MODELLING CRANIAL GUNSHOT WOUNDS AND BACKSPATTER

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Abstract

Bloodspatter from gunshot wounds may be divided into two categories; forward spatter and backspatter. Forward spatter is ejected from the exit wound and travels in the same direction as the bullet. Backspatter on the other hand is ejected from the entrance wound and travels against the line of fire, back towards the shooter. This means it is commonly deposited on the hand of the shooter or the firearm, making it a critical piece of evidence when determining the manner of death. Despite this fact, research in this area is limited and no realistic synthetic model for studying backspatter has been documented in the literature. This project was initiated in response to this, in an attempt to create a realistic cranial model that could produce backspatter from a gunshot wound.

A pig head model was developed, as it could be validated unlike a human model. This model consisted of synthetic skin, soft tissue and bone layers which completely enclosed a volume of gelatine to represent the brain. The model was tested at a firing range, along with butchered pig heads and live pigs and the results were compared. A high-speed camera was used to film each shot, in order to record key events in slow motion. The resultant wounds, the high-speed videos, and the backspatter produced were analysed and compared.

The model was comparable with pigs in relation to the backspatter produced and there were also similarities between the resultant wounds. The development of this pig model has therefore laid the foundations for creating a realistic human head backspatter model in the future. It was concluded that, with further development and testing, the model could potentially be a useful tool for forensic scientists, particularly in aiding their understanding and interpretation of backspatter from gunshot fatalities.

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°	Degrees
°C	Degrees Celsius
µs	Microsecond
BMF	Blood mimicking fluid
BPA	Bloodstain pattern analysis
cm	Centimetre
DVD	Digital video disc
E	Energy
EDTA	Ethylenediamine tetraacetic acid
ESR	Institute of Environmental Science and Research Limited
FMJ	Full metal jacketed
fps	Frames per second
g	Gram
gsm	Grams per square metre
GPa	Gigapascal
HTRU	Hercus Taieri Resource Unit
IABPA	International Association of Bloodstain Pattern Analysts
IV	Intravenous
J	Joules
kg	Kilogram
kg/m^3	Kilogram per cubic metre
kJ	Kilojoule
kPa	Kilopascal
m	Mass
m	Metre
ml	Millilitre
mm	Millimetre
ms	Millisecond

m/s	Metres per second
n/a	Not applicable
N	Newton
PC	Personal computer
r	Radius
SBS	Synthetic blood substitute
SD	Standard deviation
SEM	Scanning electron microscopy
v	Velocity
V	Volume

1. Introduction

Bloodstain pattern analysis (BPA) is a commonly used forensic technique that is employed to reconstruct the scene of a violent crime. It can be defined as “the analysis of the size, shape and distribution of bloodstains resulting from bloodshed events as a means of determining the types of activities and mechanisms that produced them” (James, et al., 2005). BPA may play a crucial role in crime scene reconstruction, especially when the manner of death is questioned. Because of this it has long been recognised as an important forensic discipline.

Bloodstains can be classified in a number of ways based on their physical characteristics. They are commonly grouped into three basic categories; passive stains (formed under the influence of gravity alone), contact transfer stains (caused by contact with a bloodied surface) and projected stains (formed under the influence of an external force) (Bevel and Gardner, 1997). The morphology of a bloodstain may be used to determine the angle of impact, the origin and direction of the blood droplet and the nature of the force that produced it (Bevel and Gardner, 1997; James, et al., 2005).

Projected stains are often referred to as bloodspatter patterns (James, et al., 2005). The analysis of these patterns at the scene of a gunshot fatality is particularly important as it may often be difficult to determine whether death was the result of suicide, homicide or an accident. Bloodspatter resulting from gunshot wounds is often classified according to the wound from which it is ejected. Blood which originates from the exit wound is referred to as forward spatter as it travels in the same direction as the bullet. However, in certain circumstances, blood may be ejected from the entrance wound. This is referred to as backspatter because it travels against the line of fire back towards the shooter.

Backspatter is significant in crime scene reconstruction as it is often deposited on surfaces in close proximity to the wound, such as the firearm or the hand of the shooter. This means it may sometimes be critical evidence when differentiating between suicide and homicide. Despite this fact, the conditions under which backspatter occurs are not well understood. While it is widely accepted that backspatter is more likely to occur in close-range shots, particularly those in the head region, the other variables which affect backspatter production, such as firearm type, remain questionable (Stephens and Allen, 1983; Pex and Vaughan, 1987; Burnett, 1991; Karger, et al., 1996; James, et al., 2005; Karger, 2008).

The literature on backspatter is limited compared to that in other areas of bloodspatter research. Observations of backspatter in a number of forensic cases have been documented and researchers have also studied backspatter experimentally using animals and models. Such case study observations are valuable as they provide information on common characteristics of backspatter patterns. Experimental studies are also of value but the problem of finding a target which is a realistic representation of the human body remains a challenge. Animal experimentation is often appropriate as the tissue properties and circulatory systems of certain animals are in many ways similar to those of humans. However, there are anatomical differences between humans and animals that cannot be ignored and there are also ethical considerations when performing animal testing.

An appropriate physical model could potentially be used to address both of these issues. Unfortunately, there are no published studies that describe a realistic model for studying backspatter. To date, the only physical models described in the literature have been primitive, such as a blood soaked sponge inside a plastic bag (Stephens and Allen, 1983; Pex and Vaughan, 1987). While sponge is often used to simulate soft tissue, the lack of skin or underlying bone structures in such models means that they are not representative of the human body. In order for a model to be appropriate it needs to be realistic in both its materials and in its design. The present study was initiated in response to this challenge in an attempt to develop a suitable model that could be used to study backspatter experimentally.

The ultimate end-point for the development of such a model would be that it is capable of producing backspatter from a gunshot wound which is realistic, in other words represents that seen in forensic cases. However, in order to get to this stage there are many steps that must be taken, including validation of the model. An obvious method for this is to use an animal model. This project involved the development and testing of a simulated pig head backspatter model. Results from this were then compared to findings from similar tests on butchered pig heads and live pigs in order to validate the model. A pig model was selected, based on the similarities in skin and bone between humans and pigs (Bustad and McClellan, 1966; Douglas, 1972; Ankersen, et al., 1999). Pigs have also been suggested as the most appropriate animal for wound ballistic studies (Sellier and Kneubuehl, 1994).

The proceeding literature review will present an overview of both backspatter and wound ballistics in order to provide the background information for this project. Wound ballistics will be discussed first, as an understanding of this is crucial for understanding backspatter. Backspatter will then be discussed, with the main focus on the methods by which it has been studied.

1.1 Wound ballistics

Wound ballistics refers to the branch of ballistics that is concerned with the motion and effects of a projectile within the body (Owen-Smith, 1981; DiMaio, 1999; Karger, 2008). It also deals with the study of injuries inflicted by projectiles (Owen-Smith, 1981; Maiden, 2009). The degree of damage that is inflicted upon living tissue by a bullet (or other projectile) is highly variable and depends on a number of factors. The mechanisms by which this occurs, as well as the key determinants of injury, will be discussed in this section. The various ways in which this subject has been studied will also be addressed.

1.1.1 Mechanisms of injury

There are said to be two main mechanisms by which a bullet inflicts local injury; the crush mechanism, and the stretch mechanism. A third mechanism of injury, known as the "shock wave" has also been suggested. However, it has been shown in more recent studies that the latter probably does not play a role in the injury process. The crush mechanism is said to be responsible for what is known as the permanent cavity, while the stretch mechanism is said to produce a temporary cavity in the tissue. These two cavities are said to be the key mechanisms by which tissue is injured following a gunshot wound and therefore will be discussed in more detail below.

The Permanent cavity

As a bullet passes through tissue, that which is directly in front of it is crushed and forced apart, resulting in a permanent wound cavity (MacPherson, 1994; Karger, 2008). As only the tissue in direct contact with the bullet is affected, it is not said to be a serious mechanism of injury unless a major blood vessel or vital organ is struck (Owen-Smith, 1981). Nevertheless, the size of the permanent cavity depends on the frontal surface area of the bullet as well as the properties of the affected tissue and in certain regions of the body it can be devastating (Owen-Smith, 1981; Sellier and Kneubuehl, 1994).

This cavity is characterised by torn and destroyed tissue (Sellier and Kneubuehl, 1994). Tissue may also be cut by sharp metal edges on some bullets which act like small knives (MacPherson, 1994). The area of tissue adjacent to the permanent cavity is referred to by Sellier and Kneubuehl (1994) as the zone of extravasation. There is said to be no macroscopic damage in this area but small haemorrhages are often present. The tissue in the zone of extravasation is not injured by the bullet directly but is stretched sufficiently to damage more susceptible structures, such as capillaries. The tissue closest to the permanent cavity will be the most extensively damaged (Sellier and Kneubuehl, 1994).

The Temporary cavity

Tissue which is not in the direct path of the bullet will commonly be accelerated radially due to kinetic energy imparted by the projectile (Owen-Smith, 1981; Sellier and Kneubuehl, 1994; Karger, 2008). This results in 'overpressures' and stretching in the surrounding tissue, forming a cavity with a diameter which is generally much larger than that of the bullet (Figure 1.1) (Butler, et al., 1945). This is referred to as the temporary cavity as it is said to have a lifetime of up to 10 ms (DiMaio, 1999; Karger, 2008). This cavity is formed behind the projectile as it passes through tissue and is said to be almost a complete vacuum at the start of its lifetime (Sellier and Kneubuehl, 1994). It reaches a maximum around 2 - 4 ms after the projectile has passed and then collapses immediately (Karger, 2008). The tissue making up the cavity oscillates a number of times following this collapse, before coming to rest (Butler, et al., 1945; Karger, 2008)

The injury caused by the temporary cavity may be thought of as being similar to blunt force trauma in that it involves stretching the tissue momentarily (Fackler, et al., 1988; Hollerman, et al., 1990; Karger, 2008). It is said that the temporary cavity caused by common handgun bullets is not large enough to cause significant damage in any tissue except the brain and liver (Hollerman, et al., 1990; DiMaio, 1999). Larger handgun bullets and many rifle bullets on the other hand will commonly induce significant temporary cavities (e.g. 10 - 25 cm in diameter) with the resultant damage depending on the nature of the tissue (Hollerman, et al., 1990).

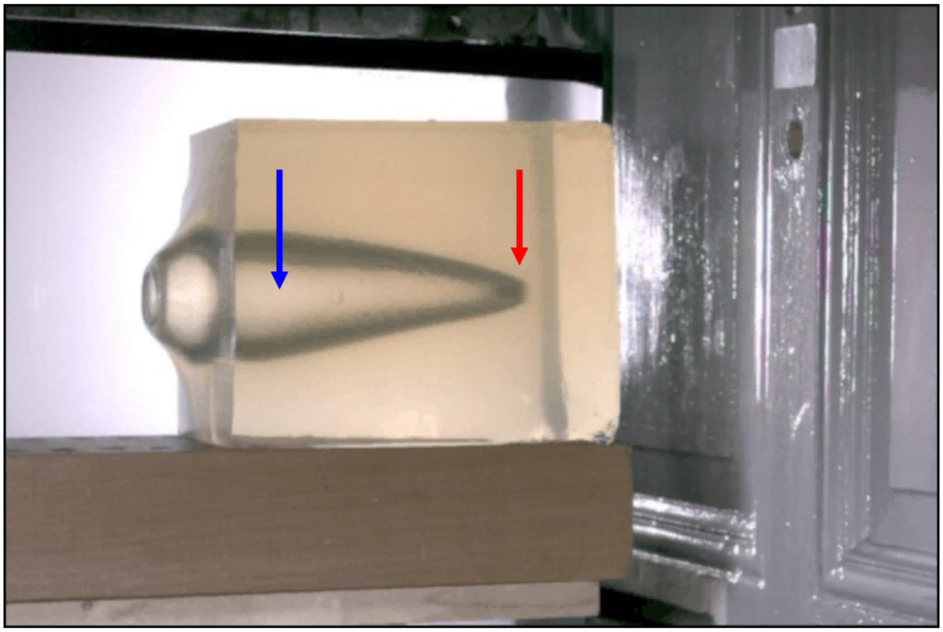


Figure 1.1 A 9 mm Luger Action-4, hollow-point bullet (red arrow) passing through a block of 10% ballistic gelatine. The temporary cavity produced (blue arrow) is much larger than the bullet. Image courtesy of Beat. P. Kneubuehl, Germany.

Shock waves

Some authors believe that tissue may also be injured by a third mechanism of injury which is referred to as the sonic pressure wave or “shock wave”. Proponents of this theory believe that compression of tissue by the bullet forms a wave which radiates out from the area of penetration (Owen-Smith, 1981). It is said to be responsible for causing damage in tissue at a considerable distance from the main wound area. The sonic pressure wave reportedly travels at speeds of up to 1500 m/s (the velocity of sound in water) and reaches pressures of up to 10,350 kPa (Owen-Smith, 1981; Hollerman, et al., 1990). Fluid filled tubes, such as arteries or veins, are believed by some to act as ideal conduction pathways for this wave and facilitate the infliction of damage in areas remote to the wound (Owen-Smith, 1981).

This theory was more commonly reported in older literature and is not often discussed in recent publications. Researchers who disagree with this theory have stated that the sonic pressure wave plays no role in the wounding process as it is too brief to move tissue (Hollerman, et al., 1990; Karger, 2008). The sonic pressure wave is said to be caused by the sound of the bullet striking the tissue, which then forms a sound wave ahead of the bullet (Fackler, 1996). This sound wave is not believed to cause enough movement in the tissue to damage it which is why this theory is said to be a myth (Fackler, 1996).

1.1.2 Determinants of injury

The severity of the resultant wound is dependent on the sizes of the permanent and temporary cavities which are determined by the characteristics of both the bullet and the affected tissue (Karger, 2008). These are therefore considered the key determinants of injury in a gunshot wound.

Bullet characteristics

The velocity and design of a bullet are said to be important wounding factors. Design refers to the mass, calibre (diameter), shape and construction of the bullet (Ordog, et al., 1987; Karger, 2008) and all of these aspects are important in determining the extent of the resultant wound. Bullets which are identical in all but one of these components may cause quite different wounds. These will be discussed in this section with the emphasis on their wounding potential.

Velocity and mass of the bullet are said to be important parameters as they determine the amount of kinetic energy that is produced ($E = mv^2/2$, where E = energy, m = mass and v = velocity) (Sellier and Kneubuehl, 1994; Coupland, et al., 2000; Karger, 2008). A number of authors have stated that the amount of kinetic energy transferred to the tissue determines the severity of the wound (DiMaio, 1999; Coupland, et al., 2000). Velocity is squared in the energy equation and therefore proponents of this theory believe that it plays a greater role in wounding than the mass of the bullet, as doubling velocity will quadruple the kinetic energy while doubling mass will only double the kinetic energy (DiMaio, 1999). However, other authors have stated that it is not as simple as this and kinetic energy alone is not a good determinant of wounding potential (Hollerman, et al., 1990; MacPherson, 1994; Fackler, 1996; Karger, 2008).

In the past, bullets were often classed as either “high velocity” or “low velocity” depending on their speed as they left the firearm. Higher velocity bullets were considered to possess greater wounding potential than lower velocity bullets. It is now widely accepted that velocity alone is not a good indicator of wound severity and therefore these terms are not commonly used (Fackler, 1996). The other problem with this means of classification was the fact that there were no consistent cut-off values for high and low velocity which often led to confusion (Fackler, 1996). The same can be said for the terms “high energy” and “low energy” which are also ambiguous (Fackler, 1996).

Bullets are more commonly classified according to their construction. Solid or homogenous bullets are composed of a single material, for example lead (Sellier and Kneubuehl, 1994). Jacketed bullets, on the other hand, consist of a core which is covered or jacketed by a thin layer of a different material. If this jacket covers the entire bullet it is referred to as a full metal jacketed (FMJ) bullet (DiMaio, 1999). If part of the bullet is not covered by this jacket, it is referred to as a semi-jacketed bullet and if the point is hollow, it is referred to as a hollow-point bullet (Sellier and Kneubuehl, 1994).

The construction of the bullet affects its tendency to tumble, deform or fragment which are important wounding factors as they increase the frontal surface area of the bullet (Karger, 2008). This increases the amount of tissue that is crushed and shredded which consequently results in a larger permanent cavity. It is said that a bullet can inflict more damage by fragmentation or tumbling then by high velocity (Hollerman, et al., 1990).

When a bullet travels through air, it may become unstable and deviate from its original trajectory in one of three ways, referred to as; yawing, precession and nutation (Owen-Smith, 1981). Yawing is the term given to the movement of a bullet when it deviates from its line of flight around its longitudinal axis (Owen-Smith, 1981; Karger, 2008). This is often referred to as "tumbling" when the bullet moves end over end (forward rotation around its centre of mass). Precession is a circular movement of the bullet about its centre of gravity where the nose forms small spirals (Owen-Smith, 1981). Nutation is when a rosette-like pattern is formed by small rotational movements of the bullet moving forward (Owen-Smith, 1981). These movements in the air are largely minimised by the spin imparted to the bullet by the firearm.

However, when the bullet strikes a denser medium such as tissue it will become unstable and its tendency to yaw is greatly increased (Owen-Smith, 1981). The bullet may end up traveling either side-on or base first rather than nose first as it rotates around its lateral axis (Light, 1963; Karger, 2008). This rotation generally ceases when the bullet is traveling base first (DiMaio, 1999). Obviously this increases the size of the wound cavity, as a bullet traveling side on or base-first will have a much greater frontal cross-sectional area (Karger, 2008). A greater cross-sectional area will also slow the bullet and decrease the penetration depth (Karger, 2008).

Certain bullets, such as hollow-point rounds, are designed to expand or "mushroom" on impact which greatly increases the surface area of the bullet (DiMaio, 1999 Sellier and

Kneubuehl, 1994). These rounds are often used by police agencies as they are more likely to stop in the intended target rather than pass straight through and injure an innocent bystander (DiMaio, 1999). The design of certain bullets (frangible bullets) makes them more likely to fragment than others (DiMaio, 1999). This also increases the surface area of the bullet by creating multiple small projectiles with their own trajectories.

A well known type of projectile is known as the Dum Dum bullet. This term was originally only used to describe cartridges loaded with soft-point bullets which were manufactured at the Indian Ordnance Department in Dum Dum, India, in the late nineteenth century (Sellier and Kneubuehl, 1994; DiMaio, 1999; Gunn, 2006). These projectiles were developed due to frustration over the insignificant injuries being caused by the British army standard projectile, the Mark II cartridge, which was loaded with round nose, full jacketed bullets (Sellier and Kneubuehl, 1994). The bullets in the Dum Dum cartridge were uncovered around the head and therefore produced more severe injuries than the Mark II cartridge as they expanded in the body (Sellier and Kneubuehl, 1994). It was for this reason that the use of these bullets in war was outlawed at The Hague Peace Convention in 1899, along with any other bullets which expanded in the body, as they were considered inhumane (Fackler, 1996; DiMaio, 1999; Gunn, 2006). Today the term Dum Dum is often used to describe any bullet which deforms or fragments in the body (Sellier and Kneubuehl, 1994).

Tissue characteristics

The anatomic location that a bullet strikes is critical in determining how devastating the wound will be (Fackler, et al., 1988). Although the bullet has an effect on the size of the wound cavities produced, the tissue within which this occurs is also very important in determining cavity size and therefore the severity of the wound. A heavier, slower bullet crushes more tissue (i.e. the permanent cavity) but induces a smaller temporary cavity while a lighter, faster bullet forms a larger temporary cavity but a smaller permanent cavity (Hollerman, et al., 1990). Either of these scenarios can be devastating depending on the type of tissue. The three key tissue characteristics that affect the severity of a gunshot wound are said to be elasticity, density and thickness (Hollerman, et al., 1990).

When a bullet penetrates an elastic tissue, such as muscle or the lungs, there are greater forces trying to move the displaced tissue back to its original position than there are in more inelastic tissues such as the liver (Sellier and Kneubuehl, 1994; Fackler, 1996; DiMaio, 1999). Therefore, large permanent cavities are commonly produced in inelastic tissues. The temporary cavity forms along the lines of least resistance which means it may often separate tissue layers and tear structures which are fixed, such as the origin of a blood vessel (Hollerman, et al., 1990; Fackler, 1996). The formation of a temporary cavity in a fluid-like organ such as the brain can be devastating (Hollerman, et al., 1990).

The penetration depth of bullets in a dense tissue such as bone compared to in soft tissue is greatly reduced and the likelihood of yawing, deformation and fragmentation is increased (Karger, 2008). Fragments of bone may also be produced causing secondary missiles which, like bullet fragments, can greatly increase the severity of the wound (Karger, 2008). The thickness of the body part that is injured also has an effect on the severity of the wound. The effect of the temporary cavity in wounds of the limbs is said to be less significant than in wounds of the head or body. The reduced thickness of limbs, compared to the body, means the bullet rarely has time to yaw (Hollerman, et al., 1990).

1.1.3 Tissue simulants

Wound ballistics is a field that has been well studied, particularly by military and forensic researchers, who have employed a number of methods to learn more about this complex topic. Ethical and comparability issues associated with animal testing mean that this method of experimentation is not common practice, or at least documenting the results in the literature is not. Instead, researchers have relied heavily on synthetic materials and models to study wounding mechanisms analytically. In order for a synthetic material to be appropriate for wounding studies, it must be homogenous, dynamically equivalent to the tissue being simulated and practical, i.e. inexpensive and easy to work with

(MacPherson, 1994). The two main tissue simulants used by researchers are gelatine and glycerine soap.

Gelatine is one of the most common materials used to study wounding. It is said to be an appropriate simulant for soft tissue as it has a similar density (at 10% and 20% concentration) and elasticity (Coupland, et al., 2000; Thali, et al., 2002c). The main advantages of gelatine are that it is transparent and can be used to measure the size of both the temporary and permanent cavities induced by certain projectiles (Fackler and Malinowski, 1985). When a temporary cavity is formed in gelatine, small cracks are formed at its periphery which means the approximate diameter can be measured after it collapses (Fackler and Malinowski, 1985). Its elastic nature means that the edges of the wound track return to almost their original position which allows the permanent cavity to be visualised and measured (Fackler and Malinowski, 1985). Gelatine is also favoured as a simulant because it is inexpensive and readily available (Sellier and Kneubuehl, 1994). Its transparent nature allows the bullet to be viewed as it passes through the tissue using techniques such as high-speed photography (Sellier and Kneubuehl, 1994).

Glycerine soap is also commonly used as a soft-tissue simulant as it provides an accurate and permanent record of the temporary cavity. It is made primarily of grease and alcohol and therefore is much more plastic than gelatine (Sellier and Kneubuehl, 1994). This means that only the size of the temporary cavity is recorded as the material does not bounce back to its original position once deformed (Fackler and Malinowski, 1985). Unlike gelatine, it can be stored for long periods of time and can be melted down and reused following testing (Coupland, et al., 2000). However a disadvantage of soap is that it is not transparent and therefore must be sectioned following shooting in order to view the wound track (Coupland, et al., 2000).

Gelatine and glycerine soap are widely accepted as appropriate ballistic simulants. However, as illustrated above, both have associated advantages and disadvantages. Gelatine seems to be used more frequently, particularly now that high-speed filming is more accessible. This allows the formation of the wound cavity to be viewed in slow-motion which is helpful for understanding this dynamic process. Gelatine is also the preferred simulant by many researchers as it is easy to prepare and work with (Sellier and Kneubuehl, 1994)

1.1.4 Handgun Ballistics

Handguns are the most commonly used firearm in gunshot fatalities in the United States and Germany (Spitz, 1993; Cina, et al., 1999; DiMaio, 1999; Karger, et al., 2002a; Faller-Marquardt, et al., 2004). Therefore, handguns are commonly used in experimental research and the wounds resulting from these weapons have been well studied. Because of this and a number of other reasons, a handgun was selected as the firearm for this project. In order to interpret the results of this study, the wound ballistics of handguns were briefly reviewed.

Although handguns are considered to be “low velocity”, “low energy” firearms, they are small and easily concealed, making them a popular weapon of choice for many criminals (DiMaio, 1999). There are two main types of handguns, revolvers and pistols, with revolvers being the most common in the United States (Sellier and Kneubuehl, 1994; DiMaio, 1999). Revolvers have a cylinder with multiple cartridge chambers which revolves to align the chamber with the barrel for each shot (DiMaio, 1999). Pistols on the other hand have a magazine which holds a number of cartridges and, in the case of auto-loading pistols, uses the energy generated from the fired cartridge to load the next cartridge and prepare the firearm to fire the next round (DiMaio, 1999).

It is believed that the temporary cavity created by many common handgun bullets is too small to be a significant wounding factor in most tissues (Hollerman, et al., 1990; DiMaio, 1999). However, in sensitive, non-elastic tissues such as the brain or liver, even a small temporary cavity can have a devastating effect on the surrounding tissue. Larger handgun bullets, such as a .44 or .357 magnum, are capable of creating a much larger temporary cavity that will cause significant damage in many tissues, depending on their properties

(DiMaio, 1999). The large calibre and high velocity of bullets such as these, compared to other handgun bullets, are responsible for the formation of this large temporary cavity (DiMaio, 1999)

1.2 Gunshot wounds

While researchers have commonly used synthetic tissue simulants to study wounding mechanisms, physical gunshot wounds are more commonly studied using autopsy reports and case studies. In order to better understand the results from this study, the characteristics of gunshot wounds were researched.

1.2.1 Range

Gunshot entrance wounds are commonly classified based on range-dependent characteristics. Up to a certain range, the characteristics of a wound are largely dependent on the distance from which the gun was fired. This section will discuss the features of contact, close-range, intermediate and distant wounds.

Contact wounds

A contact gunshot wound occurs when there is contact between the muzzle of the firearm and the skin. This type of wound is commonly seen in suicide victims (Karger, et al., 2002a; Blumenthal, 2007; Maiden, 2009). Contact wounds have unique characteristics due to the close proximity between the skin and the muzzle. The margins of the wound will often be seared by the hot muzzle gases and soot will be deposited around the wound, producing a characteristic blackening of the skin (Godley and Smith, 1977; DiMaio, 1999; Maiden, 2009). This is often present as a ring around the central defect or hole with its diameter dependent on how firmly the muzzle is pressed against the skin (DiMaio, 1999). If there is only loose contact, some of the gas may escape and the soot that is carried with it can be deposited more widely around the resultant wound (DiMaio, 1999).

The gases produced when the gun is discharged are forced into the wound as they have no other means of escaping. The expansion of these gases in the wound cavity causes the skin to balloon outwards around the muzzle of the firearm (DiMaio, 1999). When this occurs in regions where there is only a thin layer of skin and subcutaneous tissue overlying bone, such as in the head, the resultant wound is often relatively large and may be associated with radiating skin tears (DiMaio, 1999; Pollak and Rothschild, 2004). These result when the skin is stretched beyond its elastic limit (DiMaio, 1999; James, et al., 2005; Maiden, 2009). It is often referred to as a stellate wound due to its star-shaped appearance (DiMaio, 1999; James, et al., 2005; Maiden, 2009).

Contact between the muzzle and the skin also results in another characteristic feature of entrance wounds. The blown-out region of the skin will occasionally hit the muzzle with such force that an imprint of the muzzle is produced on the skin around the entrance wound (Pollak and Rothschild, 2004). Like the stellate wounds described above, a muzzle imprint is also more likely to occur in regions where there is only a thin layer of skin overlying the bone (DiMaio, 1999). The detail of the muzzle imprint depends on the force with which the skin impacts the muzzle (DiMaio, 1999).

Near-contact wounds

These wounds occur when the muzzle is very close to the skin but there is no actual physical contact. There is some debate as to what the maximum distance is for the wound to be considered near-contact. Smock (2001) defines this range as either the maximum distance at which soot is deposited on the wound, or when the muzzle is less than 15cm away from the skin. However, others consider the range to be much smaller and describe near-contact as a distance of up to 1 or 2 cm (DiMaio, 1999; Plattner, et al., 2003). This close range makes near contact wounds as well as contact wounds common in suicide victims (Karger, et al., 2002a).

The space between the muzzle and the skin means that gas can escape and therefore soot will often be deposited on the skin surrounding the wound. The diameter of this soot zone will increase in size with increasing distance between the skin and the muzzle while the concentration of soot will decrease (Plattner, et al., 2003; Gunn, 2006). When the muzzle is held at an angle to the skin, the soot will be deposited in an elliptical shape around the wound. This can be used to determine the direction of the bullet (DiMaio, 1999; Pollak and Rothschild, 2004). As there is space between the muzzle and the skin, only a small amount of gas is forced into the tissue. This means the outward ballooning of the skin may not be as large and a stellate wound is less likely to occur (Gunn, 2006).

Intermediate-range wounds

As with near-contact wounds there are discrepancies regarding the range at which intermediate wounds occur. This may be because authors often group near-contact and intermediate wounds in the same category, referring to them collectively as close-range wounds (Godley and Smith, 1977; Spitz, 1993; Pollak and Rothschild, 2004; Gunn, 2006). These wounds are said to occur at a range where the muzzle is not close enough for grains of gunpowder to be deposited into the wound but also not so far away that they are unable to reach the skin (DiMaio, 1999). This means the range may vary depending on the type and calibre of the firearm as well as the length and angle of the barrel as these variables will affect the trajectory of the gunpowder particles (Smock and Stack, 2002; Gunn, 2006).

Unlike contact and near-contact wounds which are more common in suicide, intermediate wounds are observed in all manner of gunshot deaths. In an examination of 577 case studies, Karger et al (2002a) found that out of 1004 entrance wounds, 10.8% of suicidal wounds and 14.9% of homicidal wounds were from an intermediate range. In contrast, Cina et al (1999) in a study of 120 case studies of homicide, suicide and accidental death found that 75% of accidental gunshot wounds were inflicted from an intermediate range.

Partially burned gunpowder grains expelled from the muzzle give these wounds a characteristic feature which is referred to as powder tattooing (Godley and Smith, 1977; DiMaio, 1999; Smock and Stack, 2002; Maiden, 2009). When these grains of hot propellant land on the skin they leave marks surrounding the entrance wound. There are conflicting opinions concerning how the skin is actually tattooed by the powder grains. While it has been suggested that the hot propellant burns the skin (Gunn, 2006), others believe that the marks occur due to abrasion between the grain and the skin on impact (DiMaio, 1999; Smock, 2001; Smock and Stack, 2002). It has also been reported that the powder grains penetrate the skin which leaves a permanent tattoo-like mark (Maiden, 2009)

Powder tattoo marks appear as red-brown or red-orange spots surrounding the entrance wound (DiMaio, 1999). These grains can travel up to 45 - 60 cm, meaning powder tattooing may be seen on skin some distance from the entrance wound, depending on the distance between the muzzle and the skin, as the grains spread out as they leave the muzzle (Godley and Smith, 1977). Therefore, the density of the tattooing pattern will decrease as the range increases. Powder tattooing may be used to establish the angle at which the muzzle was held as it may be denser on the side of the entrance wound where the muzzle is closest to the skin (DiMaio, 1999).

Distant wounds

Distant or long-range gunshot wounds are usually said to occur at a distance that is great enough for no powder tattooing to occur (Light, 1963; Spitz, 1993; DiMaio, 1999; Smock, 2001; Wright, 2005; Gunn, 2006). This distance is usually in excess of 60 cm – 1 m, depending on the firearm and the ammunition used (DiMaio, 1999). The literature contains less information about distant wounds than those described above, possibly because only the bullet has an effect on the target and no other substances such as gas, soot or gunpowder are involved. However these wounds are common, especially in homicide cases (Cina, et al., 1999; Karger, et al., 2002a) and key details such as the angle of the bullet may still be obtained from their appearance (Gunn, 2006).

A feature which seems to be associated more with distant range gunshot wounds than those from close range is the so-called abrasion collar or ring (Gunn, 2006). This appears as a red-brown ring surrounding the entrance wound and is said to result from friction as the bullet pushes through the skin (Thali, et al., 2002b; Gunn, 2006). While this feature occurs in almost all entrance wounds, regardless of the range, it is often discussed under the category of distant gunshot wounds perhaps due to their lack of other distinguishing features. This may also be because the abrasion is more visible in these wounds due to an obvious lack of soot or powder tattooing.

