



Irina Ellenberg

Analysis of ballistic trauma to ribs in connection to firearms used by
the German military during World War II

School of Defence and Security
Forensic Archaeology and Anthropology

Master of Science

Academic Year: 2022 - 2023

Supervisor: Dr Richard Critchley

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This thesis is submitted in partial fulfilment of the requirements for
the degree of MSc Forensic Archaeology and Anthropology

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ABSTRACT

Ballistic trauma to the thorax is often seen in victims of humanitarian conflicts, yet the specific fracture patterns to the ribs are not widely present and defined in the literature. This makes the interpretation of trauma difficult for forensic anthropologists working on human rights cases. Most experimental studies focus on long bone and cranial trauma; however, ribs have a different structure and shape so that direct comparison of trauma from fracture patterns observed on other bones cannot be accurately used for interpretation.

In this thesis, the experimental approach was chosen to provide a better understanding of how ballistic trauma presents on ribs. Pig ribs, encased in ballistic gelatine, were used as tissue substitutes and two different calibres as well as distances were chosen to compare possible changes in the trauma patterns. 9x19mm and 7.92x57mm calibres were chosen since they were the most widely used ammunition by the German military during World War II. Both calibres were fired from distances of 3m and 10m. After the firing the ribs were reconstructed and analysed using visual and metric assessments.

This study found that there are several characteristics related to ballistic trauma in ribs. Fracture patterns, which are usually connected to cranial trauma as well as other patterns connected to long bone trauma were present. Although changes between fractures can be seen when using different calibres and distances, it is difficult to positively conclude a specific calibre or distance used without further evidence. Closer analysis of small bone fragments showed that the number is not indicative of the calibre or distance used, however, the shape of some fragments can help identify ballistic trauma.

Keywords: Ballistic trauma, Thorax, Ribs, World War II, 9x19mm, 7.92x57mm, Executions, Firing squad, Forensic Anthropology, Humanitarian Conflicts

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1 Introduction

In most humanitarian conflicts, the analysis of ballistic trauma to the bones provides important insights into the procedure of the killings. Many methods have been developed within forensic anthropology to analyse ballistic trauma to the bones, however, they often focus on the cranium or the long bones like the femur or humerus. The analysis and interpretation of trauma to the ribs is not well researched and it is presenting as difficult to differentiate between trauma types. This thesis focuses on identifying and characterizing patterns connected to ballistic trauma and the differentiation of calibres and distances from ballistic wounds to the ribs.

1.1 Forensic Anthropology

Forensic anthropology is a multifaceted field that lies at the intersection of anthropology and forensic science. It is a discipline that focuses on the examination of human remains to uncover vital information about the deceased, their identity, and the circumstances surrounding their death. By applying the principles of biological anthropology to legal investigations, forensic anthropologists play a crucial role in assisting law enforcement agencies and judicial systems to bring clarity to some of the most challenging cases (Dirkmaat et al., 2008). The scope of forensic anthropology is extensive, encompassing various specialized subfields, including forensic archaeology, taphonomy, and facial reconstruction. Collaborating with other forensic experts, such as pathologists, entomologists, and odontologists, forensic anthropologists play a substantial role in recovering important evidence from human remains, offering a unique perspective that complements the broader investigation (Tersigni-Tarrant & Shirley, 2013). Not only does forensic anthropology serve as a valuable tool in solving criminal cases and identifying victims of disasters or mass fatalities, but it also plays an essential role in addressing historical and humanitarian challenges (Komar & Buikstra, 2008). In instances of mass graves, war crimes, or human rights violations, forensic anthropologists may be called upon to aid in the recovery and analysis of human remains, seeking justice for those who can no

longer speak for themselves (Kimmerle & Baraybar, 2008). As the field continues to evolve, enhanced by advances in technology and the interplay of different disciplines, forensic anthropology remains an essential aspect of modern forensic investigations. Through the scientific study of the dead, forensic anthropologists bring hope to grieving families, closure to complex criminal investigations, and contribute significantly to the pursuit of truth and justice in society.

The role of a forensic anthropologist includes the full assessment of human skeletal remains, focusing on the creation of a biological profile consisting of age, ancestry, biological sex, and stature estimation and reporting on any pathology and trauma found on the remains (Buikstra & Ubelaker, 1994; White & Folkens, 2005). To create such a biological profile, multiple different methods are applied to assess the remains morphologically and metrically and make an estimation considering different variables. Most methods focus on specific bones to estimate certain parts of the biological profile, for example, the pelvis and skull are mostly used for sex estimation (Rogers & Saunders, 1994; Walker, 2008). Pathology describes any changes to the body that happened during the lifetime and can be connected to a disease or traumatic event. It is important to note that not all diseases are visible in the body after death, especially if the person healed quickly or if they died before any long-term effects could become apparent (Roberts & Buikstra, 2019). However, some diseases affect the body for a long time before they lead to death, so changes to the skeletal system can be seen. Finally, anthropologists report on any trauma recorded on the remains. This also refers to any taphonomic changes to the body as well as scavenging. Taphonomic changes can present as discolouration based on the environment of the remains, breaking, due to drying out of the bone, and other weathering effects (Langley & Tersigni-Tarrant, 2017).

1.2 Trauma Analysis

The effects of trauma on bone can vary depending on different factors within the bone as well as variables in the cause. The structure of the bone determines how it reacts and which fracture patterns can occur.

Various functions of the human body require the skeletal system to be adaptable, strong, and flexible. Different types of bones are specialised for specific functions and therefore vary in structure. Each bone type has evolved to meet specific mechanical, protective, or physiological demands, contributing to the overall functionality of the skeletal system. There are four types of bones in the human body: long, short, flat, and irregular bones (Tersigni-Tarrant & Shirley, 2013). In this thesis, the focus will be on flat and long bones since ribs are categorised as flat bones and the trauma will be compared with skulls and femora, which are flat and long bones respectively.

Long bones, characterized by their elongated shafts and distinct epiphyses at the ends, account for a significant portion of the skeletal framework. Due to their shape, these bones are essential for locomotion and mechanical stability. Examples include the femur, humerus, and radius. They encompass both cortical and trabecular bone regions, reflecting their dual role in withstanding mechanical loads and facilitating metabolic exchange. Flat bones characterized by their flattened, plate-like morphology, offer protection, and provide expansive surfaces for muscle attachment. The cranial bones, the sternum, the ribs, and the scapula exemplify this bone type. The unique structure of flat bones combines a sandwich-like arrangement of compact bone layers with an interior of trabecular bone, optimizing their weight-to-strength ratio (White et al., 2012).

The impact of trauma on bones differs significantly depending on the state the bone is in when the trauma occurs. Generally, it is differentiated between three trauma types depending on the time of the occurrence (Blau & Ubelaker, 2016). Ante-mortem trauma describes injuries that occurred sometime before death and started or even finished healing. Peri-mortem trauma describes injuries, which happen just before or leading up to the death. This also includes injuries which

caused death. Post-mortem injuries include anything that happened to the body after death occurred. This includes any disarticulation and fragmentation of the fresh body as well as the skeletonized body. In the field of anthropology, the peri- and post-mortem injuries are usually limited to the differentiation between wet and dry bone trauma since bones will still behave the same if the injuries are inflicted after death while the body is fresh. Wet bones are less brittle and more likely to show hinging and bending before breaking. Dry bones are more likely to give away more easily and break rather than bend (Wheatley, 2008). The fracture patterns discussed in this thesis are all connected to trauma on wet bones.

Certain types of trauma patterns can provide insight into the weapons or methods used to inflict injuries. Based on this, it is distinguished between three different types of traumata: high-velocity projectile, blunt force, and sharp force trauma. While oftentimes the identification of the trauma can be obvious, some patterns can be seen in different types and therefore make interpretation complicated. Sharp force trauma describes injuries inflicted on the body with a sharp object like a knife or a spear. It can create different types of damage to the bone like puncture, incisions, or cleft wounds (SWGANTH, 2011). These types of wounds are specific to sharp force trauma and easily distinguished from other types. Puncture wounds are vertical, cone-shaped wounds, usually with a small diameter. Incision wounds are long and narrow, created by slashing with a sharp weapon. Cleft wounds are vertically inflicted wounds caused by sharp objects with a long edge.

Blunt force trauma describes any trauma that is inflicted on a large surface area of the bone. This can be caused by objects, vehicular accidents or falls. The fracture patterns are dependent on the type of bone that is affected and its structure. Flat bones like the skull often show depressed fractures with radiating, concentric and ring fractures originating from and surrounding the point of impact. Blunt force trauma to the long bones can cause many different fracture patterns depending on the angle, intensity and whether the impact was direct or indirect (Moraitis & Spiliopoulou, 2006; Reber & Simmons, 2015).

High-velocity projectile (HVP) trauma describes any injury inflicted by a fast-moving object like a bullet or shrapnel from an explosion (SWGANTH, 2011). This can cause fracture patterns that are a combination of sharp and blunt force trauma as well as other patterns, which are unique to this type of trauma. The affected areas can be limited to only a small part of a bone or expand over multiple bones. Due to the big variety of projectiles with varying sizes, weights, and velocities, it is difficult to limit and characterise all patterns associated with HVP trauma (Passalacqua & Rainwater, 2015). The studies of wound ballistics are extensive and require a lot of experimental testing to provide a large pool of different settings to compare to real-life trauma found on remains.

1.2.1 Wound Ballistics

Wound ballistics describes the impact a bullet has on the body. The extent depends on five different aspects: the direct impact the bullet has by physically shredding the tissue, the indirect injuries caused by the temporary cavity, the secondary injuries due to the breakup of the bullet, the type of tissue impacted by the bullet and the length of the wound.

The wounding characteristics also vary depending on the type of firearm used. In this thesis, the focus will be on the differentiation between handguns and rifles or generally low and high-velocity firearms. Handgun bullet injuries are usually limited to the path of the bullet itself and the temporary cavity is rather small and does not add to the injuries as there is significantly less energy being transferred from the bullet to the surrounding tissue. Significant injuries are restricted to the area directly in the path of the bullet. Additionally, the bullets do not break up, which further limits the extent of the injuries. Compared to that, bullets fired from high-velocity firearms, like rifles, cause more injuries to the surrounding tissue since the energy transferred from the bullet is greater creating a larger expanding temporary cavity. The cavities can become up to 11-12.5 times the diameter of the projectile. Velocities above a critical value of 800 m/s create wounds which are far more severe than lower velocities. The distribution of the kinetic energy within the temporary cavities is not uniform and depends on the tissue which is

affected. Further, some bullets are made to expand within the wound, therefore, causing even greater damage (DiMaio & Geberth, 2015).

A further differentiation in ballistic trauma is made between direct and indirect impacts. A direct wound describes a bullet hitting the bones and creating a defect, while the indirect trauma is due to the temporary cavity. The size of the temporary cavity varies due to the kinetic energy transferred from the bullet to the soft tissue.

The kinetic energy lost by the bullet is dependent on different factors. One of them is the angle of the yaw of the bullet. This is defined as “the deviation of the long axis of the bullet from its line of flight” (DiMaio & Geberth, 2015). Rifled barrels are counteracting the yaw by providing a spin to the bullet so it can fly in a straight line for a longer distance. As soon as the bullet comes in contact with any object the flight is disturbed, and the bullet starts rotating. This also happens as soon as the bullet enters the body, therefore, creating a larger wound cavity. Further, the kinetic energy depends on the calibre size, weight, and velocity, while the latter has a greater impact. The properties of the tissue that comes in contact with the bullet also determine how much kinetic energy is lost.

This allows the characterization of wounds created by handgun and rifle bullets since they are usually of different sizes and velocities. The temporary cavity created by handgun bullets is usually smaller as the velocity is lower.

1.2.2 Use in Humanitarian Cases

There are many institutions dedicated to providing resources and aiding in uncovering the truth about events of past and ongoing armed conflicts, wars and other crimes affecting entire groups of people and countries. The International Criminal Court provide an independent organisation with the power to convict perpetrators on a larger scale, who cannot be tried in their respective countries (ICC, 2023). It allows for a fair trial in cases where the judicial system of the affected country is compromised or when multiple countries are involved. Organisations like the International Committee of the Red Cross (ICRC) and the International Commission on Missing People (ICMP) aid in collecting evidence, encouraging public involvement, and training personnel but also help the affected

countries and the civilians with other basic resources like access to health care food and water (ICMP, 2023; ICRC, 2023). Other institutions specialise in helping recover missing people from humanitarian conflicts like World War II to repatriate the remains and give the families closure. Such organisations include the Defense POW/MIA Accounting Agency (DPAA) in the U.S. and the Association for the Rescue of the Fallen in Eastern Europe (VBGO) in Germany (DPAA, 2023; VBGO, 2023).

Trauma analysis plays a crucial role in humanitarian cases, particularly when addressing human rights violations, mass fatalities, and historical injustices (Langley & Tersigni-Tarrant, 2017). The analysis of trauma on skeletal remains by forensic experts contributes to uncovering evidence of violence, shedding light on the circumstances surrounding death, and providing valuable information for justice, accountability, and the validation of historical events. Documentation of trauma patterns serves as crucial evidence that helps establish the extent of violence inflicted on victims. By analysing trauma patterns on skeletal remains, forensic experts can reconstruct the sequence of events leading to a person's death. This information is important in understanding the dynamics of mass killings, human rights abuses, or conflict-related fatalities (Passalacqua & Rainwater, 2015). It can be identified whether victims were subjected to torture, executed, or faced other forms of violence before death. The reconstruction of events leading up to the death is not only important for recent forensic cases but also for human rights cases like the Nuremberg trials regarding World War II or the genocide in Bosnia (Brickley & Ferllini, 2007). Information on the cause of injury can help identify the perpetrators or the type of conflict involved. For example, distinctive markings on bones from bullets, shrapnel, or blade impacts can indicate the weapons used, contributing to the larger investigative process. Trauma analysis findings are often used as evidence in legal proceedings, whether in domestic or international courts. Skeletal trauma can verify eyewitness and other forms of testimonies and establish a compelling case against perpetrators of human rights abuses or war crimes (Kimmerle & Baraybar, 2008). In cases of historical injustices or mass fatalities related to past events, trauma analysis provides an opportunity to acknowledge and validate the suffering

endured by victims. This contributes to historical truth-telling and helps communities affected by these events to commemorate and seek justice. Findings contribute to raising awareness about the magnitude of violence in conflict zones or during periods of oppression. By presenting evidence of atrocities, these findings can influence public opinion, international organizations, and policymakers, fostering greater understanding and support for humanitarian initiatives. Trauma analysis in humanitarian cases requires ethical sensitivity. Experts must approach their work with respect for the dignity of the deceased and the needs of survivors. Cultural considerations, as well as the potential for re-traumatisation, must be taken into consideration when presenting findings and engaging with affected communities.

