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Applications of micro-CT in the Criminal Justice System of England and Wales

An impact assessment

by

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Declaration of previously used material

Publications:

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Baier, W., Mangham, C., Warnett, J. M., Payne, M., Painter, M. and Williams, M. A. (2019) Using histology to validate micro-CT findings of trauma in three post-mortem samples- First steps towards method validation. *Forensic Science International*. 297, pp. 27-34.

Baier, W., Warnett, J. M., Payne, M. and Williams, M. A. (2018) Introducing 3D printed models as demonstrative evidence at criminal trials. *Journal of Forensic Sciences.* 63(4), pp. 1298-1302.

Baier, W., Norman, D. G., Warnett, J. M., Payne, M., Harrison, N. P., Hunt, N. C., Burnett, B. A. and Williams, M. A. (2017) Novel application of three-dimensional technologies in a case of dismemberment. *Forensic Science International*. 270, pp. 139-145.

Norman, D.G., Baier, W., Watson, D.G., Burnett, B., Painter, M., and Williams, M.A. (2018a) Micro-CT for saw mark analysis on human bone. *Forensic Science International*, 293, pp. 93-100.

Conferences:

Baier, W., Warnett, J. M., Burnett, B. A., Payne, M. and Williams, M. A. (2018) Using Micro Computed Tomography to improve the diagnosis of strangulation deaths - Validation and initial case data. *ISFRI Conference*, 10-12 May 2018, Melbourne, Australia.

I confirm that this thesis has not been submitted for a degree at another university.

Abstract

The Criminal Justice System of England and Wales is currently facing major challenges. One is the financial pressure of government funding cuts, the other the increasing need for professionalisation and rigour within the system. This thesis presents the use of micro Computed Tomography, Additive Manufacturing, and 3D visualisation to address both challenges. By drawing on data from live murder investigations the project examines how these digital technologies can be used to improve the investigation of strangulation deaths, sharp force injuries, and fractures. Each of these categories was treated as a separate case in the overall multiple-case study research design. The increased detail enabled by micro-CT assisted pathologists in the diagnosis of strangulation as previously undetected injuries of the larynx could be identified. A validation study comparing injured to uninjured samples was conducted to increase the strength of the interpretations. For sharp force injuries analysis, micro-CT proved useful for providing the necessary injury characteristics and highly accurate measurements to allow weapon identification. The high resolution of micro-CT scanning also enabled the visualisation of trauma on the smallest of skeletal elements, often encountered in non-accidental injuries in children. The cross-case synthesis revealed the main themes of clarity, objectivity, and visualisation which were improved by using micro-CT irrespective of type of homicide. The significance of these themes further crystallised in semi-structured interviews conducted with various stakeholders of the Criminal Justice System. Management concepts proved suitable to assess the project's success as the themes used in operations management such as quality, delivery, and cost apply to the delivery of justice as well. A good working relationship with West Midlands Police's homicide investigators and researchers at WMG was crucial to providing the technology and expertise to address real-life problems whilst ultimately saving taxpayers' money.

List of acronyms

AM	Additive Manufacturing
BFT	Blunt Force Trauma
BPA	Blood Pattern Analysis
BSREC	Biomedical Science Research Ethics Council
CAST	Centre for Applied Science and Technology
CID	Criminal Investigations Department
CJP	Criminal Justice Process
CJS	Criminal Justice System
CMM	Coordinate Measuring Machine
CPD	Criminal Practice Direction
CPR	Cardiopulmonary Resuscitation
CPS	Crown Prosecution Service
CrimPR	Criminal Procedure Rule
CSC	Crime Scene Coordinator
CSI	Crime Scene Investigation
CT	Computed Tomography
FE	Finite Element
FSI	Forensic Scene Investigator
FSP	Forensic Service Provider
FSS	Forensic Science Service
FSR	Forensic Science Regulator
FTR	First-Time-Right
HM	Her Majesty's
HO	Home Office
HOLMES	Home Office Large and Major Enquiries System
HU	Hounsfield Unit
ICT	Integrated Communication Technology
ISO	International Standardisation Organisation
MRI	Magnetic Resonance Imaging
MTA	Material Transfer Agreement