Some authors report that the abrasion ring is the result of friction between the bullet and the epidermis as the skin is initially pushed inwards on impact (DiMaio, 1999; Besant-Matthews, 2000; Smock, 2001; Smock and Stack, 2002). Others have stated that it is caused by a combination of dirt and heat from the bullet and burning of the skin as it penetrates (Gunn, 2006). Yet another cause for the abrasion ring was given by Thali et al (2002) following a study that involved the shooting of their synthetic skin-skull-brain model. Their observations led them to suggest that the abrasion ring was actually a "stretch-mark" resulting from massive overstretching of the skin around the entrance wound.

The appearance of the abrasion ring may vary depending on the angle of the gun, the calibre of the bullet and the anatomical location of the wound (DiMaio, 1999; Gunn, 2006). Authors seem to agree that the shape of the abrasion ring is highly dependent upon the angle at which the bullet strikes, with non-perpendicular shots causing a more oval shaped ring (DiMaio, 1999; Smock, 2001; Smock and Stack, 2002; Thali, et al., 2002b; Gunn, 2006). From experimental studies, Thali et al (2002) observed that the widest portion of the abrasion ring points towards the bullet's origin or in the opposite direction to its trajectory.

Other features which are commonly discussed in the category of distant wounds are the 'contusion ring' and the 'ring of dirt'. A contusion ring will often be present around the abrasion ring (Thali, et al., 2002b). This appears as a purple, red or blue bruise which completely surrounds the wound. It is more commonly associated with wounds of entrance than exit, particularly in regions where skin closely covers bone (Thali, et al., 2002b). It is said to be caused by overstretching of the skin which leads to bleeding in underlying area (Thali, et al., 2002b).

A ring of dirt, also referred to as ‘bullet wipe’, is formed when grease or lubricant from the bullet is left on the skin as the bullet passes through, resulting in a fine black ring surrounding the central defect (Godley and Smith, 1977; DiMaio, 1999; Thali, et al., 2002b). This is usually surrounded by the abrasion ring and the contusion ring, however, all three features are not always easily differentiated. In contact and close range shots, the ring of dirt may sometimes be confused with soot staining (Godley and Smith, 1977).

1.2.2 Exit wounds

Less attention has been given to exit wounds in the literature, perhaps because unlike entrance wounds their appearance does not vary significantly with regards to the range (DiMaio, 1999). These wounds are produced when a bullet forces its way out of the body, thus stretching and tearing the overlying tissues. While exit wounds are often larger than their corresponding entrance wounds, this is not always the case and authors stress that size along should not be used as a determinant of wound type (Besant-Matthews, 2000; Smock and Stack, 2002; Pollak and Rothschild, 2004). Exit wounds are not normally mistaken for entrance wounds due to their irregular appearance. However, stellate exit wounds can be formed in the scalp and may be mistaken for a contact entrance wound (DiMaio, 1999). The edges of the skin surrounding an exit wound are usually everted with sharp margins (Smock and Stack, 2002).

As mentioned earlier, when a bullet tumbles in the body it results in a larger area of the bullet being presented to the tissues at the point of exit compared with the point of entry (DiMaio, 1999). This was investigated by Light (1963) who studied the effect of bullet area and velocity on the size of the exit wound. It had previously been shown that the size of a wound increases with increasing velocity of the projectile (Dziemian, et al., 1961). In theory this means that an entrance wound will be larger than its associated exit wound as the bullet loses velocity as it passes through the body. However, as this is not usually the case, Light suspected that the area of the bullet presented to the point of contact has an effect on the size of the wound and this counterbalances the effect of the loss of velocity.

Light (1963) tested this theory by shooting steel spheres at 24 goats. These spheres were unable to tumble and hard enough that they could not deform or fragment. This meant that any variation in entrance and exit wound size would be due to the loss of velocity alone. He found that in all 24 goats the entrance wound was larger than the exit wound. From this he concluded that the effect of the loss of velocity was cancelled out by the tumbling or deformation of the bullet in most gunshot wounds which is why the exit wound is often larger than the entrance wound.

If the exit wound occurs in a region of the body that is in contact with a firm surface such as the floor or a wall, the wound may have abraded margins (Spitz, 1993; Pollak and Rothschild, 2004). These wounds are referred to as 'shored' exit wounds and may sometimes be confused with an entrance wound if the body has been moved. The abrasion around the wound results when the skin is rubbed against a hard surface on impact (DiMaio, 1999). This abrasion may look similar to the abrasion ring which is commonly seen in entrance wounds and this is one reason why the two wounds may be confused.

1.2.3 Gunshot wounds in bone

When a projectile passes through a solid surface such as bone, it causes bevelling of the surface facing in the direction the bullet is traveling. Bevelling is the "scooping out" of bone and is often used to determine whether a particular wound was the entrance or exit point of the bullet (DiMaio, 1999; Quatrehomme and Iscan, 1999). Internal bevelling of the bone generally occurs in entrance wounds meaning bone is beveled on the internal side (Figure 1.2B and D) (Thali, et al., 2002c). In contrast, exit wounds generally display external bevelling which faces the external environment (Thali, et al., 2002c). Bevelling may be used to determine the angle at which the bullet impacted the bone (Quatrehomme and Iscan, 1998).

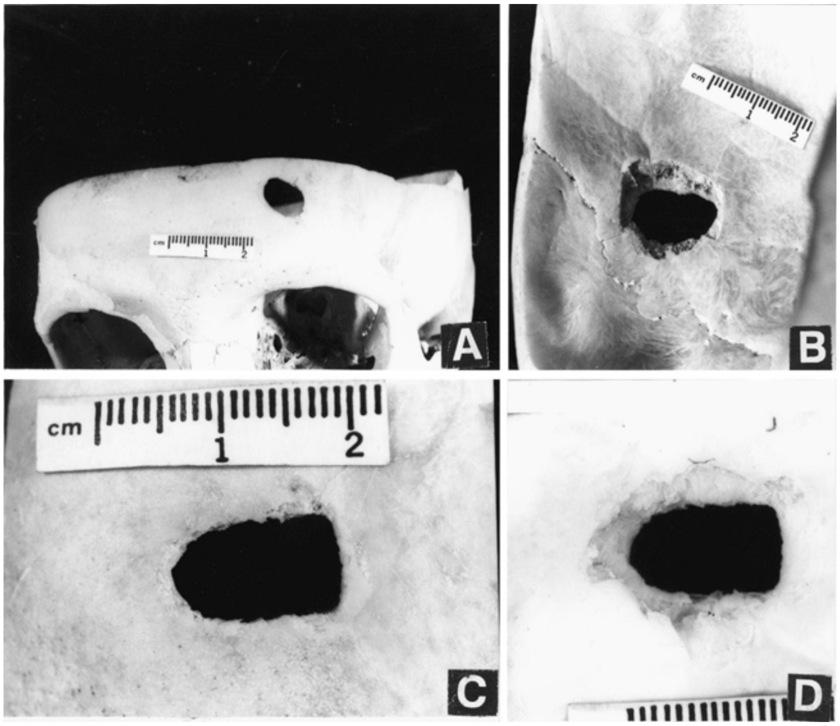


Figure 1.2 Gunshot wounds in bone. A: External wound in the left frontal bone. B: Internal bevelling of the same wound. C: External wound in parietal bone. D: Asymmetrical internal bevelling of the same wound. (Quatrehomme and Iscan, 1998).

There are two main types of fracture associated with gunshot wounds. Radial fractures are those which run away from the central defect and are directly connected to it (Smith, et al., 1987; Karger, 2008). Concentric fractures on the other hand have no direct contact with the entrance wound and are often present in a partial or complete ring around it, at some distance from the central defect (Karger, 2008). Both of these fractures are most commonly produced in the skull due to the overpressures associated with the temporary cavity formation in the head (Butler, et al., 1945; Smith, et al., 1987; DiMaio, 1999; Karger, 2008). Radial fractures are said to be caused directly by the bullets impact (Karger, 2008). Concentric fractures, on the other hand, are formed as a means to relieve the pressure in the brain tissue (DiMaio, 1999; Karger, 2008). Radial and concentric fractures are sometime referred to as secondary and tertiary fractures respectively (with the central defect being the primary fracture) (Karger, 2008).

1.3 Backspatter

Backspatter is a complex phenomenon that many researchers do not pretend to understand completely. As mentioned earlier, the literature contains a number of articles documenting the presence of backspatter. However, when it comes to explaining the processes behind backspatter, the literature is more limited. The term backspatter can be used to describe any tissue which is ejected from a gunshot entrance wound, such as skin, subcutaneous tissue, brain matter or bone. However, blood has been the main focus of backspatter research in the literature, possibly because it is often the predominant substance that is ejected and is usually visible with the naked eye. Therefore, for the purposes of this review, the term backspatter will be used in reference to blood only unless otherwise stated.

1.3.1 Significance

As backspatter is deposited on surfaces in close proximity to the wound, the hand that fired the weapon in a close range shot will often display evidence of backspatter (Pex and Vaughan, 1987; Betz, et al., 1995; Karger, et al., 2002b; Yen, et al., 2003; Karger, 2008). In homicide cases, any evidence of backspatter on the hand of the suspect will often have been washed away long before it becomes incriminating. However, in suspected suicide cases, if backspatter is present on the shooting hand it may be used to help rule out homicide. The absence of backspatter is however, not necessarily indicative of suicide. An understanding of the variables that are involved can make a significant difference in determining the manner of death. Despite this, many gaps in the literature remain. There are, however a number of studies that have made a significant contribution to our current knowledge of backspatter.

1.3.2 Mechanisms of production

Much of what we know about the production of backspatter is attributable to the research of the German pathologist Bernd Karger. Based upon his own research and the results of others, he suggested that backspatter was the result of up to three different processes: subcutaneous gas pocket production, the collapse of a temporary tissue cavity and finally, the process of 'tail splashing'.

Subcutaneous gas pocket

This theory suggests that in contact or very near contact cranial shots, the gas which is forced between the skin and skull is responsible for backspatter production. This occurs because the gas expands under the skin, causing a pocket to form momentarily (Burnett, 1991). As this collapses, blood is carried along with the escaping gas and is projected out of the entrance wound (Karger, et al., 1996; Karger, 2008). Obviously, this mechanism is only possible in contact or near contact shots when gas is forced into the wound (DiMaio, 1999; Karger, 2008).

Collapse of the temporary cavity

The second theory rests upon the assumption that cavitation in a confined organ system will result in a sudden increase in pressure and therefore the formation of a temporary cavity. These excess pressures have nowhere to escape apart from the entrance or exit wound (Stephens and Allen, 1983; Pex and Vaughan, 1987; Karger, et al., 1996; Karger, 2008). As the temporary cavity collapses, blood and tissue are ejected against the line of fire (Stephens and Allen, 1983; Pex and Vaughan, 1987). This is one of the main reasons why backspatter usually only occurs in gunshot wounds of the head, as the inelastic nature of the brain and its containment within the skull means it is particularly susceptible to temporary cavitation (Karger, 2008). It has been suggested that this mechanism of backspatter production is also the only logical explanation for the backspatter of brain matter, which has been documented in a number of cases (Kleiber, et al., 2001; Verhoff and Karger, 2003; Padosch, et al., 2006; Karger, 2008).

Tail splashing

It has been suggested that as a bullet travels through tissue, backward streaming of blood and other fluid or tissue particles may occur (Amato, et al., 1974; DiMaio, 1999; Karger, 2008). These particles flow along the sides of the bullet in the opposite direction to which it is traveling. Some of this material will be ejected out of the entrance wound (Black, et al., 1941; Karger, et al., 1996; Karger, 2008). Karger (1996) suggests that tail splashing "may be considered an early stage of temporary cavitation", as it is said to occur as soon as the bullet enters the target (Black, et al., 1941).

Karger (2008) suggested that in most cases, backspatter is the result of all three mechanisms. He also stated that backspatter is in no way related to the spin of the bullet or suction from the muzzle. His work is frequently referenced by other authors and there does not seem to be any debate concerning his theories as he has carried out extensive research in this area (Karger, et al., 1996; Karger and Brinkmann, 1997; Karger, et al., 1997; Karger, et al., 2002b; Verhoff and Karger, 2003). Obviously this is an area which is difficult to research and consequently, not many studies have been carried out.

Backspatter production is thought to be affected by the type of weapon, the calibre of the bullet, the range and the anatomical location (Karger, et al., 1996; DiMaio, 1999; James, et al., 2005). High energy rifles and shotguns are said to produce more backspatter (James, et al., 2005). The range is also an important factor with backspatter rarely occurring when the distance from muzzle to target is greater than 1 metre (Bevel and Gardner, 1997; James, et al., 2005). This indicates the gas pocket may be a critical factor in backspatter production. It is likely that the degree of backspatter is dependent on tissue density which obviously depends on anatomical location (Padosch, et al., 2006). Backspatter is considerably more likely to occur in regions where there is a thin layer of skin and soft tissue overlying bone (e.g. the head) as gas becomes trapped between the skin and the bone and there is no space for it to expand (Stephens and Allen, 1983; Padosch, et al., 2006; Karger, 2008).

1.3.3 Case study observations

The literature contains a small number of articles where researchers have analysed the backspatter patterns produced from suicidal gunshot wounds. The following are some observations that have been documented about the general characteristics of backspatter patterns.

Traveling distance and distribution

Backspatter has been documented at a maximum distance of more than 4 m from the victim in one case study (Verhoff and Karger, 2003). More commonly reported traveling distances are 2 m or less (Karger, et al., 1996; Karger, et al., 1997; Karger, 2008)**.** Backspatter stains are commonly distributed in a semi-circular pattern which radiates out from the entrance wound (Yen, et al., 2003).

Morphology and size of stains

Backspatter stains are characteristically small and circular, elongated or exclamation mark shaped, depending on the angle at which they strike a surface (Kleiber, et al., 2001; Yen, et al., 2003; Karger, 2008). Circular stains result when blood hits a surface at an angle that is close to 90° (James, et al., 2005). At any other angle, the stain is more likely to be elongated in shape. Exclamation-mark shaped stains result when blood impacts a surface at an angle that is closer to 0° (Yen, et al., 2003; James, et al., 2005). These are formed when a drop skids along the impacted surface and a small satellite drop breaks away from the parent stain (James and Eckert, 1998; James, et al., 2005). The satellite stain points in the direction the drop is traveling when it impacted (James and Eckert, 1998; James, et al., 2005). Objects in close proximity to the wound, such as the hand, often have surfaces facing in multiple directions, resulting in a mixture of stain morphologies (Yen, et al., 2003).

A mist-like pattern is common, where the stains are described as very small (e.g. less than 1 mm in diameter) and circular (Kleiber, et al., 2001; Yen, et al., 2003). In fact, it is reported that some of these stains may be so small that they can only be viewed under magnification (Pex and Vaughan, 1987; Karger, 2008). However, stains between 1 - 3 mm are also common and these may be intermixed with mist-like stains (Yen, et al., 2003). Stains larger than this are considered to be the result of secondary spatter which seeps from the wound, often in large volumes, after the initial impact (Yen, et al., 2003).

Number of individual stains

As backspatter patterns are variable, the number of individual stains which have been documented range from "a few" through to "extensive" (Pex and Vaughan, 1987; Verhoff and Karger, 2003; Karger, 2008). Although these terms are relative, they give a general idea of the variability of backspatter patterns, due to the numerous variables which affect its production. Documenting each individual stain may often be an impossible task at the scene of a gunshot fatality due to time constraints usually associated with crime scene investigation.

Backspatter on the hands

The distribution of backspatter on the hands may be important for reconstructing the manner in which the shooting was carried out, particularly in suicide cases. The morphology of stains and their position on the hand are two important factors. These characteristics can often be used to determine how the gun was held and at what angle (Yen, et al., 2003). This can be crucial for determining whether suicide was the manner of death as it may show that the victim fired the gun. Backspatter patterns on the firing hand have a characteristic appearance. If blood is present on the hand from a victim because they attempted to fight off an offender before being shot, it is likely to have a different appearance to that which would result if they pulled the trigger themselves.

The characteristics of backspatter patterns on the hands of suicide victims were documented by Yen et al (2003). The authors gave a detailed description of the blood present on the hands of five victims, documenting their distribution, size, morphology and directionality. They found that individual stains were characteristically between 1 - 3 mm in diameter and either round, elongated or exclamation mark shaped. In terms of the distribution of stains, the authors noted that backspatter was more likely to be present on the dorsal aspect of the hand, in regions facing the entry wound (e.g. the fingers and thumb). Obviously this distribution depends on how the gun is held and backspatter will generally not be found in regions covered by the weapon or other parts of the hand (e.g. the palm) (Yen, et al., 2003).

Backspatter on the firearm

Blood will occasionally be present inside the muzzle of the weapon following relatively close-range shots (Karger, et al., 1996; DiMaio, 1999; James, et al., 2005). However, there is some disagreement as to how it is projected there. James et al. (2005) stated that this is due to blood being drawn backwards by the suction of the muzzle and that the distance blood is drawn into the barrel depends on the calibre of the weapon and the distance between the muzzle and the target. It has also been reported that a vacuum created by firing the projectile sucks blood back into the barrel (Thali, et al., 2002a). Karger et al. (1996) on the other hand stated that there is no suction effect by the barrel. Other authors have not discussed a separate process for backspatter being ejected into the barrel of the weapon so it may be that it is simply projected there if the muzzle is close enough to the wound.

1.3.4 Experimental research

The case-study based literature focuses on backspatter patterns seen in suicide cases. Because of this, there is not a lot of information on backspatter from wounds that are more distant than those that occur in most suicides. This is where experimental studies have played an important role. These studies have allowed researchers to control variables such as range and type of firearm using animal as well as non-animal models. They have used the results from these studies to make assumptions about backspatter resulting from human gunshot wounds under the same conditions. These studies have mainly been conducted using animals and synthetic models.

Animal studies

There are only a few published studies where animals have been used to study backspatter. The largest, and arguably most successful animal study, was conducted by Karger et al. (1996). This experiment was conducted on nine New Jersey calves which were destined for slaughter. The calves were shot in the temporal region from various ranges and the resultant backspatter was documented. A 9 mm SIG P210 pistol was used with two different kinds of ammunition; a 9 x 19 mm Parabellum (Luger) full metal jacket (FMJ) round and a 9 x 19 mm Parabellum Action-1 round (non-jacketed). The ranges they used were tight contact, loose contact, 5 cm and 10 cm. A high-speed camera was used to film the backspatter ejected from the wound and thick white paper was used to document the position and morphology of the individual bloodstains. The results from this study were divided into three categories and published separately.

Their first study (Karger, et al., 1996) focused on macro-backspatter, which they classified as stains with a diameter greater than 0.5 mm. To distinguish between bloodstains resulting from the initial impact and those produced later, they divided the stains into two categories; primary backspatter and secondary backspatter. Primary backspatter was blood that was projected directly onto the paper while secondary backspatter resulted from blood pouring from the wound in a larger volume, creating a pool with secondary bloodstains surrounding it. Secondary backspatter was only present following three shots while primary backspatter was present after every shot. The authors excluded results from shots where secondary backspatter was produced in their analysis as it was not the focus of the study.

They found that the average number of macro-backspatter stains produced was 99, with a minimum of 31 and a maximum of 324. These were mostly distributed between 0 - 50 cm from the target, with maximum traveling ranges of between 72 and 119 cm. The distribution of stains for all the shots combined resembled a semi-circular shape, radiating out from the wound, with stains present in all aspects of the 180° radius. The stains showed variable morphology with circular through to elongated and exclamation mark shaped stains present. They found that the number of bloodstains did not decrease as the shooting distance increased however the FMJ bullet produced more bloodstains than the Action-1 bullet when used at the same range. The authors suggested differences in bullet design may have been responsible for this since the propellants were similar in both. However, with such a small sample size, the possibility of a coincidence could not be ruled out.

Micro-backspatter stains included those with a diameter between 0.1 and 0.5 mm (Karger, et al., 1997). Those smaller than 0.1 mm were not visible with the naked eye so were excluded from the analysis. In the six shots which exclusively produced primary backspatter, the number of micro-backspatter stains ranged between 39 and 262 with an average of 122. A majority of the stains were present between 0 and 40 cm from the target with a maximum traveling distance of 31 – 69 cm. The distribution pattern of these stains was similar to that of the macro-backspatter stains but the micro-backspatter stains were more densely distributed closer to the wound. The morphology was consistent between stains with most being circular to slightly oval in shape.

Although the maximum traveling distance of the micro-backspatter stains was less than that of the macro-backspatter stains, the authors surprisingly found no correlation between size and traveling distance. They suggested this was due to the fact that the phenomena said to be responsible for backspatter (described earlier) are dynamic processes, meaning the kinetic energy they impart to individual blood droplets is dependent on the location and the time since impact. This means that drops of the same size exit at different velocities which influences the distance they travel.

The third aspect of this study was the documentation of backspatter present on the firearm or the person shooting (Karger, et al., 2002b). The shooter wore white surgical gloves and a single use coat and these were examined, along with the firearm, following the shooting of each calf. The firearm was examined using a magnifying glass, while the gloves and coat were examined using a stereomicroscope. The bloodstains present were documented along with any other particles that were present. A Kastle-Meyer presumptive test was used if it was unclear whether an individual stain was blood. This test contains a colour indicator (phenolphthalein) which is oxidized by haemoglobin in blood. If the stain turns pink when treated, it indicates that blood may present (Gunn, 2006). Other chemicals may also cause a colour change and therefore false positives can sometimes occur. Histological analysis was carried out on backspattered tissue particles to determine their origin.

Blood was detected on the firearm in five of the nine cases. This included two of the three tight contact shots, both loose contact shots and one of the two shots at a 5 cm range. In four of these cases, a fine mist of small bloodstains was mixed with larger distinguishable stains which were circular or slightly elongated in shape. The distribution of the bloodstains was random and in some cases, blood was detected in regions of the firearm which were not directly in line with the wound. The authors suggested this was due to blood drops being carried along in the backward streaming air.

The gloves in six cases and the right sleeve of the coat in four cases had backspatter present, with similar stain morphologies to those seen on the firearm. These stains were mainly present on the extensor (dorsal) sides of the fingers and the radial aspect of the sleeves. Importantly, backspatter was not detected on the firearm, hand or sleeve in two of the nine cases. This highlights the variable nature of backspatter as one of these cases was a tight contact shot with the Action-1 round while the other was at a range of 10 cm with the FMJ round. In other animals, shots at these ranges did produce backspatter patterns on the hands and firearm, meaning the absence of backspatter in these areas must always be carefully considered. The authors suggested backspatter may sometimes be present in the area immediately below the wound instead, for example, on the shoes of the shooter.

Backspatter of material other than blood also occurred with tissue particles of varying origin present on the white paper in front of the animal. These included bone, skin, muscle and fat particles and were present between 14 and 199 cm from the animal. Bone fragments were present on the paper in five cases and on the firearms and sleeves in one case. Soft tissue particles were present on the paper in four cases.

The authors suggested that the backspatter produced was similar to that documented in humans. They found this surprising considering the smaller brain volume and thicker subcutaneous tissue layer in calves compared to humans, as well as the fact that calves possess a temporal subcutaneous space unlike humans. This would presumably result in reduced subcutaneous pressures in the calf as there is more room for the hot gases to expand, meaning less backspatter would be expected. This was not the case and the authors suggested that the characteristics of the resultant backspatter pattern were comparable with those from humans. The authors also stated that it is likely that backspatter can be produced from ranges greater than 10 cm in both calf and humans.

These studies by Karger et al (1996, 1997, 2002b) were important in terms of the documentation of backspatter patterns under various conditions and were valuable additions to the backspatter literature. Although other animal studies have been carried out, none have focused solely on backspatter of blood, or covered as many aspects of backspatter. The design of their calf study was simple but it was conducted in a way that allowed a large amount of information to be obtained, which is important in animal studies considering the ethical implications.

Another animal study that investigated the characteristics of backspatter was carried out by Burnett (1991). He used pigs in his research but his focus was almost exclusively on backspatter of bone fragments. This study was prompted by a homicide case in which backspattered bone fragments were produced and the range of fire was in doubt. A Smith & Wesson 9 mm pistol and Winchester 9 mm STHP ammunition were used to shoot seven pigs, each with a frontal shot. The ranges used were contact (2), loose contact, 37 cm, 40 cm, 76 cm and 150 cm. The author provided no details of the experimental set-up.

Burnett found that calcium-phosphorous particles associated with bone backspatter were present on the muzzle of the pistol following shots at a range of up to 37 cm. He reported that blood was present in backspatter at this range but did not document the characteristics of the stains or mention whether blood was found in shots at a greater range. He suggested that backspatter of bone is also likely in humans even though the anatomy of a pig skull is quite different.

Non-animal studies

There are a small number of studies in the literature where investigators used physical models to study backspatter. In most cases, these experiments were initiated following a homicidal shooting where backspatter was involved, often in an attempt to determine an unknown variable. Most of these models involved a very simple design and were constructed from only a small number of materials. It is questionable how relevant the backspatter seen in these models is to humans as those described to date have not been representative of the human anatomy. Nevertheless, a few of the observations are valuable in understanding some of the variables involved in backspatter.

One of the more simple models in the literature is a blood-soaked sponge. Stephens and Allen (1983) and Pex and Vaughan (1987) used this model to experiment with the variables responsible for backspatter. Pex and Vaughan (1987) shot into a blood-soaked sponge inside a plastic bag, using a .22 rim-fire revolver, at ranges between contact and 30 cm. They found that backspatter was only produced in contact and near contact shots. For some of the shots, they added layers of fabric to the outside of the sponge to simulate clothing. Under these conditions, they found that backspatter was significantly reduced or even absent, depending on fabric thickness. The maximum distance that individual drops of blood traveled was 60 cm and they found this was dependent on drop size. They also examined the backspatter patterns seen when a .38 Special was fired into the blood-soaked sponge and found that the larger caliber weapon produced a denser pattern of blood stains than the .22 calibre handgun.

Stephens and Allen (1983) took the blood-soaked sponge concept one step further, encasing it in various materials such as plastic, rubber and tape. They then shot it using a .38 calibre revolver and observed the backspatter that was produced. Backspatter from this model was seen in tight, loose and angled contact shots as well as near contact shots. The individual blood droplets had a maximum traveling distance of 30 – 50 cm and showed a variable distribution. No backspatter was produced when the muzzle was further than 1 cm away from the model.

Stephens and Allen (1983) recognised the need for the blood-soaked sponge (representing the brain or soft tissue) to be encased in an elastic material, in order to represent skin. They suggested that backspatter is produced as the result of gas expansion between the skin and the skull. For a model to reproduce this, it must have at least two layers so there is a potential space for the gas to expand, like in the human head. They also suggested that skin tearing must occur for backspatter to be produced. However, other authors disagree and it has been shown that this is not always the case (Karger, et al., 1996) This model is slightly more advanced than the sponge model tested by Pex and Vaughan (1987) and it is obvious that the authors at least considered the anatomical design of the head when creating this model. However, it is nonetheless a primitive model and the results may not be extrapolated to real cases.

Another model that was used to study both backspatter and forward spatter of blood was developed by James and Eckert (1999). This model consisted of a hollowed out Styrofoam wig support which was filled with gelatine. A small section of human bone was placed in a depression on either side of the head at the sites where the bullet would enter and exit the model. Polyurethane sponge was then placed over these bone sections, following which fresh pig skin was taped over the top. Human blood was injected into the sponge layer to act as a blood reservoir in both of the wound regions. Synthetic hair was placed over the exit wound site in order to further simulate a real human head.

The exact details of the testing of these models were not provided but the authors found that both forward and backspatter of blood were reduced in these models, compared to what would be produced in uncovered polyurethane sponge. They attributed this to the hair, skin and bone as these would all have a blocking effect on the blood. This model is far superior to the simple blood-soaked sponge models in terms of both its design and the materials used and was a step in the right direction for further developing realistic bloodspatter models.

1.4 Summary

There is a vast amount of literature on the topic of wound ballistics, perhaps because it is of interest to researchers from multiple disciplines. Because of this, and also because there are many factors to consider, there are often conflicting opinions on many of the important mechanisms involved. In contrast, there is limited literature on the process of backspatter and the studies that have been conducted in this area have mainly been carried out by a small group of researchers. As illustrated by this review, the ways in which it has been researched by these investigators have been quite variable.

It is obvious from the literature that while there are well established methods and tools available for the study of wounding, the same cannot be said for backspatter. Few studies have attempted to develop a realistic model that can be used to reproduce backspatter. Such a model would be a useful tool for forensic investigators and would have the potential to greatly contribute to our current knowledge of backspatter. Gaining a greater understanding of the phenomena of backspatter, in particular of its production would be a step towards a better understanding of evidence in fatal shooting cases.

1.5 Aims and Objectives

The aim of this project was to develop a synthetic backspatter model in the form of a pig head and validate it by comparing the results to those from both butchered pig heads and live pigs. If successful, this model could eventually be adapted into an equivalent human model. Such a model could potentially make an important contribution to the current knowledge in this area and be of use to forensic scientists in their interpretation of gunshot fatalities.

The aim of this project was broken down into three main objectives:

1. To develop a synthetic pig head backspatter model

2. To assess the effects of a gunshot wound on butchered pig heads and compare these results to the pig head model
3. To compare the backspatter produced from gunshot wounds in live pigs with that seen in the pig head model

1.6 Experimental Approach

The extensive set-up and equipment that was required for the experimental component of this research meant that both time and financial constraints were an issue. Because of this, only a limited number of targets could be tested and these were carefully selected in order to maximize the information that could be gained from this study. Minimal replicates of the model were tested as it was considered that the validation experiments were more important in building up good data. A larger number of butchered heads were tested as these were readily available and there were no ethical considerations since the animals were slaughtered for human consumption. In contrast, a smaller group of live pigs were tested for the opposite reasons. We endeavoured to obtain the maximum amount of information from the smallest possible number of animals.

Although similar testing has been carried out before, details of the experimental set-up are often not provided in the literature. Therefore, there were many unknowns surrounding this research and initiative was often required when designing the experiments. For some of the testing we also had to compromise in terms of the available resources.

1.7 Experimental Design

Many of the methods used in the testing of each target were consistent and therefore are discussed in a general methods section (Chapter 2). The development and testing of the pig head model is addressed in Chapter 3. Chapters 4 and 5 address the testing of butchered pig heads and live pigs respectively, with the findings from both compared to those from the pig head model. In Chapter 6, the model is evaluated in relation to all three targets and conclusions about its performance are discussed.

During this research, it was also possible to initiate the development of a synthetic human head model, based on the findings from the pig head model experiments, and to conduct a series of pilot experiments. Chapter 7 describes these exploratory experiments and presents some of the important findings. Finally, Chapter 8 focuses on the future and discusses further experiments that could be carried out.

2. General Methods

This chapter addresses the basic methods used for testing the pig head model, the butchered pig heads and the live pigs, since the experimental set-up remained consistent throughout the study.

The general process of testing each target involved three main steps:

- Construction or preparation of the target
- Shooting the target, which was filmed using a high-speed camera
- Analysis of the results

The shooting set-up, and the equipment used are described in this chapter, along with the methods used for analysing the results. The preparation or construction of each target is described in subsequent chapters, as this was specific for each.

2.1 Testing

2.1.1 Shooting Set-up

The shooting of the pig head model and the butchered pig heads was carried out the Otago Pistol Club in Waldronville, Dunedin which is an outdoor firing range. The live pig shooting was performed at the University of Otago, Hercus Taieri Resource Unit (HTRU) in Mosgiel. This shooting took place in an open shed which protected the equipment and pigs against the elements.

The testing set-up was essentially the same for each stage of the experiment. The target was placed on a table and where necessary was held in place using clamps and a wooden holder (Figure 2.1). A background covered with white paper was erected on one side of the target and white paper was placed directly beneath it. In some cases, white paper was also placed between the shooter and the target. The paper used was 80 gsm (grams per square metre) Bleach Kraft paper (MJ Shardlow and Co., Christchurch) and measured 900 mm in width. The length differed depending on both the target and the specific location of the paper. The main purpose of the paper was to collect backspattered material but it also served to create a good background for the high-speed camera filming. This paper was replaced following the shooting of each target. The person firing the gun was positioned directly in front of the target (Figure 2.1).

Figure 2.1 Experimental set-up. A: The model (light blue) surrounded by a white paper background with the light (black) and high-speed camera (grey) slightly in front. B: A view of the whole set-up, including the shooter.