The classification of trauma has been researched and used for different applications like clinical and forensic cases. Most information is derived from clinical literature; however, often fatal injuries need to be analysed in forensic anthropology (Brickley & Ferllini, 2007). As ballistic trauma to the thorax is more likely to be fatal than trauma on long bones, due to the organs located inside of the ribcage, this type of trauma is underrepresented in clinical literature. Further, ribs are usually less well preserved than skulls and long bones, which makes them harder to analyse for anthropologists. Still, a lot of important information can be gathered from analysing trauma to the ribs, especially since trauma to the chest is common in humanitarian cases like World War II. During excavations connected to historical human rights cases, many injuries are found on all parts of the remains and analysed. A study showed that within a sample from a mass grave in Rudnica, Serbia thoracic trauma was more present than head/neck and limb trauma (Haliti et al., 2023).

Many mass graves are still being uncovered from World War II with the hope of identification of the victims but also to find evidence of the committed crimes to better understand the history and validate the suffering of the people involved. The analysis of remains from mass graves can help establish the motivation of the perpetrators by examining certain patterns for example ethnic cleansing actions in concentration camps (Drath et al., 2023). However, there are still

problems regarding the recovery of human remains, especially since different countries are involved with various laws and protocols in place (Márquez-Grant & Errickson, 2021).

During World War II many people, civilians as well as soldiers, were executed with different methods. The two which were mostly used for individual executions were hanging or shooting (Kaienburg, 2021). There were special protocols in place for public executions at concentration camps, which were implemented by the Nazi regime and enforced by the military (*Archive KZ Neuengamme, Interviews with Survivors*, n.d.). Since this thesis is focusing on ballistic trauma, the executions by hanging will not be further discussed, however, it is important to remember when examining trauma on remains from World War II mass graves.

Many scheduled executions were carried out by special organised groups of soldiers, the so-called firing squads. Since shooting was seen as a more honourable way of execution this method was mostly used on war prisoners and sentenced German soldiers. Firing squads of the German military consisted of multiple soldiers who were lined up and shot at the chest of the victim in front of them (*Archive KZ Neuengamme, Interviews with Survivors*, n.d.). Such firing squads were further present in other countries as a form of execution for various acts deemed illegal at different times. A firing squad was also used for military executions in the United States (US War Department, 1944). Special facilities were built to accommodate executions; however, some were also carried out after forcing the victims to dig their own mass graves.

Other executions were carried out in specially created rooms with a shot to the neck. The victim was led inside a room with the explanation that a medical examination needed to be carried out. When they stood by the wall to measure their height, a soldier on the other side would place the firearm at the opening behind the victim's neck and shoot them (Kaienburg, 2021). Additionally, some executions were carried out without any protocols, for example when people tried to flee the concentration camps. Soldiers would fire at the fleeing victim to immobilise or kill them (*Archive KZ Neuengamme, Interviews with Survivors*,

n.d.). In order to be able to distinguish between the different methods, trauma analysis is necessary.

1.3 Previous Experimental Research

Throughout the years a lot of experimental research has been conducted to analyse trauma to the bones in an attempt to better understand bone mechanics and allow anthropologists to identify different types of traumata. Many different types of tissue substitutes were tested to avoid the ethical problems that come with using real human materials, although experiments on human cadavers are also occasionally conducted. The most frequently used substitutes are Synbone and animal bones, specifically pig bones, as they are structurally most similar to human bones (Pullen et al., 2021). Additionally, gelatine is used to substitute soft tissue to analyse the trauma in the most realistic environment. Different percentages are used; however, most experiments are conducted using 10 or 20% as these are the standards set by the FBI and NATO respectively (Carr et al., 2018). Skin substitutes can also be added; however, this is rarely done since the effect of the soft tissue is more relevant and easier to replicate. The extent of the wound is also depending on clothing or body armour worn by the victim at the time of the killing as this affects the energy being lost by the bullet before hitting the body.

Many methods have been developed for the analysis of ballistic trauma on bones. Patterns specifically seen on skulls and long bones help reconstruct how the victims were killed. A typical pattern that is connected to ballistic trauma on skulls is bevelling. This describes the breaking away of bone at the side opposing the force (Quatrehomme & Işcan, 1998). Bevelling is also present in long bones; however, it is less well understood and often deformed due to the localisation of the shot (Rich et al., 2005).

Radiating and concentric fractures are also typical for trauma to the cranium and are often seen in ballistic wounds. Radiating fractures are running vertically from the impact site and radiate away from it, while concentric fractures form

perpendicularly to them. Analysing these fractures can help distinguish between entrance and exit wounds (Berryman & Jones Haun, 1996; Smith et al., 1987).

Typical fractures on long bones include false and double butterfly fractures (Martrille & Symes, 2019; Veenstra et al., 2022; Wedel & Galloway, 2014). False butterfly fractures are wedge-shaped fractures, which resemble the butterfly pattern created by blunt force trauma to long bones (Veenstra et al., 2022). A double butterfly fracture is more specific to ballistic trauma and describes two wedge-shaped fractures originating at the impact site and radiating away from it along the shaft (Martrille & Symes, 2019).

Most information regarding ballistic trauma to the ribs is derived from case studies including human remains found with directly connected ballistic evidence like bullets or casings next to them as well as gunshot residue on the ribs (Kimmerle & Baraybar, 2008). A study which focused on the ribs is the master's thesis by Aaron Caister. The thesis aimed to record the performance of ribs when impacted by different projectiles at a high velocity. It was shown that the bones react similarly to brittle material when the projectile hits with high velocity but presents different properties of an elastic, plastic and brittle material when impacted at lower velocities (Caister, 2018).

1.4 Aim & Objectives

There is little literature on the classification and identification of ballistic trauma to the ribs. Most literature focuses on long bones and crania; however, ribs have a different morphology and therefore show different patterns of trauma. The identification of ballistic trauma is difficult since there is not much material from experimental studies to compare with and draw similarities from. In human rights cases, it is often necessary to reconstruct the events leading to the death of the victims in order to prosecute the perpetrators and provide closure to the families. When no witness records or written documents are available, the only possibility to find answers is to analyse the remains and evidence connected to them. Anthropologists analyse the trauma and provide information on what could have

caused it, however, if the previous research is limited, the correct analysis is often difficult or impossible for some trauma patterns.

To provide a better insight into rib trauma patterns, an experimental approach was chosen, where pig ribs were placed in gelatine blocks as simulants for human hard and soft tissue. Two different firearms were used with different-sized ammunition and impact velocities. Further two distances were chosen to compare the damage from 3m and 10m. The trauma to the ribs was then recorded and analysed and the bones were reconstructed for better visualisation of the impact site.

This thesis aims to find patterns connected to ballistic trauma to ribs as well as specific patterns correlating with different calibres and distances to assist with identification by forensic anthropologists in human rights cases. This could help provide more accurate interpretations of trauma to the ribs and identify ballistic trauma in comparison to other types of traumata. The specific focus is on the visual assessment of the bones before and after reconstruction as well as the analysis of the smaller fragments resulting from the damage.

The objectives of this thesis are:

- To identify and characterise fracture patterns caused by ballistic trauma,
- To establish, which patterns provide the most conclusive evidence of ballistic trauma,
- To analyse whether the identification of ballistic trauma is possible from single fragments of ribs.

2 Materials and Methods

2.1 Sample Preparation

2.1.1 Cleaning

For the experimental setup, twelve *Sus scrofa* (pig) ribs were purchased from the local butcher and kept in the fridge for 72 hours until the cleaning. The bones were defleshed prior to placing them in the gelatine since a lot of fragmentation was expected and the cleaning process is easier with complete ribs. To properly be able to analyse the trauma, complete cleaning would have still been necessary before reconstruction. Figure 1a shows a rib rack as purchased before the cleaning, and 1b shows a rib after cleaning.

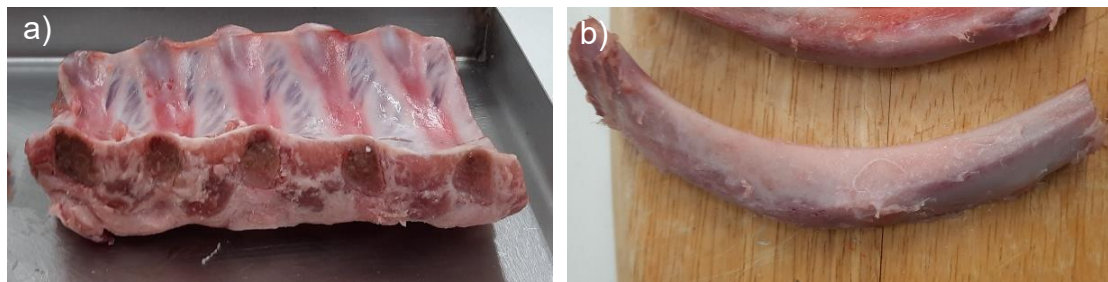


Figure 1 a) Photo of rib rack before cleaning, b) rib after cleaning

The ribs were chosen to be as similar to each other as possible to avoid differences in the injuries due to morphology, however, different ribs, depending on their location in the body will have slightly varying shapes. Preferably longer ribs were chosen to ensure the longest possible shaft for better visualisation of the defects caused by the bullets. Since the ribs all came from the same butcher and were purchased in racks it is reasonable to assume that biological variables were kept to a minimum since the ribs came from the same animal or at least from animals that were likely kept under the same conditions and were of similar age at the time of death. To clean as much of the flesh off the ribs as possible, scalpels were used. Best results were achieved by scraping down the long axis of the ribs.

2.1.2 Gelatine Preparation

The gelatine chosen for the experimental set-up was the Ballistic 1 gelatine from GELITA. It is a Type B gelatine with a gel strength of 250-290 g Bloom (GELITA, 2020). For the preparation of the gelatine block the instructions provided by the company were followed (Appendix B). 20 % gelatine was used as this is according to the NATO standard.

Due to animal bones and gelatine being used, the observed trauma could be different to trauma on human bones. However, the substitutes are accepted alternatives, which are widely used in the forensic field to conduct experimental research with ethical considerations (Mabbott et al., 2016). Further, no replacement for clothing or skin was considered during the firing. This could alter the results; however, the gelatine was used as a soft tissue substitute, which has a bigger effect on the trajectory and wound patterns than clothing and skin.

Two gelatine blocks (200mmx200mmx400mm) were prepared with each containing six ribs (Figure 2). The ribs were connected using string and lowered into the gelatine mould using a long metal rod. In order to prevent floating on the liquid gelatine, pieces of a metal rod were used to add weight to the ribs. Two ribs were placed over each other vertically with 110mm between them. Three ribs were placed in the block horizontally, so it is possible that the shots could have affected each other. This was avoided by placing the ribs at a distance from each other so that the temporary cavity of each shot was only affecting the gelatine and not transferring onto the surrounding bones.

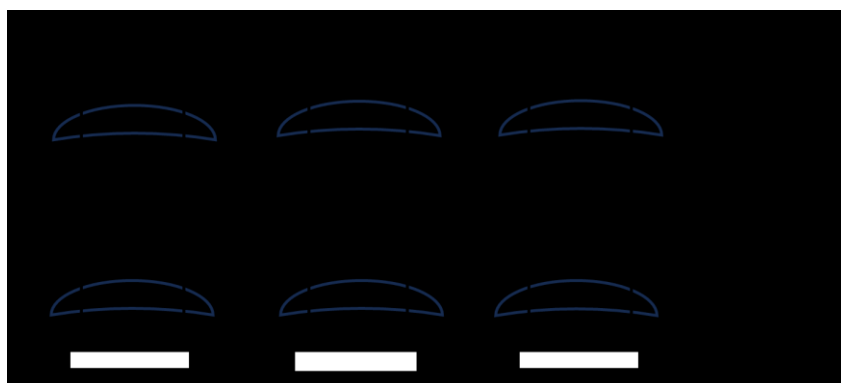


Figure 2 Schematic image of the positioning of the ribs in the gelatine block

The ribs were placed in the middle of the gelatine block and a uniform depth of 125 mm was kept for all soft tissue on the external rib surface. This distance, however, is greater than it would be in the average human body. This could have slowed the bullet down more than in a real-life scenario, however, it is reasonable to assume that the change in velocity and yaw of the bullet within the gelatine would not have been great enough to change the resulting trauma to the bones. For further experiments, it is recommended to adjust the distance to create more realistic settings.

The block was then left to set for 48 hours in a fridge at approximately 5°C.

2.2 Experimental Procedure

2.2.1 Firing

The firing took place at the SAER (Small Arms Experimental Range) at the Ministry of Defence site in Shrivenham using the Number 3 proof mount with the 9mm and 7.92 standard Mauser barrel with 9mm sk ptr m/39B and Mauser 7.92x57mm ammunition (Figure 3), as this ammunition was the most used by the German military during World War II (Bishop, 1998; *Janes: 7.92 x 57 Round*, 2018).