NAI	Non-Accidental Injury
NAS	National Academy of Science
NPM	New Public Management
PMCT	Postmortem Computed Tomography
QCD	Quality-Cost-Delivery
SEM	Scanning Electron Microscopy
SFT	Sharp Force Trauma
SOP	Standard Operating Procedure
UHCW	University Hospital Coventry and Warwickshire
WMG	Warwick Manufacturing Group
WMP	West Midlands Police
µCT	Micro Computed Tomography

Glossary of medical terms

Anterior	Towards the front of a person's body
Costochondral junction	Junction between the costal cartilage and the rib bone
Cricoarytenoid muscle	Muscle connecting the cricoid and arytenoid cartilages of the larynx
Cricothyroid muscle	Muscle connecting the cricoid and thyroid cartilages of the larynx
Endochondral ossification	Process of ossification (i.e. becoming bone) occurring within cartilage
Fibrin	Protein involved in blood clotting
Hyaline cartilage	Avascular collagen-rich type of cartilage, most prevalent type of cartilage
Inferior	Towards the bottom (foot end) of a person's body
Lateral	Towards the sides of a person's body
Medial	Towards the midline of a person's body
Medulla	Middle region of an organ
Mesenchyme	Embryonic connective tissue type
Omohyoid muscle	Depressor muscle of the hyoid at the anterior neck, originates from the upper border of the shoulder blade
Osteoblast	Cell type that secretes bone substrate
Osteoclast	Cell type that absorbs bone substrate
Osteocyte	Cell type found in mature bone
Perichondrium	Fibrous layer that covers cartilage
Periosteum	Highly vascular layer that covers bones
Petechiae	Small pinpoint bleeding caused by burst capillaries

Phagocyte	Cell type that absorbs harmful bacteria, foreign substances, or other dead cells
Posterior	Towards the back of a person’s body
Sternohyoid muscle	Muscle on the anterior neck connecting the hyoid bone to the sternum
Superior	Towards the top (head end) of a person’s body

Chapter 1: Introduction

1. Background to the research

Crime is costly, both financially and socially. The annual direct economic impact of fatal inter-personal violence has been estimated at almost £2billion in England and Wales which amounts to 6% of the overall cost of crime against individuals and households (Heeks et al. 2018). Approximately half of the cost is spent on victim services, thus emphasising the social cost of crime, whereas 20% are required by the Criminal Justice System (CJS) with homicide being the costliest per case. Crime reduction measures therefore serve to create a safer environment but also to relieve the financial burden on the public. Public spending in many countries including the United Kingdom has been subject to severe cuts due to the political climate of austerity following the financial crisis of 2008. The Criminal Justice System (CJS) is no exception as it has been put under immense strain with funding cuts affecting all branches of the system: the police, courts, and prisons. This has put all agencies under immense pressure to re-evaluate their service delivery in order to be able to maintain their standards. Police, courts, and prisons are expected to maintain their pre-austerity quality of service and in addition continue to strive to improve it with fewer financial resources available through government funds. This is often referred to by the term "better value-for-money service" which is a reoccurring phrase in government publications on the issue (Barton and Barton 2011, Grayling 2014, Garside and Ford 2016). The CJS is therefore required to develop strategies to reduce spending without compromising the level of justice delivered which has been realised in different ways by the individual organisations, for example through the establishment of partnerships both within the system and with external institutions (Home Office 2016, Garside and Ford 2016). These are crucial for the constantly evolving nature of police work as modern police are expected to embrace and exploit technological advances and incorporate them into their daily work. This improves the quality of evidence gathered and to maintain credibility in the eyes of the public (Ministry of Justice 2013). Achieving this goal without external specialists can be difficult under the present financial constraints as police simply cannot afford their own specialists for every area of science. Another aspect of professionalisation of police work is to produce the best possible data, which can be facilitated by technology in many cases. By taking advantage of all available resources and demonstrating a high level of evidence quality, the police can justify their actions when they are held accountable for them. Since the introduction of these policies police forces have initiated a variety of economic and technological changes to their policing strategies with the majority of technological improvements taking place within their IT systems. A similar trend can be seen in other criminal justice agencies like the Crown Prosecution Service (CPS) and the courts. These changes are in accordance with the overall government vision of fully digitising the justice system, initially set out to be completed by 2016 (Ministry of Justice 2013) but the individual partners have succeeded in this process to a varying degree (HM Inspectorate of Constabulary 2016).