2.1.2 High-speed Camera and Lighting

The shooting of each target was filmed using a high-speed camera (Figure 2.1). High-speed photography is commonly used in ballistic and impact studies as it allows for fast occurring events to be filmed in slow motion. These events can then be viewed frame by frame in order to analyse the events in detail. High-speed photography was a key feature in the "skin-skull-brain model" study by Thali et al. (2002). In the current study it was critical for visualising events such as the impact of the bullet and the ejection of backspatter.

The high-speed camera used in this study was a Fastcam SA1 (Photron, USA) which captured the shooting at a rate of 10,000 frames per second (fps). Two different lenses were used (depending on the target); a 55 mm Nikkor lens and a 90 mm Tamron lens, both of which were manual focus. Prior to filming, the black and white balances of the camera were set. Before each shot was fired, the focus of the camera was checked. Following each shot, the video files were downloaded to a laptop PC and analysed using the Photron Fastcam Viewer software, version 3.0 (Motion Capture Technologies, USA). These files were saved to a DVD in media player format (Appendix 1).

In order for the high-speed camera to capture images at such a fast rate, a high intensity light source was required. A Xenon 4 kW arc lamp (Tek Lighting Corporation, Nashville, Tennessee), which is normally used for movie lighting, was used (Figure 2.1). With high intensity lighting a very fast shutter speed (5 – 10 μs) was possible. This enabled the bullet to be seen clearly focused in the videos, with little or no motion-blur. Both the high-speed camera and the lamp were positioned side-on to the target (Figure 2.1), at a distance that was standardised for each target. The approximate angle between the camera and target was also standardised for each target.

2.1.3 Firearm and Shooting Distance

The firearm was standardised for the testing in order to allow for valid comparisons between the model and the biological targets. A 9 mm Glock (Model 17) was selected (Figure 2.2) which is a semi-automatic pistol with a 9 mm Parabellum (or 9 x 19 mm Luger) calibre (serial number CKG003). The ammunition used was American Eagle, 9 mm Parabellum (lot number NOV22W525) and the bullets were 115 grain, full metal jacket (FMJ). The muzzle velocity (as stated on the ammunition packaging) was 354 m/s and the muzzle energy was 468 J. The 9 mm Parabellum is the handgun cartridge that is most widely used in the military worldwide (DiMaio, 1999). It is also the pistol cartridge that is used by most police agencies in the United States and in many other countries (DiMaio, 1999). The shooter was a firearms examiner from the Institute of Environmental Science and Research (ESR) in Auckland.

The shooting distance (distance between the muzzle and the target) ranged from contact to 1 m for each target. This was varied in order to assess the effect of distance on the resultant wound as well as backspatter production. For the distant shots (1 metre) to the butchered heads and models, a Ransom Master Series Rest (Ransom International Corporation, USA) was used to hold the firearm (Figure 2.2). This device is designed to hold and fire a handgun in a similar way that a human hand would and allows for highly accurate shots to be fired. For the contact and near contact shots, the shooter held the firearm with his elbows resting on a small table.

Figure 2.2 A Ransom Master Series Rest holding the 9 mm Glock.

2.2 Analysis of results

Due to time constraints associated with conducting these experiments, the sample size used in each group was small, precluding meaningful statistical analysis of the results. The results were therefore analysed qualitatively in most cases. However, measurements were made where possible. There were three components to the results analysis for each target: the physical wounds, the high-speed camera videos showing the wound formation and backspatter, and the backspatter on the paper.

2.2.1 Entrance wounds

The entrance wound on each of the targets was photographed and measured. When measuring the wound, the diameter was measured at its widest point, often where a ring of gunshot residue ("ring of dirt") was present. An assessment of the physical characteristics of the wound was also carried out. This included detailing the wound morphology and whether any tearing of the skin had occurred.

2.2.2 High-speed videos

As well as a physical description of the wounding process, some measurements were made from the high-speed camera videos. The technique used for this will be described in the results section of the following chapter. The timing of key events was also noted.

2.2.3 Backspatter

This involved a thorough analysis of the paper surfaces positioned around the target. Following each shot, the paper was briefly analysed *in situ* and photographed before being removed. Where there was obvious bone fragments deposited on the paper, a circle was drawn around them to record their position in case they detached from the paper during transportation. A more thorough analysis of the paper was completed in the laboratory where there was good lighting available.

When there was uncertainty regarding the composition of a stain, a presumptive test for blood was carried out using Combur^3-Test® E test strips (Roche Diagnostics). The bottom pad of the stick was moistened with water and the strip was pressed gently on the stain. If a colour change from yellow to green occurred within a few seconds, it was likely that blood was present in the stain. A control test was made on a blank sheet of paper to ensure the water was not contaminated.

Where appropriate, all of the stains or fragments present on the paper were counted and measured and their distribution was noted. Material was considered a fragment if it was raised from the paper. If there were too many stains to assess each individually, sections of the paper were selected randomly using a system where the entire paper was divided into numbered 5 cm x 5 cm squares. Starting on one side of the paper, a random number generation was used to select two squares from each "row" and the stains within those squares were analysed. This meant stains from all areas of the paper had an equal chance of being analysed. A "Maggylamp", which is an illuminated magnifying instrument, was used to view the stains more easily.

3. Pig Head Model

3.1 Introduction

A pig head model was developed which incorporated synthetic skin, bone and brain components. The basic design of the model consisted of a synthetic soft tissue layer overlying an imitation bone layer, completely enclosing a volume of gelatine. The models were made using a mould system which meant that multiple models could be produced relatively easily. An actual pig head was used to create the mould for the model, as well as providing realistic tissue thickness values. Six models were constructed and then shot from various ranges using a 9 mm pistol. The resultant wounds and backspatter were analysed in order to draw some preliminary conclusions about the model. This chapter discusses the development and testing of this model as well as the results that were obtained.

3.2 Aim

The aim of these experiments was to develop a pig head backspatter model and assess its performance under ballistic impact.

3.3 Materials and Methods

3.3.1 Materials

Skin simulant

The use of silicone as a skin substitute has been well documented in the literature, particularly in wounding studies and it is said to be an accurate simulant of human skin

(Jussila, et al., 2005; Shergold and Fleck, 2005; Whittle, et al., 2008; Wong, et al., 2008). Because of this and also because it is readily available, inexpensive and easy to handle, it was selected to represent skin in the pig head model.

The particular silicone selected for the model was Deguform® (DeguDent, Germany). This is a two-component, addition cured silicone which is commonly used as a duplicating material in dental technology. Hence, it was also used to create the moulds that were used to construct each model. The silicone was mixed in a ratio of 1:1 with a dosing device which mixed the components into a homogenous liquid. The curing time at room temperature (approximately 23°C) was at least 30 minutes. Once set it had a final hardness or "Durometer" (a material's resistance to permanent indentation) of 14 - 16 (Shore A). Durometer is a dimensionless quantity and the range is 0 - 100. A higher value represents a harder material.

Soft tissue simulant

Polyurethane sponge has been used in a number of wounding and bloodspatter reconstruction studies both to simulate soft tissue and provide a method for containing blood within a model (Whittle, et al., 2008; Wong, et al., 2008, Stephens and Allen, 1983; Pex and Vaughan, 1987). Open-cell polyurethane sponge (Dunlop Enduro™, Australia), measuring 5 mm in thickness, was therefore used in two of the models to act as a blood reservoir. This sponge has a density of 38 - 40 kg/m³ and a hardness of 185 - 200 N which refers to the amount of force required to compress the sponge to 40% of its original size.

Bone simulant

The material used to represent bone in this study was Masterflow 622® (BASF Construction Chemicals, Australia) which is an epoxy resin. This is a two-component resin which is made up of a resin and a hardener and mixed at a ratio of 10:1 (resin to hardener). For this study it was mixed vigorously by hand for 3 minutes, under a fume hood, before being poured immediately into the required mould. It has a working time of up to 30 minutes and a curing time of approximately 8 hours. This resin reached its maximum physical strength after 7 days of curing (according to the manufacturer).

This resin was selected because it has a similar elastic modulus to that of human bone. Elastic modulus (or Young's modulus) is a measure of the intrinsic stiffness of a material (Turner and Burr, 1993). The manufacturers of this resin state that is compressive modulus is 4.0 GPa (after 7 days of cure) but no value for elastic modulus is provided. Therefore, we conducted a simple experiment in order to determine the elastic modulus.

Eight resin blocks were assembled measuring approximately 6 mm in thickness, 12 mm in width and 80 mm in length, and left to cure for 7 days. Three-point bending tests were then carried out on each block using a Universal Testing Machine. (Instron 3369 with Bluehill software, USA). A 5 kN load cell was used with a crosshead speed of 1 mm per minute and tests were carried out to failure for each block. Block dimensions were entered into the Bluehill software which then calculated the elastic modulus. The average elastic modulus for the 8 blocks was calculated as 4.94 GPa (SD = 0.875). The individual results for each block are presented in Appendix 2.

A literature search was conducted in order to determine elastic modulus values for various human bones. They have been reported as 14.0 GPa for cortical bone and 0.49 GPa for medullary bone (Ichim, et al., 2006). Turner and Burr (1993) stated that the elastic modulus varied, depending on location, with the values for cancellous bone ranging from 0.1 – 4.5 GPa. Another study (Delille, et al., 2007) specifically attempted to determine the elastic modulus of skull bones. The authors found that the average of all the bones was 5.2 GPa, with individual bones giving values of 5.0 GPa for the right parietal, 4.9 GPa for the left parietal and 3.8 GPa for the frontal bone. Our experimentally determined modulus value, for 6 mm thick resin blocks, was considered to be similar enough to the literature values for human bone to be an appropriate bone substitute.

Although this resin had a similar elastic modulus to human bone, it was not necessarily similar to that of pig bone. However, pigs have been used in a number of trauma studies and their bone is said to be biomechanically similar to human bone (Burnett, 1991; Tucker, et al., 2001; Calce and Rogers, 2007; Thompson and Inglis, 2009). The model would eventually be adapted into a human model and therefore it was considered important that the elastic modulus was representative of human bones.

Brain simulant

Gelatine (Davis Gelatine, Gelita New Zealand) was used as a brain simulant in the models. This gelatine was mixed at a concentration of 10% following a similar recipe to that suggested by Jussila (2004). Depending on the volume of gelatine required, an appropriate amount of gelatine powder (10% weight) was mixed by hand with half the required volume of tap water (5° C), until a reasonably smooth consistency was achieved. The remaining volume of tap water, heated to 50° C, was then added to the cold water/gelatine mix and mixed.

The mixture was then poured into the model and left at room temperature (approximately 23° C) overnight. Allowing the gelatine to cool slowly reportedly allows any air bubbles to float to the surface (Jussila, 2004). The following day the model containing the gelatine was placed in the refrigerator (at 4° C) to set further. This remained in the refrigerator for at least another 24 hours and was only removed a few hours before the shooting was carried out. As the shooting was mostly carried out outdoors in cool conditions (10 – 15° C), the temperature of the models would most likely not have risen any more than a few degrees before being shot.

The main differences between this method of preparing the gelatine and that described by Jussila (2004) were the water used and the amount of mixing of the final solution. In Jussila's method, the tap water was filtered before use in order to remove most of the microbes and impurities. The solution was also vigorously mixed prior to being poured into moulds. Filtered water was not used in the present study as the gelatine was made only a few days before it was used and thus the elimination of microbes was not critical. Excessive mixing was avoided as it was found, during trials of preparing the gelatine, that this made it cloudy and less transparent. Jussila (2004) also stated that the exact water temperature is not critical, as long as it does not reach excessive temperatures and therefore only approximate temperatures were used.

Blood

Porcine blood, preserved with ethylenediamine tetraacetic acid (EDTA), was used in models. The blood was obtained from a meat processing plant (Alliance Group's Sockburn Plant, Christchurch) in 500 ml glass bottles containing 3.5 g of EDTA. The blood was refrigerated at 4°C and used within 2 weeks of collection. Pig blood is said to have similar properties to human blood and is therefore commonly used in bloodspatter studies (Douglas, 1972; Raymond, et al., 1996a; Raymond, et al., 1996b).

3.3.2 Methods

Design

As mentioned earlier, a mould system was used to create the model. This consisted of a negative mould and two different sized positive "plugs" which were all made from silicone (Figure 3.1). To create each layer of the model, either silicone or resin, in a liquid form, was poured into the negative and when one of the plugs was inserted it forced the liquid into position. The larger plug was used to create the outer silicone layer while the smaller plug was used for the resin layer. These plugs produced layers with standard thicknesses.

Figure 3.1 The mould for creating the pig head model. A: The smaller "plug". B: The negative mould. C: The larger "plug" being inserted into the negative.

A butchered pig head was obtained (from Home-kill butchery, Outram) and sectioned sagitally in order to measure tissue thicknesses and view the brain position (Figure 3.2). It was important that the shots passed through the brain so that cavitation occurred, as this is an important factor in backspatter production. From this it was determined that if a shot was fired into the mid line of the frontal bone, at a point directly above and between the eyes, it would penetrate the brain. The soft tissue and bone thicknesses were measured, using digital calipers, at three different points in this area. The average of these values was calculated to provide thickness values for the tissue layers of the model.

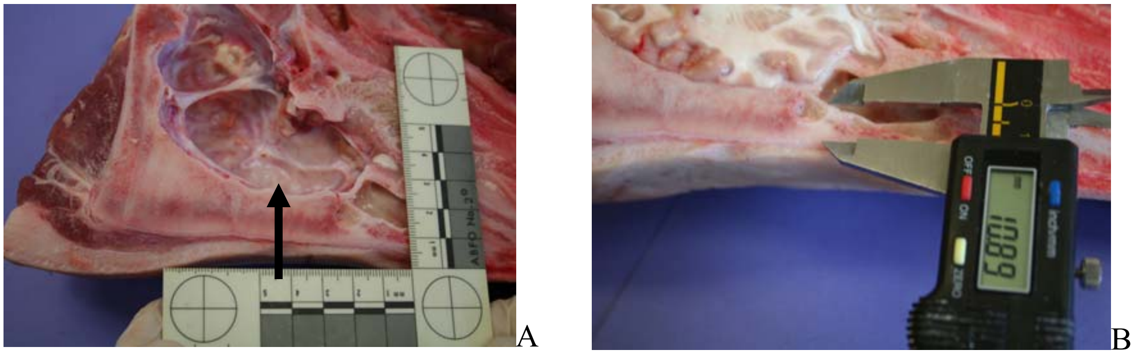


Figure 3.2 A sectioned pig head. A: The brain cavity in the skull (with brain removed) The arrow indicates the target area and direction of the bullet. B: Measuring bone thickness.

Creating the mould

A second butchered pig head was used to cast the original negative mould. The ears and snout were sliced off and sealed with alginate (a dental impression material). These were removed since it was only necessary to replicate the region where the bullet would penetrate (the frontal region) and areas immediately surrounding it. The pig head was placed in an upright position in a large plastic container. Agar jelly, another dental impression material, was then poured into the container until it reached a level that was about 5 cm lower than eye level. This was to eliminate the jaw region from the model as, like the snout and ears, it was not required. Silicone (the same material used to simulate skin in the models) was then poured into the container, on top of the agar, until it completely covered the pig head. Once set, the silicone block was removed from the container. The result was a negative impression of the pig's head in the silicone block.

The aim was for the silicone layer of the model to be 6 mm in thickness and the resin layer to be 13 mm as these were the average values obtained from the sectioned pig head. This meant that the two plugs needed to differ in size by these values compared to the negative. To create the larger plug, 3 layers of 2 mm thick dental wax were used to build up the inside of the negative by 6 mm and create the space where the silicone layer of the model would be formed. The inside of this wax mould was then coated with petroleum jelly (Soft White Paraffin BP – Multichem, Auckland) to ensure that the plug could be easily removed when set. A plastic guard was then constructed around the top edges of the silicone mould to retain the liquid silicone when creating the two plugs. Silicone was poured into the negative, up to a level that was 2 cm higher than the top of the original silicone block. Once set, the plug was removed from the negative, leaving the wax behind, which was then built up by another 13 mm. The process was then repeated, resulting in a slightly smaller plug that was identical in shape.

Constructing the models

The mould and the larger plug were both coated in petroleum jelly. Silicone was then poured into the negative until it was about one third full. The plug was then pushed into the mould, forcing the silicone into a 6 mm thick uniform layer between the negative mould and the plug. Once the silicone had set, the plug was removed, leaving the 'skin' layer in the mould. The inside of the silicone layer was wiped in order to remove the petroleum jelly and enable the resin to adhere to the silicone. Resin was then poured into the centre of the mould, on top of the silicone layer. The smaller plug, coated in petroleum jelly, was then inserted into the mould. The resin was forced into a 13 mm layer between the skin layer and the plug and then allowed to set for at least 8 hours. The thicknesses of the resin and silicone layers were verified using digital calipers.

These models were made with a flat base (Figure 3.3) by pouring a 13 mm layer of resin onto a tray in the shape of the base of the model and then pressing the model down onto it. This meant that once set, the resin base was incorporated into the model. A small opening in the base was made in order to fill the model with gelatine. A thin plastic bag was inserted into the model to act as the dura layer of the brain and contain the gelatine. The models were then filled with approximately 500 ml of gelatine. This was poured through a funnel into the inner plastic bag within the model.

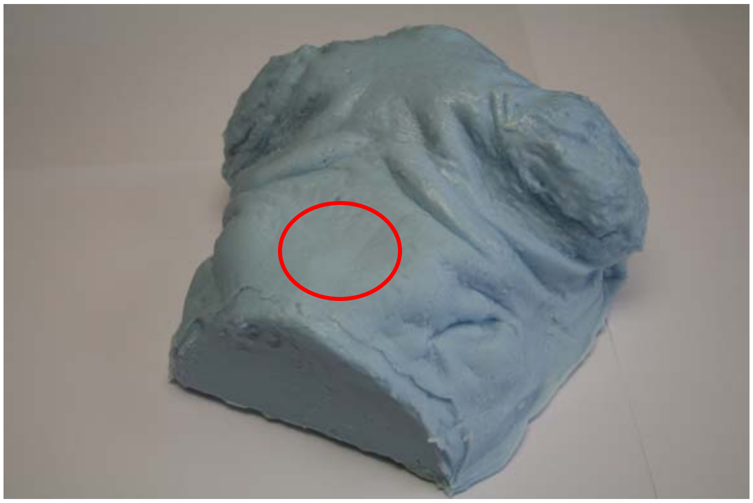


Figure 3.3 The pig head model. The red circle represents the area where the models were shot and where a layer of sponge was present in the blood models. The small slit to the right of this circle was where the eye was in the original pig head used to cast the mould.

Two of the six models incorporated sponge between the skin and bone layers, in the region where the models were to be shot (Figure 3.3). This was glued to the inside of the silicone layer (using Spray Bond, clear spray adhesive, Fuller, Australia), before the resin layer was poured, and covered with a layer of sealing film (Parafilm-M, SPI Supplies). This meant that the silicone was indirectly anchored to the underlying bone. Immediately prior to shooting, the sponge was injected with 10 ml of porcine blood, using a syringe inserted under the silicone layer. The puncture sites in the silicone were then sealed with silicone to prevent blood from leaking out.

The intention was to have three blood models and three non-blood models so that the group sizes were equal. However, a construction problem meant that one of the intended blood models had to be made into a non-blood model. This occurred when liquid resin leaked into the sponge layer of one of the models, meaning the sponge could no longer act as a blood reservoir. Unfortunately, there was not enough time to produce a new model in time for the scheduled testing day as each model required a full day for construction.

Shooting set-up

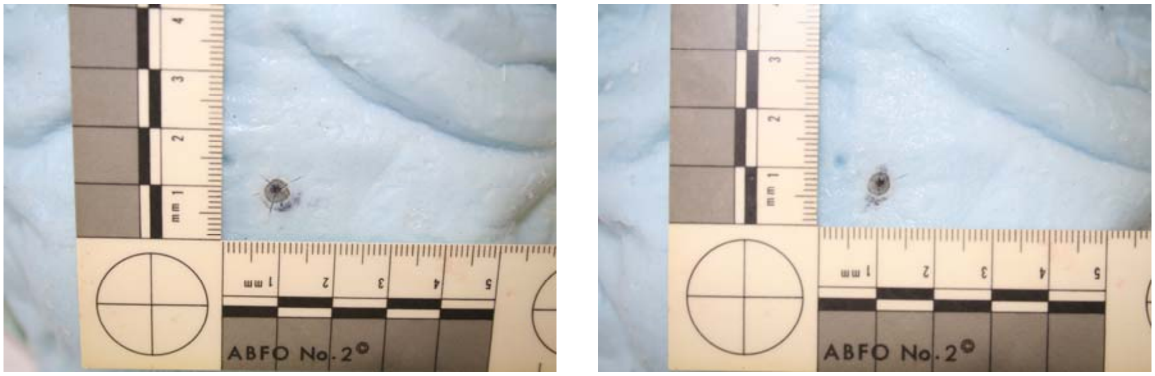
The shooting set-up has been described in Chapter 2. The models were positioned so that the target area (Figure 3.3) was vertical (at a 90° angle to the table). The high-speed camera was positioned approximately 98 cm from the models, at a 30° angle. The 55 mm Nikkor lens was used on the camera which was set at an aperture of F2.8. The light was positioned 132 cm away from the model at a 35° angle. Three models were shot from 1 m (one containing blood and two without) and two were shot at contact range (one with blood and one without). One model, without blood, was also shot from 20 cm in order to assess the effects of an intermediate shot on the model. The 1 m and 20 cm shots were considered to be distant shots for the purposes of these experiments. The angle of the muzzle was perpendicular with the target area for all of the shots.

3.4 Results

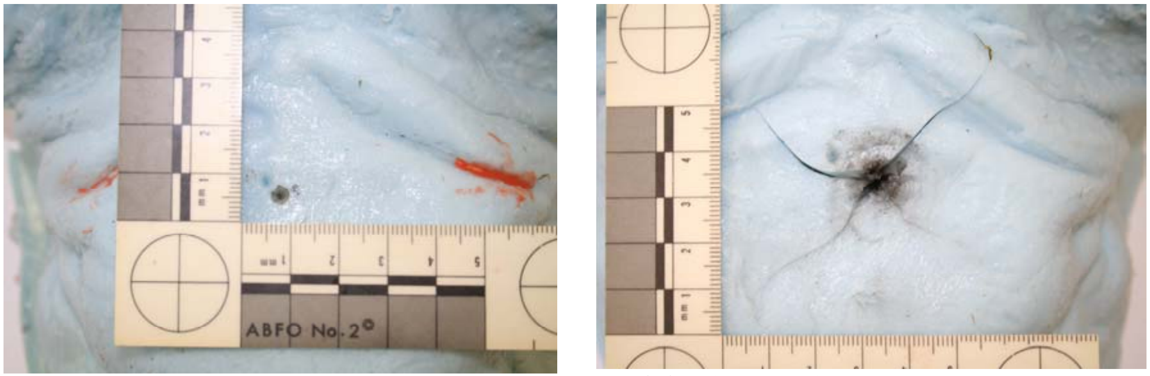
3.4.1 Entrance Wounds

Silicone

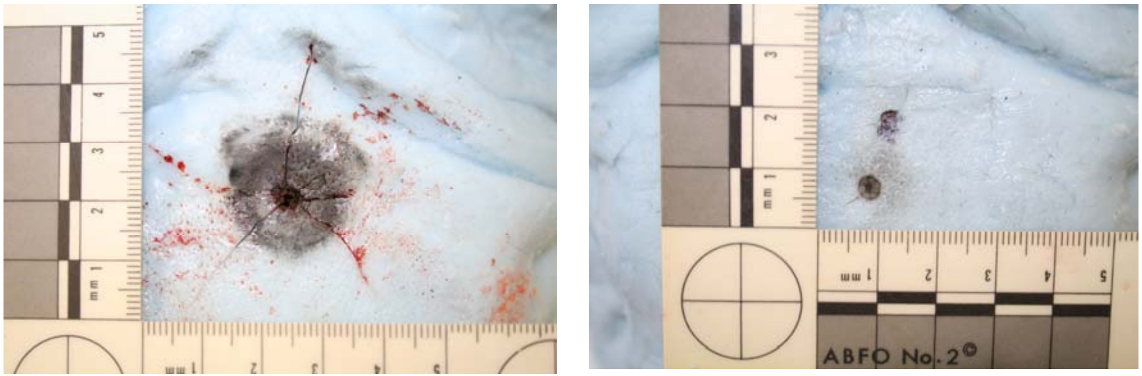
The entrance wounds in each of the models are shown in Figure 3.4. The characteristics of these wounds are presented in Table 3.1. The most important factors considered were shape and size of the wound.



Model 1 (1 m) Model 2 (1 m)



Model 5* (1 m) Model 4 (Contact)



Model 6* (Contact) Model 3 (20 cm)

Figure 3.4 The entrance wounds in the models. The range at which they were shot is indicated in brackets.
* Models containing blood.

Table 3.1 Characteristics of the entrance wounds in the silicone skin of the models.

ID	Range	Diameter	Comments
1	1 m	5 mm	Circular wound, 5 radiating tears (3 - 5 mm in length)
2	1 m	5 mm	Circular wound, 3 radiating tears (4 - 6 mm in length)
5*	1 m	4 mm	Circular wound, no radiating tears
4	Contact	8 mm	Star-shaped central defect, 4 radiating tears (20 - 40 mm in length), soot zone = 10 mm diameter
6*	Contact	8 mm	Circular wound, 4 radiating tears (10 - 30 mm in length), soot zone = 20 mm diameter
3	20 cm	4 mm	1 radiating tear (3 mm in length), some soot present around wound

Diameter refers to the central defect of the wound
Bullet diameter = 9 mm
* Models which contained blood.

In three of the four models shot from a distant range (20 cm and 1 m), the entrance wound displayed a small circular central defect, with tears radiating from it (Figure 3.4). The radiating tears in the 1 m wounds were all very short and representative of what DiMaio (1999) referred to as “micro-tears”. There was only one model where tears were not produced in the silicone. The diameters of the two wounds produced at contact range were larger than those produced in the distant shots and the tears were also larger. Soot was present around the entrance wound in both of the models shot at contact range, as well as the model shot at a 20 cm range (Figure 3.4)

Gelatine

In three of the models, the gelatine inside the model remained largely intact following the gunshot and the permanent wound cavity could be viewed. This was achieved by removing the gelatine from the plastic bag and slicing it along the path the bullet had taken. Both bullet and resin fragments were present along the length of the permanent cavity in these three models (Figure 3.5). In the other three models, the gelatine was too disintegrated to view the whole permanent cavity clearly but bullet and resin fragments could be seen in some regions.

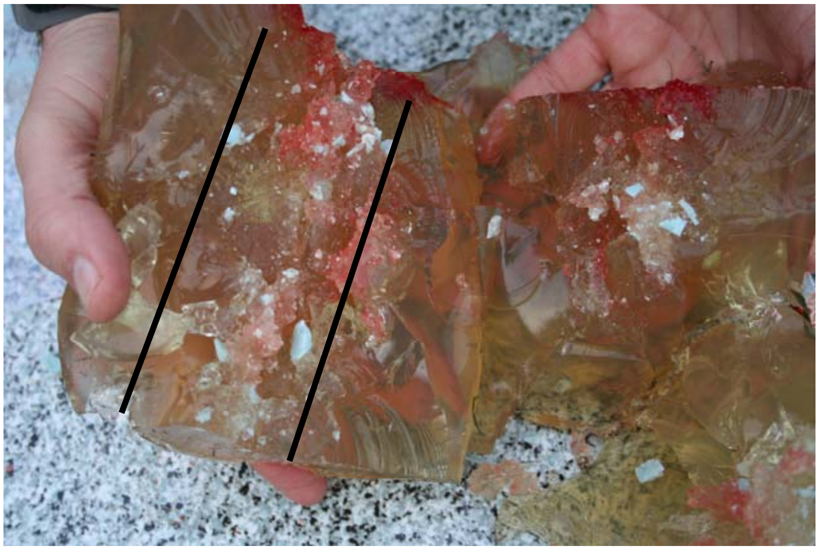


Figure 3.5 Resin fragments in the gelatine of model 5. These were present in the permanent cavity which is indicated between the black lines.

Resin

The entrance wounds in the resin were photographed but fragments making up the periphery of the central defect were often absent, meaning an accurate measurement of diameter could not be taken. Multiple radiating fractures were produced in five of the six models (Figure 3.6). Concentric fractures (fractures not connected with central defect) were also present in these same five models (Figure 3.6). Internal bevelling and fragmentation of the resin around the entrance wound was produced in all of the models (Figure 3.6).

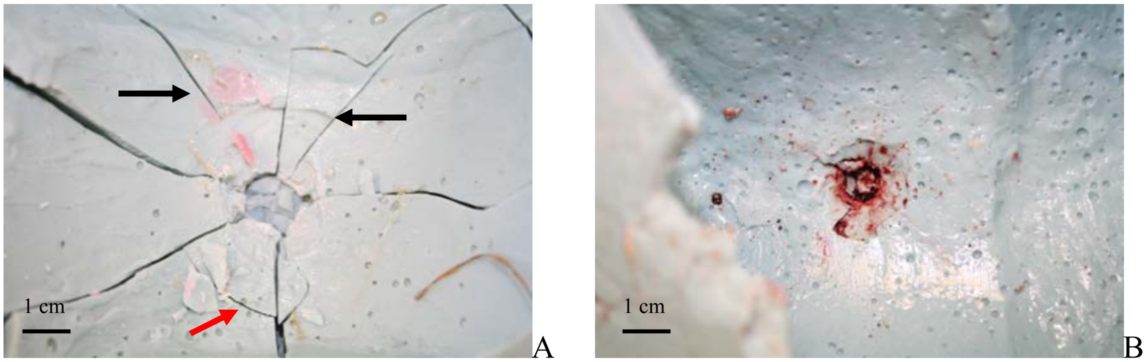


Figure 3.6 The entrance wounds in the resin, as viewed from inside the model. A: Model 1, range = 1 m. Internal bevelling is present around the central defect. Seven radiating fractures (black arrows) and two concentric fractures (red arrow) are present. This was the typical fracture pattern seen in five of the six models. B: Model 5, range = 1 m. Internal bevelling is present but there are no radiating or concentric fractures.

In model 5, a mistake made during construction resulted in an interesting outcome. A small amount of gelatine had leaked from the model, before it was set, through an undetected hole resulting in a reduction in the overall "brain" volume. This seemed to affect the fracture pattern in the resin, with no radiating fractures produced (Figure 3.6). Internal bevelling and fragmentation around the entrance wound were still produced. The wound in the silicone was also different to the entrance wounds in the other models as no tearing was produced and it was also slightly smaller.

Exit wounds were produced in the base plate of the models which was completely destroyed in 5 of the 6 models, making any analysis difficult. Interestingly, the base plate was still intact in model 5 (Figure 3.7) and the exit wound was easily viewed. External bevelling of the bone around the exit wound was produced with the exit wound measuring 13 mm in diameter.

Figure 3.7 The exit wound in model 5. External bevelling was present around the central defect.

3.4.2 High-speed videos

The general sequence of events seen in the high-speed videos was consistent between the models. In the non-blood models the silicone initially ballooned away from the resin (in a backwards direction) reaching a maximum convexity approximately 8 - 9 ms after the bullet had pierced the silicone (Figure 3.8B). The terms “ballooning” and “blow-out” are used interchangeably to describe this phenomenon for the remainder of this thesis. Following this, the silicone was sucked inwards beyond its original position, into the model. The silicone then ballooned outwards again, although not as much as the primary ballooning. After this, the silicone around the entrance wound oscillated for a few milliseconds before coming to rest. Backspatter of resin fragments began 1 - 2 ms after the initial impact of the bullet in the models shot from a distant range (Figure 3.8). Both the blow-out and backspatter could not be seen clearly in the videos as the view was blocked by the muzzle of the firearm.

In model 5, where the blow-out of the silicone could be seen, it was much smaller than that in the non-blood models. This was quantified by measuring the height and width of the blow-out at its maximum point in the models using the bullet length (15 mm) as a reference. The high-speed video frames which showed the blow-out of the skin were printed as single images. The image where the blow-out reached its maximum size was selected and measurements were made on this single image (Figure 3.8). A 1 cm x 1 cm transparent grid was used to assist with the measurements. The length of the bullet was measured to determine its size on the image and then the difference between this and its actual size was calculated. The margins of the silicone blow-out were identified following which its width and height were measured on the image. These values were then converted into actual distances. These results are presented in Table 3.2. This analysis was not carried out for the contact shots as the processes could not be clearly seen.