Figure 3 Photograph of ammunition used: 7.92x57 mm (left) and 9mm sk ptr m/39B (right)

The gelatine blocks were positioned at 3m and 10m from the mount and the mount was fired remotely using an electronic solenoid. To change the target between shots the block was moved and the laser on the mount was adjusted if necessary. A calibration shot was fired with both barrels for both distances before firing at the ribs. Figure 4a shows the proof mount with the Mauser barrel, and 4b shows the set-up of the gelatine block at the range.



Figure 4 Photos of **a)** the proof mount with the Mauser barrel, **b)** the set-up of the gelatine block at the range

The distances were chosen since during executions the victims were usually shot from distances of a few metres depending on the protocol which was followed (*Archive KZ Neuengamme, Interviews with Survivors*, n.d.; US War Department, 1944). The bullets were fired from the external to the internal side of the rib. Since the ribs were fresh and encased in gelatine at the time of the firing, the properties of wet bones were preserved, and the trauma can therefore be classified as perimortem.

Table 1 shows the overview of the fired shots with impact velocities and residual velocities where present.

Table 1 Overview of the fired shots with impact velocities and residual velocities where present

<i>Shot No.</i>	<i>Rib No.</i>	<i>Distance (m)</i>	<i>Calibre (mm)</i>	<i>Impact Velocity (m/s)</i>	<i>Residual Velocity (m/s)</i>
1	1.1	3	9x19	268.6	/
2	1.1	3	9x19	210.4	/
3	1.2	3	9x19	/	/
4	1.3	3	9x19	210.4	/
5	1.3	3	9x19	253.5	/
6	1.4	3	7.92x57	815.8	/
7	1.5	3	7.92x57	815.8	/
8	1.6	3	7.92x57	820.4	/
1	2.1	10	7.92x57	819.2	269.8
2	2.2	10	7.92x57	822.7	/
3	2.3	10	7.92x57	825.1	/
4	2.4	10	9x19	381.5	270.9
5	2.5	10	9x19	383.8	/
6	2.6	10	9x19	380.4	/

2.2.2 Data Collection

The Phantom v1212 High-Speed Camera was used to capture the firing. The footage was viewed using the Phantom Cine Viewer Application 3.8. The settings for the camera are shown in Figure 5.

Camera Version	25001 (Phantom v1212)
Serial	18519
Resolution	896 x 352
Acq Resolution	896 x 352
Post Trigger	12166
Bits per pixel	P10 (Packed 10 log)
Acquisition bpc	12
Sample Rate(fps)	37000 fps
	Real: 37004,4053 fps
	Period: 27,02 μ s
Exposure (μ s)	4,000
EDR (μ s)	0,000
Frame Delay (μ s)	0,000
Sync	Internal
AutoExposure	Off
Lens Description	-
Lens Aperture	-

Figure 5 Settings used for high-speed camera footage

However, not all shots could be captured since within a block of gelatine three ribs were positioned in a line behind each other. A back light was used to provide better lighting conditions and allow to film through the gelatine. Due to a combination of back light issues, gelatine transparency and rib arrangements not all temporary cavities were observable via High-Speed Video. To avoid this in future experiments it is recommended to cut the gelatine blocks so that each rib can be placed individually. This would also prevent the different shots from affecting each other. For the gelatine block set at 10m, the camera was positioned at a different angle, which showed the exit of the bullet from the gelatine. This allowed for a comparison of the temporary and permanent cavities but did not provide a complete view of the trajectory throughout the gelatine block. The temporary cavities could only be observed in the high-speed camera footage and the permanent track could also be seen in the gelatine after the firing.

The Doppler radar Weibel W700 was used to measure the impact velocity, which was varying between 200 and 400m/s for the 9mm ammunition and approximately around 820m/s for the Mauser rounds. It is unclear why there was a wide range in the velocities measured for the 9mm rounds. For the purpose of this thesis, it was enough to compare the high- and low-velocity firings of the 9mm and Mauser ammunition but for further studies it is advised to keep the velocities as similar as possible throughout the different settings. The residual velocities could mostly not be measured; however, the impact velocities were used for analysis.

After recording the bullet tracks within the gelatine by taking photographs, the ribs and small fragments were cleaned by removing the remaining gelatine and using scalpels to scrape off residual flesh. To remove the gelatine, the blocks were first cut into smaller pieces so that each rib was only surrounded by a small amount of remaining gelatine for transport from Shrivenham to the laboratory. To record the fragmentation of the ribs in situ the top layer of gelatine in front of the rib was cut off first with a scalpel and photos were taken using a phone camera and a forensic scale. After that, the rib could be removed by manually taking it out.

Then the bones were left under a fume hood at room temperature to dry for two days. To reconstruct the impact site, super glue was used, and the fragments were manually fixated. The liquid super glue by Bostik contains ethyl cyanoacrylate, which has been proven to work well as an adhesive on bones (Böker et al., 2019). The fragments, which were collected from inside the gelatine were compared to the edges of the rib and reconstructed as much as possible. Magnifying lamps were used for better visualisation.

Photographs of the reconstructed ribs were taken using the Imaging Lab facilities at the university. A Canon camera was used with a zoom lens for the best quality photographs. All analysis involving calculations were carried out in Excel.

3 Results

3.1 Soft Tissue Substitute

The temporary as well as permanent cavities caused by the 9mm calibre were smaller compared to the cavities caused by the Mauser rifle ammunition. Figure 6a shows the temporary cavity caused by a 9mm bullet shot at 3m missing the rib, while 6b shows the temporary cavity of another 9mm bullet at 3m which hit the rib, with the permanent cavity of the first shot partially visible above. The permanent cavities were also visibly different between the two calibres. The same observations were made as with the temporary cavities, as the Mauser ammunition produced a bigger permanent cavity. Figure 7 shows a comparison between the permanent cavity of the 9 mm bullet at the top and the Mauser bullet below it from a cross-section of the gelatine block both fired at 3m. 7a) shows the wound before and 7b) after the bullet hit the ribs. The arrows indicate the direction of the bullets.

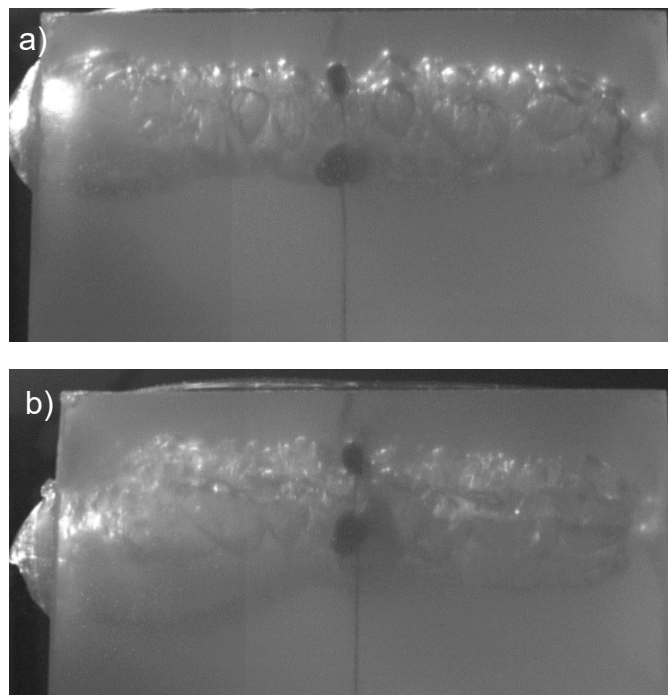


Figure 6 Footage from the HSC of the side view of the gelatine block right after the bullet passed through, the disturbance in the gelatine is the temporary cavity caused by a 9mm bullet **a)** Temporary cavity of a missed shot **b)** Temporary cavity of a bullet, which hit the rib

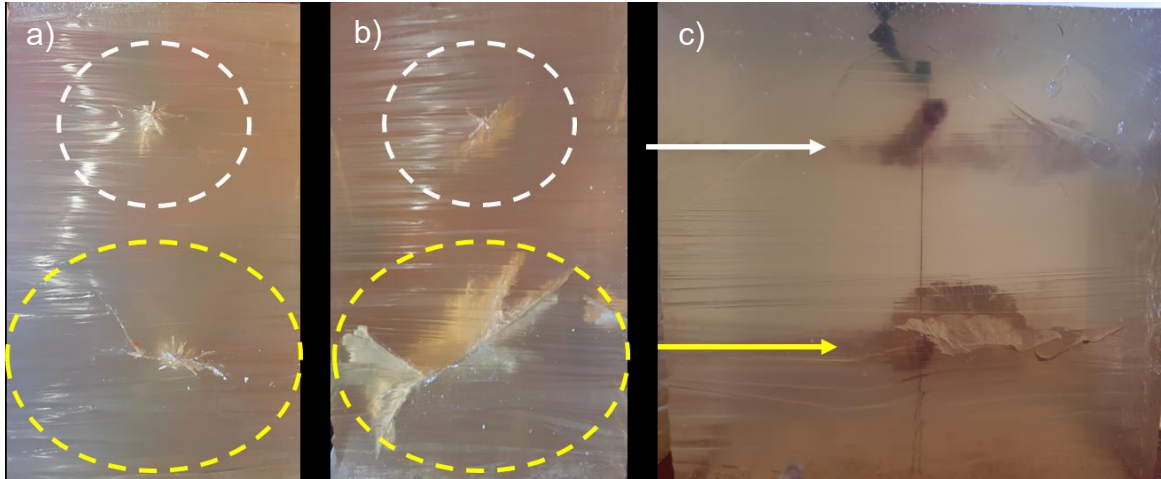


Figure 7 Photo of a cross-section of the gelatine block showing the permanent cavity of the 9mm bullet at the top (white) and the Mauser bullet below (yellow) **a)** before and **b)** after the bullet hits the rib **c)** side view of the ribs with arrows indicating the direction of flight

The yaw of the bullet changed after impacting the rib. Figure 8 shows a 9mm bullet fired at 3m before and after hitting the rib. When entering the gelatine, the bullet is still at the same angle as when it was fired. After coming in contact with an obstacle, in this case, the rib, the bullet is deflected and starts tumbling and rotating forward. This can cause more damage to the body since the surface area of the bullet, which is directly hitting the tissue, is larger.

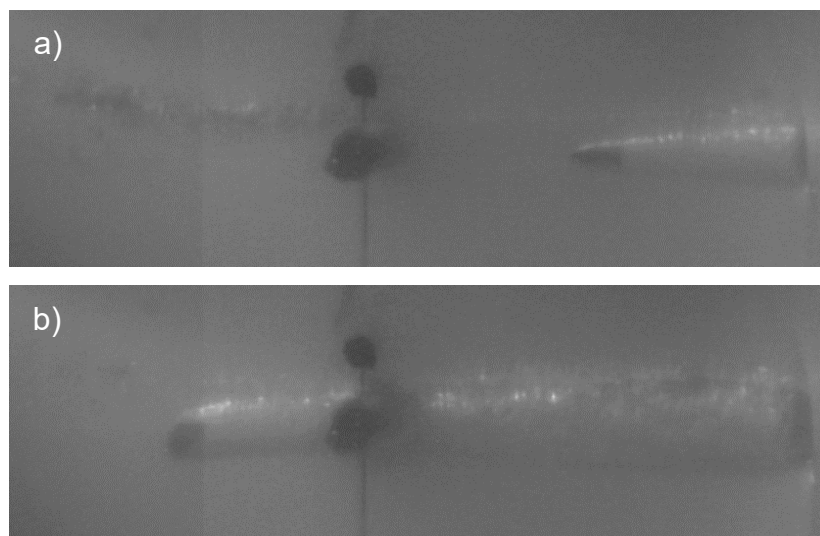


Figure 8 Photos of 9mm bullet within the gelatine block fired at 3m **a)** before and **b)** after hitting the rib

3.2 Individual Descriptions of Ribs

Each rib was analysed separately, and the findings were recorded by taking measurements and photographs of the trauma. All ribs were positioned the same direction in the gelatine block, so that the projectile passed through the main body of the bone from external to internal, simulating a shot to the chest with the victim facing the perpetrator. The descriptions of the individual ribs are listed below.

Consistent terms were used in the description to avoid confusion about the different parts of the ribs:

Vertebral half - the half of the rib which has the rib head and would be connected to the vertebral body in a real thorax.

Sternal end - the rib end which is closer to the front of the chest / the sternum.

Superior edge - the upper part of the rib facing towards the skull.

Inferior edge - the lower part of the rib facing towards the abdomen.

External surface – surface facing towards the exterior of the thorax / the skin

Internal surface – surface facing towards the inside of the body / the organs

Rib 1.1 (9mm, 3m)

The rib was impacted by the projectile in the central inferior part. Before the impacting shot, a projectile was fired which missed the rib superiorly. Three small bone fragments were collected, with a length ranging from 15 to 25mm. There was bevelling present around the exit wound. The bevelling on the vertebral half was measured to be 10mm and on the sternal half 15mm. A comminuted fracture was observed. There were linear fracture lines present: one on the superior edge and three on the vertebral half, originating from the entry wound. A fracture pattern resembling a double butterfly was present originating from the entry wound with two wedge-shaped fractures running towards the superior and inferior edges. A concentric fracture was observed on the internal surface of the rib. A

linear break originating from the exit wound on the internal surface was connected with an oblique fracture running towards the superior edge on the sternal half. Combined with another oblique fracture on the vertebral half they formed the edges of the largest fragment from the internal surface.