Technological advances in Crime Scene Investigation (CSI) are predominantly focused on the forensic lab sciences but this research is often in experimental settings and not validated in live investigations. Other technological innovations are aimed at frontline policing and one project which has gained nationwide support is the use of body-worn cameras (HM Inspectorate of Constabulary 2016). This widespread technological success is unusual as the acceptance of innovation and change amongst police personnel has been described as notoriously slow (Ashby et al. 2007, Barton and Barton 2011). In many cases, police purchase equipment without having the appropriately trained staff. The new equipment can therefore not be used to its full potential and the money spent on it is wasted (HM Inspectorate of Constabulary 2016, Koper et al. 2014). The police and their forensic services are currently experiencing major changes towards a professionalisation of their work, new technology is required to be rigorously tested prior to implementation (House of Commons Science and Technology Committee 2013, Forensic Science Regulator 2014). This increases the demand for research resources which is not commonly accommodated in their budget. These problems can be avoided by entering into partnerships with external specialised institutions who have the state-of-the-art equipment and staff who are able to operate it and who possess the resources required to conduct the validation and verification studies. For the external institutions, this constitutes an opportunity to get access to previously untapped resources for research and to test their research in real-life scenarios.

This thesis is the result of one such innovative partnership between a police force (West Midland Police, WMP) and an external institution (WMG, University of Warwick) whereby both parties benefit from the work and research conducted. Funding was provided by the Forensic Investigation Research Scanning and Training (FIRST) initiative in cooperation with WMP's Criminal Investigations Department (CID), which investigates serious offences such as homicide which formed the basis of this PhD project. The nature of this partnership resulted in the research focus resting on the benefits for the police. Utmost care was given to an impartial view which benefits the entire justice system including the courts as the ultimate aim is to assist the truth-finding process. The third main branch of the CJS, prisons, was not considered in this study.

The partnership between West Midlands Police and WMG was initiated by personal contacts between representatives from both sides. An initial pilot project was conducted to explore the potential of three-dimensional visualisation technologies in a case of dismemberment (Baier et al. 2017) which was deemed successful, leading to the establishment of a three-year project exploring further applications. In the early stages, the project scope was still very broad and unspecific as it was uncertain which technologies would be most appropriate for specific types of cases. Soon police learnt more about the university's capabilities and researchers at the university became aware of the police's needs, resulting in the project's objectives being shaped.

2. Definition of the research problem

The initial research problem investigated in this thesis has developed from this exploratory pilot study and further trial cases which raised interest amongst both sides to explore:

How can digital three-dimensional technologies benefit the Criminal Justice System?

Following a preliminary literature research, the working hypothesis of this thesis is that criminal justice in the modern age can be greatly improved by the use of modern methods and technologies such as micro-CT and 3D printing. By employing these novel technologies, the police and other criminal justice agencies are better equipped to face the challenges imposed by government funding cuts and quality requirements and thus provide the desired "better-value-for-money" service. However, little is known about the case-by-case benefit of these technologies as the positive predictions in the literature are often speculation based on the success of a single case. This research gap led to further overarching questions:

- Can these 3D technologies be used to generate new, better types of evidence?
- What fields of study profit from the introduction of these methods?

- How can these technologies be incorporated in the operation of the Criminal Justice Process?
- What social and economic impact do these novel methods create?

3. Justification for the research

The importance of this research project is expected to be its socio-economic impact. One of the most pressing objectives set out by the government is for public agencies to find more efficient and cost-saving strategies to deliver their services without compromising quality. This is a tough challenge and short-term measures such as staff reductions might appear attractive solutions at first but they can lead to a loss of quality as the remaining employees struggle to cope with the workload. Investing in research and technological advancement, which can save money in the long term, is therefore crucial to create a sustainable and self-sufficient police force and has a longer lasting positive effect than short-term measures. Only few police forces have embraced such an approach which puts West Midlands Police at the forefront of modern policing. The use of novel technologies in creating more detailed and more objective evidence not only has the potential to reduce police spending, it can also lead to better informed decisions and therefore a fairer justice system with benefits for both sides of an investigation. Previous research by Ma et al. (2010) indicates that the evidentiary value produced by the digital models is likely to increase clarity in court as three-dimensional images are easier to understand for laymen without medical knowledge, thus enabling a fairer judgement.