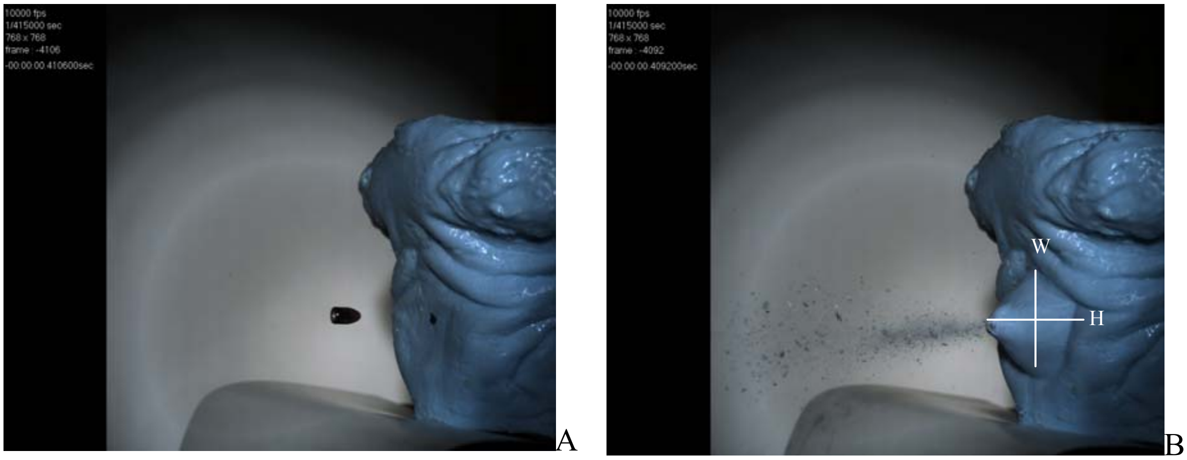


Figure 3.8 High-speed video frames from Model 1. A: The bullet before it impacted the model. Bullet length = 15 mm. B: Blow-out of silicone around the entrance wound at its maximum point. H = height measurement, W = width measurement. Backspattered resin fragments can be seen exiting the wound.

Table 3.2 Skin blow-out and backspatter results in the distant shots to the model.

Skin blow-out				**Backspatter**
Model	Height (mm)	Width (mm)	Time (ms)	Time (ms)
1	42.8	53.5	9	2
2	47.1	57.8	9	3
3	38.6	51.4	8	3
5*	25.7	34.2	9	3
Average	**38.6**	**49.2**	**8.75**	**2.75**

Bullet penetration = 0 ms.
* Model containing blood.

The average height of the blow out in the non-blood models was 38.6 mm and the average width was 49.2 mm. These values are relatively large compared to those from model 5 (25.7 mm and 34.2 mm respectively). This blow-out reached a maximum size 8 - 9 ms after bullet impact in all of the models. The shape of the skin blow-out was also quite different between the blood and non-blood models. The non-blood models displayed a more circular shaped skin-blow out (Figure 3.8), while in the one blood model in which the blow-out could be seen (model 5), it was more pyramidal in shape (Figure 3.9).

Backspatter was first ejected on average 2.75 ms after the impact of the bullet. This occurred much earlier than the maximum silicone blow-out in all of the models where it could be seen. Backspatter in the non-blood models was composed of resin fragments only. The amount of backspatter produced in model 5 was visibly less than was seen in the non-blood models (Figure 3.9B).

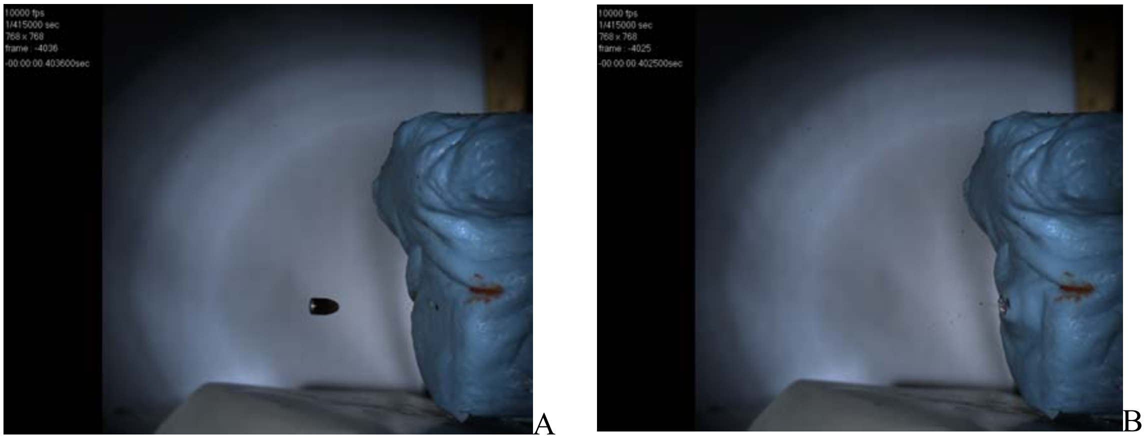


Figure 3.9 High speed video frames from Model 5*. A: Bullet before it impacted the model. Bullet length = 15 mm. B: Blow-out of the silicone around the entrance wound at its maximum point. The amount of backspatter was less than in the non-blood models.

3.4.3 Backspatter

As mentioned earlier, backspatter of resin fragments occurred in all of the non-blood models. However, as there was no associated liquid, the fragments did not adhere to the surrounding paper and therefore could not be analysed.

Backspattered material was only visible on the white paper from one of the two blood models. As mentioned earlier, only a very small amount of backspatter was ejected from model 5, which was probably why there was no evidence of this on the paper. In model 6 however, a significant amount of blood was present on the ground paper (Figure 3.10). Resin fragments were also present on this paper.

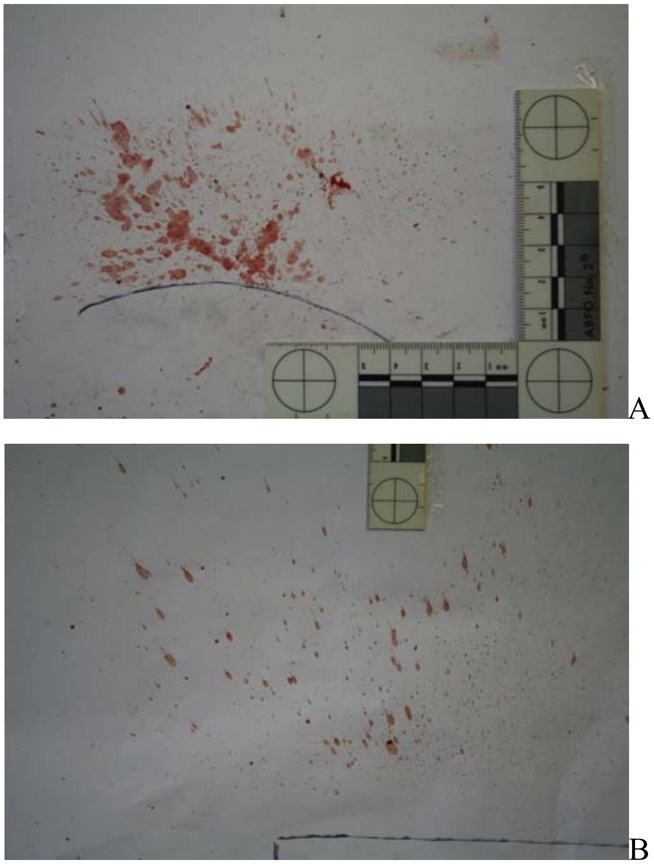


Figure 3.10 Backspattered paper from model 6. A: The curved line represents the position of the front (snout) of the model. A number of individual stains in this region could not be differentiated and therefore were excluded from the analysis. B: Stains further from the model. The black line in the bottom of the figure represents the edge of the paper that the model was resting on (shown in 'A').

The bloodstains were densely distributed directly in front of the model, but individual stains were not always distinguishable and no clear directionality was evident in those that were (Figure 3.10A). The stains were more spread out with increasing distance from the model and stains were present up to the edge of the paper (60 cm). The more distant stains were mostly elongated (Figure 3.10B) and therefore their direction could be determined. Lines were drawn through the long axis of selected stains and these intersected in the general region where the model was positioned.

All of the individual stains that could be differentiated were less than 4 mm in diameter. In order to determine the sizes of a random selection of stains, the technique described in Chapter 2 was used to select stains to measure. Stains which could not be differentiated were excluded from the analysis. The results are presented in Figure 3.11.

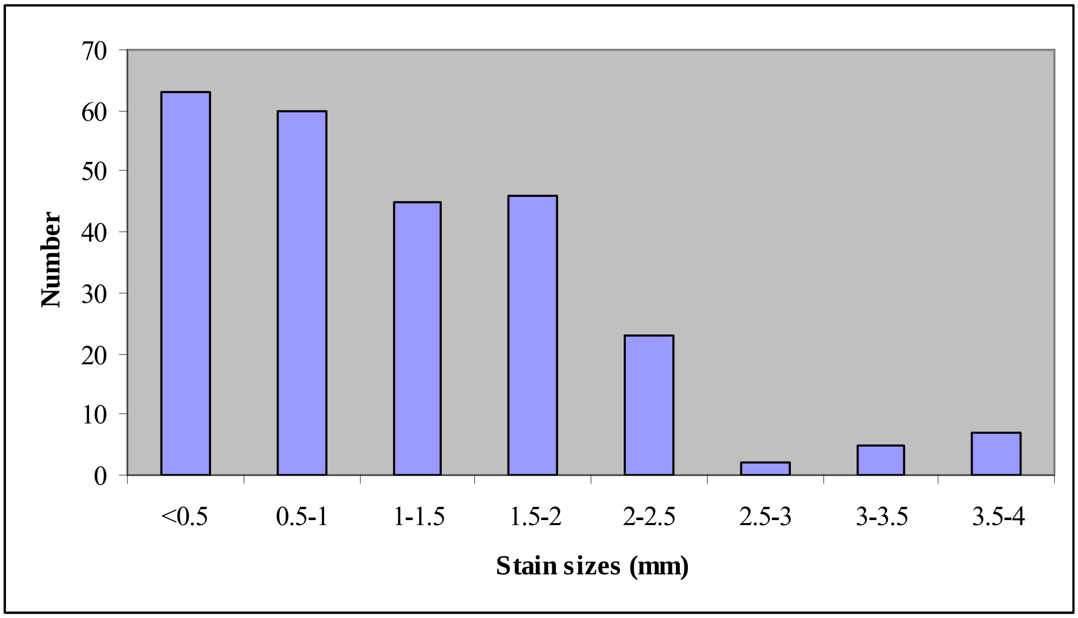


Figure 3.11 Stain sizes on the ground paper from model 6.

Blood was present on the hand of the shooter from model 6 and also on the firearm (Figure 3.12). However, this was not analysed as the stains were faint and difficult to measure. The blood was quite concentrated on the underside of the firearm (Figure 3.12C). The blood on the hand was mostly present in the distal region of the third digit (Figure 3.12A).

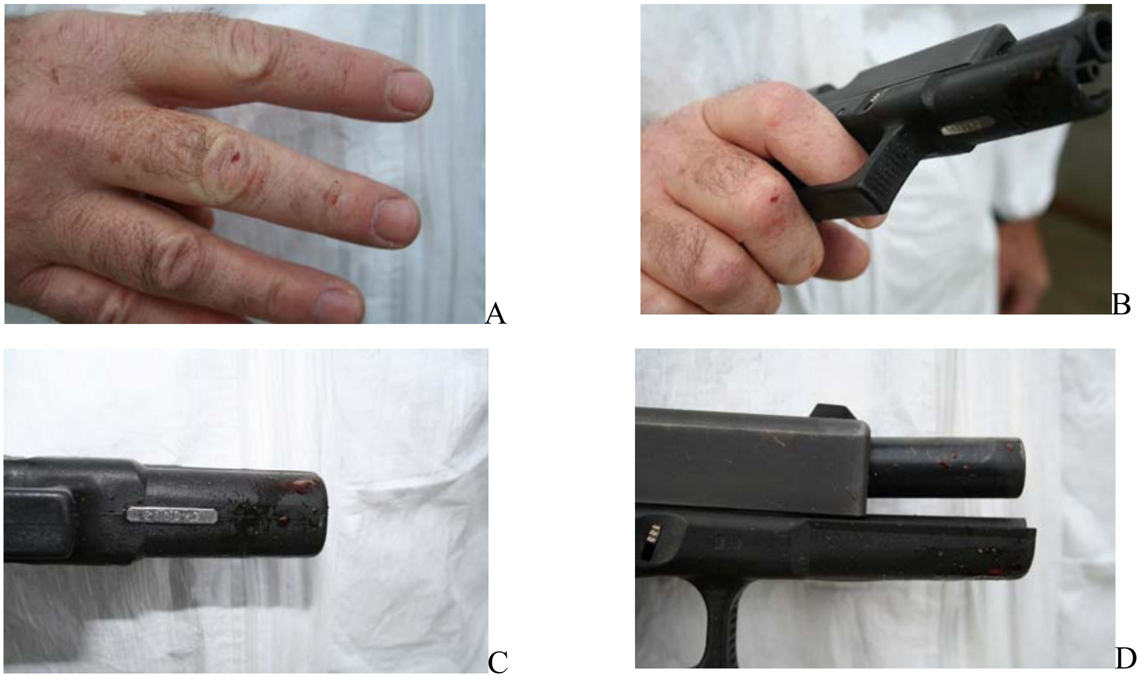


Figure 3.12 Bloodstains present on the hand of the shooter and on the firearm. A and B: The hand of the shooter displayed bloodstains mostly in the distal region of the third digit. C: Bloodstains on the underside of the muzzle. D: Bloodstains under the slide.

3.5 Discussion

The development of a synthetic pig head backspatter model was one of the main objectives of this project. As such a model had not previously been reported in the literature, the materials used for its construction were carefully considered. The materials were selected using information from the literature as well as considering the biomechanical properties of various materials. It was anticipated that by using materials with similar properties to animal tissue, the results would be representative of gunshot wounds and backspatter documented in the literature. This section highlights the key findings and compares the results from the model to the literature. As gunshot wounds and backspatter have not been well documented in pigs, the results were mostly compared to human cases at this stage of the project.

3.5.1 Entrance Wounds

Skin is an irregular structure and therefore simulating it with a homogenous material will have its limitations. Nevertheless, silicone has been used to represent skin in a number of studies (Bellamy and Waters, 2005; Shergold and Fleck, 2005; Whittle, et al., 2008; Wong, et al., 2008). As pig skin is also said to be an accurate simulant of human skin, it was assumed that silicone was an appropriate simulant of pig skin too. Silicone was used as a skin substitute in the “skin-skull-brain model” developed by Thali et al. (2002c) and the resultant wounds were representative of those seen in the literature (Figure 3.13). The same can be said about the wounds produced in the current model as many of the features, such as the radiating tears and wound shape, are characteristic of gunshot wounds in humans.

Figure 3.13 Bullet entrance wounds in: A: The “skin-skull-brain model” developed by Thali et al. (2002c). B: A human (Thali et al., 2002c). C: The pig head model.

The entrance wounds in all of the models were relatively small compared to the calibre of the bullet, most likely due to the elastic nature of the silicone. This was particularly evident in the more distant wounds, where only the bullet itself had an effect on the wound production. In the contact shots, the muzzle gases forced into the wound caused larger wounds and longer tears to be produced. This is a common feature of contact wounds, particularly in the head, where there is only a thin layer of skin and subcutaneous tissue overlying bone (DiMaio, 1999). The muzzle gases expand between the bone and skin, causing the skin to stretch, with tears resulting if the elasticity of the skin is exceeded (DiMaio, 1999).

The damage to the resin in the models was representative of gunshot wounds in human bone. The internal bevelling that was seen was particularly similar although this has been described in other materials such as glass (Thornton, 2001). Radiating fractures around the entrance wound have also been documented in human gunshot wounds of the head. This pattern was also very similar to that reported by Thali et al (2002c) in their "skin-skull-brain model" where they used a similar material (polyurethane resin) to simulate bone. Another feature that was common with the "skin-skull-brain model" was the presence of multiple bone fragments in the gelatine. The concentric fractures that were produced around the entrance wound in the current model have also been documented in the literature (Smith, et al., 1987; Karger, 2008).

Interestingly, in model 5 where the model was not completely filled with gelatine, no radiating fractures were produced. This may have been because the gelatine had space to expand and therefore less force was transferred to the resin than in the other models. In experiments conducted by Owen-Smith (1981) where dry human skulls were shot, the pressure produced in an empty skull was found to be much less than that produced in a skull filled with gelatine. The author stated that this was because of the hydrodynamic pressure associated with the temporary cavity. This caused the skull to expand past its limit in the full skull, resulting in fractures around the point of entrance (Owen-Smith, 1981). The wounds present in the empty skulls from his experiments displayed neat entrance and exit wounds, with no radiating fractures. However, in the gelatine-filled skulls, large "egg-shell" fractures were produced around both the entrance and exit wounds. This may have been what caused the different fracture pattern in Model 5. A reduced pressure in this model may also have been responsible for the smaller entrance wound that was produced as well as the reduced amount of backspatter.

3.5.2 High-speed Videos

The elastic nature of the silicone material was also likely to be responsible for the extensive ballooning seen in the non-blood models, as well as the fact that the skin was not anchored to the underlying bone. However when adhered to the sponge and resin as it was in the two blood models, the skin was not able to stretch to the same extent. This is more realistic of human and animal tissue, as the skin is anchored to the underlying subcutaneous tissue in most regions of the head.

Backspatter was seen to be projected from the wound within 3 ms after the bullet penetrated. Because of the skin blow-out at this point and the extensive stretching of the skin, the entrance wound was momentarily very large meaning material could easily escape. Therefore, the amount of backspatter produced in the non-blood models was possibly more than what would be seen in humans or animals, as skin is not as elastic as silicone. When the skin was anchored down (in the blood models), the amount of backspatter produced was visibly reduced.

3.5.3 Backspatter

Backspatter of material was produced in all of the models. This mainly consisted of resin fragments however in one of the blood models extensive blood backspatter was produced. In the models which did not contain blood, the number of resin fragments that were ejected was much greater than in the blood models. This may have been due to the fact that the sponge between the silicone and resin layers restricted the passage of the fragments. As mentioned in Chapter 1, the presence of bone fragments in backspattered material has not been well described in the literature. It is said to be a logical outcome however, particularly from contact and close-range head wounds, and has been documented experimentally in live pigs (Burnett, 1991).

The only blood model where blood backspatter was seen on the paper was the model shot from contact range. The muzzle gases forced under the silicone resulted in a large amount of ballooning and meant that blood was easily able to be ejected. It would be expected that backspatter would also occur in a near contact shot to this model, as some gas could still be forced under the skin from this range. It was not expected to be seen in the model shot from 1 metre as backspatter is not commonly produced from distant ranges.

3.5.4 Summary and conclusions

Six pig head backspatter models were constructed and tested, two of which contained blood. The blood models incorporated a sponge layer which contained the blood and also anchored the silicone layer to the underlying resin. The results in these models were quite different to those in the models without blood. A large blow-out of the silicone was seen in the non-blood models, with backspatter of resin fragments occurring almost immediately after bullet impact. A smaller blow-out of the entrance wound was seen in the blood models. While backspatter of resin fragments occurred in all models, blood backspatter only occurred following a contact shot to one of the blood models. This produced a large number of small bloodstains on the paper below the model.

There were a number of similarities between the wounds seen in the model and those from human gunshot wounds in the literature such as wound shape and the extensive tears produced in the contact wounds. There were also differences, such as wound size, which were expected due to the fact that we used non-biological materials to simulate living tissue. It was concluded at this stage of the project that the model had the potential to be realistic, providing it could be validated by further studies in butchered and live pig heads.

4. Butchered Pig Heads

4.1 Introduction

The work described in the previous chapter was valuable in terms of initiating the development of the backspatter model. However, to validate the materials and design of the model, it was necessary to assess how real animal tissue behaved under ballistic impact. This chapter will describe the testing that was carried out on a number of butchered pig heads. The main purpose of these tests was to compare the wounds produced to those in the pig head model. Fourteen pig heads were obtained from local butchers and shot under similar conditions to the pig head model. The shooting distance was varied in order to assess the effect of range on the wounds produced.

4.2 Aim

The aim of these experiments was to gain a better understanding of the effects of a bullet on animal tissue, in order to assess the validity of the pig backspatter model. This was achieved by analysing both the wound formation, as viewed in the high-speed videos, and the physical wounds produced in the pig heads.

4.3 Methods

4.3.1 Pig Heads

Fourteen pig heads were used for these experiments, sourced from two different butchers. Seven heads were purchased from the butchery at the local New World Supermarket (Centre City, Dunedin) and another seven were provided by the Outram Home-kill

Butchery (Outram, Dunedin). Of the latter, four heads were from domestic farm pigs and three were from wild pigs (Figure 4.1). All 14 heads were from pigs killed for human consumption. The exact age and sex of the pigs was unknown but the size of the heads indicated they were from adult pigs. Unfortunately, the seven pigs sourced from the Home-kill Butchery were all slaughtered by a gunshot wound to the head which may have affected the results. All of the farm and wild pigs had been slaughtered the previous day and so were relatively fresh. It was unknown precisely when the supermarket pigs had been slaughtered but it was assumed it was in the previous few days before testing. All of the heads were refrigerated overnight and removed on the morning of shooting.

Figure 4.1 A selection of butchered pig heads. The left three heads were from wild pigs, the middle four from domestic farm pigs and the right three from supermarket butchery pigs.

The supermarket pig heads were hair-free with pink skin, which meant that wound formation was easily seen in the high-speed videos. In contrast, the farm pigs and wild pigs were hairy with mostly dark skin. Hair was removed with a scalpel before shooting, but it was difficult to remove it completely without cutting the skin. This made it hard to see wound formation clearly in some of the high-speed videos. Furthermore, the supermarket pig heads had had their ears removed by the butcher, which meant that the skin between the ear and mandible (including around the eye) was missing. This may have had an effect on the wounds as the skin would not have been pulled as taut as it was in the heads with intact skin.

4.3.2 Shooting Set-up and Variables

The butchered heads were attached by tape to a wooden holder which was held in place using a large clamp stand. This was propped up on wooden blocks as necessary to adjust the height and angle. The heads were positioned so that the impact surface was vertical (90°) to ensure that the trajectory of the bullet was through the brain. A single shot was fired at each head.

The camera was on an angle of approximately 30° to the head, while the light (4 kW Xenon lamp) was on a 35° angle. The distances between the camera and the head and the light and the head were approximately 83 cm and 132 cm respectively. The 55 mm lens was used on the high-speed camera at an aperture of F2.8. White paper was placed on the table, directly below the head. A board to the side of the head (at a distance of 20 cm from the impact point) was also covered in white paper.

The two main shooting distances that were used were 1 m (six heads) and contact (three heads). Shots were also fired at other heads from distances of 2 cm, 5 cm, 10 cm and 20 cm. The details of the firearm and ammunition are described in Chapter 2.

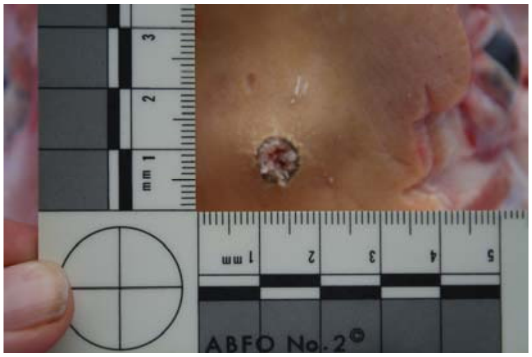
The heads came from three different sources which introduced another variable into the testing as they all differed slightly. Because there were only 14 heads in total, it was not possible to test all of the ranges on each of the different heads. For the contact shots, each of the three types of pig were shot but the 1 m shots were mostly carried out on the supermarket pig heads.

4.4 Results

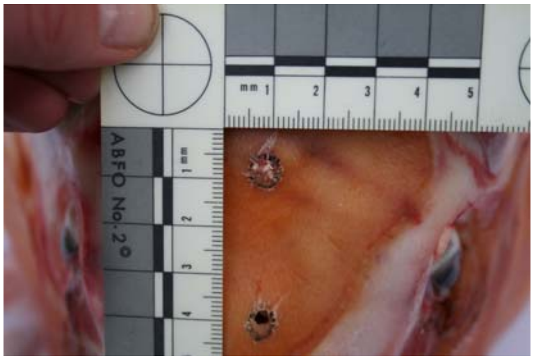
4.4.1 Entrance Wounds

Entrance wounds were produced in the frontal bone of all 14 pig heads (Figure 4.2). The characteristics of these wounds in the skin are presented in Table 4.1.

1. 1 m (SM)

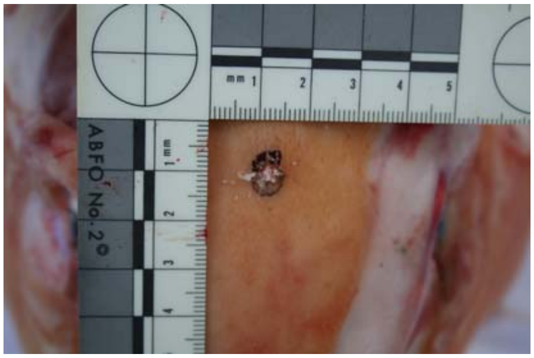


2. 1 m (SM)

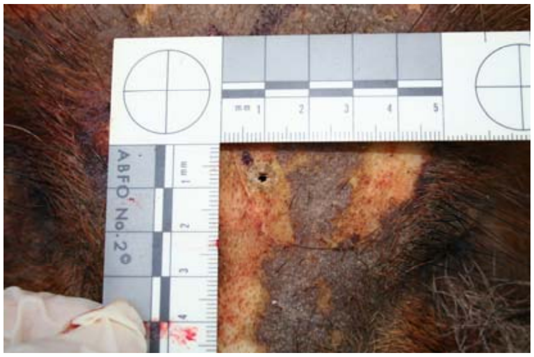


3. 1 m (SM)

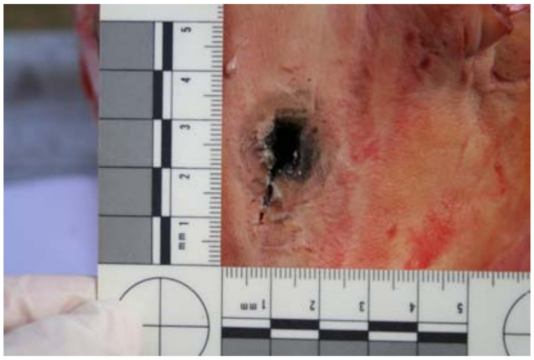
4. 1 m (SM)



5. 1 m (SM)

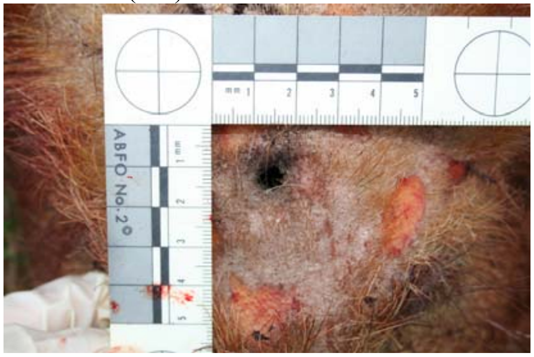


6. 1 m (Farm)



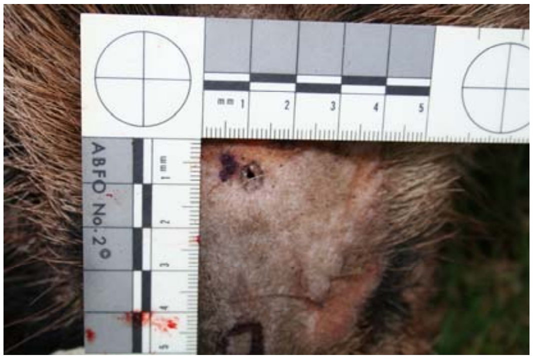
7. Contact (SM)

8. Contact (Farm)



9. Contact (Wild)

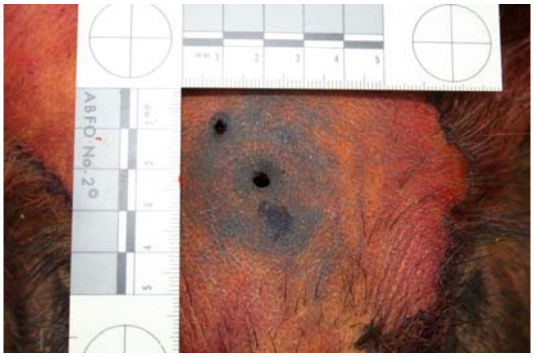
10. 20 cm (Farm)



11. 20 cm (Wild)

12. 10 cm (Wild)

13. 5 cm (SM)



14. 2 cm (Farm)*

Figure 4.2 Entrance wounds in the 14 butchered pig heads. SM = supermarket. * The lower wound was the experimental wound (upper wound fired by slaughterer).

Table 4.1 Characteristics of the entrance wounds in the butchered pig heads.

ID	Range	Source	Diameter (mm)*	Comments
1	1 m	Supermarket	7	Circular
2			8	Circular, raised in centre, white partial tears
3			7	Circular
4			7	Circular
5			7	Circular
6		Farm	2	Circular, small
7	Contact	Supermarket	12	Irregular shape, black margins, large skin tear (11 mm)
8		Farm	13	Irregular shape, black margins, multiple skin tears and white partial-tears
9		Wild	8	Circular, black margins, no skin tears
10	20 cm	Farm	3	Circular, small
11		Wild	3	Circular, small
12	10 cm	Wild	6	Irregular, ragged edges, small skin tears, soot on surrounding skin
13	5 cm	Supermarket	10	Irregular shape, skin tears, large soot zone surrounding wound
14	2 cm	Farm	5	Circular, no tearing, large soot zone surrounding wound

* Diameter is the width of the entrance wound in the skin, at its widest point. Any wound that was not circular was described as irregular. Bullet diameter = 9 mm.

Exit wounds were present in all of the heads but were not analysed as they were often difficult to locate. This was because the wounds were in the region of the amputation site between the body and head of the animal.

As mentioned earlier, the 1 m and contact shots were those that were of most interest. The entrance wounds in the 1 m group were very consistent between heads, with most being circular in shape and 7 - 8 mm in diameter. The exception was the farm pig head, in which the wound was markedly smaller. The characteristics of the wounds in this group were consistent with those of distant wounds described in the literature.

The entrance wounds in the contact group were quite different to those produced from the 1 m range. These wounds were larger, with diameters between 8 and 13 mm, and more irregularly shaped than the distant wounds. The main difference with these wounds was the skin tearing that was produced. This occurred in two of the three heads, with one also displaying white partial tears in the skin. These had a stretch-mark like appearance and radiated away from the entrance wound. Skin tears are characteristic of close contact wounds in the head (Faller-Marquardt and Pollak, 2002; Karger, 2008). The entrance wound in the wild pig head contrasted with those in the two other heads as it was smaller with no skin tears.

4.4.2 High-speed videos

The effect that the bullet had on the tissue was quite consistent between the heads, regardless of range. A blow-out of the skin around the entrance wound occurred, as it did in the models. However, there was a noticeable reduction in the degree of skin blow-out compared to that seen in the models. This was measured where possible and the results are presented in Table 4.2. Because the margins of the skin blow-out could not be differentiated, no measurements were carried out for the close range wounds (contact – 5 cm). Measurements were also not made where the skin blow-out or backspatter could not be seen clearly due to gas, hair or the muzzle obstructing the view (head 10).

Table 4.2 Skin blow-out and backspatter results in the distant shots to the butchered pig heads

Skin blow-out				Backspatter
Head	Height (mm)	Width (mm)	Time (ms)	Time (ms)
1	19.0	30.3	5	3
2	18.3	49.3	3	2
3	24.4	43.9	4	4
4	21.7	46.1	4	3
5	35.3	49.2	4	3
6	40.7	50.0	4	3
11	30.4	33.0	5	5
12	25.3	38.5	5	4
Average	**26.8**	**42.5**	**4.3**	**3.4**

Bullet penetration = 0 ms.
Height represents the distance the skin moved away from its original position and width represents the diameter at the base of the skin blow-out.