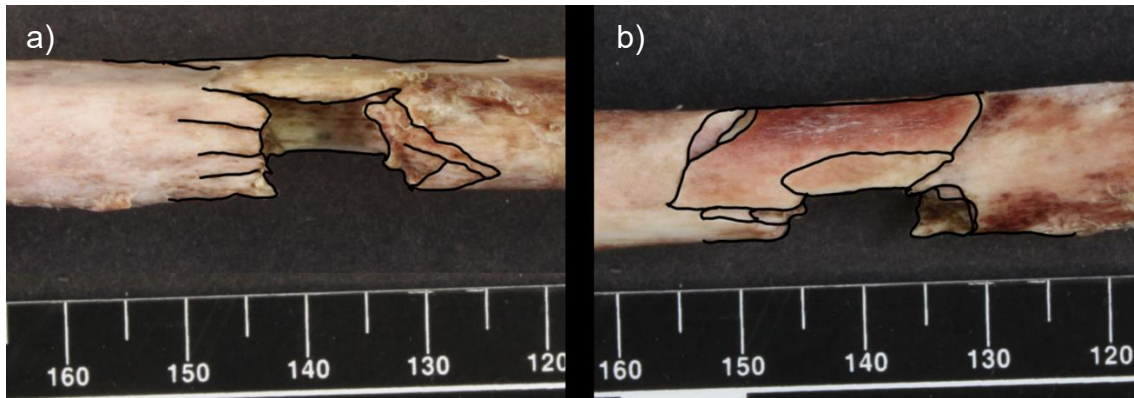


Figure 9 Photo of a) external side of rib 1.1 / entry wound, b) internal side of rib 1.1 / exit wound

Rib 1.2 (9mm, 3m)

The rib was impacted by the projectile in the central part. 13 small bone fragments were collected, with a length ranging from 5 to 34mm. There was bevelling present around the exit wound. The bevelling on the vertebral half was measured to be 25mm and on the sternal half 12mm. A comminuted fracture was observed. There were two linear fracture lines present on the internal surface of the sternal half. Fracture patterns resembling a double butterfly were present originating both from the entry and the exit wounds each with two wedge-shaped fractures running towards the superior and inferior edges. Concentric fractures were observed on the external and internal surfaces of the rib. One fracture on the superior and inferior side of the entry as well as exit wound combined to a total of four. A linear break originating from the exit wound on the internal surface was connected with an oblique fracture running towards the superior edge on the vertebral half. Combined with another oblique fracture on the sternal half they formed the edges of the largest fragment from the internal surface. Radiating transverse fractures originating from the entry and exit wounds running towards

the inferior edge of the rib further divided the fragments created by the inferiorly directed wedge-shaped fracture.

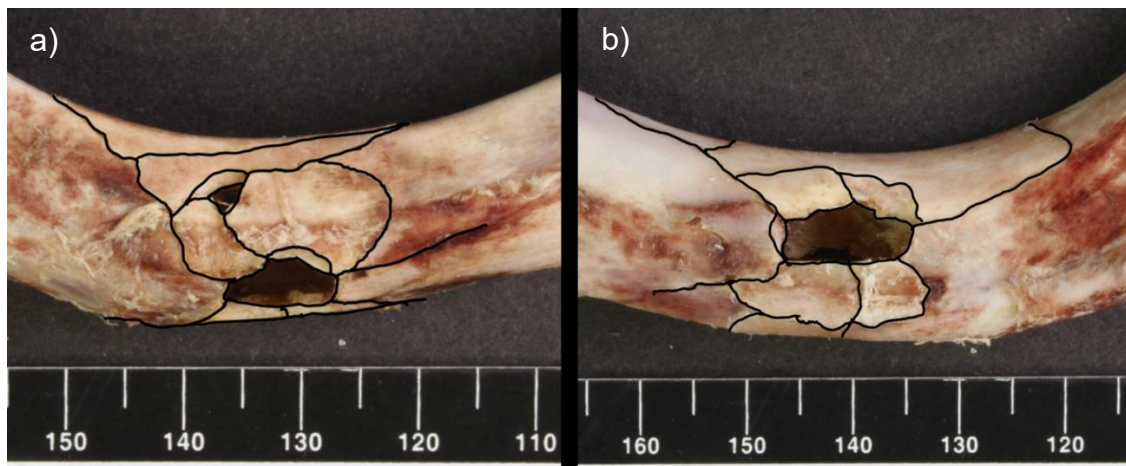


Figure 10 Photo of a) external side of rib 1.2 / entry wound, b) internal side of rib 1.2 / exit wound

Rib 1.3 (9mm, 3m)

The rib was impacted by two projectiles: once in the superior central part, and once in the centre to the left of the first shot. This is because, after the first shot, it was assumed that the bullet missed since no trauma was visible through the gelatine and the rib was shot at again. Figure 11 shows rib 3 within the gelatine with the two impact sites highlighted by white circles. Figure 11a shows the rib fully enclosed so that the impact is seen as a path through the gelatine, while Figure 11b shows the gelatine peeled off and making the damage to the rib visible.

Five small bone fragments were collected, with a length ranging from 8 to 16mm. There was bevelling present around the exit wound on the sternal end over 25mm, which was matched with the largest found fragment. A comminuted fracture was observed. There were two linear fracture lines present on the external surface of the sternal half. An oblique fracture around the entire rib on the vertebral half was present. Another oblique fracture around the sternal half was observed which was interrupted by a linear fracture on the external and

another linear fracture on the internal surface. During the reconstruction, it was not possible to connect the two halves since not enough fragments were recovered.

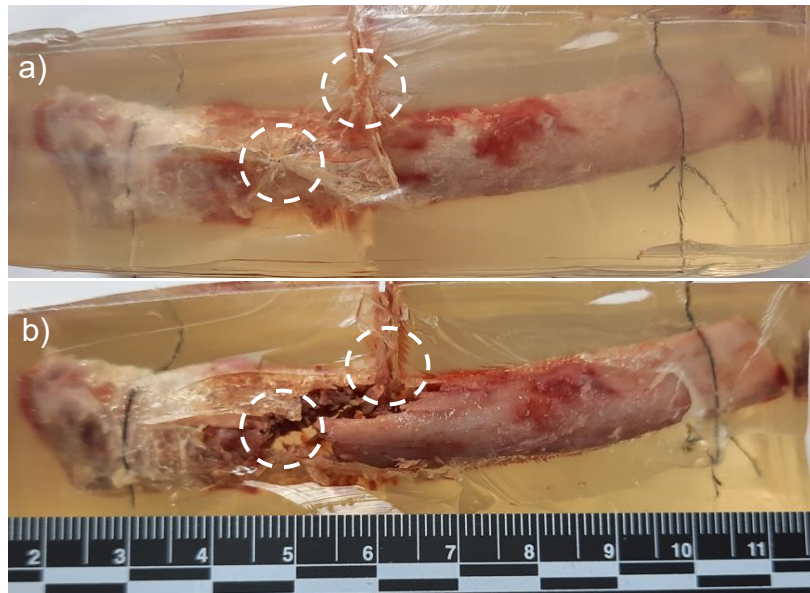


Figure 11 Photo of **a)** rib 1.3 showing the tracks of both shots through the gelatine with impact points marked by circles, **b)** the damage to the rib inside the gelatine with impact points marked by circles

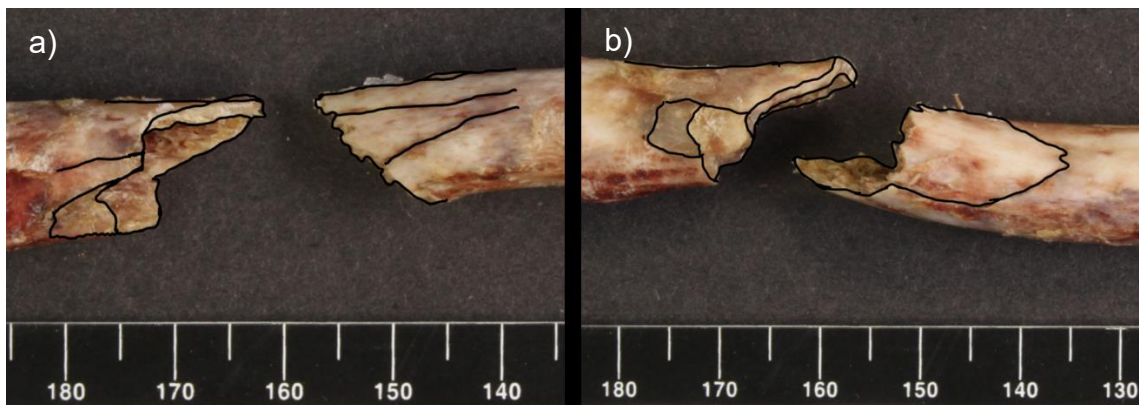


Figure 12 Photo of **a)** external side of rib 1.3 / entry wound, **b)** internal side of rib 1.3 / exit wound

Rib 1.4 (7.92x57mm, 3m)

The rib was impacted by the projectile in the central part. 26 small bone fragments were collected, with a length ranging from 3 to 19mm. One of the fragments was an entire segment that was reconnected to the sternal half. There was bevelling present around the exit wound. The bevelling on the vertebral half was measured to be 20mm and on the sternal half 13mm. A comminuted fracture was observed. There were two linear fracture lines present on the external surface: one on the vertebral and one on the sternal half. A transverse break on the segmental fragment was observed. An oblique fracture around the entire rib on the sternal half was present. Another oblique fracture was present around the internal surface of the vertebral half. This was interrupted by linear fractures which were caused by hinging of the bone. Wedge-shaped fractures were observed towards both the superior and the inferior edges on the external as well as internal surface of the sternal half which create a fracture pattern resembling a double butterfly. However, due to the heavy fragmentation, a certain determination of the pattern was not possible. During the reconstruction, it was not possible to connect the two halves since not enough fragments were recovered.

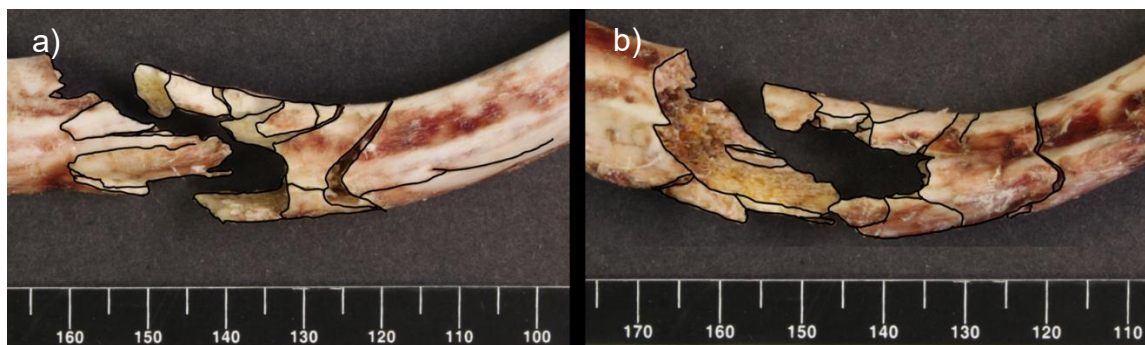


Figure 13 Photo of a) external side of rib 1.4 / entry wound, b) internal side of rib 1.4 / exit wound

Rib 1.5 (7.92x57mm, 3m)

The rib was impacted by the projectile in the central part. 12 small bone fragments were collected, with a length ranging from 4 to 15mm. There was no bevelling present around the exit wound. A comminuted fracture was observed. A fracture

pattern resembling a double butterfly was present originating from the entry wound with two wedge-shaped fractures running towards the superior and inferior edges. An oblique fracture around the entire rib on the sternal half as well as another oblique fracture around the vertebral half were present. Along the superior edge a combination of linear and transverse fractures formed square patterns on both halves. A linear fracture originating from the entry wound and stopping at the oblique fracture on the sternal half on the external surface was observed after reconstruction.

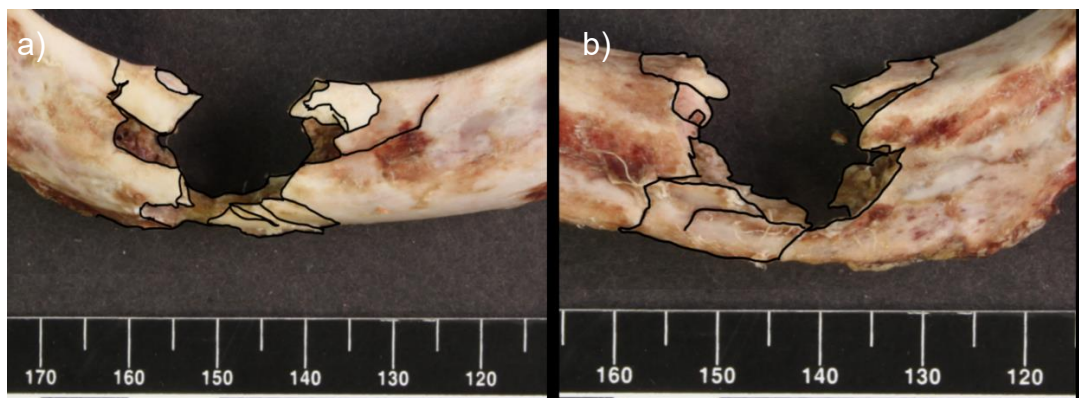


Figure 14 Photo of a) external side of rib 1.5 / entry wound, b) internal side of rib 1.5 / exit wound

Rib 1.6 (7.92x57mm, 3m)

The rib was impacted by the projectile in the central superior part. Eight small bone fragments were collected, with a length ranging from 6 to 25mm. There was bevelling present around the exit wound on the sternal end over 13mm. A comminuted fracture was observed. An oblique fracture around the internal surface on the vertebral half was observed, interrupted by a linear fracture on the external surface which was matched with the largest found fragment during reconstruction. Another oblique fracture around the sternal half of the rib was interrupted by a transverse and two linear fractures, which form a rectangular shape along the superior edge. Concentric fractures were observed on the internal surface of the rib.

