organ injury. Before using the injury curves developed here to do that, the contribution towards the retardation of the fragment by other torso organs along the path of the fragment prior to reaching the heart or the liver needs to be considered. Nguyen et al. measured the V_{50} values of thoracic tissues such as the intercostal muscle and ribs which can be used to determine the retardation force of a 0.78-g-RC cylinder (Nguyen, Breeze and Masouros, 2022). There, however, are no further data for other projectiles and other torso organs such as skin. Moreover, velocity reduction through clothing and body armour is also needed for the more accurate estimation of the civilian and military casualties.

The simulation using sophisticated injury models helps to improve the design of infrastructure and body armour. For infrastructure, these simulation results can help identify the area of large congregations at a high risk of terror attacks. In such area, the flow of people can be controlled by building barricades to reduce the number of casualties in terror incidents. The location and material of structural elements can also be determined; for instance, pillars and walls made of composite metal or composite fabric can significantly reduce the energy of fragments during their impacts (Marx, Portanova and Rabiei, 2018; Crouch, 2019). For body armour, the injury model simulations can help optimise design and coverage areas as the physical performance of the wearer decreases due to a heavy load and stiffness of body armour (Park *et al.*, 2011; Gijsbertse *et al.*, 2021).

The MRI scanning of the penetrating hepatic injury may have further potential for the examination of tissue damage. In some MR images of the bovine liver, bright regions extended over the permanent wound cavity from the entry to exit side of a projectile (Figure 8.1). These bright regions were identifiable in only 3 out of 11 samples so were not consistent with each sample in this study. It is hypothesised that

this region was associated with tissue damage but could become blurred on the MR images depending on the state of hepatic tissue. For further experiments, the tissue state will be improved using the smaller block of the liver and shorter storage time than this study, because these parameters affect the development of post-mortem decomposition in the hepatic tissue (Dunford, LeRoith and Kemper, 2018).

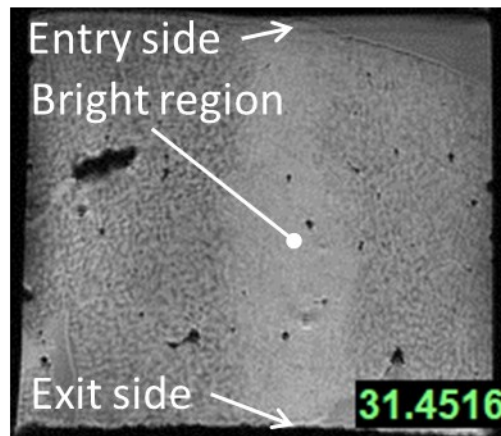


Figure 8.1 Coronal plane MRI of liver sample S2 obtained from the T1 sequence described in Chapter 6.

The quantitative assessment of penetrating injuries in this thesis was derived from the impacts of low yaw angles using three representative fragments of IEDs. In this research, the cylindrical projectiles over the impact angle of 60° were removed from the experimental data because the cylindrical projectiles at large yaw angles are highly likely tumbling in the human tissue. The tumbling in the tissue results in high retardation force, thus generally causing large tissue damage. In reality, the yaw angle of an energised fragment may also increase due to reaching other structures in the thorax such as rib bone. All these factors as well as the different shape and mass from the three projectiles assessed here generally affect the pattern of injury (Woodcock *et al.*, 2006). In order to predict a wider range of these injury patterns, future work will be required to quantify the organ injuries in these various experimental conditions.

The penetrating injury to other organs can be quantified using a similar method to the one developed here to assess penetrating cardiac and hepatic injury. In the torso

organs, either DoP or perforation is associated with an AIS score for the spleen, kidney, stomach, large bowel and small bowel (Gennarelli and Wodzin, 2008). These fresh organs of a cadaveric animal which have similar anatomical parameters and material properties to the human could be used to quantify a penetrating injury. From the DoP or perforation examined with radiography, the injury-risk curves can be established.

In this research, only the individual fragment impact was quantified although the prediction of multiple impacts from a single explosive event is also possible in the hepatic injury model developed here. Multiple penetrating injury to the heart and liver are highly likely to occur in bombing attacks due to a large number of energised fragments from IEDs. In the heart, the perforation of cardiac wall is classified as critical injury in the AIS system, so the penetrating cardiac injury can be quantified to determine whether the individual impact perforates the cardiac wall, regardless of multiple impacts. In the liver, the multiple impacts profoundly affect the probability of an AIS 4 injury, which is evaluated based on the volume of tissue disruption. DoP in the liver due to all fragments from one event can be used to calculate approximately the total volume of tissue disruption (Equation 6.1) from the DoP due to each impact. Potential overlap in tissue disruption per fragment could also be calculated to offer a good estimate of total tissue disruption.

The gelatine surrogates are suitable for the estimation of the permanent cavity but surrogates for estimating the temporary cavity need to be developed through further experiments. This study found that gelatine can be used to predict the permanent cavity due to the three fragments. The expanding and contracting movements of the temporary cavity may not be replicated with the gelatine although tissue disruption due to the temporary wound cavity enables us to estimate an AIS 4 hepatic injury. There, however, is no research on the development of radial cracks due to projectile penetration into gelatine. Moreover, the viscosity of the surrogate and human tissue would not be negligible at high velocity impact. It is difficult to control the viscosity of the gelatine as only the strength of the gelatine is variable using different blooms of gelatine powder. For controlling viscosity and strength, a synthetic polymer, such as silicone rubber of different ratios of the different silicon elastomer agents can be used and is available commercially. Typically, the synthetic polymer can

be stored at room temperature; it slowly degrades its material properties due to it being a non-biological material unlike gelatine. These characteristics of the synthetic polymer may enable the investigation of penetration behaviour with high repeatability.

8.3 Conclusion

Penetrating injuries due to energised fragments are the most common type of blast injuries. The heart and liver have the high risk of penetrating injury in the torso organs. In this thesis, penetrating cardiac and hepatic injury risks were quantified as a function of fragment velocity, and the appropriate concentrations of ballistic gelatine were identified as biofidelic tissue surrogates for the heart and liver. These new injury models can now be readily incorporated into computational models to predict penetrating cardiac and hepatic injuries more accurately, and inform the design of body armour, of infrastructure, and of emergency response to mass casualty events.

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