The average skin blow-out in the pig heads where it was able to be measured was 26.8 mm in height and 42.5 mm in width. This occurred at an average time of 4.3 ms after the bullet impacted. Backspatter of material was produced from the entrance wound in all of the heads. This was first ejected at an average time of 3.4 ms after the initial impact of the bullet (range = 2 - 5 ms). Material was ejected until the skin blow-out had disappeared in all of the heads. This material was a white or yellow colour in all of the heads. No blood backspatter was seen in any of the videos but this was expected since the animals had been slaughtered the previous day.

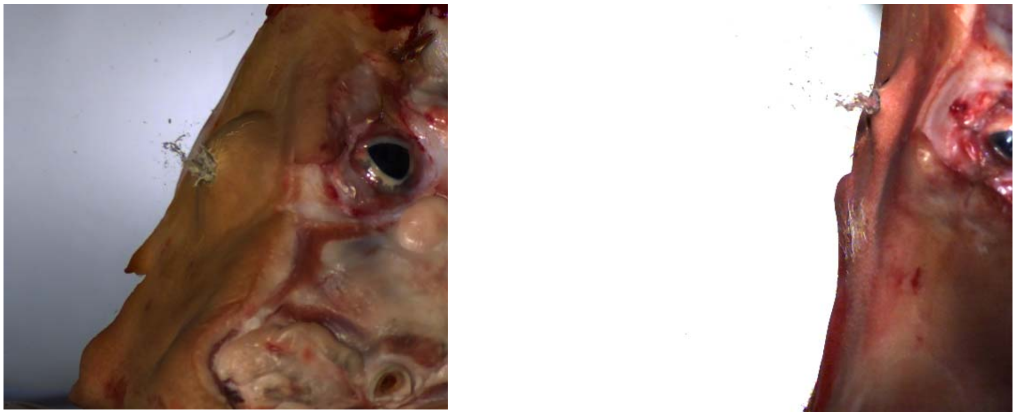


Figure 4.3 High-speed video frames showing the maximum skin blow-out and backspatter in two of the butchered heads.

4.4.3 Backspatter

Just as there was no blood backspatter seen in the high-speed videos, there were no obvious bloodstains present on the white paper from any of the heads. However, there were many white, yellow and brown coloured stains and fragments present on a majority of the papers collected. Some of these stains caused a colour change on the blood test strips which shows that blood was most likely present, even though they did not appear to be bloodstains. A brief analysis of this backspattered material was carried out and the results are shown in Table 4.3. If the material was raised from the surface of the paper, it was considered to be a fragment otherwise it was recorded as a stain.

Table 4.3 Characteristics of the backspattered material present on the surrounding paper.

ID	Range	Source	Ground paper	Side paper
1	1 m	SM*	-	-
2		SM	-	-
3		SM	Numerous fragments and stains (<0.5 mm)	-
4		SM	Numerous fragments and stains (<0.5 mm)	-
5		SM	Numerous fragments and stains (<0.5 mm)	21 Fragments (0.5 - 2 mm), no visible stains
6		Farm	1 fragment (1 mm), 3 stains (0.5 mm)	-
7	Contact	SM	3 fragments (1 – 2 mm), numerous stains (<0.5 mm)	-
8		Farm	No fragments, 17 stains >0.5 mm, numerous stains <0.5 mm	No fragments, 13 stains (>0.5 mm), numerous stains (<0.5 mm)
9		Wild	5 fragments (0.5 - 1.5 mm), numerous stains (<0.5 mm)	No fragments, numerous stains (up to 4 mm)
10	20 cm	Farm	No fragments, numerous stains (up to 1 mm)	-
11		Wild	-	3 fragments (1.5 – 2.5 mm), no stains
12	10 cm	Wild	1 fragment (1 mm), minimal stains (>0.5 mm)	No fragments, numerous stains (>0.5 mm)
13	5 cm	SM	No fragments, numerous stains (<0.5 mm)	-
14	2 cm	Farm	No fragments, numerous stains (>0.5 mm)	-

SM = supermarket. Where there is a dash, it indicates that no material was visible on the paper.

As can be seen from the Table 4.3, the presence of backspattered material was quite random, with no readily identifiable pattern. Backspatter was present on the ground paper more often than it was on the side paper. This was expected, however, as the material would have had to travel approximately 20 cm to reach the side paper from the wound and if it did not reach it, it would have fallen onto the ground paper. The composition of the backspattered material was also random, with only fragments present on some sheets, only stains on others, or both types of material on others.

The distribution of backspattered material was quite random, with stains and fragments generally present in a semi circle around the wound. Those with smaller diameters, in particular the smaller stains, were more commonly positioned close to the wound. The maximum traveling distance of the fragments and stains that was recorded was 59 cm. However, this was on the very edge of the paper so it was possible that fragments traveled further but were not collected. It was difficult to determine directionality in the stains as most were either circular or irregular in shape.

It was difficult to determine the anatomic origin of much of the backspattered material in the absence of a chemical and/or histological analysis. The hardness of many of the fragments would tend to suggest that they originated from bone, while there were numerous other fragments that were more likely to be skin and soft tissue. Some of the stains which tested positive for blood were a red-brown colour and may have been blood mixed with other body fluids. Other stains were almost transparent and had an oily appearance.

One aspect that was not analysed from the contact and closer range shots was backspatter on the firearm, and the hand of the shooter. In the literature, backspattered particles are commonly reported in and around the barrel of the firearm and it was likely this was the case in these experiments also. However, the main focus of these experiments was the wounding and due to time constraints, the characteristics of the backspattered material on surfaces other than the paper were not recorded.

4.5 Discussion

The shooting of the 14 butchered pig heads produced interesting results, some of which were similar to those seen in the pig head models and others which were quite different. Either way, the results were valuable in terms of the overall project and some important information was obtained from these experiments. This section will discuss the findings and compare them to those from the model. The limitations of these experiments and aspects which could be improved will also be addressed.

4.5.1 Entrance Wounds

One aspect we wanted to investigate was the effect of distance on the size and shape of the entrance wound, in particular the difference between contact wounds and distant wounds. The results from this were important in terms of selecting appropriate shooting distances for the live pig experiments.

The 1 m shots produced wounds that were quite different to contact wounds. The contact wounds were on average larger than the 1 m wounds and displayed characteristic skin tears. As mentioned in the previous chapter, these skin tears were likely to be the result of muzzle gas expanding beneath the skin, causing it to stretch beyond its elastic limit. The 10 cm and 5 cm shots produced wounds that were similar to contact wounds, in terms of the skin tearing and irregular nature of the wound. The 20 cm shots on the other hand produced wounds that were more similar to the 1 m wounds as they were small and regularly shaped. These results suggest that shots from a range of greater than 10 - 20 cm may produce wounds that are consistent, regardless of the exact distance.

There were some similarities between the entrance wounds in the butchered heads and those in the model. The entrance wounds in the butchered heads were mostly slightly larger than the model wounds from the same distance but the shape was quite similar. This was particularly the case in the distant wounds, with circular wounds produced in both the models and butchered heads. The small skin tears produced in the distant wounds in the models were not seen in the butchered heads. Skin tears were only produced following close range shots in the butchered pig heads. In both the butchered heads and models, the general trend was an increase in wound size with decreasing range.

4.5.2 High-speed Videos

One similarity between the butchered heads and the models was the general wound formation. An initial blow-out of the skin occurred, with backspatter first being ejected during this phase. This was similar to the sequence described in the previous chapter. However, in the models there was a lot more movement of the ‘skin’ and the effects were more widespread. The skin blow-out recorded in the butchered heads was much smaller than that in the non-blood models and of a similar size to that seen in the blood models. This was immediately obvious when viewing the videos but was confirmed by making measurements of the height and width of these skin blow-outs.

In most of the butchered pig heads, the ejection of backspatter began only slightly before the skin blow-out reached its maximum point. In the models, backspatter was first ejected at similar time following the bullet impact as it was in the butchered heads. However, the maximum blow-out occurred later in the models than it did in the butchered heads and therefore backspatter in the models occurred relatively early compared to the butchered heads.

4.5.3 Backspatter

Bone fragments were the main component of the backspatter produced in the butchered pig heads. There was some apparent backspatter of soft tissue and fluids but it was difficult to determine the precise origin of this. ‘Bone’ fragments were also the main component of backspatter from the models. Although obvious bloodstains were not produced, many of the stains were likely to have contained blood. The lack of obvious bloodstains was most likely due to the fact that the blood in the heads would have coagulated.

4.5.4 Limitations and Problems

There are many obvious limitations associated with this type of experimentation which will not be discussed, such as the comparability of results from animals to humans. However, a limitation that is specific to this particular experiment is the fact that the heads were sourced from two different butchers and were different in appearance. This was unavoidable under the circumstances due to the large number of freshly slaughtered heads that were all required on the same day. The shooting had to be completed in one day due to time constraints as well as the facility and equipment availability. Ideally, all 14 pig heads should have been similar in size and appearance and sourced from one place.

Another problem with the pig heads was that some were heavily pigmented and hairy which affected the interpretation of the high-speed videos. This resulted in some of the key events in the wounding sequence, such as the skin-blow out, being difficult to visualise. The hair issue could have been avoided with better hair removal techniques, as using a scalpel was not ideal. This was a valuable lesson which was important in improving the design of the subsequent live pig experiments. Another issue was the fact that in the contact shot videos, the key events were obscured by the muzzle. This was also kept in mind when designing the live pig experiments.

4.5.5 Summary and Conclusions

The shooting of the 14 butchered pig heads provided valuable data contributing to the validation of the pig head model. Some aspects were comparable with the model, such as the wound formation and backspatter of bone fragments but other aspects, such as the appearance of the wound, were different. The results from the butchered pig heads were more comparable with the blood-containing pig head models than the non-blood models, in terms of both the size of the skin blow-out and the amount of backspatter produced.

Based on the results from these experiments a preliminary conclusion was made about the performance of the model. The fact that comparable backspatter was produced was particularly important as the main purpose of creating the model was to replicate this process. The backspatter produced in the blood-containing models was considered similar enough to that in the butchered heads for the model to be valid at this stage of the project.

5. Live Pig Experiments

5.1 Introduction

The final stage of the project involved the shooting of live pigs. Anaesthetised pigs were shot from various ranges to assess the effects of a bullet on living animal tissue and study the backspatter produced. These experiments were designed using information from both the literature and experiments described in the previous two chapters, in order to maximise the information that could be obtained from this important resource.

Backspatter research involving live animals has been limited to only a handful of studies. As mentioned in Chapter 1, calves and pigs have been used to study various aspects of backspatter. Pigs have been used to study backspatter of bone fragments (Burnett, 1991) but not backspatter of blood. This meant it was difficult to anticipate the amount of blood backspatter that would be produced from the pigs in this study. The experiments conducted by Karger et al. (1996, 1997 & 2002) provided a comprehensive analysis of backspatter produced in live calves and therefore these results were considered when designing this experiment. Where possible the experimental set-up was kept as similar as possible to that used by Karger et al. in order to compare the results to their findings.

As these experiments were carried out in order to validate the pig head model, the experimental set-up was similar to that used for the previous experiments. The high-speed camera was once again used to film the shots and the resultant videos were analysed, together with backspatter patterns, in order to assess the backspatter produced and compare it to that seen in the pig head models.

5.2 Aim and Objectives

The overall aim of this experiment was to assess backspatter resulting from gunshot wounds in anaesthetised pigs in order to compare it to that produced in the pig head model.

Specific objectives were as follows:
- To assess the characteristics of the resulting backspatter patterns including the number, size, shape and distribution of bloodstains.
- To determine the timing of backspatter and therefore the relationship between wounding and backspatter.
- To compare the backspatter seen in live pigs to that documented in the literature.
- To collect data for the evaluation of the physical pig head model.

5.3 Methods

5.3.1 Ethical Approval

Ethical approval for these studies was obtained from the University of Otago Animal Ethics Committee (Appendix 3).

5.3.1 Pigs

Five domestic bred, mature female pigs, weighing 79 – 91 kg were obtained from a local piggery. The pigs were hybrids, with their mothers being a mixture of Large White and Landrace breeds and their fathers Hampshires. Prior to shooting, each pig was sedated, using an intramuscular injection of ketamine and then anaesthetised by gas inhalation. The pig was maintained on fluothane for the length of the experiment. The depth of anaesthesia was confirmed using pedal withdrawal reflexes, jaw tone and heart rate monitoring and intravenous (IV) fluid (10 mls/kg/hr of 0.9% saline) was administered via an ear vein.

The pig was then positioned on a heat pad on a surgical table in ventral recumbency (Figure 5.1). The skin above and between the eyes in each pig was shaved using electric clippers and then treated with depilatory hair removal cream to remove the remaining hair. This was to make the wound more visible in the high-speed camera videos. This was carried out on a butchered pig head before being used on live pigs, in order to ensure it would adequately remove the hair. In the first pig, this cream caused a rash to form and therefore was not used for the second pig. However, not using it made the wounding and backspatter difficult to see in the high-speed videos and therefore the cream was used in the remaining pigs.

Figure 5.1 The pig positioned on the surgical table, with the anaesthetic and monitoring equipment to the right of the figure. Sandbags were placed below and behind the pig for safety reasons. The arrow indicates the 1 cm x 1 cm grid drawn on the pig's head.

Immediately before each shot, a 1 cm x 1 cm grid was drawn in black ink on the skin in the region described above (Figure 5.1). This was mainly done in order to facilitate mathematical modeling of the results at a later date by other researchers. However, the grid also proved useful in clearly illustrating the deformation of the skin in the high-speed camera videos.

Following the shooting of four of the pigs, the head was removed using a large sharp knife and loppers, in order for the wound to be further analysed. Two of the heads were then put in the HTRU beetle colony to remove all of the soft tissue from the skull. This was carried out so that the damage to the bone could be analysed for another study. In the other two heads, the area containing the wound (soft tissue and bone) was removed as a small plug, in order for other researchers to examine the microscopic damage to the bone using Scanning Electron Microscopy (SEM). The pig carcasses were disposed of by HTRU staff.

5.3.3 Shooting Set-up and Variables

The shooting took place in a three-sided, covered shed, measuring 4.5 m in width, 6 m in length and approximately 3 m in height. The pig on the surgical table was positioned in one corner of the shed with sandbags built up in a U-shape around it (Figure 5.1). The light, high-speed camera and anaesthetic equipment were positioned on the pig’s left. The camera was placed at an average distance of 122 cm from the impact site (centre of pigs head) and at an angle of 25° to the pig. The light was positioned 150 cm away from the impact site, at an angle of 30°. The firearm and shooter were positioned directly in front of the pig, with the distance between the muzzle and pig varying depending on whether it was a contact or distant shot. A 90 mm, manual focus Tamron lens, set at an aperture of F2.8 was used on the high-speed camera.

The white background for these experiments was slightly different, as a paper-covered board, with a small aperture for the bullet to pass through, was positioned between the shooter and the pig for the distant shots (Figure 5.2). This board was set-up approximately 107 cm from the impact site on the pig and measured 180 cm (height) x 105 cm (width). The board to the right of the pig was at a distance of approximately 38 cm and also measured 180 cm (height) x 105 cm (width). A board measuring 110 cm (length) x 105 cm (width) was also placed on the ground below the pig. The impact site on the pig was at an average height of 86 cm from ground level, depending on the size and position of the pig. Before each shot, the boards were completely covered with sheets of white paper (Figure 5.2). The width of the paper was slightly smaller than the boards and therefore two overlapping sheets were used on each.

Figure 5.2 The shooting set-up for the contact shots. For the distant shots the shooter stood behind the board which is directly behind him in this figure. A small hole was made in the board for the bullet to pass through.

Range

Seven shots were fired in total as one pig was shot three times. Five of these seven shots were fired from a distant range (approximately 120 cm) and two were from contact. The exact distance was not considered important as when the shooting range is greater than 1 metre the effects on the target are not said to be altered by distance (DiMaio, 1999). For the contact shots, the muzzle was held so that it was touching the skin but not with firm downward pressure (loose contact) (Figure 5.2). The pig that was shot three times (pig 5) received an initial contact wound followed by two distant wounds at different sites in the frontal region. These were filmed separately and the white background paper was replaced following each shot.

Distant shots

A small opening, measuring 7.5 cm in height and 3.5 cm in width, was cut in the front board and the paper covering it, in order for the shooter to sight the target and the bullet to pass through unimpeded. This was made at a height of 85 cm from the ground and a distance of 34 cm from the side wall. The shooter was positioned behind the board and used a table to rest the firearm on when shooting. The shooting distance was approximately 120 cm.

Contact shots

The shooter stood directly in front of the pig wearing white disposable overalls and gloves in order to document any backspatter on his person (Figure 5.2). No board was placed between the pig and the shooter for these shots. The shooter held the firearm in his left hand to fire each shot as the camera was on his right and it allowed for a better view of the impact site. It was anticipated that blood would seep from the wound some time after the shot was fired and therefore the shooter moved away immediately in order to preserve any backspatter present on his overalls or gloves.

Shooting procedure

Safety checks and lighting adjustments were completed before shooting each pig. The shot was then fired, killing the pig. A drip-tray was immediately placed below the wound to catch any blood pouring from it and preserve the surrounding paper. The ground paper was then removed, followed by the removal of the surgical table holding the pig. Photographs were taken of the paper on the two walls before removal.

Safety

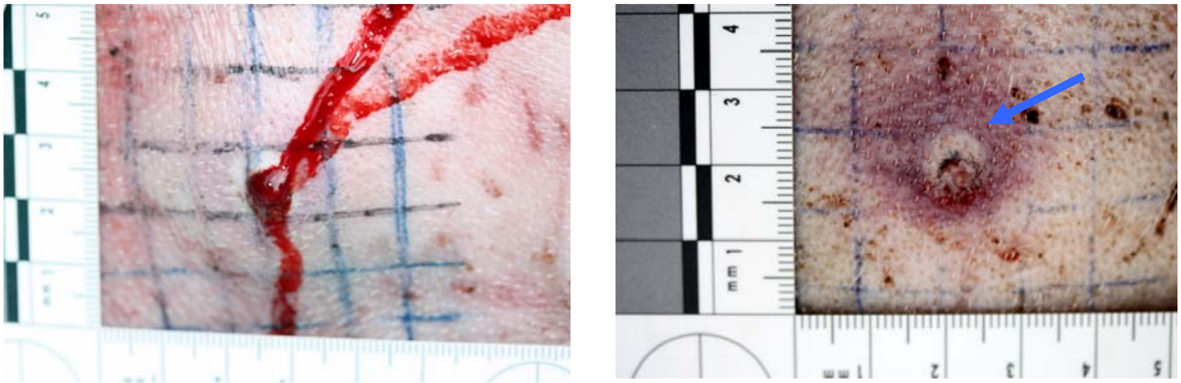
As this testing was not carried out at a firing range like the previous experiments, there were extra safety considerations. A sandbag wall, consisting of 30 military sandbags was constructed in a U-shape around the surgical table with the pig on it (Figure 5.1) to stop any bullets should they exit the pig. However, the angle of the pig meant this was unlikely to occur. Bullet proof vests were also placed underneath and behind each pig in order to prevent the bullet from penetrating or ricocheting off the surgical table if it exited on the underside of the animal.

5.4 Results

The main focus of this section will be the high-speed video analysis and the backspatter analysis. The entrance wounds will also be discussed briefly and compared with those created in the model.

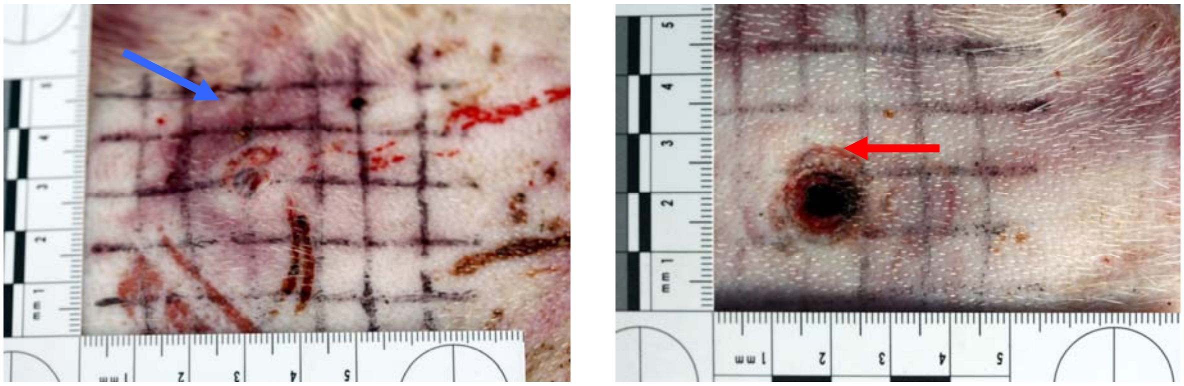
5.4.1 Entrance Wounds

Entrance wounds were produced in the frontal region of each pig (Figure 5.3). The characteristics of each of these are shown in Table 5.1. The bullet exited in one of the pigs, through the chin region, but this was not analysed as the main focus was the entrance wounds.



Pig 1 (1 m)

Pig 2 (1 m)



Pig 3 (1 m)

Pig 4 (Contact)

Figure 5.3 The entrance wounds in four of the five pigs. The blue arrows indicate contusions and the red arrow shows an abraded area above the wound. The wounds in pig 5 did not photograph well, as there was a large amount of blood present, and therefore are not shown.

Table 5.1 Characteristics of the entrance wounds in the live pigs.

Pig	**Range**	**Diameter* (mm)**	**Shape**	**Comments**
1	Distant	5	Circular	Large amount of blood present around wound
2	Distant	5	Circular	Contusion around wound
3	Distant	4	Circular	Wound raised in the middle, bruising around wound are
4	Contact	11	Circular	Black ring and blood present around periphery of wound
5a	Contact	12	Circular	Periphery of wound blackened, large amount of blood present
5b	Distant	4	Circular	Wound in unshaved region, difficult to distinguish
5c	Distant	4	Circular	Large amount of blood around wound

* Diameter refers to the central defect of the wound. Bullet diameter = 9 mm.

The central defects in the distant wounds were similar in size and appearance. These shots caused minimal damage in the skin, with small wounds produced and no skin tears present (Figure 5.3). The contusion seen in pig 2 was present as a purple ring surrounding the wound, approximately 25 mm in diameter (Figure 5.3). A contusion around the wound was also produced in pig 3 but it was larger and more irregular than that seen in pig 2.

The two entrance wounds produced at contact range were both larger than those from the distant wounds. No skin tears were produced in these wounds. In pig 4, an abraded area immediately above the wound was present. This may be have been produced by the skin hitting the muzzle. The contact wounds both displayed black margins.

5.4.2 High-speed videos

In all pigs, a blow-out of the skin occurred, similar to that observed in the butchered pig heads and models (Figure 5.4). The timing of the maximum skin blow-out was noted for the distant shots and the size of this was measured. The time at which backspatter was first ejected was also recorded. These results are presented in Table 5.2.

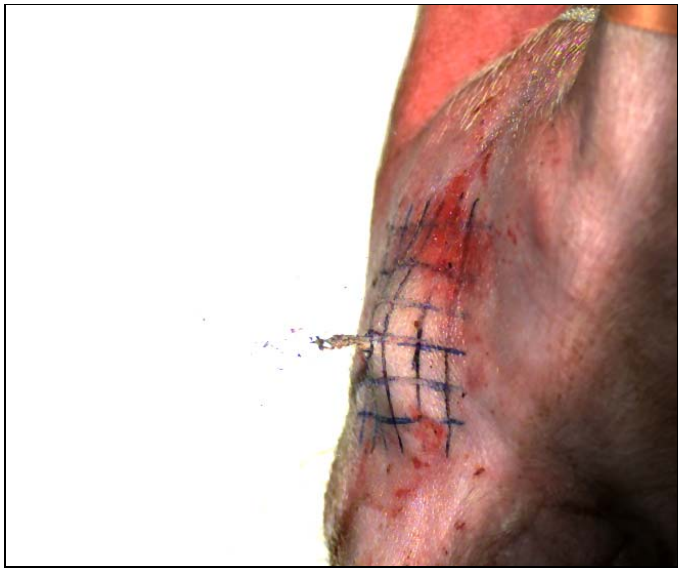


Figure 5.4 Blow-out of the skin around the entrance wound at its maximum point in Pig 1. Backspatter was first ejected from the entrance wound slightly before this point. Time = 5 ms.

Table 5.2 Skin blow-out and backspatter results from the distant shots.

Skin blow-out				Backspatter
Pig	Height (mm)	Width (mm)	Time (ms)	Time (ms)
1	23.6	64.3	5	3
2	15.0	51.4	4	2
3	19.3	36.4	4	3
5b	-	-	-	-
5c	25.7	49.2	6	0
Average	**20.9**	**50.3**	**4.75**	**2**

Bullet penetration = 0 ms.

Height represents the distance that the skin ballooned away from its initial position in a backwards direction. Width represents the diameter at the base of the skin blow-out.

Although 5b was a contact shot, the amount of hair present on the skin meant that the margins of the skin blow-out could not be differentiated and therefore were not measured. The timing of this was also difficult to determine.

The timing and size of the skin blow-out was similar to that in the butchered heads and blood-models. Backspatter of material, where it could be seen, occurred on average 2 ms after the bullet impacted. This was more difficult to see in some pigs than others. In pig 2, the depilatory cream was not used and therefore the surface hair made it difficult to distinguish tissue backspatter from hair and dirt in the videos. As in the model and butchered heads, the blow-out of the skin was blocked by the muzzle in the contact shots (Figure 5.5) and therefore its size was not measured.

Figure 5.5 Blow-out of the skin in shot 4 was blocked by the muzzle. Time = 5 ms.

Figure 5.6 Backspatter of blood from pig 5a. This is indicated by the blue arrow. A large amount of gas was also ejected from the wound.

Blood was not visible in the backspatter from any of the three distant shots. The backspattered material was pale and appeared to be fragments of bone or soft tissue (Figure 5.4). In pig 5, an initial ejection of material also did not appear to contain any blood. However, a small amount of blood was ejected from the wound approximately 35 ms after the initial impact of the bullet (Figure 5.6). Gas also streamed from the entrance wound for up to 135 ms (Figure 5.6).

As mentioned earlier, pig 5 was shot three times. The first shot, which was inflicted at contact range, caused a large volume of blood to pour from the wound a few seconds after the shot was fired. This blood was still flowing from the wound when the second and third shots were fired, which was up to 15 minutes after the first shot. The second shot was aimed above the first wound and therefore missed the blood but the third shot struck below the first wound, directly in the stream of blood. This caused a large amount of surface blood to be backspattered in a characteristic cone pattern (Figure 5.7). Blood was also ejected from wound 5b when 5c was inflicted (Figure 5.8).

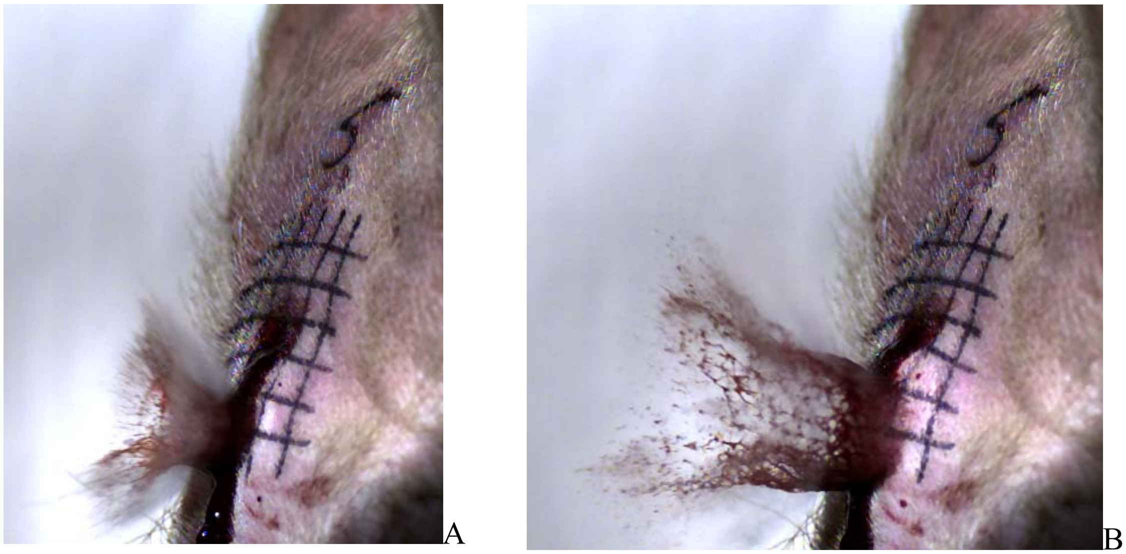


Figure 5.7 Backspatter of surface blood following shot 5c. A: 1 ms after bullet impact. B: 3 ms after bullet impact.

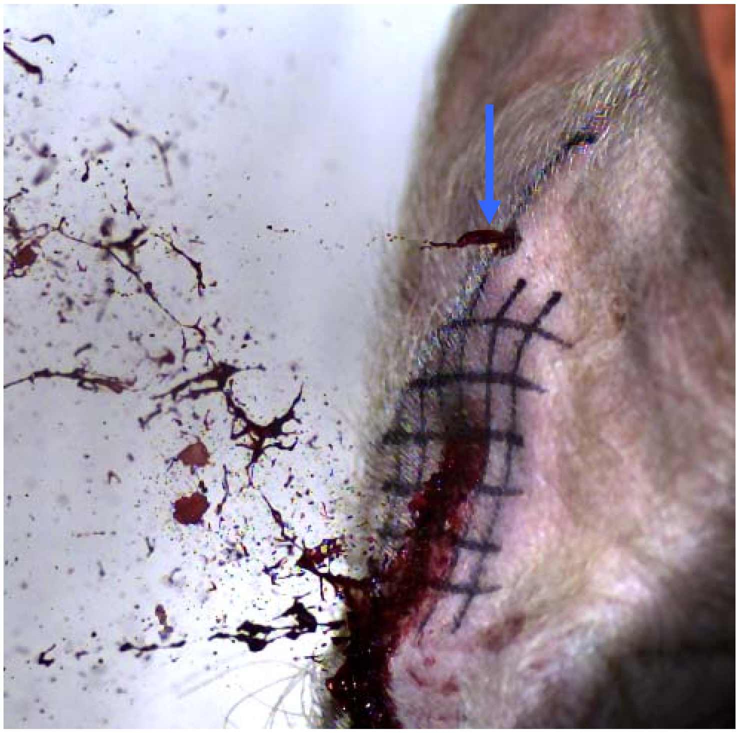


Figure 5.8 Backspatter ejected from wound 5b when wound 5c was inflicted. This is indicated by the blue arrow.

5.4.3 Backspatter

An unexpected reaction occurred in two of the pigs which affected the backspatter analysis. After the wound was inflicted in the first two pigs, there was no movement of the animal. However, in pigs 3 and 4, the animals began to spasm a few seconds after the shot was fired. Initially it was thought that the bullet had not killed the animal and therefore an overdose of ketamine was immediately injected in order to euthanase the animal. However it was later realised that the pig was in fact dead but experiencing a reaction to the wounding. This involved large uncontrolled body spasms lasting up to 20 - 30 seconds. These were very powerful and resulted in one of the pigs falling off the surgical table (Figure 5.9)

Figure 5.9 Pig 4 on the ground following uncontrolled body spasms.

Unfortunately, this essentially ruined any backspatter evidence that was present on the white paper, as a large amount of blood was ejected from the wound and onto the paper in both cases as the pig moved around (Figure 5.9). This meant it was impossible to determine which bloodstains were from the initial impact (i.e. backspatter) and which were ejected later. Therefore, most of the paper was not collected from these two pigs. For the fifth pig, an attempt was made to prevent this reaction. The animal was euthanased with an overdose of ketamine and then shot seconds after it stopped breathing (while the heart was still beating). It was anticipated that this would prevent the spasms from occurring and allow for a valid analysis of any backspattered material.

Where possible, the white paper was analysed for backspatter. The shooters clothing from the contact shots was also analysed.

Paper

The white paper below, in front, and to the side of the pig was photographed and collected following most of the shots. The material present on the paper was analysed and the results are presented in Table 5.3. Selected stains were tested in order to determine whether blood was present. Where the paper was not collected it was due to the pig reactions described earlier causing the results to be invalid. There were no obvious blood stains present on the paper from the first and second shots to pig 5 (a and b) and therefore this paper was not collected. In 5c, only the middle portions of the front and side paper were collected and analysed as the bottom half of these papers were affected by splashes from the drip tray.