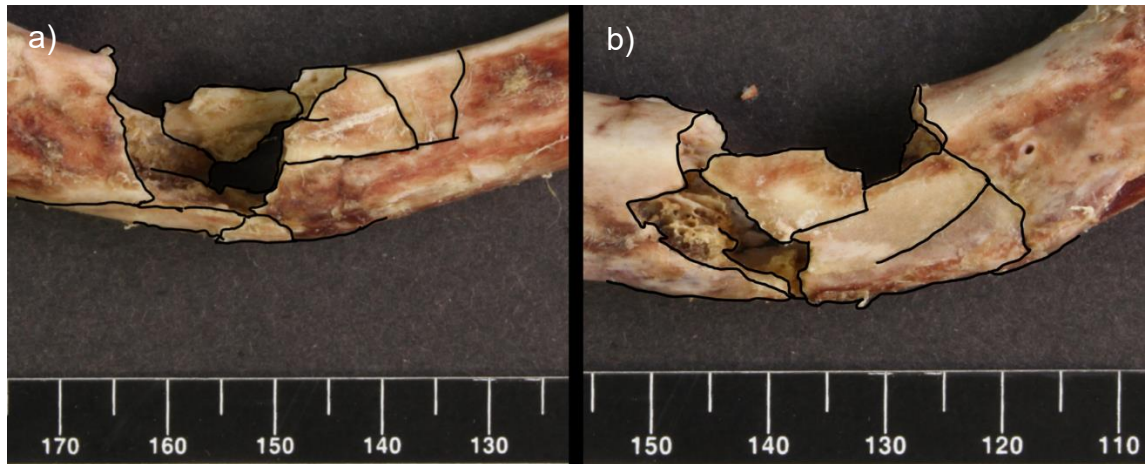


Figure 15 Photo of a) external side of rib 1.6 / entry wound, b) internal side of rib 1.6 / exit wound

Rib 2.1 (7.92x57mm, 10m)

The rib was not impacted by the projectile. The bullet missed the rib, passing superiorly through the gelatine. There was no comminuted fracture pattern and no small fragments present, however, the rib was broken in two halves. An oblique fracture pattern on the external side and a transverse fracture on the internal side were displaced, wrapping around the entire rib, and causing a full break. After closer analysis, a second oblique fracture line was observed forming a wedge-shaped fracture pattern with the displaced oblique fracture on the side opposing the origin of the force.

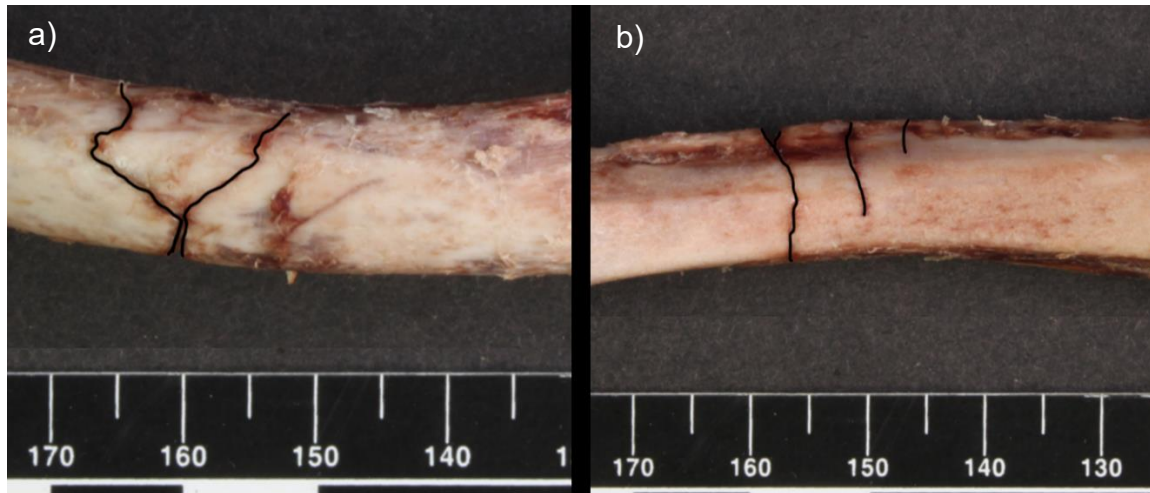


Figure 16 Photo of a) external side of rib 2.1 / entry wound, b) internal side of rib 2.1 / exit wound

Since the aim of this thesis does not focus on indirect ballistic injuries and only one rib was affected no further analysis was conducted, however, it should be noticed that the pattern was very distinct, therefore confirming that all characterisations made in this thesis are only applicable to direct shots at ribs.

Rib 2.2 (7.92x57mm, 10m)

The rib was impacted by the projectile in the central left part of the main body. Seven small bone fragments were collected, with a length ranging from 6 to 15mm. There was no bevelling observed around the exit wound. A comminuted fracture was present. There were two linear fracture lines present: one on the internal surface of the sternal half originating from the exit wound and one on the external surface of the sternal half originating from the entry wound. An oblique fracture around the entire rib on the vertebral half was present. Another oblique fracture around the sternal half was observed which was interrupted by a linear fracture on the external and another linear fracture on the internal surface connected by a transverse fracture across the inferior edge. A concentric fracture was observed on the external surface of the rib. A radiating transverse fracture originating from the exit wound running towards the inferior edge of the rib further divided the fragments created by the oblique fractures.

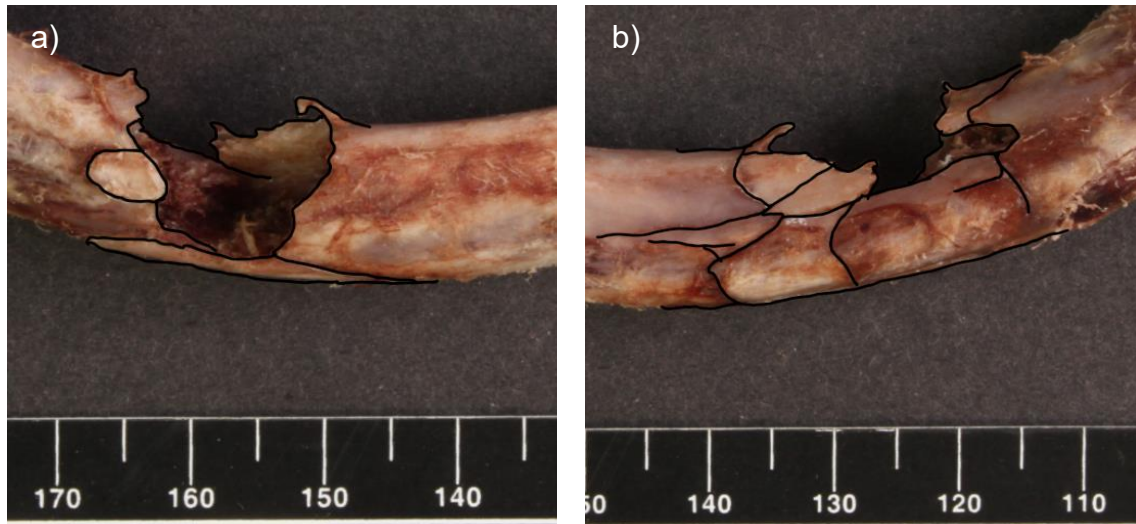


Figure 17 Photo of a) external side of rib 2.2 / entry wound, b) internal side of rib 2.2 / exit wound

Rib 2.3 (7.92x57mm, 10m)

The rib was impacted by the projectile in the central inferior part on the right side of the main body. Four small bone fragments were collected, with a length ranging from 8 to 24mm. There was bevelling present around the exit wound. The bevelling on the vertebral half was measured to be 10mm and on the sternal half 13mm. A comminuted fracture was observed. There were three linear fracture lines present: two on the internal surface of the sternal and the vertebral halves, and one on the external surface of the vertebral half. An oblique fracture around the external surface of the vertebral half was present, which was interrupted by two linear fractures on the internal surface connected by a transverse fracture. Another oblique fracture around the sternal half was observed, which was interrupted by two linear fractures on the internal surface connected by a transverse fracture as well as a linear and connected transverse fracture on the inferior edge. A linear break on the external surface of the sternal half originating from the impact site was observed.

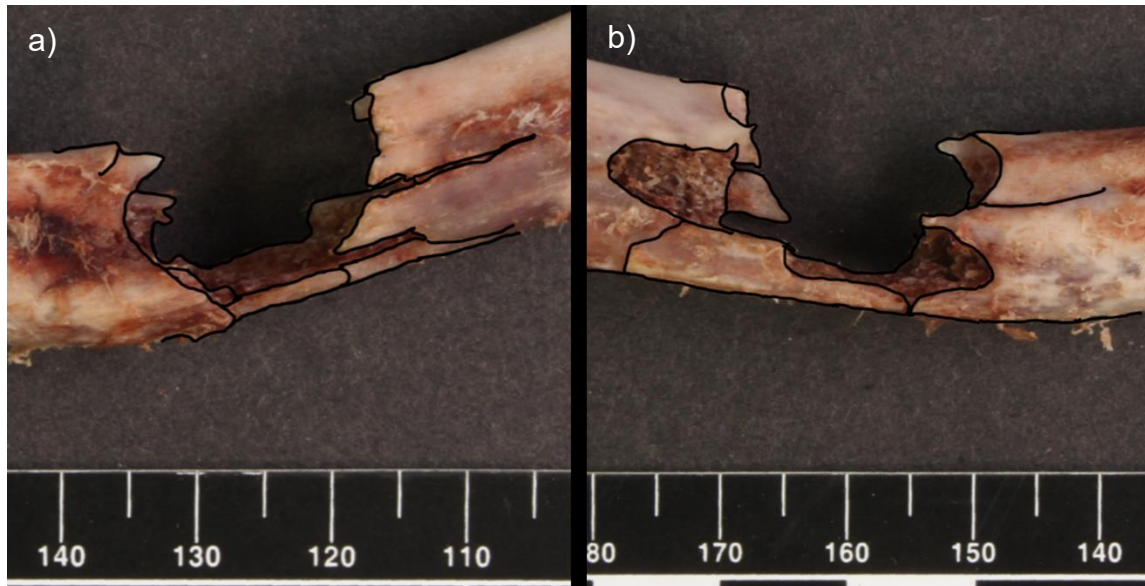


Figure 18 Photo of a) external side of rib 2.3 / entry wound, b) internal side of rib 2.3 / exit wound

Rib 2.4 (9mm, 10m)

The rib was impacted by the projectile in the central part on the right side of the main body. Seven small bone fragments were collected, with a length ranging from 6 to 15mm. There was bevelling present around the exit wound. The bevelling on the vertebral half was measured to be 14mm and on the sternal half 14mm. A comminuted fracture was observed. There were five linear fracture lines present on the external surface: two on the vertebral and three on the sternal half. Hinging is present on the external surface of the sternal half with a linear fracture dividing the hinging part of the bone. Another linear fracture line was observed along the superior edge on the sternal end. An oblique fracture around the external surface of the vertebral half was present, which was interrupted by two linear fractures on the internal surface connected by a transverse fracture. Another oblique fracture around the sternal half was observed which was interrupted by two linear fractures on the internal surface connected by a transverse fracture close to the superior edge.

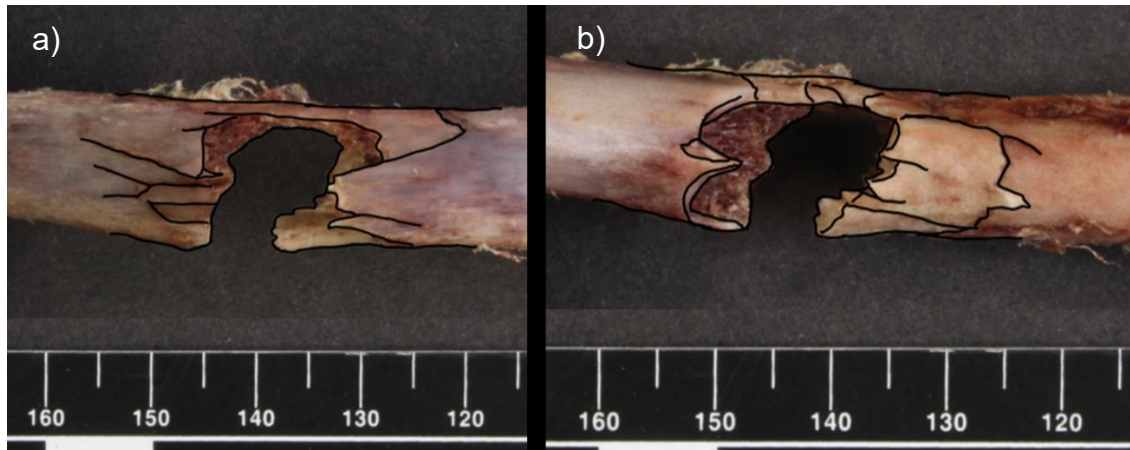


Figure 19 Photo of a) external side of rib 2.4 / entry wound, b) internal side of rib 2.4 / exit wound

Rib 2.5 (9mm, 10m)

The rib was impacted by the projectile in the central part on the right side of the main body. 13 small bone fragments were collected, with a length ranging from 8 to 15mm. There was bevelling present around the exit wound. The bevelling on the vertebral half was measured to be 14mm and on the sternal half 15mm. A comminuted fracture was observed. There were three linear fracture lines present on the external surface: two on the sternal and one on the vertebral half. Another linear fracture line originating from the exit wound on the internal surface of the sternal half was observed. Fracture patterns resembling a double butterfly were present originating both from the entry and the exit wounds each with two wedge-shaped fractures running towards the superior and inferior edges. However, the double butterfly pattern on the internal surface around the exit wound was only visible after reconstruction. Radiating transverse fractures originating from the entry and exit wounds running towards the inferior edge of the rib further divided the fragments created by the inferiorly directed wedge-shaped fracture. Concentric fractures were observed on the external and internal surfaces of the rib. One fracture on the superior and inferior side of the entry as well as exit wound combined to a total of four. Two transverse fractures were present on the internal surface: one on the vertebral and one on the sternal half.