To date there are very few examples of digital 3D models being used in courts in the United Kingdom and the evidence for physical 3D prints is even more limited. The few instances that exist are limited to news articles (Vaughan 2016) and academic publications are nearly absent. Taking into consideration examples from other countries demonstrates that 3D technology is still far from standard practice in most Criminal Justice Systems. As different countries have different admissibility criteria for criminal evidence (Edmond et al. 2013), more country-specific studies are necessary. UK-specific information is also required in order to quantify the impact of such technology on the CJS which no previous study has attempted. Demonstrating economic viability is critical to promote further, similar projects and secure funding for future research. Demonstrating the helpfulness of certain measures or policies is also a fundamental aspect of evidence-based policing which is becoming increasingly popular (Fyve 2017). A prerequisite for evidence-based policing is assessing “what works”; this thesis proposes borrowing existing assessment criteria from management studies to evaluate the changes introduced by it.

The academic knowledge gained from this collaborative project is based on the unique access to human tissue samples from forensic contexts which hold important information about different aspects of violent injuries not previously studied at such level of detail and complexity. These novel methods provided new insights into the mechanisms and effects of trauma as they drew on a combination of the physical injuries and the contextual information regarding the case circumstances. This assists the disciplines of forensic pathology and anthropology in improving the interpretations of trauma.

4. Overview of the research methods

The research conducted for this thesis is based on the well-established case study research design as outlined by Yin (2014), more precisely the multiple-case study approach because of the breadth of possible homicide cases investigated by police. The level of detail at which each scenario is examined therefore depends on the uniqueness and the number of examples for each case resulting in some high-profile cases with a large base of supporting examples.

The project was characterised by four phases:

Phase 1: Establishment of the theoretical framework including: the definition of the research problem, the development of the research hypothesis and research questions, and the selection of the research design.

Phase 2: Initial exploratory studies to identify potential research cases and extract high-profile cases.

Phase 3: Conducting case studies, including individual case reports and impact assessment interviews as appropriate.

Phase 4: Cross-case comparison and reporting on findings.

5. Thesis outline

A schematic representation of the thesis outline is shown in **Figure 1.** The present chapter introduced the research area and identified the major problems addressed in this thesis. The challenges faced by the CJS have been briefly introduced which provided a justification for conducting research in this field, and a brief description of the methodology employed was provided.

Chapters 2 and 3 are the main literature review chapters that provide a critique of the two overarching fields of "The Criminal Justice System" and "Digital 3D Technologies". Chapter 2 introduces the individual agencies which form the Criminal Justice System and details their role in delivering justice. It further elaborates on the pressures acting upon these agencies and highlights aspects requiring improvement. Chapter 3 examines existing digital tools which could be used to address the problems identified in Chapter 2 and reviews their advantages and disadvantages. The overlap of these two fields defines the areas where the most benefits are expected and which have therefore been selected as the main study areas.

Chapter 4 details the methodology starting with a definition of the research hypothesis, followed by a refinement of the research questions raised in the present chapter, taking into account the information provided in the review chapters. It will then continue to describe the case study research design in more detail.

Chapters 5 to 8 present the observations made during the conduction of the case studies and provide further case study-specific literature reviews for context. They will focus on the academic and scientific knowledge created by the introduction of the proposed technologies and how this contributes to the CJS.

Chapter 9 presents and discusses the results of key informant interviews which were conducted to evaluate the impact created by this study. These provided valuable insights into the perceived success of the project.

Chapter 10 is an overall discussion of the observations presented in the previous chapters including a cross-case comparison and an assessment of the impact created by this research. It critically evaluates the limitations of the research and provides an outlook of its impact on the future delivery of criminal justice in the UK.

Chapter 11 summarises the conclusions drawn from the study and suggests further research on the topic.