Table 5.3 Characteristics of the backspattered material present on the surrounding paper

	Blood Detected	Number of stains/fragments	Size range (mm)	Height(h)/distance (d)	Comments
Pig 1					
Front	No	28	0 – 5	63 – 100 cm (h)	
Side	No	8	0 – 1	45 – 85 cm (h)	
Ground	Yes	25	0 – 2	40 – 125 cm (d)	
Pig 2					
Front	No	1	1	110 cm (h)	
Side	Yes	5	2 – 6	40 – 120 cm (h)	
Ground	No	1	1	45 cm (d)	
Pig 3					
Front	No	3	1 – 2	20 – 80 cm (h)	
Side	No	0	n/a	n/a	
Ground	No	n/a			Paper not collected
Pig 4 Paper not collected	n/a	n/a	n/a	n/a	
Pig 5 (shot C)					
Front	Yes	200 +	0 – 7+	Max	
Side	Yes	200 +	0 – 2.5+	Max	
Ground	n/a	n/a	n/a	n/a	Paper not collected

Fragments were considered to be any material that was raised from the paper.

Fragments ranged in size from 0 – 7 mm in diameter. Typical fragments are shown in Figure 5.10. Some stains did not appear to be blood stains but tested positive for blood (Table 5.3)

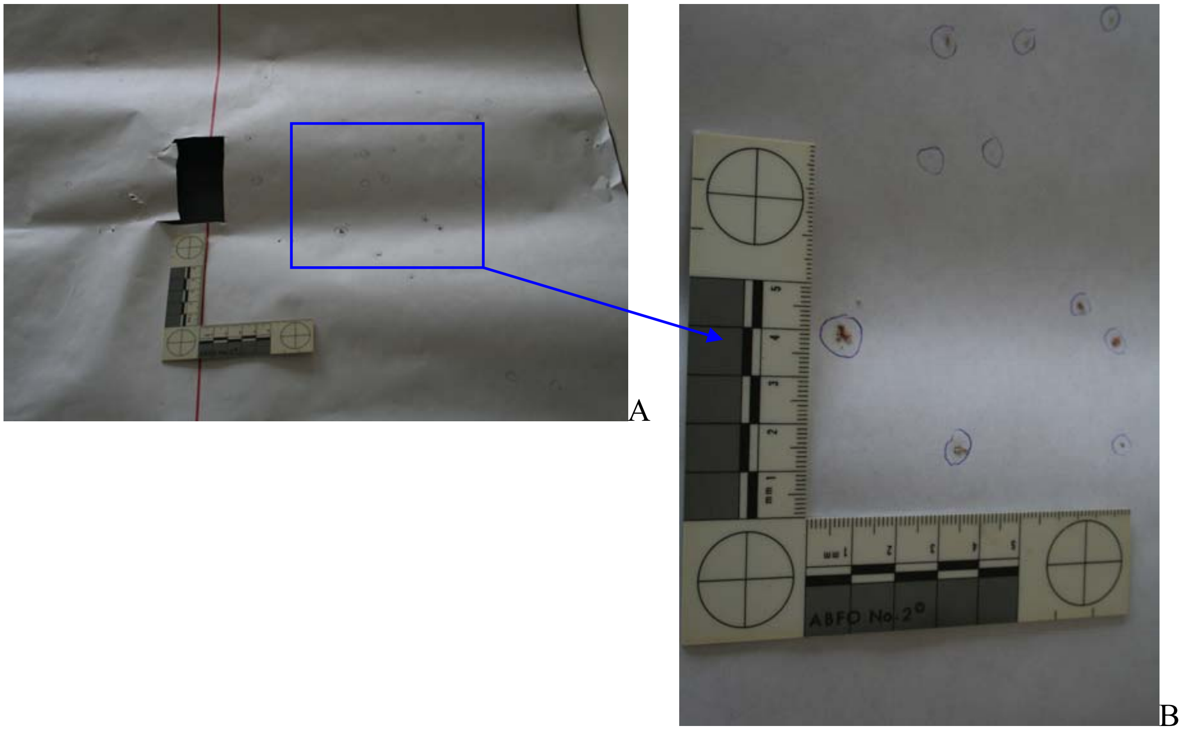


Figure 5.10 Backspattered fragments on the front paper from pig 1. A: The square hole above the scale was where the bullet passed through and was at the same level as the entrance wound. B: Close up from a region of this paper.

The only paper which displayed obvious bloodstains was from pig 5c (Figures 5.11 and 5.12). Figures 5.13 and 5.14 show the distribution of stain sizes from the front and side paper for this pig.

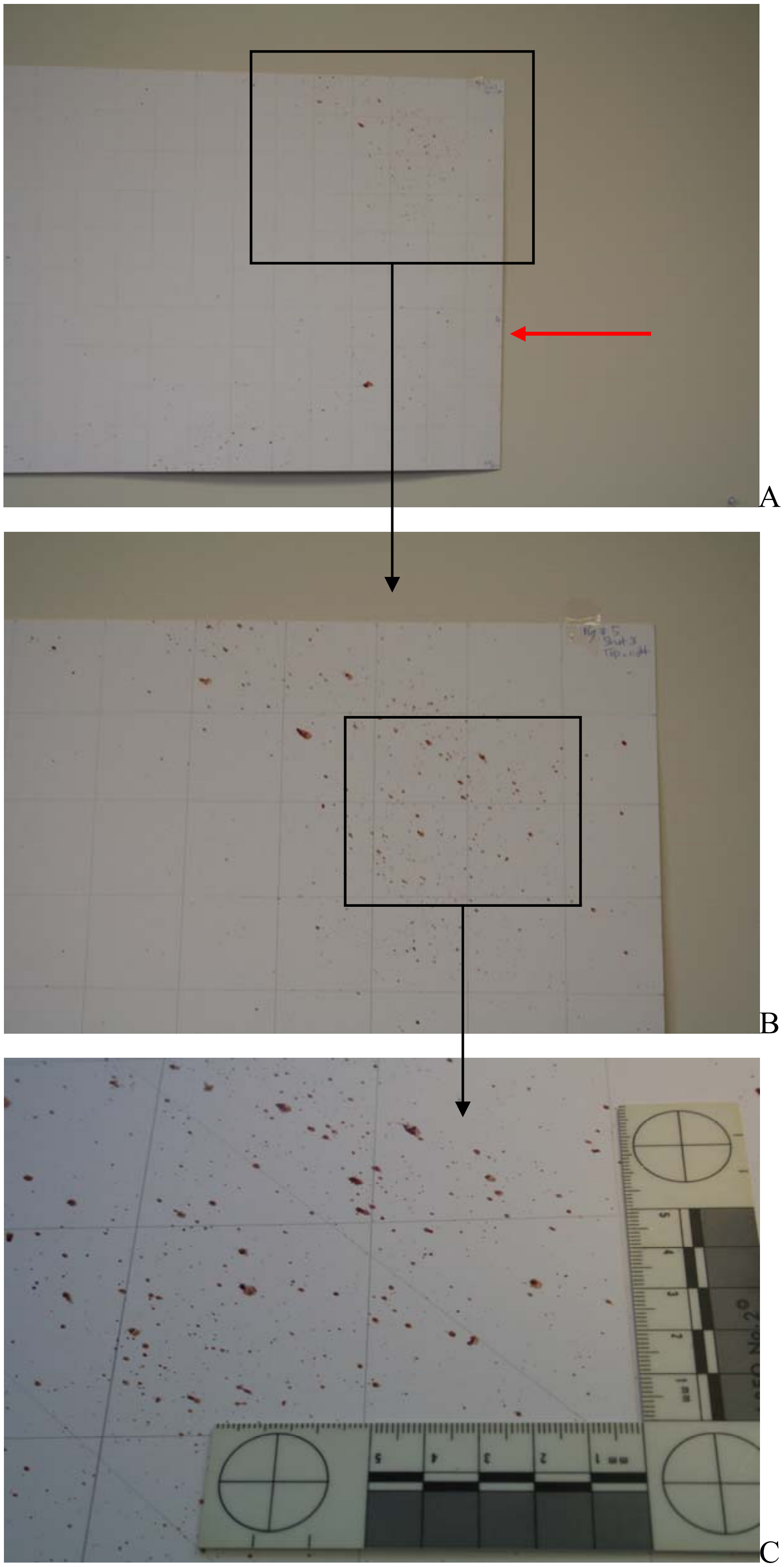


Figure 5.11 Bloodstains on the side paper from pig 5c. A: The red arrow indicates the height of the entrance wound. B: Top right-hand corner of the paper. C: Close-up of top right-hand corner. The diagonal line indicates the direction of the blood droplets.

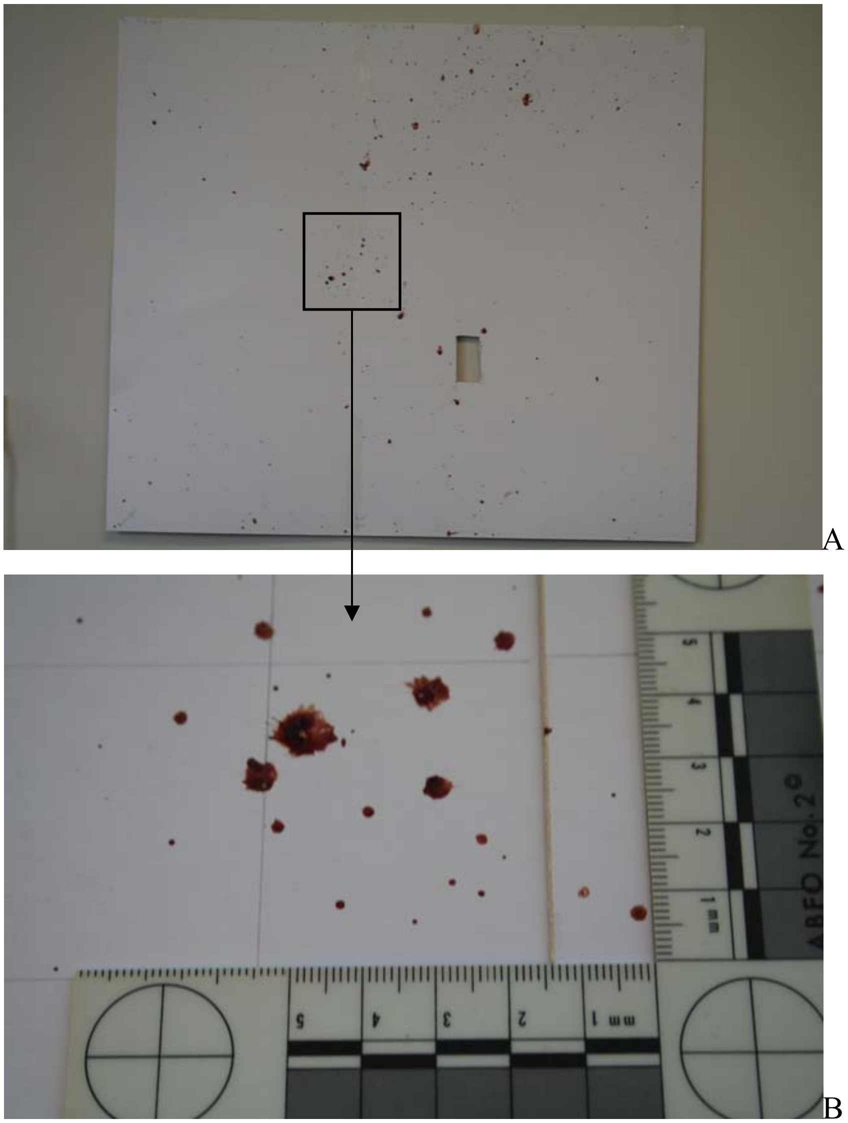


Figure 5.12 Bloodstains on the front paper from pig 5c. A: The square hole is at the level of the entrance wound. B: A close up of this paper.

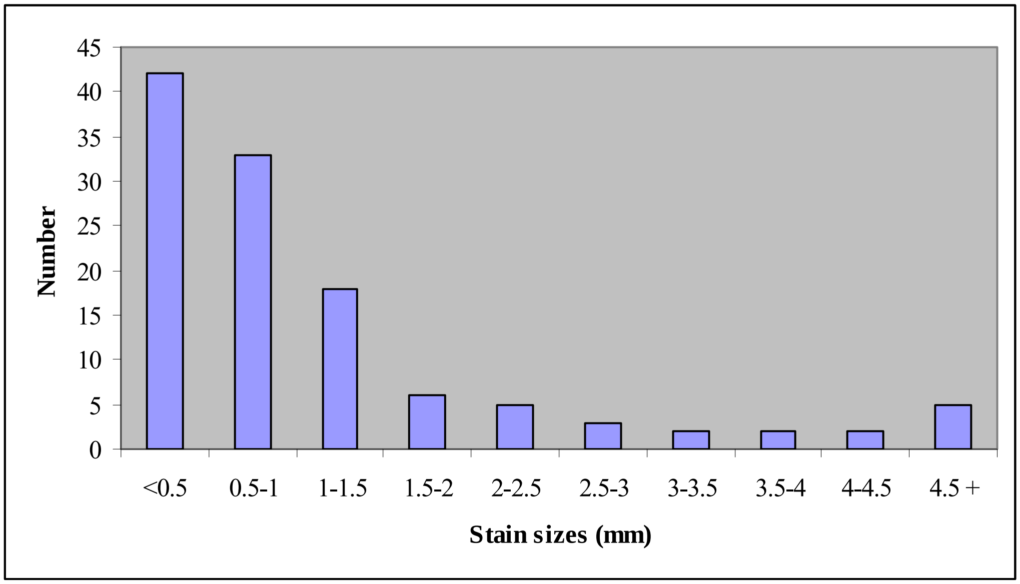


Figure 5.13 Stain sizes from the front paper in pig 5c.

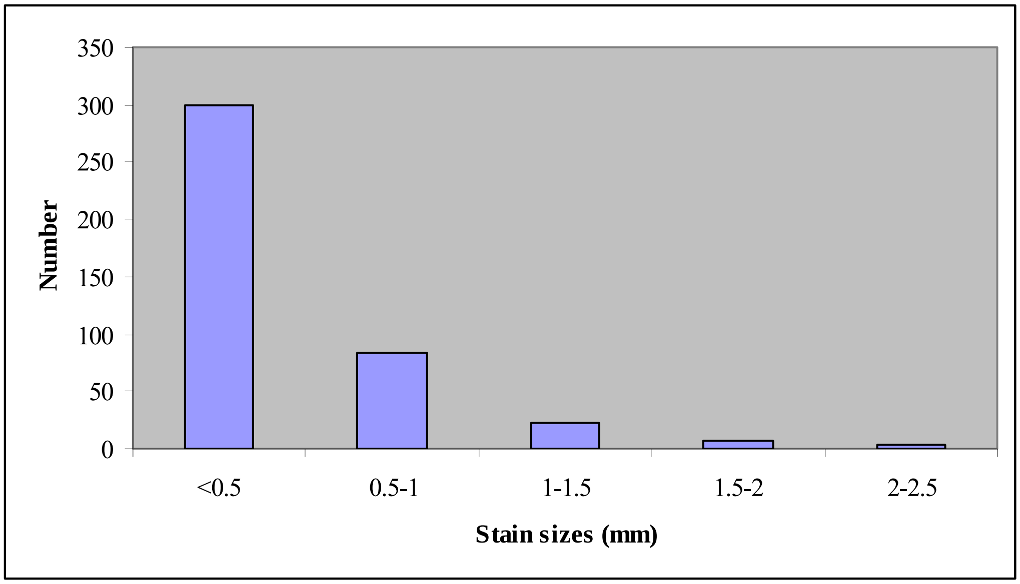


Figure 5.14 Stain sizes on the side paper in pig 5c.

Clothing

The shooters gloves and overalls were carefully analysed following the two contact shots (pigs 4 and 5a). Blood was detected on the overalls from both pigs and the left glove from pig 5a. The only stains present on the left glove from pig 4 were small black marks and blood was not detected in any. There were 21 stains present on the overalls from pig 4

(Table 5.4). Blood was detected in all five of the stains that were tested even though they did not look like bloodstains. These stains were all very faint and therefore did not photograph well.

Table 5.4 Stain sizes on the overalls from pig 4.

	<2 mm	**2 - 3 mm**	**3 - 4 mm**	**4 - 5 mm**	**Total**
Right abdomen	-	3	4	3	10
Right underarm	1	4	-	-	5
Right side of hood	1	3	2	-	6
Total	2	10	6	3	21

The left glove from pig 5c displayed three small stains, all of which tested positive for blood. All three stains were elongated with one displaying a characteristic exclamation mark shape (Figure 5.15B). Two were present on the dorsal aspect of the base of the thumb and one on the dorsal aspect of the hand, immediately proximal to the index finger (Figure 5.15). The shape of the stains indicated that they were traveling towards the wrist. The diameter of these stains was no more than 0.5 mm and the longest stain was 2.5 mm in length (Figure 5.15B).

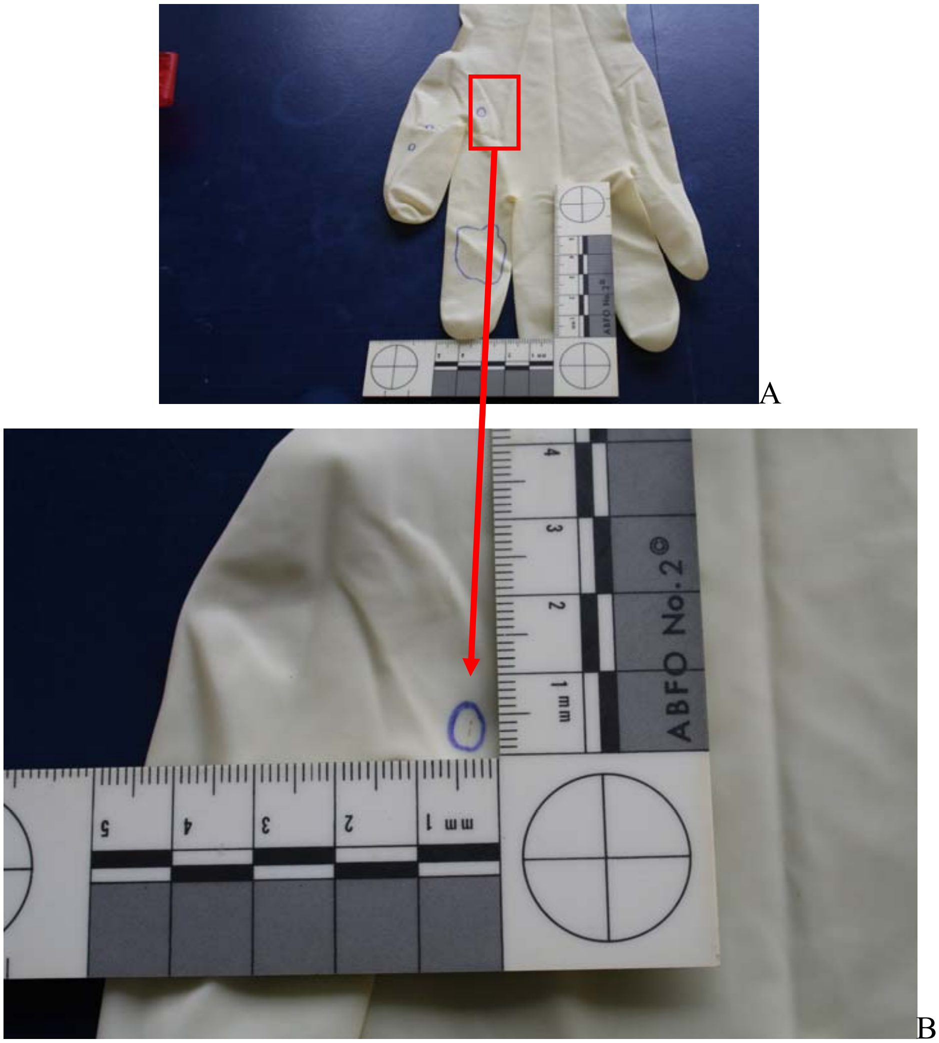


Figure 5.15 The left glove from pig 5. A: Bloodstains were present on the dorsal aspect of the thumb, index finger and hand. B: An individual bloodstain at the base of the thumb displaying the characteristic exclamation mark shape.

The bloodstains present on the overalls were quite random in their distribution, with some clustered around the abdominal region and others present on the sleeve in the forearm region. All of these stains were measured and the results are presented in Table 5.5.

Table 5.5 Stain sizes on the overalls from pig 5a.

Region	**<0.5 mm**	**0.5-1 mm**	**1-1.5 mm**	**1.5-2 mm**	**2-2.5 mm**	**Total**
Left abdomen	4	1	9	0	1	15
Left forearm	-	-	-	4	6	10
Left wrist (front)	10	14	10	2	2	36
Left wrist (back)	-	3	4	-	-	9
Total	14	18	23	6	9	70

Unless otherwise stated, stains are on the front of the overalls. For the left wrist, front represents the side of the overalls facing the body and back represents the side of the arm facing away from the body.

The stains ranged in size from 0 – 2.5 mm in diameter and were mostly irregular in shape (Figure 5.16).

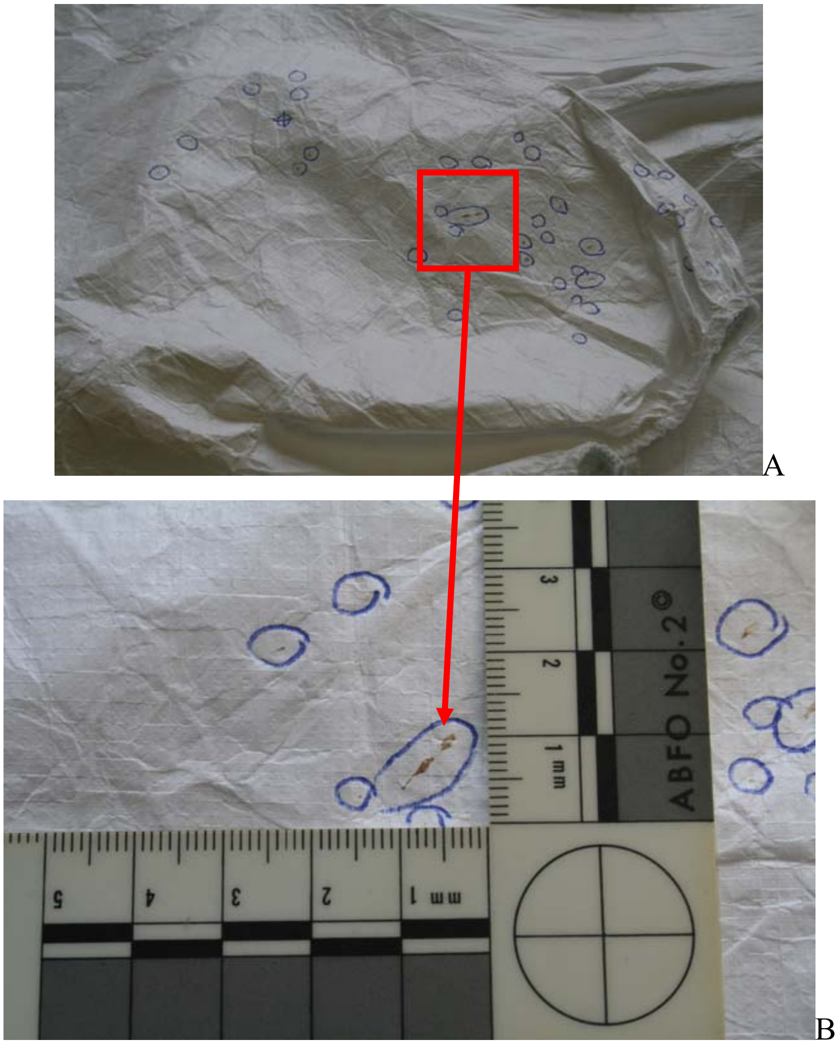


Figure 5.16 Stains on the overalls from pig 5a. A: The wrist area of the left sleeve. B: A close-up of the left sleeve.

5.5 Discussion

The aim of these experiments was to assess backspatter produced from live pigs and compare it to that produced in the pig head model. Five pigs were shot under similar conditions to the model and the results were analysed in the same way. The most notable result was the absence of obvious blood backspatter from most of the wounds. However, a significant amount of bone fragments were backspattered, which was an important result in terms of furthering our understanding of backspatter and its production. The main results and their relevance to the model will be discussed in this section.

5.5.1 Entrance Wounds

The entrance wounds within each group (distant and contact shots) were consistent in both size and morphology. The distant wounds were of a similar size to the wounds produced at this range in the models. The damage to the skin in most of the distant wounds was very minimal with no tears produced. The contact shots produced wounds with diameters that were slightly larger than the contact wounds in the model. The contact wounds were also quite different in appearance to those in the models, with no skin tears produced.

Some interesting characteristics were produced in a few of the wounds which were comparable with those documented in the literature. In one of the distant wounds, a contusion ring was produced around the wound. Contusion rings are caused by bleeding under the skin around the entrance wound due to overstretching (Thali, et al., 2002b). Another distant wound had a raised centre, a feature which was also produced in a few of the butchered heads. One of the contact wounds displayed a feature which may have been similar to a muzzle imprint where the skin was abraded in a regular pattern around the wound.

5.5.2 High-speed Videos

The maximum skin blow-out was similar in width to that produced in the blood-containing model but slightly smaller in height. The general wound formation sequence was very similar between the models and the live pigs, however, the maximum skin blow-out occurred much earlier in the live pigs than in the model. Backspatter was ejected before the maximum skin blow-out in most of the pigs which was similar to the models. However, the timing of backspatter in the pigs was much earlier, relative to the skin blow-out, than in the models.

5.5.3 Backspatter

Backspatter of visible blood was only produced in the two contact shots and in the distant shot where there was already blood present on the skin. Blood backspatter was only seen in the high-speed video from one of the contact shots. This was ejected much later than the other backspattered material. In the other contact shot, it was only determined that blood was ejected after analysing the overalls worn by the shooter. These droplets may have been too small to be seen in the high-speed videos or the view of them may have been blocked by the muzzle.

The amount of blood backspatter that was produced was much less than what was expected. This expectation was mainly based on the results of experiments by Karger et al. (1996, 1997, 2002), as a large amount of backspatter was produced from the animals in their study. However the anatomy of pigs and calves is quite different which may explain this result. The backspatter of bone fragments was expected as this has previously been documented in pig experiments (Burnett, 1991). It is likely that bone fragments are a key feature of backspatter in humans also. If so, it is important that this is recognised by forensic investigators as in some cases it may be a critical piece of evidence. Bone fragments may be less obvious than bloodstains and could possibly be overlooked at a crime scene.

The final shot to pig 5 produced two interesting results. The first was the backspatter of surface blood and the second was the backspatter of blood from the pre-existing wound. These are both important results as blood was deposited on the hand and body of the shooter. A scenario such as this could occur in a homicide case where multiple shots were inflicted.

5.5.4 Pig reactions

The post-shot reaction that occurred in two of the pigs was an unexpected result which affected the analysis of backspatter. However, it was an interesting result nonetheless and although not the focus of this study, it could not be ignored due to the potential implications for forensic cases. The thrashing of the animal caused large amounts of blood to be deposited on the surrounding surfaces, in a pattern uncharacteristic of that usually produced from gunshot wounds. If this reaction occurred in a human following a gunshot wound with a similar amount of movement, the resultant bloodstain patterns could be very difficult for investigators to interpret. This may be an area where future research is required.

5.5.5 Summary and Conclusions

The shooting of the five live pigs in this experiment was crucial for determining the effectiveness of the pig head backspatter model. In terms of the backspatter produced, the results were similar to the model in that bone fragments were dominant in the distant wounds and blood backspatter was only produced in the contact wounds. Some features of the wounds produced, such as shape and size, were also similar between live pigs and the model. Although the results differed from animal studies in the literature (i.e. Karger et al. calf experiments) no known blood backspatter studies have been previously performed on pigs. The anatomy of calves and pigs are obviously quite different, which could explain the difference in results. It may be that, unlike calves, blood is not a key component of cranial backspatter for pigs.

6. Assessment of the Model

A realistic synthetic model for studying backspatter has not been documented in the literature and therefore many assumptions were made when designing the model described in this research. The materials were selected based on their reported success in both ballistic and non-ballistic wounding models and because of their physical properties. It was assumed that materials with similar properties to animal tissue would perform similarly following a gunshot wound. The design was also important as we wanted to simulate the tissue layers of the pig as closely as possible.

The validation experiments were critical in assessing the model and determining whether it was accurate. A study such as this, where an animal backspatter model was developed and validated by live animal tests, has not been documented in the literature and therefore it was difficult to predict how successful it would be. This section focuses on the model design, materials and production and assesses how comparable it was to real pigs.

6.1 Model Design and Materials

The use of a real pig head to cast the mould for the model meant that its shape was as realistic as possible, with the most important area being the region where the bullet entered. In terms of the layers of the model, the inclusion of sponge as a soft tissue layer greatly improved the design of the model as it allowed the layers to be anchored like animal tissue layers are.

Although the design was important, the materials were always going to be the key factor in producing a realistic model. As mentioned in Chapter 3, using synthetic materials to simulate living tissue is not ideal and, in wounding and bloodspatter studies, will not necessarily result in an outcome that is completely realistic. However, with appropriate materials, results can be achieved that are accurate enough to draw conclusions about the process being studied. The key materials used in this model were silicone, epoxy resin, polyurethane sponge and gelatine. When comparing the results of ballistic impact in these materials to the tissues they were meant to simulate, there were more similarities than differences.

It was difficult to compare the performance of both the gelatine and the polyurethane sponge between the models and pigs, particularly because the pig heads were not dissected following each shot. However, the sponge proved to be a simple and effective method of containing the blood. The injected blood was contained in the sponge until the model was shot but was also able to be ejected on impact. The performance of the silicone and resin used will be discussed in the following section

6.2 Entrance Wounds

Silicone is an elastic material and has a regular structure, unlike skin which is irregular and viscoelastic (Ankersen, et al., 1999). With this in mind, it was anticipated that the resulting gunshot wounds in the silicone would have a slightly different appearance to those in the pig skin. This was mostly true in that the entrance wounds in the silicone were in general more regular in shape than the pig entrance wounds and they also displayed a clear central defect (unlike many of the pig wounds) (Figure 6.1). The silicone wounds were of a similar size to those in the pigs for the distant wounds. However, for the contact shots the wounds were larger in the pigs than in the models, which was also most likely due to the elastic nature of the silicone. The silicone was also similar to the pig skin was in the blow-out that occurred around the entrance wound (Figure 6.2). This was probably the most important aspect as this process is likely to be related to backspatter production. This similarity was particularly important since producing realistic backspatter was the main aim of the model.