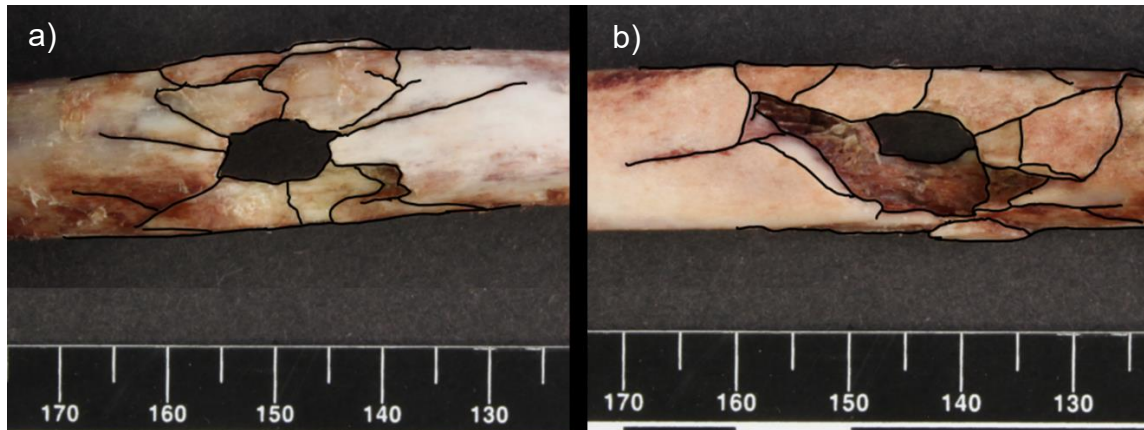


Figure 20 Photo of a) external side of rib 2.5 / entry wound, b) internal side of rib 2.5 / exit wound

Rib 2.6 (9mm, 10m)

The rib was impacted by the projectile in the central part. 12 small bone fragments were collected, with a length ranging from 4 to 22mm. There was bevelling present around the exit wound. The bevelling on the vertebral half was measured to be 14mm and on the sternal half 22mm. A comminuted fracture was observed. There were two linear fracture lines present on the external surface: one on the sternal and one on the vertebral half. Another linear fracture line originating from the exit wound on the internal surface of the vertebral half was observed. Fracture patterns resembling a double butterfly were present originating both from the entry and the exit wounds each with two wedge-shaped fractures running towards the superior and inferior edges. However, the double butterfly pattern on the internal surface around the exit wound was only visible after reconstruction. Concentric fractures were observed on the external and internal surfaces of the rib. One fracture on the superior side of the entry as well as exit wound combined to a total of two.

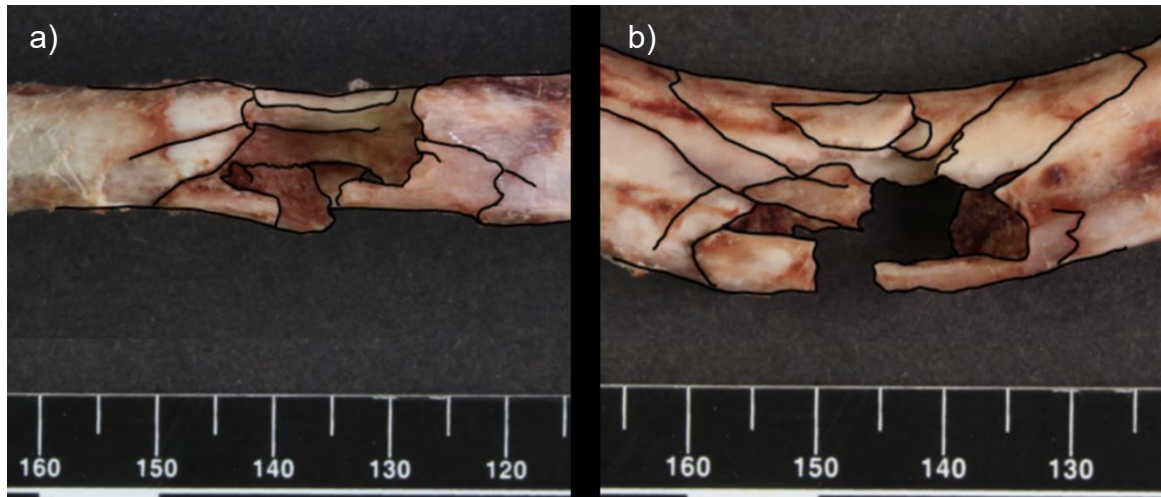


Figure 21 Photo of a) external side of rib 2.6 / entry wound, b) internal side of rib 2.6 / exit wound

Table 2 summarises the results of the primary analysis. Table 3 summarises the prevalence of fracture patterns recorded on the ribs.

Table 2 Summary of primary fragment analysis

<i>Distance + Calibre</i>	<i>Rib No.</i>	<i>Fragment No.</i>	<i>Fragment length (mm)</i>	<i>Bevelling vertebral (mm)</i>	<i>Bevelling sternal (mm)</i>
3m 9mm	1.1	3	15-25	10	15
	1.2	13	5-34	25	12
	1.3	5	8-16	X	25
3m 7.92mm	1.4	26	3-19	20	13
	1.5	12	4-15	X	X
	1.6	8	6-25	X	13
10m 9mm	2.4	7	6-15	14	14
	2.5	13	8-15	14	15
	2.6	12	4-22	14	22
10m 7.92	2.1	X	X	X	X
	2.2	7	6-15	X	X
	2.3	4	8-24	10	13

Table 3 Summary of fracture patterns observed after reconstruction

Distance + Calibre	Rib No.	Comminuted	Linear	Transverse	Oblique	Concentric	Double Butterfly (Entry)	Double Butterfly (Exit)
3m; 9mm	1.1	✓	1	X	2	1	1	X
	1.2	✓	1	2	2	4	1	1
	1.3	✓	2	X	2	X	X	X
3m; 7.92mm	1.4	✓	3	1	2	X	(1)	(1)
	1.5	✓	5	2	2	X	1	X
	1.6	✓	3	1	2	2	X	X
10m; 9mm	2.4	✓	4	2	2	X	X	X
	2.5	✓	X	4	X	4	1	1
	2.6	✓	X	X	X	2	1	1
10m; 7.92mm	2.1	X	X	1	1	X	X	X
	2.2	✓	2	1	2	1	X	X
	2.3	✓	4	2	2	X	X	X

3.3 Compiled Results

3.3.1 Fracture Patterns

Fracture Lines

All fracture lines present on the directly hit ribs followed the long axis of the bones leading away from the impact point on both sides. Further, the fracture lines appeared to be more clearly defined for the 9mm rounds and were very thin on the ribs shot with the Mauser rounds. Figure 22 shows the external view of the fracture lines coming from the impact site of a 9mm projectile fired at 10m.



Figure 22 Photo of the external view of the fracture lines coming from the impact site of a 9mm projectile fired at 10m (rib 2.6)

Entry and Exit Wounds

Especially on the bones hit by 9mm rounds semi-circular defects were seen before the reconstruction of the entry wounds. “Bullet wipe” was seen on some edges of the entry as well as exit wounds. In the ribs shot with the Mauser rounds the entry wounds were not defined, however, the 9mm rounds produced round entry wounds with a diameter of 9mm. The 9mm bullets left more rounded, clean edges, while the Mauser rounds left sharp, irregular edges.

Linear and Transverse Fractures

A pattern which was observed on the superior edge of the ribs was the combination of linear and transverse fractures at an angle close to 90 degrees. Figure 23 shows the superior view of the damage caused to rib 2.4 by a 9mm bullet at a 10m firing distance. The arrow shows the direction of the bullet, and the white circle highlights the pattern of connecting linear and transverse fractures along the superior edge of the rib.



Figure 23 Photo of the superior view of the damage caused to rib 2.4 by a 9 mm bullet at 10 m firing distance after reconstruction

Concentric Fractures

All concentric fractures were directed towards the superior and inferior edges and no fractures were observed along the main body of the shaft directed to the right and left of the impact.

Double Butterfly Fractures

In some directly hit ribs, a pattern similar to a double butterfly fracture was created on the external as well as the internal surface around the entry and exit wounds, however, the angle in the ribs lead to a more warped appearance where

the fragments showed a distinct shape depending on the part of the rib they were from. The fractures running toward the superior side of the rib had a wider opening angle and continued along the rib at the same angle. The fractures running toward the inferior side of the rib had a smaller angle, that cut off and continued along the rib as parallel transverse fractures on both sides of the impact.

Figure 24 shows the distribution of fracture patterns on the ribs.

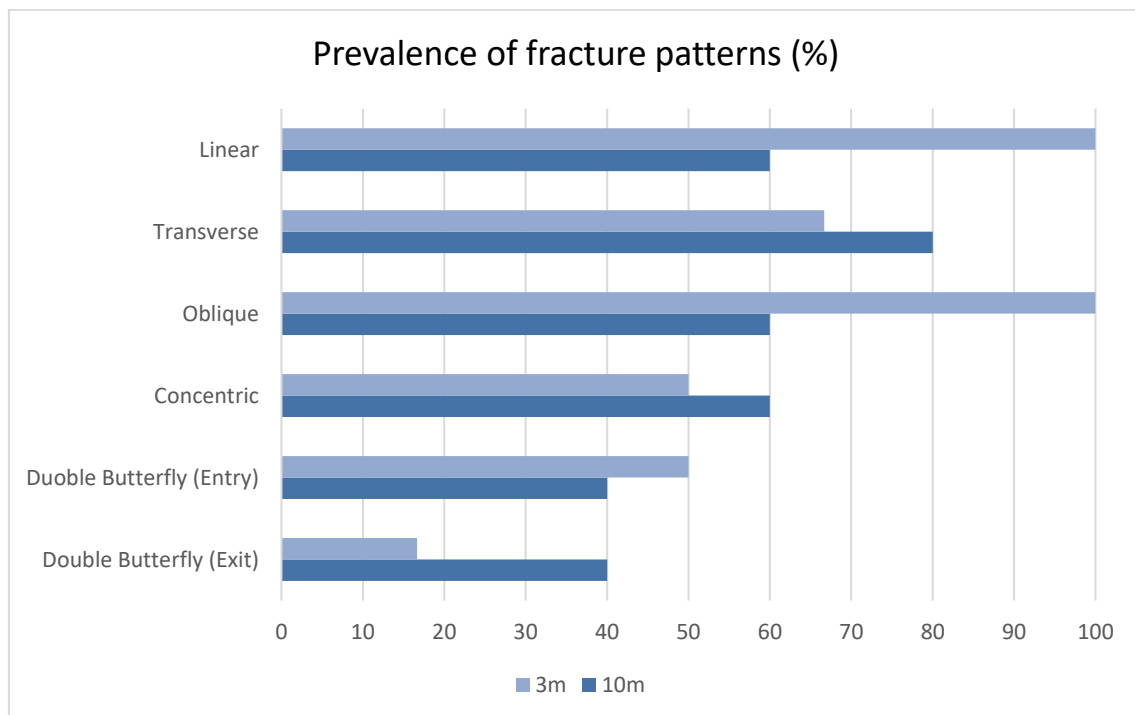


Figure 24 Graph showing the prevalence of fracture patterns across the ribs at 3m and 10m in %

It was observed that linear, transverse, and oblique fractures appeared to be the most prevalent fracture patterns, while the double butterfly pattern, especially around the exit wound, was less abundant. For the calculation of the prevalence in Figure 24 rib 2.1 was excluded since it had trauma from an indirect impact and showed a very different combination of fracture patterns.

Bevelling

The edges of the break on the bigger fragments of the ribs were more sloped for the low-velocity 9mm ammunition and cleaner for the high-velocity Mauser ammunition. This created the appearance of bevelling on the ribs shot with 9mm rounds. Figure 25 shows the internal surface of rib 1.1 before reconstruction, illustrating the bevelling around the exit wound. Some bevelling was present on all ribs after impact with the 9mm round, however, only 60% of the ribs impacted by the Mauser rounds showed bevelling. The ribs which did not have the pattern, had edges which were broken away equally on both sides of the rib, the entry as well as exit wounds.

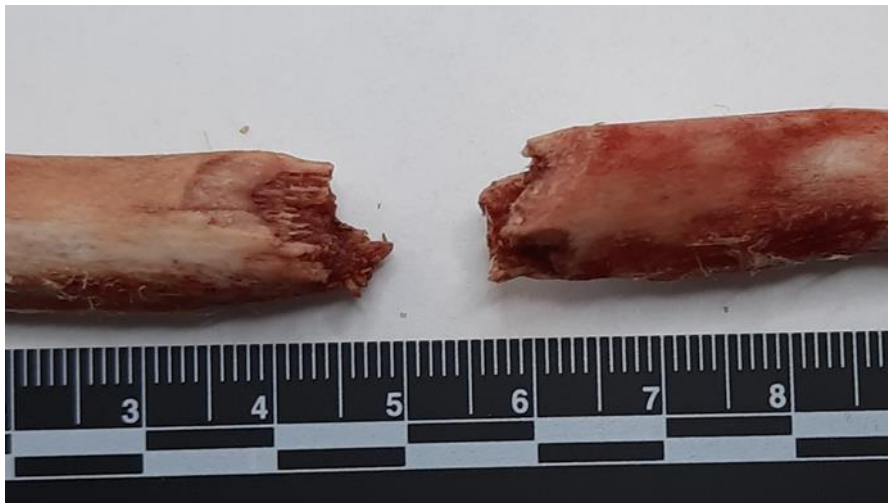


Figure 25 Photo of internal side of rib 1.1 before reconstruction showing the bevelling

3.3.2 Fragmentation

All ribs, with the exception of rib 2.1, were hit directly by the projectile and showed comminuted breaks with multiple fragments of different sizes. Figure 26 illustrates the distribution of the number of fragments produced by the firing with different settings, each bar represents a rib.