6. Summary

The present chapter has fulfilled its role to introduce the field of research and the principal research problem and to raise some key questions which this thesis aims to answer. Having also outlined the research justification and methodology, the groundwork for the in-depth research as presented in the remainder of this thesis is laid. The following literature review serves to introduce the reader to the more detailed problems and opportunities this research aims to address.

Thesis outline

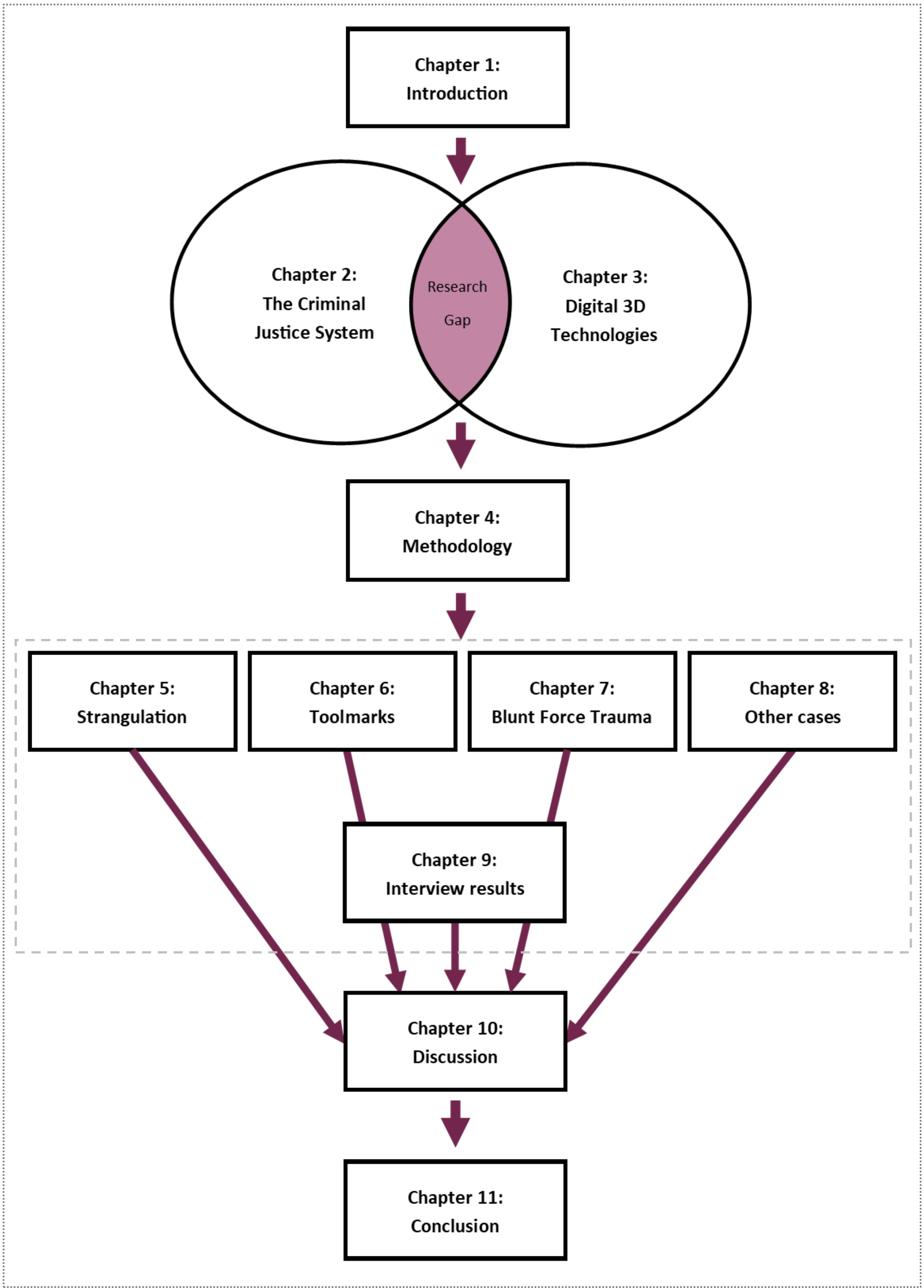


Figure 1: *Schematic representation of the thesis outline, starting with the present chapter at the top and following through to the final conclusion at the bottom.*