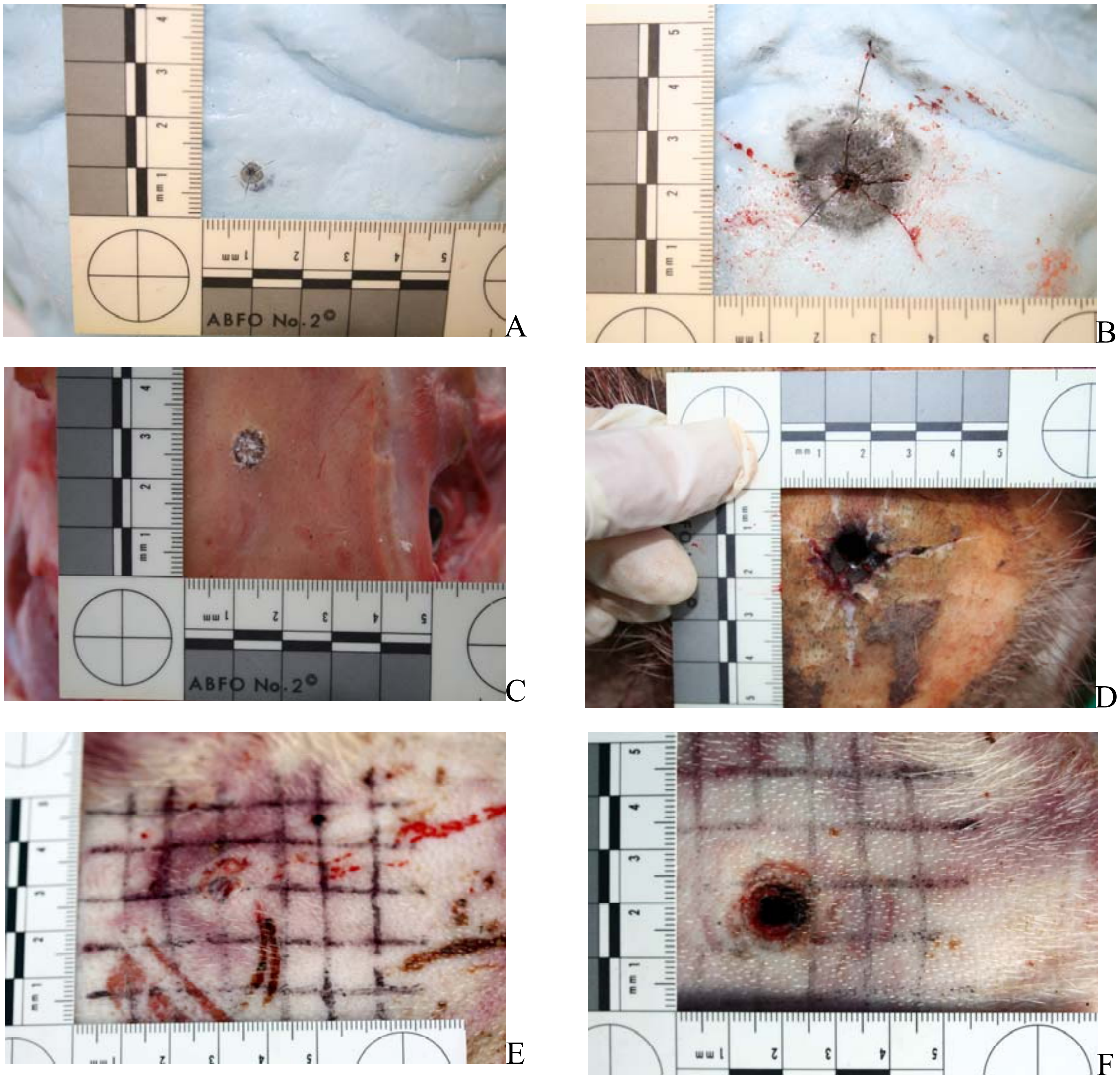


Figure 6.1 Comparison of entrance wounds between the targets. The images in the left column are distant wounds and those in the right are contact wounds. A & B: pig head model. C & D: butchered pig heads. E & F: Live pigs.

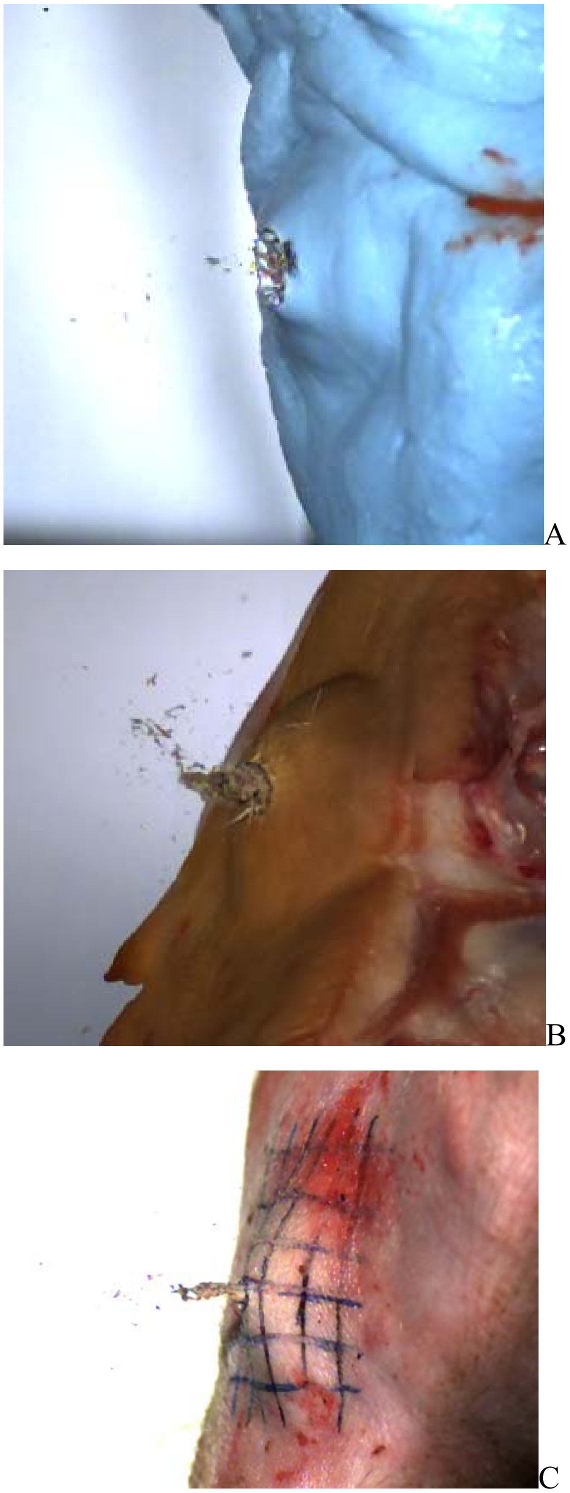


Figure 6.2 Comparison of skin the skin blow-out and backspatter between targets. A: Pig head model containing blood. B: Butchered pig head. C: Live pig.

The epoxy resin that was used has a similar elastic modulus to human bone. This means that both have a similar intrinsic stiffness. We wanted a material that would fracture in the same way as bone so that the model would be as realistic as possible. The bone in the butchered pig heads and live pigs was not analysed as the heads were not dissected but the bone was sometimes visible through the entrance wounds. From this it seemed that the bullet caused considerably more damage in the models than in the pigs, with extensive fractures in most models. This difference is probably due to the brittle nature of the resin compared to living bone.

6.3 Backspatter

Backspatter of blood was not seen in the distant shots to any of the targets. However, it was produced in the contact shots to both the models and the live pigs. This was present in a similar pattern from both of the above targets. Bone and soft tissue backspatter on the other hand was produced in all of targets (Figure 6.2). These results are important as the model behaved similarly to live pigs in terms of the backspatter produced.

It is possible that blood backspatter does not occur from distant shots in pigs. This would mean that the subcutaneous gas pocket, produced in contact shots, is a critical factor in blood backspatter production for pigs. On the other hand, non-blood backspatter was produced in all of the distant shots to both the butchered pig heads and live pigs. This shows that there may be different mechanisms of backspatter production for different tissues and body fluids.

6.4 Production of the model

Although being realistic is the most important quality of any physical model, it also needs to be cost-effective and relatively easy to produce in order for it to be appropriate for experimentation purposes. This is particularly the case for ballistic models as they can generally only be used once. This model was easy to construct once the moulds were created and the materials used were inexpensive and readily available. This means that large numbers of these models could easily be produced if necessary.

6.5 Limitations

There were many limitations associated with these experiments, with the obvious one being sample size. Six models, 14 butchered pig heads and five live pigs were tested and in some of the groups only one was tested from a particular range. As mentioned in Chapter 1, these experiments involved an extensive set-up and were therefore time consuming and expensive to carry out. Because of this, we were limited in the number of tests that could be performed and had to carefully select what would be tested. These were also largely preliminary experiments as work such as this has rarely been carried out.

A limitation of the model was the fact that the blood was not circulating or under pressure like it is in living pigs which may have had an effect on the resultant backspatter. This would be difficult to simulate in a model but a system could possibly be set-up where blood was being pumped into and out of the model.

In terms of the analysis of the model, ideally all of the backspatter stains produced would have been analysed rather than a random selection. However, time constraints prevented this from being possible when there were large numbers of stains present. An analysis of the bone from the butchered pig heads and live pigs would also have been optimal for assessing the performance of the resin used in the pig head model.

6.6 Conclusion

The validation experiments were a critical part of this study as they allowed us to compare the model to real animals. The butchered pig heads were particularly useful for studying the wounds produced at various ranges as well as the backspatter of bone and soft tissue fragments that occurred. The live pig experiments were crucial for determining what was realistic in terms of backspatter from pigs. When the pig results were compared to the model results there were many similarities which is a positive outcome in terms of further developing the model. A summary of comparisons between the targets is presented in Table 6.1.

Table 6.1 Summary of comparisons between the targets

	Live pigs	**Butchered pigs**	**Artificial model**
Realistic anatomy	Yes	Yes	Yes
Intact blood supply	Yes	No	No
Skin thickness	Comparable	Comparable	Comparable
Bone thickness	Comparable	Comparable	Comparable
Average wound size			
- Contact	11.5 mm	11 mm	8 mm
- Non-contact	4.5 mm	6 mm	4.5 mm
Average skin blow-out size (height)	20.9 mm	26.8 mm	25.7 mm* 38.6 mm**
Backspatter			
- Non-blood	Yes	Yes	Yes
- Blood	Yes	No	Yes

*Blood models
** Non-blood models

Reconstructing living events in non living tissue will always be a challenge and the results will never be identical. This fact must be accepted when carrying out experimentation such as this. In terms of this model, further testing must be carried out before more conclusions can be drawn about its performance. However, the results are promising and these tests provide valuable data for continuing the development of the model.

The primary aim of this project was to develop a synthetic backspatter model in the form of a pig head and validate it by comparing the results to those from both butchered pig heads and live pigs. This was achieved and the results were comparable between the model and the pigs. We are now in a better position in terms of our knowledge of backspatter and well on the way to developing a better tool for studying it experimentally.

7. Human Head Model - Pilot Experiments

7.1 Introduction

A series of pilot experiments were carried out in order to explore different options for creating a human head model. These included the development and testing of three different models under various conditions. All of the models were very similar in concept to the pig head model but at least one component was different in each. The initial model was essentially a spherical version of the pig head model with the same artificial skin and bone layers, as well as artificial brain and blood components. This design was similar to the “skin-skull-brain model” which was developed by Thali et al (2002). After testing the first spherical model, a second model was then developed which differed only in its blood component. Finally, a third model was developed which was essentially a square, transparent version of the first two models. Each of these three models will be discussed separately within this chapter.

7.2 Aims

The primary aim of these experiments was to initiate the development of a human head backspatter model. An additional aim was to experiment with different variables such as the firearm and shooting distance and assess their effects on the models.

7.3 Spherical Model 1

This model was essentially a spherical version of the non-blood pig head models, constructed using identical materials but with the addition of a blood component. In this model blood was injected into the space between the resin and the gelatine and it was also injected into the potential space between the silicone and resin layers. The purpose of this was to experiment with different methods of containing blood. The testing of this model was also different as a rifle was used instead of a pistol and the shooting distance was much greater. The spherical model was produced using a similar mould system to that used for the pig head model.

7.3.1 Methods

Design

We designed a spherical model using average anatomical values for human skin and skull thickness as well as brain. The aim was for the skin/soft tissue layer to be 4 mm thick and the bone layer to be 6 mm thick, as these are typical values for human soft tissue and average skull bone thickness (DiMaio, 1999; Li, et al., 2007). An average human brain volume of 1450 cm^3 (Raven and Johnson, 1995) was used to design the dimensions of the model. To achieve this volume, it was calculated (using the formula: $V = 4/3\pi r^3$, where V = volume and r = radius) that an inside diameter of 14 cm was required, meaning the outer diameter needed to be 16 cm after accounting for 1 cm of skin and bone on each side.. The mould used to create the model was therefore designed to fit these dimensions.

The mould was very similar to that used for the pig head models in that it consisted of three main components: a 16 cm diameter half-sphere negative and two, slightly smaller, half-sphere plugs (positives) with diameters approximately 15.2 cm and 14 cm, respectively. As in the pig head model, the larger plug was used to create the outer silicone layer while the smaller plug was used for the resin layer. The model was made from two halves which were joined together, following which “brain” and blood components were added. Due to the different shape of this model, there were some differences in the method of constructing the mould which will be described below. Unless otherwise stated, the materials used were the same as those used for the pig head model.

Creating the mould

A plastic half-sphere, with a diameter of 14 cm, was completely covered in five layers of softened dental wax, each of which was 2 mm thick. The sphere was then placed on the bottom of an open, square, plastic container with the convex surface facing outwards. In each corner of the container, a small half sphere (3 cm in diameter) was placed, flat side down, to act as orientation holes for the positive plugs. A wax strut was placed on each side, running from the edge of the sphere to the side of the container. This was done to create run-off channels for the silicon and resin when making each layer. All surfaces were coated with petroleum jelly to ensure the spheres could be easily removed afterwards. Silicone was then poured into the container to a level approximately 1 cm above the highest point of the sphere. After two hours, when the silicone was set, it was removed from the plastic container and the half-spheres were removed. The end result was a square block of silicone with a large concave half-sphere set in the middle and a smaller concave half-sphere in each corner (Figure 7.1).

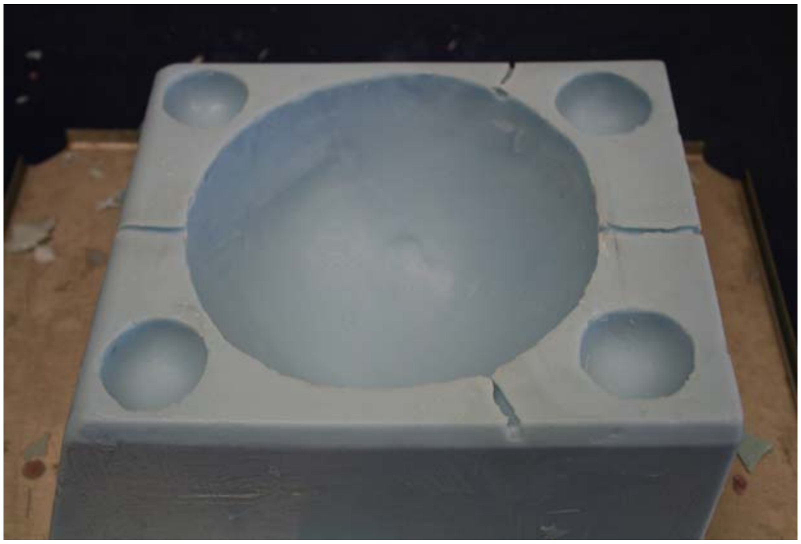


Figure 7.1 The negative mould for creating Spherical model 1. The holes in each corner lined up with those in the positive plugs and therefore acted as orientation points. Run-off channels on each side allowed excess material to escape.

The method of creating the plugs was very similar to that used in the pig head model mould. To create the larger plug, the top two layers of wax were firstly removed from the original plastic sphere and placed into the negative mould. This was to create the 4 mm space where the silicone layer would be formed. A plastic guard was then constructed around the top edges of the silicone mould to retain the liquid silicone when creating the two plugs. All surfaces were again coated with petroleum jelly so the plug could be easily removed. Silicone was then poured into the negative (on top of the wax) until it reached a level which was 2 cm higher than the top of the first silicone mould. A flat sheet of hard plastic was placed just under the surface of the silicone before it had set, to give the plug some stability. Once this had set, the first plug was removed (Figure 7.2), with the two layers of dental wax remaining in the mould.

To create the smaller plug, the remaining three layers of dental wax were removed from the plastic sphere and molded onto the first two layers already in the mould. This was to create the 6 mm space where the resin layer would be formed. The negative was again filled with silicone, in the same manner as described above. When set, the plug was removed from the mould (Figure 7.2), along with the five layers of dental wax and wax struts.

Figure 7.2 The two different sized positive plugs. The larger plug (left) was used to create the “skin” layer, while the smaller plug (right) was used to create the “bone” layer. The orientation plugs, in each corner, correspond to the orientation holes on the negative mould (Figure 7.1).

Constructing the models

Four models were made in total and the construction process was the same as that described for the pig head model. The only difference with these models was that two halves were created which were then joined. To do this, the resin on the flat surface of each sphere was sanded using a belt-sanding machine to ensure it was flat and would easily adhere to its other half. A half circle of approximately 2 cm in diameter was drilled at one point on the flat edge of each half using a burr. This created a small opening so that the model could be filled with gelatine once the halves were joined. A small amount of resin was then used to join the two halves together. Finally, a thin layer of silicone was used to seal the join on the skin layer to prevent the halves from splitting apart once the bullet hit. This step was only carried out for models 2 - 4 after the first model shattered down the middle when shot.

Two thin plastic bags (one inside the other) were now inserted through the opening of each model, to mimic the dural layer of the skull and to contain the gelatine and blood. The models were then filled with approximately 1350 ml of gelatine which was mixed in the same way described in Chapter 2. This was poured through a funnel into the inner plastic bag within the model. The amount of gelatine used was slightly less than the total inside volume of the model in order to allow room for the plastic bags and blood. Approximately 60 ml of porcine blood was then inserted into the space between the plastic bag containing the gelatin and the outer plastic bag, using a syringe. Immediately before shooting, 20 - 30 ml of porcine blood was also injected into the space between the silicone and resin layers, in the area that was to be shot.

Shooting set-up

The shooting was performed at an indoor firing range using a similar set-up to that described in Chapter 2 (Figure 7.3). A sheet of white paper, with a hole to shoot through, was placed between the shooter and the model to record any backspatter. The distance between this paper and the model was approximately 20 cm. White paper was also placed below and to the side of the model. The high speed camera was set up at a distance of 1.5 m from the model (on a 20° angle). Two Videolight lamps (Kaiser, Germany), each fitted with two 1 kW bulbs, were used as the light source for the high-speed camera. These lamps are small and portable unlike the Xenon arc lamp used in the previous experiments. One lamp was set up slightly in front of the camera (closer to the shooter) and one was behind (Figure 7.3). Both were at an approximate distance of 130 cm from the model

Figure 7.3 The shooting set-up for Model 1. The model was held in place by a clamp stand which was anchored by bricks. The white paper surrounding the model was set-up to catch any backspatter. The high-speed camera is to the right of the picture but is obscured by the light (front).

Variables

A .22 calibre rifle with lead round nose ammunition (.22 long, 40 grain) was used to shoot all of the models, from a distance of 5 metres. The diameter of this bullet is 5.58 mm. It has a muzzle velocity of 383 ms and a muzzle energy of 189 J. The shooter was a member of the Dunedin Police, Armed Offenders Squad.

7.3.2 Results

The results were only briefly analysed, in order to provide preliminary information for the development of the human head model. The results described here represent an overview of what was seen and highlight the main findings.

Wounds

The characteristics of the entrance wounds are presented in Table 7.1. There was no exit wound present in any of the models and in each case the bullet was lodged in the gelatine on the opposite side to the entrance wound. The physical damage was consistent between models.

Table 7.1 Characteristics of the entrance wounds in the spherical models.

Model	**Diameter - skin (mm)**	**Diameter – bone (mm)**	**Skin tears**	**Radiating fractures**	**Concentric fractures**	**Internal bevelling**
1A	1.5	6	-	6	4	Yes
1B	3	8	-	7	5	Yes
1C	2.5	6	-	6	4	Yes
1D	3	9	-	5	3	Yes

Bullet diameter = 5.58 mm

Apart from the lack of tears in the silicone, these wounds were very similar in appearance to those in the pig head mode. As can be seen from Table 7.1, the damage to the bone was similar in each of the models. Numerous bone fragments were also produced in each of the models and these were distributed along the length of the permanent cavity, together with bullet fragments.

Figure 7.4 The inside view of Model 1A (gelatin removed) showing inward bevelling of the bone simulant. Six radiating fractures and four concentric fractures were produced. This fracture pattern and internal bevelling was similar to that seen in the three other models.

High-speed videos

Because the videos were reasonably consistent between models they will not be discussed individually. In all of the models, the silicone initially ballooned away from the resin reaching a maximum convexity approximately 7 - 11 ms after the bullet had pierced the skin (Figure 7.5A). Following this, the silicone was sucked inwards beyond its original position, into the model. It then ballooned outwards again, although not as much as the primary ballooning. After this, the silicone around the entrance wound oscillated for a few milliseconds before coming to rest. In three of the models, the resin could be seen fracturing under the silicone.

In models 1C and 1D, a small amount of backspatter was ejected, some time after the initial penetration. This was seen to occur following the secondary blow-out as the silicone began to move inwards again (Figure 7.5B). Only two drops were ejected from one model and four from the other and these were small and very slow moving. The trajectory of these drops was in a horizontal direction.

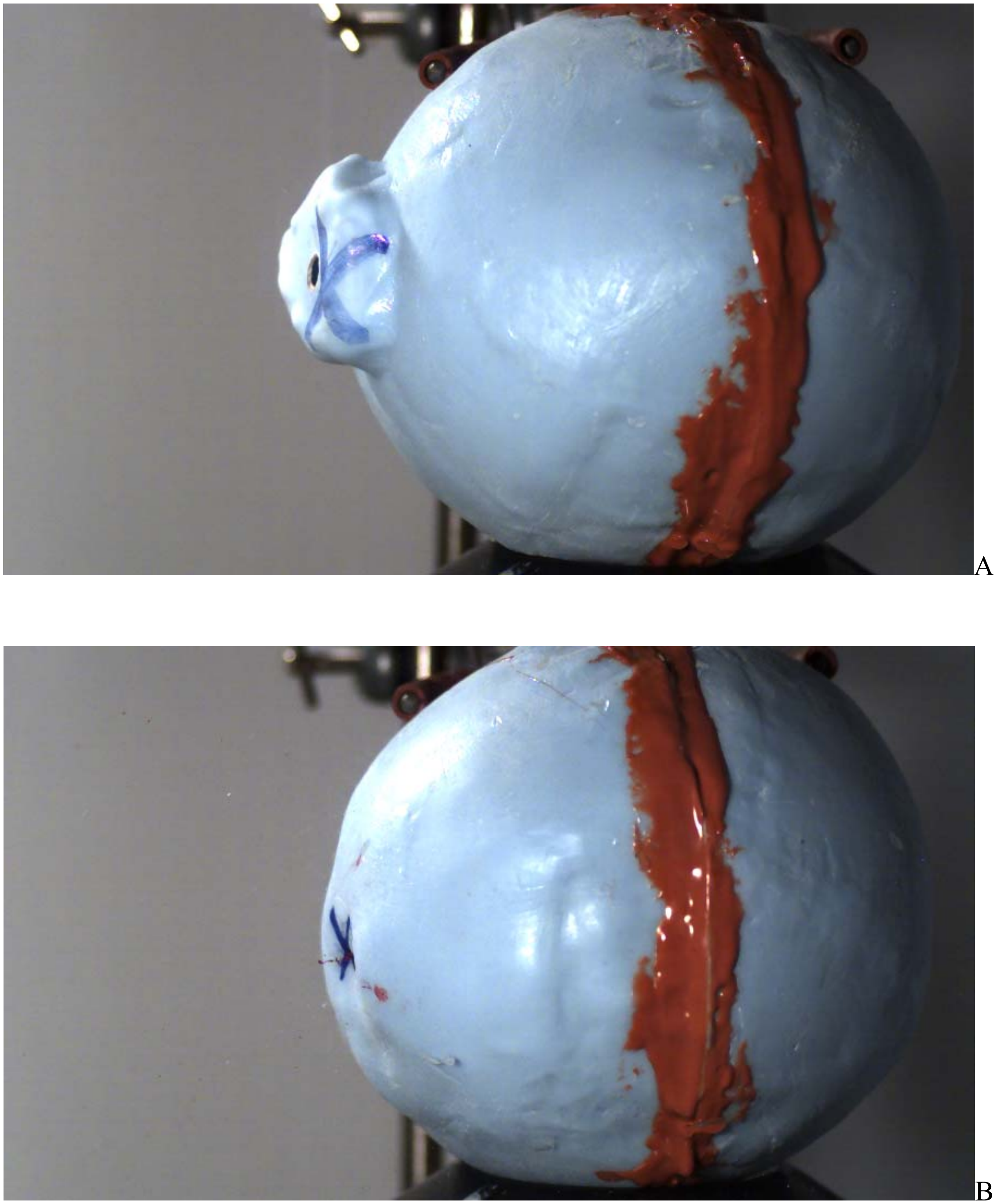


Figure 7.5 High-speed video frames showing skin blow-out (A) and backspatter (B).

Backspatter analysis

No bloodstains were visible on any of the sheets of white paper.

7.4 Spherical Model 2

7.4.1 Methods

Design

This model was similar in concept to the blood-containing pig models in that it incorporated a sponge layer. However, the production of this model was slightly more complicated as the region where the bullet would strike was not flat. Ideally, we wanted the sponge to sit flat in order for the blood to be distributed evenly.

Constructing the mould

A new plug was created in order to produce a resin layer which had a flat recess for the sponge to sit it. This plug was made using a similar method to the original plugs but a round plastic container lid was placed in the bottom of the mould before pouring the silicone. The end result was a plug with a recess (Figure 7.6) which then created a recess in the bone layer (Figure 7.7). This measured 7.5 cm in diameter and 6 mm in thickness. The thickness of the resin remained unchanged (6 mm). The ‘exit’ side of the model remained the same as in Spherical Model 1.

Creating the model

To make the model, the silicone layer was constructed in the same way as the preliminary model 1 (using the larger plug), while the resin layer was made using the new flat plug. When this half was removed from the mould, a 7.5 cm diameter hole was cut in the silicone layer to reveal the recess in the resin (Figure 7.7). The two halves of the model were prepared and joined using the same techniques described for Spherical Model 1. Two plastic bags were again inserted into the models with the inner plastic bag filled with 1300 ml of gelatine at 10% concentration. The reduced amount of gelatine in these models was due to the flat portion taking up extra space.

Figure 7.6 The plug with a recess

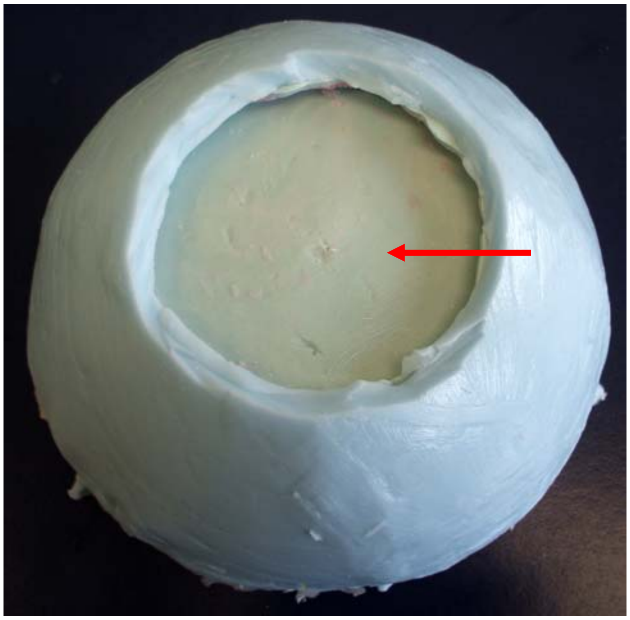


Figure 7.7 The model with a recess for a sponge layer in the area that was to be shot (arrow).

The sponge was 4 mm thick and was cut into a 7.5 cm diameter circle in order to fit it into the recess in the resin. Silicone was then poured into a thin layer (2 mm thickness) on a flat tray and the sponge was placed on top so it would bond to the silicone. This sponge-silicone circle was then sprayed with contact adhesive (Spray bond, clear spray adhesive, Fuller, Australia), on the sponge side, and inserted into the resin recess on the model. The periphery of the insert was sealed with silicone (Exahiflex Hydrophillic vinyl, polysiloxane impression material, GC Corporation, Japan) to prevent blood from leaking out. This silicone was slightly different to that used to simulate the skin and was administered from a hand-held dispensing gun.

Blood

Synthetic blood, rather than porcine blood, was used in the model in order to determine whether it was an appropriate substitute. The use of a non-biological substitute would be an easier and safer option for the model. The properties of synthetic blood substitutes (SBS) or blood mimicking fluids (BMFs) have been documented in a small number of studies (Wander, 2001; Millington, 2002; Fawehinmi, 2005; Bond, 2008). Glycerol is commonly used in SBS as at 20% concentration it is said to have a similar relative density and viscosity to human blood (Fawehinmi, 2005). Therefore, the composition of the SBS used in this model was 20% glycerol, 10% dye and 70% water. A red version and a blue version were made with the red SBS (50 ml) injected into the plastic bag between the gelatine and the resin and the blue SBS (10 ml) injected into the sponge under the skin. It was anticipated that the used of two colours would make it easier to determine where the blood had originated.

Shooting set-up

The testing was carried out at an outdoor firing range, with the models positioned on a table approximately 1 metre off the ground. The camera and lights were set up side-on to the model, both at a distance of 1 metre and at an angle of approximately 20° (Figure 7.8). Two white sheets of paper (measuring approximately 45 x 70 cm) were set up in front of and to the side of the model (beyond the camera) to record the bloodspatter. The paper in front of the model was at a distance of 20 cm (from the model) and had a hole, measuring approximately 15 cm in diameter, cut out for the bullet to pass through.

Figure 7.8 The shooting set-up for Model 2. The white paper (left) was positioned in front of the model to record any backspatter. The high-speed camera is in the bottom right of the picture.

Variables

Two firearms were used for the shooting, both at a distance of 5 m. A Bushmaster M4 rifle was used to shoot Model 2A, with .223 calibre, hollow-point ammunition. This had a muzzle velocity of 1140 m/s and a muzzle energy of 1524 J. A 9 mm Glock was used to shoot model 2B. This was the same firearm that was used for the pig testing except it was loaded with hollow-point ammunition which had a muzzle velocity of 368 m/s and muzzle energy of 643 J. These firearms are the standard weapons issued to Armed Offenders Squad members of the New Zealand Police. It was anticipated that these firearms would cause more damage to the models, particularly due to the use of hollow-point bullets. As mentioned in Chapter 1, these bullets mushroom on impact, presenting a larger surface area with which to crush and shred the tissue. It was anticipated that an exit wound would also be created.

7.4.2 Results

Entrance Wounds

The bullet impact had a devastating effect on both models. While there were clearly discernable entry wounds, the exit sides of the models were so damaged that the wounds could not be reconstructed. Entrance wounds in the skin of both models differed from those in the preliminary model 1, with large tears radiating from the entry point. The entrance wound diameters measured 6 and 8 mm, with tears measuring up to 56 mm in length radiating away from both wounds.

Large fragments of resin and gelatine were projected up to 5 metres from the model. There were multiple fractures in the resin on both sides of the model with a similar pattern to that seen in preliminary model 1. Internal bevelling was again present around the entrance wound. Multiple bone fragments were scattered throughout the permanent cavity in the gelatine.

High-speed videos

The destruction of the models made it difficult to interpret the results by viewing the physical damage and photos alone. This meant the high-speed camera videos were critical to the evaluation of the results. Unfortunately the high-speed camera had a fault at the time of shooting resulting in a slight graininess in the bottom half of the videos (Figure 7.9). However this did not greatly affect the analysis as all the important events could still be seen. The series of events differed slightly between the two models and therefore will be discussed separately.

In 2A, upon impact of the bullet, the entire model appeared to expand in size, and the skin around the entrance wound ballooned outwards. As the bullet traveled through the model, the bone could be seen fracturing under the skin. There was an immediate backspatter of material as the bullet impacted and the skin ballooned outwards (Figure 7.10). This material was a grey/green colour suggesting that it was most likely composed of bone fragments. This continued for up to 30 ms as the model began to implode. The model then collapsed in on itself with the front half being projected forward. As this occurred, a second stream of grey/green coloured backspatter was ejected from the entrance wound. At this point the model was too fragmented to view further processes clearly.