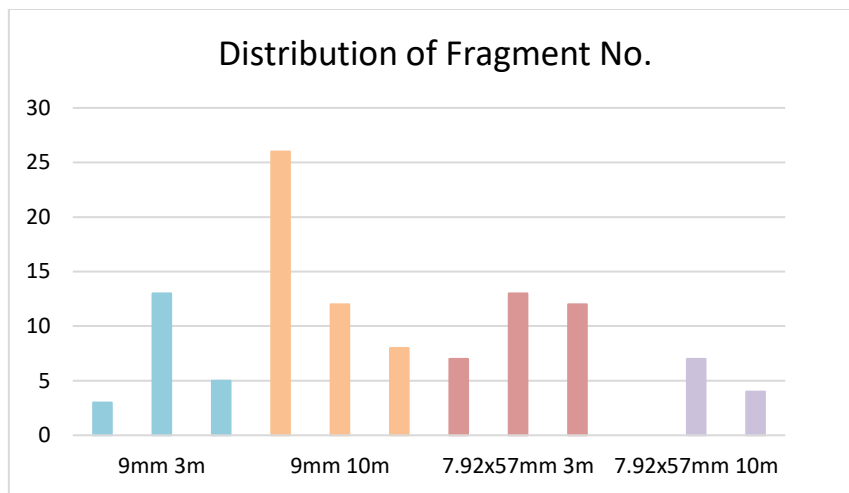


Figure 26 Graph showing the distribution of the fragment number between different calibres and distances

The average number of fragments for 9mm ammunition was 8.83, while for 7.92mm it was 11.4. The averages were also calculated for the two differences: 11.17 for 3m and 8.6 for 10m. Using the t-test ($p=0.05$), statistical analysis was conducted and the observed t-value for the two calibres was 0.51 showing there is no significant difference between the number of fragments produced by different calibres. The same test was repeated for the two distances and the observed t-value was 0.57 showing there is no significant difference between the number of fragments produced by different distances.

The length of all small bone fragments from the shots was within a range of 3mm to 25mm. This range was present throughout most comminuted fractures with the longest fragment recovered being 34mm from a shot with 9mm rounds at 3m and the shortest 4mm, present from a shot with 7.92x57mm at 3m and 9mm at 10m. Figure 27 shows the distribution of the minimal and maximal fragment lengths.

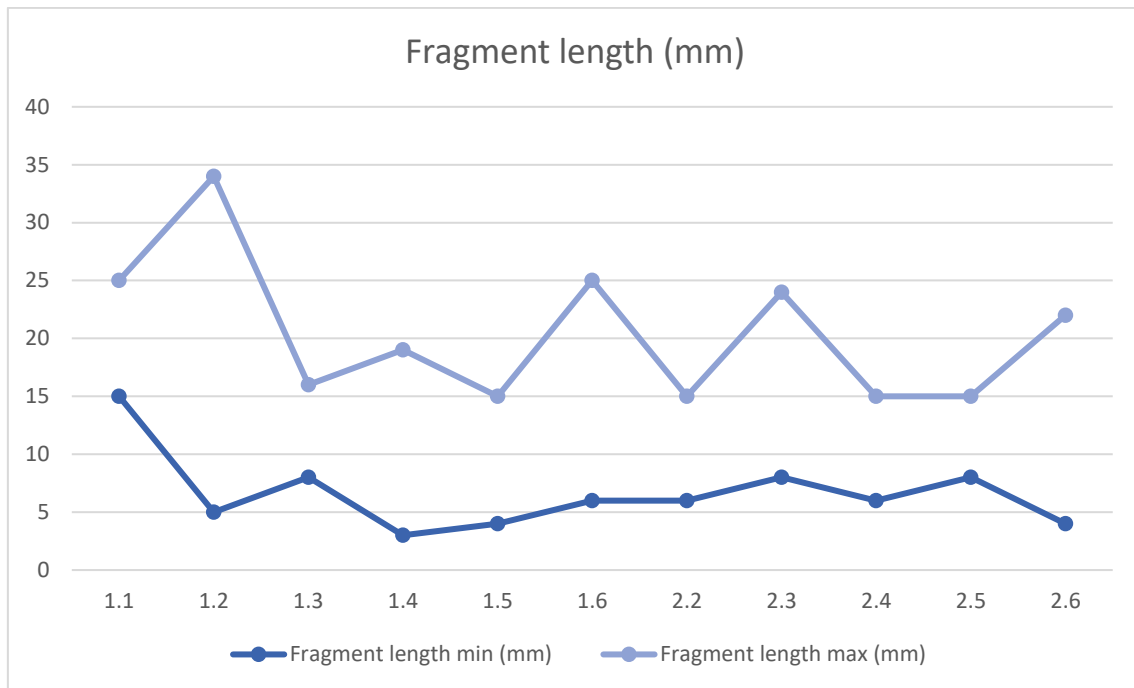


Figure 27 Graph showing the maximal and minimal length of the fragments collected for each rib (mm)

The shape of the fragments was mainly rectangular, often with sharp edges. Depending on where on the rib the fragment originated from, the form of the fragment could differ and help with reconstruction. It is important to mention that not all fragments could be recovered from the range since they were ejected out of the gelatine.

The superior edge broke away in a crescent-shaped fragment, which can be found as a whole or further fragmented into smaller pieces. The edges of the fragments appeared rectangular with rounded or squared edges and expanded beyond the diameter of the bullet. Due to the shape of the superior edge, the fragments have a thicker wall and sometimes broke around the angle of the edge making the reconstruction easier. The fragments from the inferior aspect of the rib had an arrow-like appearance on both the external and the internal surfaces pointing away from the impact point. The fragments tend to be thinner due to the structure of the cortical bone in the middle of the shaft and flat rather than angled. The fragments had a similar appearance coming from the external and the

internal side so reconstruction was more difficult, especially if many fragments were lost.

Figure 28 shows an exemplary overview of all fragments recovered after rib 2.6 was shot with a 9mm projectile at 10m. The white circle indicates a fragment from the superior edge of the rib, characterised by the thickness of the cortical bone. The yellow circle indicates a fragment from the inferior edge, identified by the arrow-like shape and flat cortical bone.



Figure 28 Photo of the overview of all fragments recovered after a rib (2.6) was shot with a 9mm projectile at 10m. The white circle indicates a fragment from the superior edge of the rib, and the yellow circle indicates a fragment from the inferior edge

Generally, more bone loss was observed in the bones shot with the Mauser bullets. During reconstruction, it was more difficult to reconnect fragments from ribs that were shot at with the Mauser rounds and the defects after reconstruction appeared bigger or the two halves could not be connected at all.

4 Discussion

All directly hit ribs showed a comminuted fracture pattern. Mostly linear, transverse, and oblique fractures were seen, however, double butterfly fractures appeared on some ribs, especially if the shot hit the shaft directly in the middle, allowing the fractures originating from the impact to spread along the flat surface of the rib before being diverted by the edges. The same observation appears to be true for concentric and radiating fractures since they require a larger flat surface to appear. The number of fragments showed no significant difference when establishing the calibre or distance used. The shape of the fragments could be used to help with reconstruction, however, since especially the external and internal surfaces have a similar cortical bone thickness it is not always possible to assign the fragments. Bevelling was present on all ribs shot with 9mm rounds, however only 60% of the ribs shot with the Mauser rounds showed characteristics of bevelling.

4.1 Soft Tissue Substitute

The temporary cavity was larger for the Mauser rounds because the 7.92mm ammunition was fired with a higher velocity and therefore had higher kinetic energy on impact. This means that more energy could be transferred to the tissue and therefore expand it further (DiMaio & Geberth, 2015). The difference in the size of the permanent cavity before and after hitting the bone with the Mauser round can be explained by the change of the yaw of the projectile and the sudden forceful fragmentation of the rib creating a bigger disruption of the soft tissue behind it.

The effects of the kinetic energy differences and change in the yaw are not always directly visible on one rib; however, it can lead to fractures on the adjacent ribs and therefore be seen in skeletal remains. However, since this thesis is focussing on the specific patterns caused by direct ballistic impact to the bone, the results connected to soft tissue damage were not further analysed.

4.2 Fracture Patterns

Fracture Lines

Linear fracture lines were present on most ribs originating from the entry as well as exit sites. This was confirming the assumption that the ribs used were still fresh, therefore showing patterns more similar to wet bone fractures since the presence of fracture lines has been previously associated with peri-mortem trauma (Byers, 2008; Wheatley, 2008).

Another characteristic of peri-mortem trauma is hinging (Blau & Ubelaker, 2016). If hinging is present, it is indicative of trauma to the wet bone because bones as fragile as ribs break easily especially when dry. Hinging can be present in ballistic trauma caused by projectiles, as seen on rib 2.4, however, since ribs are more fragile than long bones, the damage is more severe, and the bones are less inclined to hinging as the cortical bone is thinner and therefore gives in and breaks faster.

Entry and Exit Wounds

If the impact site is not identifiable as such by the presence of a round entry defect or “bullet wipe” around the edges it is still possible to identify the trauma as caused by a high-velocity projectile. Some patterns can be attributed to ballistic trauma and allow identification as well as a better analysis of it. However, since most of the bone that was in contact with the bullet itself was lost, the absence of the bullet wipe cannot be used as evidence of the absence of ballistic trauma.

The exit wounds were rather irregular, and bigger and did not show a defined round projectile pattern like the entry wounds. This finding is similar to the results of a study analysing ballistic trauma to crania and its characteristics, where it was observed that exit wounds presented in more different shapes and were more irregular than entry wounds (Quatrehomme & Işcan, 1999).

If full reconstruction is possible it can help with differentiating between large and small calibres by measuring the diameter of the entry defect in crania as well as long bones (Berryman et al., 1995; Phillips, 2022). Although especially in the ribs

shot with the Mauser rounds the entry wounds were not well defined, however, the 9mm rounds produced bullet holes with a diameter of 9mm, so that just the presence of an entry wound appears to be indicative of a low-velocity bullet. Even after the reconstruction of the ribs hit with the Mauser rounds, defined entry wounds were not visible, making a measurement of the diameter impossible.

The edges of the two bigger halves showed differences in their appearance between the two calibres used. The high-velocity Mauser ammunition caused rather sharp edges, while the ones caused by the low-velocity 9mm calibre had a more rounded appearance. This result agrees with findings from a previous study, which showed that when impacted at lower velocities the ribs showed more elastic properties while higher velocity impacts caused the ribs to perform as brittle material (Caister, 2018).

Linear and Transverse Fractures

The combination of linear and transverse fractures has a similar pattern to step fractures connected to heat-induced trauma (Schmidt & Symes, 2015). However, heat-induced step fractures are usually incomplete fracture lines rather than actual breaks of the bones which create fragments (Mata Tutor et al., 2021).

Typical Cranial Bone Fractures

Fractures similar to the radiating and concentric fractures on the skull were visible around the entry and exit wounds. This is most likely due to the similarities in bone structure since both ribs and the skull are flat bones with thin layers of compact bone around spongy bone without a marrow cavity. The skull has a bigger surface area, so that the fractures can expand further around the impact wound, while the ribs only have a small flat area where the fractures can expand around and the edges stop the spreading. The surfaces of the ribs are small and the diameter of the bullet impacts most of the vertical area, not leaving much space for the fractures to expand before being stopped by the edges. Further, concentric fractures were only recorded if the fragments were collected and could be reconstructed showing the specific rounded pattern of a concentric fracture. A

limitation of this is that the analysis of the prevalence of these fractures is skewed depending on the number of fragments found.

The radiating fractures scatter in all directions away from the impact, however, most of them appear to be running towards the superior and inferior edges of the ribs. The concentric fractures are present as bigger and smaller variants on the flat surfaces of the rib externally and internally. Figure 29 shows the pattern in the reconstructed rib 2.6, shot with a 9mm bullet at 10m with black lines enhancing the fracture pattern in comparison with a fracture on a skull, which was drawn and presented on a globe as a substitute.

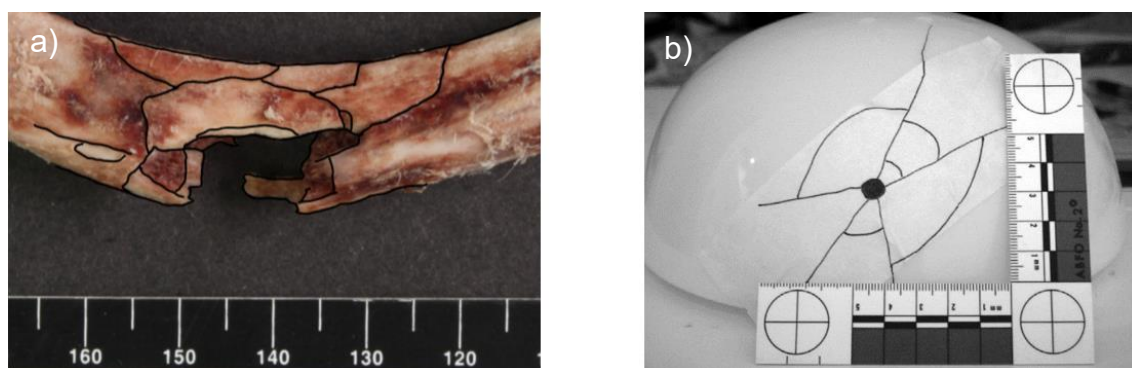


Figure 29 a) Photo of rib 2.6 shot by a 9mm bullet at 10m, the break pattern was traced for better visualisation, **b)** Photo of a break pattern to a skull drawn on a globe (Martrille & Symes, 2019)

Typical Long Bone Fractures

At the same time, there were patterns present that are usually seen in long bones such as false butterfly and double butterfly fractures (Kieser et al., 2014). Even though the appearance was slightly more warped than is usually the case on long bones, the double butterfly fracture was visible and distinguishable as such after reconstruction. However, this pattern was more difficult to observe when only fragments were present. The similar shapes of ribs and long bones allow for a pattern to be comparable after similar trauma causing a defect in the bone. Although this pattern was not present in all bones, it is reasonable to use its

presence as an indicator of ballistic trauma, however, the absence of it does not identify a different type of trauma and more characteristics need to be analysed.