Chapter 2: Setting the Scene - Criminal Justice in England and Wales

1. Introduction

In order to introduce a new technology to the CJS it is crucial to understand the current system and its structures which influence current technological and methodological choices. Only then can innovation take place in an effective and helpful manner. Working with West Midlands Police, this research project and therefore this literature review focusses on the Criminal Justice System of England and Wales only as the Scottish and Northern Irish counterparts are organised somewhat differently. The CJS consists of several agencies such as the police, the Crown Prosecution Service (CPS), the Courts and Tribunals Service, prison and probation services, the Serious Fraud Office, and other agencies (Chapman and Niven 2000). While all of these are vital to the functioning of the entire system this review will focus on the first three which are the agencies involved in the truth-finding process in the cases examined over the course of this project. This process relies on the work of the police and the courts and the CPS which acts as a mediator between them. Each of these individual agencies are faced with unique political and social challenges which determine many of their actions and influence the manner in which the proposed technological innovation might be employed. The following review will take a closer look at these challenges and their potential impact on the introduction of novel three-dimensional technologies. Frequent reference will be made to West Midlands Police whose investigative methods and needs are at the centre of this project by the nature of this cooperation.

This chapter will provide an overview of the three organisations (police, CPS, courts) and the state of forensic sciences, followed by a detailed review of the Criminal Justice Process (CJP), offering a new perspective on the process. With the process outlined, the following section then examines the challenges faced by the CJS, beginning with instances where the process has failed, so-called miscarriages of justice, and at what stages in the process this failure occurred. It will become apparent that forensic science has an important role to play in these injustices, the following section will therefore discuss controversies surrounding the quality of forensic evidence and its admissibility. Other problems arise from economic issues, most recently resulting in the introduction of New Public Management (NPM) measures in the justice sector as discussed in the following section. These challenges prompt new responses - the final section of this chapter will therefore look at police innovation and research.

2. Organisation

2.1 The Police

Police in England and Wales consist of 43 individual forces of varying size, population covered, and degree of urbanisation, which operate largely independently from each other. West Midlands Police, who sponsored this project, is the second largest police force after the Metropolitan Police Service and covers an area of 348 square miles, providing their service to 2.8 million people (HM Inspectorate of Constabulary 2016). Each police force consists of a uniformed branch, an investigative branch, and various special units depending on the size and demands of that particular force. The Criminal Investigations Department (CID) is the police department which investigates serious crimes such as homicide, rape, serious assault, and fraud, all of which require more resources and specialist knowledge. The CID receives the majority of its funding directly from the Home Office (HO).

2.2 The Crown Prosecution Service

The Crown Prosecution Service (CPS) is headed by the Director of Public Prosecution and was introduced in 1986 to replace police-led prosecution with legal professionals and was intended to increase fairness in the justice process. The CPS was created as an independent body at the centre of the CJS to make charging decisions based on the evidence produced by the police and to carry cases on to court where they are presented by a CPS-instructed barrister (Chapman and Niven 2000). While the original intent was to create an independent body, the practical implementation was perceived differently, starting with the creation of 42 CPS areas corresponding to police forces which led to some confusion whether the two agencies were actually distinct from each other (House of Commons Justice Committee 2009). Another aspect which has received criticism from the public is the CPS's power to decide what crime to charge a defendant with as this is considered to be best decided by the court (House of Commons Justice Committee 2009). However, it ought to be acknowledged that if this power was to be transferred to the courts, the entire justice system would be altered from adversarial to inquisitorial which is the approach taken by many other European countries (Chapman and Niven 2000) and it would create an unmanageable caseload for the courts. This charging power of the CPS has increased even further over the past years with the CPS now being involved in plea bargaining, thus moving much of the justice towards the prosecutor and reducing the image of an independent body even further (House of Commons Justice Committee 2009). The aim of granting such powers to the CPS was to reduce the number of cases discontinued in court since these are perceived as a waste of time and financial resources. This approach has proven successful as the number of cases discontinued in court has dropped over the years and the success rate therefore increased (House of Commons Justice Committee 2009), raising new concerns whether the CPS is in fact "undercharging" out of fear of losing in court (Malleson and Moules 2010). This concern also affects the CPS's relationship with the police. Cooperation between the police and the CPS during the investigation process cannot be avoided as legally trained CPS staff advise detectives on the evidential requirements for a successful charge. Critics of this arrangement argue that it represents a loss of independence and perhaps neutrality for the CPS (House of Commons Justice Committee 2009) while supporters contend that this challenges the police to produce better evidence (CPS 2013). This pressure to satisfy the demands of the CPS is possibly one of the driving factors causing investigators to embrace research into new technologies to produce the most objective and scientifically uncontested evidence possible. The central role taken by the CPS suggests that any impact assessment should involve representatives from the CPS as they ultimately decide whether and how to use the evidence presented by the police.