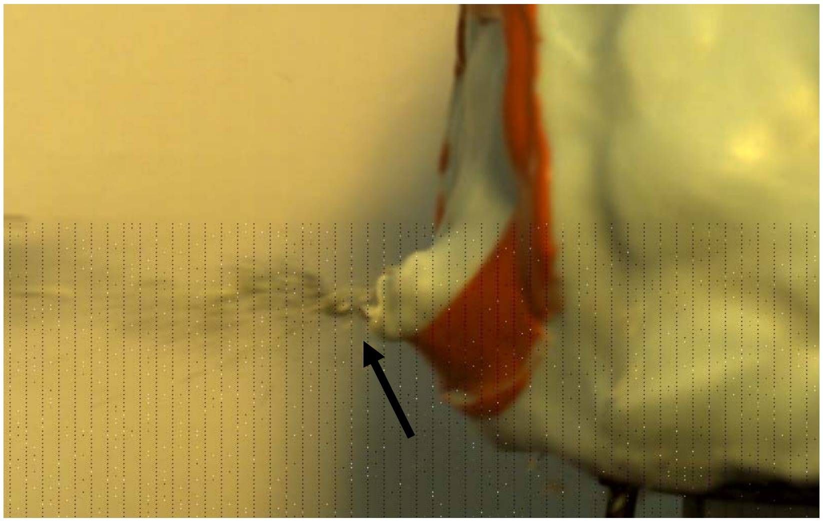


Figure 7.9 Backspatter from the entrance wound in Model 2A. Note the ballooning of the skin at the entrance wound and the fractures of the bone beneath the skin on the side of the model facing the camera. The grainy vertical lines present on the lower half of the image were the result of a fault in the high-speed camera. Arrows indicate backspatter of resin fragments

In model 2B, the skin immediately ballooned outwards around the entrance wound. This ballooning appeared to be much larger than that seen in Model 2A and when it was at its peak, a number of holes formed in the silicone, away from the entrance point of the bullet. When the skin moved inwards again, blue "blood" was ejected from the entrance wound and also out of the holes caused by the stretching of the silicone (Figure 7.10). The model then collapsed in on itself similar to Model 2A. As this occurred both red and blue "blood" was ejected from the entrance wound (Figure 7.11). Large pieces of resin were also projected forwards. A large amount of blood was projected backwards (in the opposite direction to the bullet) from the sides of the model where the seam between the two halves split (Figure 7.11).

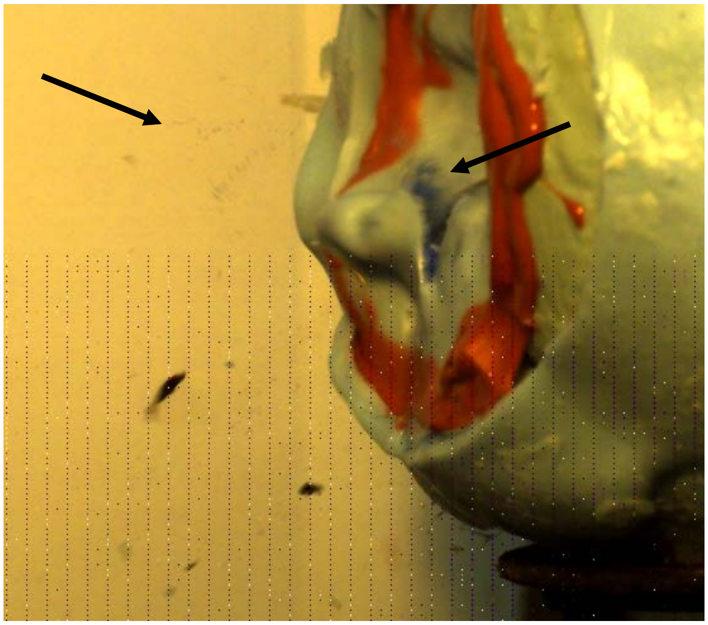


Figure 7.10 Backspatter of blue blood in Model 2B, indicated by arrows. This is prominent in the centre of the picture at the bullet entrance wound but can also be seen projecting away from the model towards the top left of the picture.

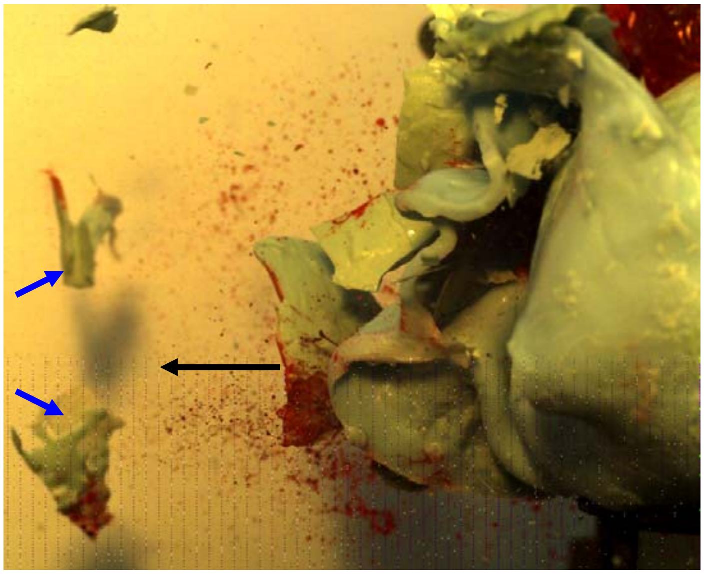


Figure 7.11 Model 2B as it collapses in on itself. Large bone fragments (blue arrow) can be seen on the left of the image and blood droplets, traveling in a backwards direction (indicated by black arrow), can be seen in the middle of the image.

Backspatter analysis

Due to the models collapsing in on themselves, there was a large amount of blood ejected in both a backwards and forwards direction. This meant that a large number of bloodstains were present on the background paper. Because it was impossible to determine which of these originated from the entrance wound (i.e. backspatter of interest), they were all included in the analysis.

On the background paper from model 2A, there was a large amount of blood present on the paper between the firearm and the model (Figure 7.12). The bloodstains were extensive around the region where the bullet passed through the paper and in many places the volume of blood was such that individual drops could not be differentiated. There were long lines of blood in some places indicating that some of the blood contacted the paper and then ran or dripped off. There were also a number of smeared stains where large pieces of the model contacted the paper.

Red stains were dominant on the bottom half of the paper while there was a mixture of blue and red stains on the top half of the paper. In some instances, red and blue stains had combined to create a purple stain. The stains present on the top half of the paper were much smaller and more widely spaced than those on the bottom half. All of the blue stains were relatively small with the largest diameter measuring approximately 3 mm. The largest individual red stain that could be differentiated was approximately 8 mm in diameter.

As well as blood, resin and gelatine fragments were present on the paper around the hole where the bullet passed through (Figure 7.12B). The largest resin fragment present measured 8 mm in length and 4 mm in width. Approximately 16 fragments were counted with lengths or widths greater than 3 mm but there were numerous smaller fragments. There were also small fragments present on the ground which had not stuck to the paper.

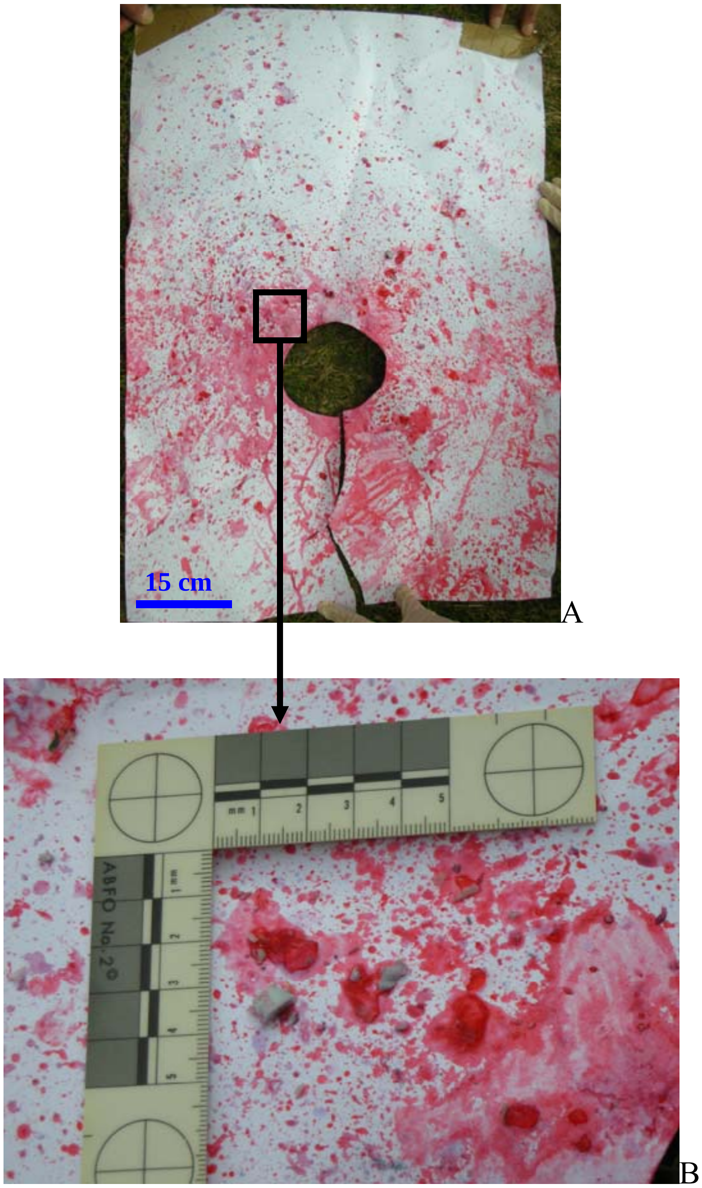


Figure 7.12 Synthetic bloodstains on the paper in front of Model 2a. A: Note the extensive bloodstains present around the hole where the bullet passed through. Just above this hole there were multiple fragments of bone and brain present. Some blue bloodstains can be seen on the top left of the paper. B: A close-up of the paper seen in A. Note the "bone" fragments in the centre of the picture and the mixture of blue and red synthetic bloodstains.

The bloodstains resulting from model 2B were less variable than those from model 2A and there were fewer of them (Figure 7.13). The stains were also more regularly shaped and most individual stains were able to be differentiated. Most of the stains were red and these were mainly distributed in the lower half of the paper. There were a number of large stains which were at least 5 mm in diameter but there were also very finely spattered stains present measuring no more than 1 mm in diameter. There were only 5 stains that were completely blue and 2-3 that were purple.

Figure 7.13 Bloodstains on the paper in front of Model 2A. The bloodspatter was less extensive than that seen from Model 2A. The few blue bloodstains that were present were very fine and are not visible in this figure.

7.5 Transparent Model

7.5.1 Methods

Design

These models shared the same basic design as Models 1 and 2. In contrast, the gelatine was contained in a transparent plastic container and a square silicone-sponge-resin 'plate' was attached to the front of it. The purpose of this was to view the bullet as it passed through the model which was not possible in the first two models. It was anticipated that being able to see the bullet passing through the model would be valuable in terms of further developing the model and determining the relationship between backspatter and the temporary cavity.

Construction

Four models were made in total. Each was designed using a square plastic container which measured 14 cm in height**.** The front plate was constructed in a similar way to the insert in Model 2. A square mould was made out of wax in order to make the silicone-sponge-resin front plate of the model. This was made with the same dimensions as the lid of the container (14 cm x 14 cm)**.** Silicone was poured into the mould until it was 4 mm thick. While it was still setting, a piece of 4 mm thick sponge was placed on the liquid silicone so it would be bonded when set. This silicone/sponge layer was then removed from the wax mould and resin was poured in until it was 6 mm thick. Once the resin had set (8 hours) it was removed from the mould and glued to the sponge side of the silicone and sponge layers using contact adhesive. The sides of the sponge layer were sealed with more silicone in order to contain the blood.

The plastic container was then filled with 1750 ml of gelatine (10% concentration). This was refrigerated and allowed to set overnight. The silicone-sponge-resin front plate was then glued to the open end of the container using MDS adhesive (MDS Products Inc., USA). This was taped on for two of the four models after it detached prematurely in the first two models when shot.

Blood

A total of 20 ml of porcine blood was injected into the sponge layer. The needle was inserted as far as possible into the sponge from the side and the blood was slowly injected. This was then repeated on each of the four sides of the sponge.

Shooting set-up

The models were clamped on to a table and the Xenon 4kW arc lamp was shone directly at the model to illuminate the gelatine and enhance the view of the bullet. A mirror was placed on the opposite side in order to maximise the amount of light available. The firearm used was the same as that used for shooting the pigs (9 mm Glock with FMJ bullets) and the shooting distance was 1 m.

7.5.2 Results

Wounds

Small entrance wounds were produced in both the silicone and the resin in all of the models. The diameters of these are presented in Table 7.2. Small tears were produced in the silicone in models 1 and 4. Internal bevelling and radiating fractures were produced in the resin of all models. Concentric fractures were only present in model 4.

Table 7.2 Characteristics of entrance wounds in the silicone and resin in the models.

Model	Diameter – skin (mm)	Tears	Diameter – resin (mm)	Radiating fractures	Concentric fractures
1	4	Yes	15	Yes	-
2	4	-	12	Yes	-
3	4	-	10	Yes	-
4	4	Yes	16	Yes	Yes

Bullet diameter = 9 mm

The permanent wound cavity could be viewed in the models (Figure 7.14). Blood was generally present in only the first half of the cavity (the entrance side) in all of the models. Small resin fragments were also present at various points in the cavity.

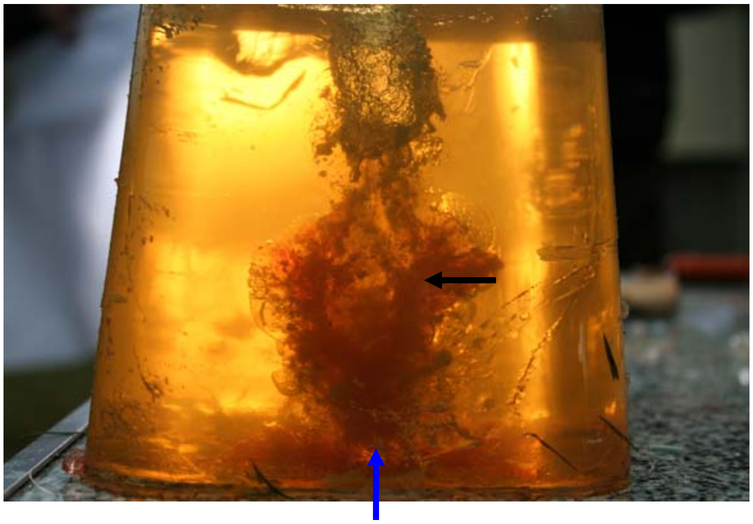


Figure 7.14 The permanent wound cavity visible in the gelatine from model 3. The bullet entry point is indicated by the blue arrow. Blood was present in the first half of this cavity (black arrow).

High-speed videos

A large blow-out of the silicone around the entrance wound was created in all of the transparent models, similar to that seen in the previous targets. This was accompanied by backspatter of bone fragments (Figure 7.15). A large temporary cavity was created in all models (Figure 7.15) which generally caused the plastic containing the gelatine to shatter. As the temporary cavity began to collapse (Figure 7.16), the front plate was sucked inwards momentarily following which blood backspatter was ejected in two of the four models (1 and 3) (Figure 7.17).

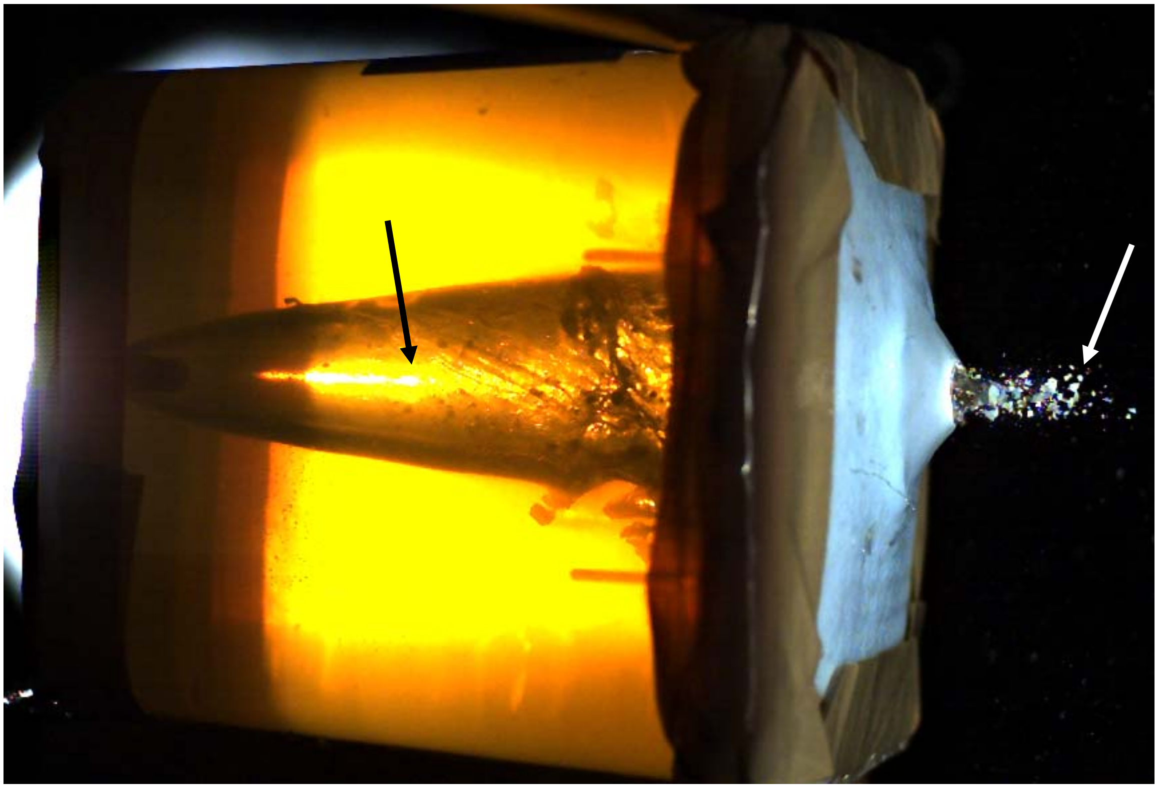


Figure 7.15 The beginning of the temporary cavity in model 3. This is indicated by the black arrow. Backspattered bone fragments are indicated by the white arrow.

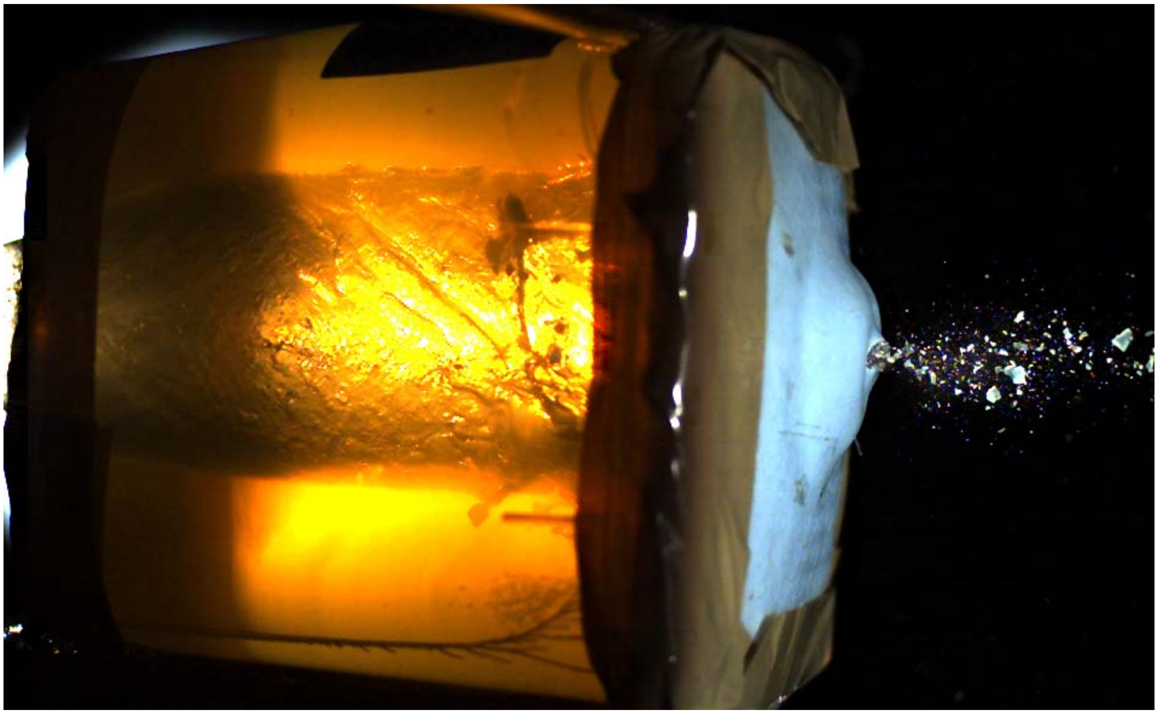


Figure 7.16 The temporary cavity just before it begins to collapse.

Figure 7.17 Backspatter of blood following the collapse of the temporary cavity. The backspatter is indicated by the white arrow.

Backspatter analysis

A small number of stains were present on the paper in model 1. Approximately ten of these stains had a diameter of at least 0.5 mm while the rest were smaller. These stains appeared to be randomly distributed with some present off to the side of the paper.

There were a large number of stains (more than 200) on the paper from model 3 (Figure 7.18). The sizes of a random selection of these stains are represented in Figure 7.19.

Figure 7.18 Backspattered paper from model 3. The black marks at the bottom of the paper represent the position of the model.

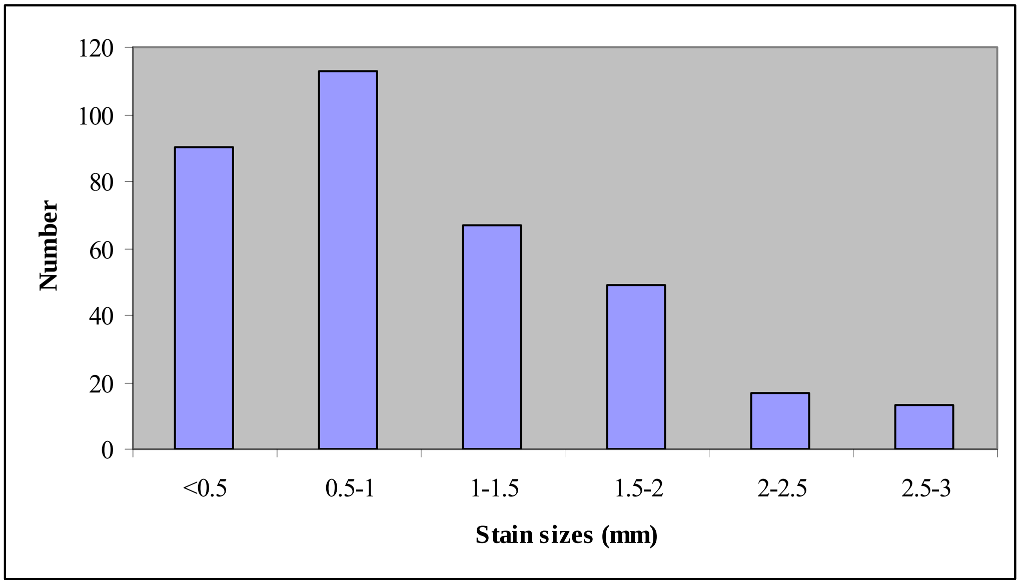


Figure 7.19 Stain sizes from model 3

7.6 Discussion

7.6.1 Spherical Model 1

This spherical model behaved in a very similar way to the non-blood pig head models. Extensive ballooning of the silicone was seen, most likely due to the fact that it was not anchored to the resin layer and small entrance wounds were once again produced. The fracture pattern in the resin was also similar to that produced in the pig head model, with radiating fractures and internal bevelling present. The main difference in this model was the lack of an exit wound. This was most likely due to the type of bullets used as the .22 round was obviously of a smaller calibre and lower energy than the 9 mm used in the previous testing.

It appeared from the results that the method of containing the blood, particularly that injected between the silicone and resin layers, was not effective. As the blood was injected into a potential space, it was free to move away from the area and may have pooled at the lowest point of the model due to gravity. It is also likely that the blood was forced away from the entrance wound as the bullet penetrated, preventing it from being ejected. The sponge incorporated into the pig head models appeared to be a better alternative for containing the blood.

7.6.2 Spherical Model 2

As mentioned earlier, Model 2 was designed with a flat impact site, in order to incorporate a flat circle of sponge containing blood. The sponge was bonded to the silicone skin on one side and glued to the resin on the other, in order to provide some adhesion between the ‘skin’ and ‘bone’ layers. This was thought to be more realistic of human skin and soft tissue, which is bound to the underlying subcutaneous tissue in most regions of the head. The tears present around the entrance wounds in both models were most likely due to this adhesion between the layers as the silicone was not free to stretch to the same degree as it was in Spherical model 1 (as seen in the high-speed videos). Skin tears are commonly seen in human gunshot wounds of the head, especially where skin is pulled tightly against the bone, such as in the scalp (Di Maio, 1999; Pollak & Rothschild, 2004).

The use of two different colours for the blood substitutes proved to be valuable in determining where each had originated. This was particularly so in model 2B as the first backspatter to be ejected was blue, meaning it originated from the sponge. Red backspatter, from beneath the bone layer, was only seen later. Although only two models were analysed, we could tentatively conclude that the use of internal blood in the model was probably unnecessary and the most important component was the subcutaneous sponge layer.

The SBS was not any easier to see in the high-speed videos than porcine blood and it was also more time consuming to use. Therefore, the porcine blood is probably the better option for the model as its properties are more similar to human blood and therefore is more realistic than the SBS.

As mentioned earlier, the ballistic destruction of the models made it difficult to interpret some of the results. This may mean that the model is not suitable for testing with high-powered firearms.

7.6.3 Transparent Model

These results provided valuable information on the relationship between backspatter and the temporary cavity. As mentioned in Chapter 1, backspatter is said to be caused, in part, by the collapse of the temporary cavity. When it collapses it forces material out through any available opening, which is generally the entrance wound. This was seen in the high-speed videos, with a large amount of blood ejected from the entrance wound as the temporary cavity collapsed. These transparent models were particularly useful for viewing this relationship and gaining a better understanding of how backspatter occurs. As they were shot from a distant range, these models demonstrated how backspatter could be produced in the absence of a subcutaneous gas pocket.

7.6.4 Summary and Conclusions

The three models described in this chapter each contributed novel information regarding the processes involved in gunshot wounds and backspatter. Spherical model 1 highlighted the need for appropriate blood containment and demonstrated that the sponge used in other models was most likely the best option. Spherical model 2 showed that the use of the SBS was probably not a better option than using real blood and that the model may not be suitable for use with more high-powered firearms or ammunition. The transparent model illustrated the relationship between backspatter and the temporary cavity and was valuable in terms of viewing the timing of backspatter in relation to other key events.

These experiments were important in terms of developing a human head model. As mentioned earlier, experimentation such as this is time consuming and often expensive and therefore it is critical to get as much information as possible from each test. Although altering more than one variable at a time (e.g. blood component and firearm) was not an ideal way of testing the models, it was successful in terms of eliminating certain components (e.g. the SBS). In other words, if part of the model is not going to be appropriate, it generally became apparent after only one test and therefore obviated the need for further tests there. These experiments involved a number of variables which were unsuccessful (e.g. method of blood containment in spherical model 1) and which therefore can be eliminated from future tests. There were also a number of aspects which were very successful (e.g. transparent model) and which probably should be considered for future versions of the model. In conclusion, these tests have provided a good foundation for the development of a realistic human head model of cranial gunshot wounds.

8. Conclusions and Future Directions

This project focused on the development of an artificial pig head model which could be used to study cranial gunshot wounds and backspatter. The aim was to produce a model which reacted in a similar manner to real pigs when shot, in terms of the resultant wounds and backspatter produced. By shooting the developed model and pig heads (live and butchered) under similar conditions, we were able to make valid comparisons between the two groups.

The results that were focused on for this comparison included wound size and shape, degree of skin blow-out around the entrance wound and the amount of backspatter produced. The model differed slightly to the pig targets in terms of wound size, possibly due to the elastic nature of the artificial skin. However, the morphology of the wounds was similar between the model and the pig targets. The model also behaved similarly to the pig targets in terms of the wound formation (degree of skin blow-out) and amount of backspatter produced, as seen in the high-speed videos. These similarities are important as they show that this non-biological model is capable of producing results which are representative of biological tissue. This validation is significant as it shows that a human equivalent of the model would be a realistic option.

These experiments have made an important contribution to the development of a human cranial backspatter model. Prior to this study, no realistic non-biological model for studying backspatter had been documented in the literature. This is surprising considering the significance of backspatter in cases of gunshot fatalities. Very little is known about why it occurs in some situations but not in others. The development of a realistic model could lead to an increase in the current knowledge of backspatter and potentially a better understanding of gunshot fatalities where it is an issue. A successful model would eliminate the need to perform animal testing and mean that experiments could be performed on a larger scale. It could also allow for the establishment of standards for when to expect backspatter e.g. a particular firearm or shooting distance.

8.1 Future Directions

In order to further develop the model, aside from more extensive testing, there are a number of key things which need to be achieved. Firstly, mathematical modeling of our existing model will be critical for quantitatively determining the similarities between the model and the live pigs. Clearly, this was beyond the scope of this project. Further testing of various materials is also recommended in order to ensure that those used in the model were the most appropriate. This is particularly the case for the silicone and resin as it is critical that these are accurate simulants of human skin and bone, respectively. Although they behaved in a similar manner to the pigs in this study, it may be that there are new materials becoming available which would be more appropriate. Further research on the fracture behaviour of bone following ballistic impact would also help to validate the choice of material used for this element.

The results from this study show that the model behaves in a similar manner to a pig head subjected a gunshot. Therefore, with appropriate modifications, it has the potential to be an accurate representation of a human head, due to the similarities between pigs and humans mentioned in Chapter 3 (skin, bone and blood properties). The preliminary human head models developed in this study differed from the pig head model in both shape and tissue thicknesses. These models were made in a spherical shape for simplicity. To further develop this model, a shape that was more anatomically realistic of a human head would eventually be required, particularly as many parts of the human skull are quite flat rather than spherical. This could be achieved by making a cast of a human skull to create the negative component of the mould.

Another aspect which could make the model more realistic would be the inclusion of a pressurised, circulating blood system. This could be achieved by having blood contained in a sponge within a plastic pocket with two small tubes entering and leaving. Blood could then be pumped in and drained out again creating a closed circuit. This would be more realistic of blood in the human circulation system which is always under pressure.

Following adjustments to the model, it will obviously need to be tested on a much larger scale, using various firearms and shooting distances, with a larger number of targets to investigate reproducibility. Results that were seen in this study which may also warrant further research include the pig reactions that occurred and the backspatter of bone fragments. Improved knowledge of these factors could also be important for the interpretation of gunshot fatalities. There are still many aspects that need to be investigated before we can say we have the best possible model.

8.2 Summary of Key Outcomes

Key outcomes from this study included:

- The development of a pig head model which showed similarities in wounding and backspatter compared to butchered pig heads and live pigs.
- A greater understanding of wounding and backspatter in live pigs.
- The preliminary development of a human head model.

The pig head model developed in this study showed many similarities to both butchered pig heads and live pigs when shot, particularly in its production of backspatter. From these experiments and the development of the model, we gained a considerable amount of information about the performance of various materials and tissues under ballistic impact. We also learned more about the backspatter produced from live animals and the likely relationship between the subcutaneous gas pocket and blood backspatter in pigs. Many questions about the causation and extent of backspatter from gunshot wounds remain unanswered. While this study has established a firm basis from which to proceed, a number of exciting research avenues need to be explored in the future.

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10. Appendices

10.1 Appendix 1: High-speed Videos

The high-speed videos from all of the targets were saved to a DVD which is attached to the inside back cover of this thesis. The videos can be viewed using Windows Media Player. Copies of these videos may not be produced without the permission of the author.

10.2 Appendix 2: Resin Elastic Modulus Results

Specimen label	Maximum Load (N)	Extension at Maximum Flexure stress (mm)	Flexure strain at Maximum Flexure load (mm/mm)	Flexure stress at Maximum Flexure load (MPa)	Modulus (Automatic) (MPa)
1	420.73	-0.86825	0.01111	44.68222	4520.92499
2	436.18	-0.6935	0.01118	41.12836	4037.84745
3	459.94	-1.86975	0.01252	66.2039	5688.8668
4	341.82	-0.83313	0.01129	37.80488	3689.56852
5	148.36	-0.952	0.00689	41.19246	6180.02024
6	477.81	-0.688	0.01205	63.57439	5670.7251
7	238.62	-1.73038	0.01021	49.09922	5131.79973
8	506.38	-0.75019	0.01291	54.94338	4560.0482
Mean	378.73	-1.04815	0.01102	49.8286	**4934.97513**
Standard Deviation	126.39649	0.47398	0.00188	10.72462	875.57665
Minimum	148.36	-1.86975	0.00689	37.80488	3689.56852
Maximum	506.38	-0.688	0.01291	66.2039	6180.02024

10.3 Appendix 3: Animal Ethics Approval

The animal ethics approval letter for this project is included on the following page.