There were fracture patterns observed which were resembling the cone of percussion that is often found in ballistic trauma on long bones (Rich et al., 2005; Veenstra et al., 2022). This result agrees with a previous study, which has shown similar patterns from ballistic trauma to the ribs using different projectiles (Caister, 2018). Figure 30 shows a comparison of a schematic drawing of the cone of percussion pattern next to ribs 2.2 and 2.3, which were both shot with a 7.92mm calibre at 10m.



Figure 30 a) Schematic image of a cone of percussion trauma in long bones (Veenstra et al., 2022), b) superior view on rib 2.2, c) superior view on rib 2.3

Bevelling

Although in previous literature it was stated that bevelling on crania is not reliable to conclude the direction of the projectile (Quatrehomme & İşcan, 1998), in this study the bevelling only occurred around the exit wound on the ribs or was not present at all. It is reasonable to assume that due to the different shape of the ribs compared to the skull, the bone is less likely to break away and create bevelling around the entry wound. Therefore, the presence of bevelling could be

used to determine the direction of the projectile in ribs, however more research is needed.

Indirect Trauma

Especially the trauma caused by the indirect shot was very similar to blunt force trauma (Hipp & Hayes, 1998; Prins et al., 2020; Wedel & Galloway, 2014). No impact defect was present since the bullet did not come in contact with the rib and a false butterfly fracture was visible on the opposite side to where the energy from the bullet impacted the rib. The temporary cavity likely expanded around it and the energy was transferred onto the bone causing high pressure to the side closer to the bullet. The fracture pattern is most similar to a transverse fracture with a partial wedge described in a previous study connected to blunt force trauma to long bones (Reber & Simmons, 2015).

This makes identification difficult since it can easily be mistaken for blunt force trauma without further evidence. In such cases, it can be helpful to analyse adjacent ribs or other bones and check for ballistic trauma since the ribcage is usually affected on more than one bone. This could also be the case with blunt force trauma, however, if a projectile hit the thorax, it likely hit or scraped at least one bone due to the proximity within the thorax leaving evidence of ballistic impact.

4.3 Fragmentation

Due to the nature of the burials, it is usually not possible to collect all fragments of the ribs from the burial site, especially if the grave has been robbed. This makes reconstruction difficult and there is only a limited amount of information that can be used for the identification of trauma. Since with ballistic trauma, most breaks are comminuted and produce many small fragments of different sizes, a reconstruction of the complete rib is often not possible. This is why it is important to define characteristics that can be seen on single fragments to identify ballistic trauma to the ribs.

The number of fragments varies between different shots. If the outlier, which is the indirect shot, is excluded, the number varies from 5 to 26 fragments. The outlier was chosen since the indirect shot has a very different fracture pattern compared to the direct shots. There does not appear to be a trend, and the statistical analysis showed no significant difference between the number of fragments when using different calibres or distances. This corresponds with results from a similar study on long bones (Phillips, 2022). In real-life scenarios, the number of fragments is often difficult to compare, especially when it comes to small fragments under 1cm². These fragments are often lost or discarded during sieving of the soil.

The shape of the fragments can provide information on the origin of the fragment and allow reconstruction as well as interpretation from the fragments alone. Due to the irregular form of the rib, depending on the part, the structure of the cortical bone can change and create different shapes.

Generally, it is difficult to interpret trauma from small fragments, however, the presence of long pieces of bone with a lunate shape indicates ballistic trauma since this is the fragment pattern created by the warped double butterfly fracture. For this pattern to occur from a normal butterfly fracture following blunt force trauma, the impact would have to come from the inferior to the superior side of the rib and have enough energy to displace the fragment in question. A previous study has shown that a fragment with a lunar/convex shape has a positive statistical association with the nonimpact side of the bone (Reber & Simmons, 2015). Figure 31 compares a fragment collected within the gelatine and an image from a fragment recorded in the study regarding blunt force trauma to long bones.

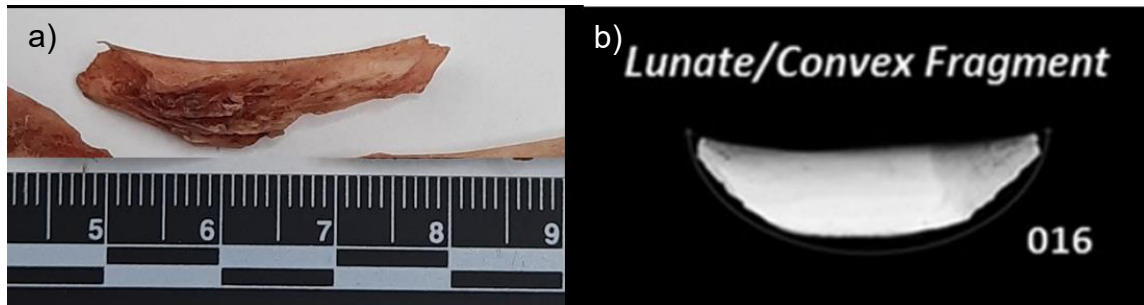


Figure 31 a) Photo of largest fragment from rib 1.2, b) Image of a lunate/convex fragment (Reber & Simmons, 2015)

When many small fragments are present, it is usually indicative of ballistic trauma, since more kinetic energy is transferred by a high-velocity projectile than by blunt force. This is also the case when bevelling is present on the bigger fragments. Due to the projectile moving through the body and pushing at the bone with high energy, which is transferred onto the bone and radiates away from the impact site, weakening the bone in a cone shape. Bevelling appears to be mostly present in the damage caused by the low-velocity firearm. This is most likely due to the fact that the higher velocity projectile does not leave enough time for the bone to break away due to the transfer of kinetic energy but rather destroys it by physically breaking the tissue.

The higher amount of suspected bone loss in ribs shot with Mauser rounds is likely to be connected with a higher impact velocity, therefore causing more damage, and transferring more energy onto the small bone fragments, which are then ejected out of the soft tissue (DiMaio & Geberth, 2015).

4.4 Summary of Characteristics

After the analysis of the results, it can be concluded that the identification of ballistic trauma to the ribs is possible from a visual assessment of the fractures. There are also patterns that can help differentiate between calibres and distances, however, a positive identification would not be possible from the examined features. The presence of a round defect as an entry or exit wound as

well as “bullet wipe” is the most apparent feature that can be used to identify ballistic trauma. However, this is often not present, so other patterns need to be analysed in order to interpret the trauma correctly. A double butterfly fracture is also indicative of ballistic trauma in ribs. Although not always present, it does not resemble a pattern observed by other trauma types, therefore, being unique to high-velocity trauma. This pattern further creates features on the big as well as small bone fragments which can be used for identification if not enough bone is present to reconstruct it. The combination of linear and transverse fractures on the superior edge is present where the wedge-shaped fragment on one side of the double butterfly breaks away. This also creates a lunate fragment, which can occur in blunt force trauma, however, due to the direction of the force necessary to cause this, it is more likely to be indicative of ballistic trauma if it is observed on the superior edge. Additionally, if bevelling is present, it can help identify the direction of the projectile through the body.

4.5 Limitations

For this study, no body armour was added to the experiments. This was omitted since ballistic trauma to the chest was mainly caused by executions, which were rarely carried out on the battlefield. Since mostly civilians were executed, no body armour would have been worn by the victim at the time of the firing. However, if comparing the results of this study to real trauma found in soldiers, it needs to be considered as a factor, which would change the appearance of the trauma and would not allow for accurate comparison with the results described here.

A possible limitation was that two shots were missed at ribs 1.1 and 1.3 in Block One during the first firings. This was noticed at the range and the firing was repeated, however, it is possible that the first shots could have caused indirect damage to the bones, and this, therefore, could have altered the resulting pattern. Especially rib 1.3 appears to have fracture patterns correlating to two bullets hitting the rib in two different locations, which are consistent with the two fired bullets and their track within the gelatine. This needs to be considered within the

analysis of the results to interpret the trauma most accurately. The trauma observed on rib 1.3 appears to have been caused by two projectiles hitting the bone. Since the gelatine was not fully transparent it can sometimes be difficult to see if the projectile missed the rib or not, which lead to a repeated firing to the bone. Due to two different points of impact, the fracture patterns were likely changed, and more bone loss was observed. The fractures from the second shot could not fully continue around the bone because it was stopped by the fractures from the first impact.

The different ammunition used in this thesis also had different impact velocities, which introduced an additional variable. However, this is due to the fact that different ammunition is used for different types of firearms, which also correlates to the velocity reached by the bullets. Therefore, the size of the ammunition is usually correlating to the impact velocity.

Finally, only two different calibres were used in this study with a relatively small sample size. For the purpose of this thesis, it is sufficient, however, it does not provide enough data to differentiate between other calibres and distances. The utilized calibres were the most abundant in the German military during World War II but were also often used in other humanitarian conflicts like the Spanish Civil War, therefore providing an experimental study which is applicable to a wider variety of real cases.

5 Conclusions

This thesis aimed to find patterns connected to ballistic trauma to ribs as well as specific patterns correlating with different calibres and distances to assist with identification by forensic anthropologists working in human rights cases and allowing a better interpretation of events. Since ribs are not widely analysed in the literature yet and the trauma is often difficult to interpret due to a lack of research to compare the damage to, the purpose of this study was to compile a number of characteristics to distinguish ballistic trauma and provide a more accurate interpretation of it. The results showed that ballistic trauma to the ribs produces patterns, which are already known in the literature in connection to other bone types, however, due to the shape of the ribs, fracture patterns which are a combination of known patterns to the skull and long bones are present. Since the shape of the ribs is more similar to long bones like the femur and the structure is more comparable to the skull, it was expected and confirmed that both fracture patterns are present. The results are consistent with previous literature and confirm former findings.

To provide answers to the research questions, an experimental approach was chosen, where pig ribs were placed in gelatine blocks as simulants for human hard and soft tissue. Two different firearms were used with different-sized ammunition and impact velocities. Further two distances were chosen to compare the damage from 3m and 10m. After the experimental shooting at the range, the trauma observed on the ribs was recorded, and analysed and the bones were reconstructed. The reconstruction was conducted using photographs of the ribs within the gel and by comparing the edges of the fragments to connect them by matching them physically. During the analysis, multiple patterns were observed and recorded. Differences in soft tissue damage were seen, however, as this study is focusing on hard tissue trauma the results were not further analysed. Two ribs had to be analysed separately since one was not hit directly by a projectile but showed patterns of indirect trauma and the other showed impact sites of two separate bullets since the firing was repeated after assuming that the first bullet did not hit the target due to the limited transparency of the gelatine.

In summary, multiple characteristics of ballistic trauma to the ribs were observed:

- Typical break patterns for ballistic trauma include bevelling around the exit wound and round entry defects, as well as fracture lines originating from the point of impact and continuing across the long axis of the rib.
- The appearance of the edges can help estimate the calibre used, especially when determining between high- and low-velocity firearms.
- The number of fragments is not correlated with the calibre used or the distance it was fired from. However, the shape of the fragments can be used for analysis since the crescent-shaped fragment appears to be indicative of ballistic trauma.
- Due to the high fragility of the ribs, accurate identification of calibre without reconstruction might not be possible for most ballistic trauma. However, the direction of the bullet can be detected from the breakaway of the bone. Since more bone is lost around the exit wound, the identification of the bullet path is made by following the defect on the bone from less to more bone loss.

Without direct ballistic evidence, it is not possible to positively conclude a calibre from the trauma, however, an approximation can be made by visual assessment, especially regarding the differentiation between low-velocity and high-velocity firearms like handguns and rifles respectively. The distances did not show any significant differences. Further research is necessary to confirm and expand on the findings and provide a better overview of patterns, which allow identification and differentiation of ballistic trauma.

5.1 Further Research

Arising from the findings of this study there is a number of recommendations for future research:

- The missed shot to one of the ribs suggests that the patterns caused by indirect ballistic trauma are different to direct trauma. This is also known in the wider literature; however, no specific description and characterisation is available. Further research into differences between direct and indirect shots, specifically to the ribs would provide anthropologists with a better ability to identify ballistic trauma and reconstruct the events leading to the death of the victims. Especially the similarities between indirect ballistic and blunt force trauma should be studied, characterising patterns which could differentiate between them.
- Based on the aforementioned limitations it is recommended to adjust the experimental procedure for future studies to achieve the most realistic results, while also considering ethical limitations regarding the use of human material. The methodology can be used and adapted for the study of other calibres and distances and applied to different humanitarian cases.
- Additionally, the findings can be compared to real trauma found in remains from known ballistic incidents and a study of significance and applicability can be conducted.

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APPENDICES

Appendix A Ethical Approval Letter



25 May 2023

Dear Ms Ellenberg ,

Reference: CURES/18759/2023

Project ID: 21892

Title: Comparing ballistic trauma to the ribs caused by two commonly used guns by the German military during World War Two to establish whether a differentiation can be made based on the observed trauma and if an identification of the cause is possible

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/18759/2023 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team