2.3 The courts

Criminal offences in the English court system are tried at several levels of courts (Magistrates' Court, Crown Court, High Court, and Court of Appeal) with each level trying different types of cases. Homicide cases are classed as an indictable offence and are tried before a Crown Court. Lesser offences brought before a Crown Court might be headed by a less senior Circuit judge or a Recorder, whereas homicide cases are usually presided over by a High Court judge or a Senior Circuit judge (Malleson and Moules 2010). The structure of the trial follows a largely standardised pattern where the first days will usually see opening speeches and clarification of formalities, followed by evidence presentations and then expert witnesses which feature in approximately 1/3 of indictable crimes in Crown Courts. The prosecution traditionally begins the presentation of their case although the defence has a right to cross-examine every witness called by the prosecution and vice versa (Roberts and Zuckerman 2010). The evidence presented depends predominantly on oral statements detailing the methods used and conclusions reached for a particular aspect of the investigation. Where appropriate this is supported by documents, drawings or sketches, photographs, video, and audio recordings. The use of physical exhibits in court is limited as photographs thereof are considered sufficient and are easier to present (Errickson et al. 2014).

2.3.1 Expert evidence presentation

Evidence of scientific or technical nature is presented by an expert witness who will have adequate knowledge and experience in the field of science or technology the evidence relates to. A major challenge is to communicate the evidence in layman's terms since the judge and the jury will not normally have any prior discipline-specific knowledge. The main aim is to eliminate confusion to allow the jury to reach their conclusion "beyond any reasonable doubt" which can be difficult to achieve by a verbal account alone. Morse (2009) further observed that most jurors will have grown up in a modern digital age exposed to daily visual stimulations which causes them to expect similar stimulation in the courtroom, purely verbal evidence might fail to capture their full attention. Experts witnesses might choose to use illustrative material to support their testimony but few do which has created the opinion that expert testimony can be dry and monotonous risking losing the jury's attention (Cooper 1999). While visual aids are sometimes used to support statements, they are not appropriate for all types of evidence. Pathological findings, which are crucial in all murder cases, are particularly difficult to present visually because of their graphical nature which can cause unnecessary emotional distress in the courtroom (March et al. 2004). This calls for new ways of dealing with such evidence, ideally a holistic crime-scene-to-court approach whereby even the initial evidence collection is conducted with its later court presentation in mind. As section 3.3.2 below argues the reliance on experts can also have negative consequences as they have contributed significantly to some miscarriages of justice.

Some of the solutions proposed to address this demand for new courtroom displays (Tung et al. 2015, Schofield 2017) might be challenging to implement as the digitisation of courtrooms is a fairly recent concern to the government and the government agenda to digitise the CJS by 2016 has had mixed success (Morse 2018). From a modern perspective, one would expect that the planned digitisation of courtrooms is swiftly implemented to allow the presentation of digital or digitally produced evidence as people are used to access even complex digital content on their laptop or mobile phone in everyday life, but the reality in the courtroom is often different. Only recently have courts made the move to change to Integrated Communication Technology (ICT) systems which allow court users to connect remotely to media outlets in the courtroom but many court buildings only have one courtroom fitted with these or have to share equipment between rooms. Sometimes this equipment is hired from external companies who install and operate it if needed, adding to the overall costs of the trial. This lack of digitalisation might limit the technology choice used in this project as it would be futile to create 3D visual outputs if the courts cannot adequately display them.

2.3.2 Jury research

As mentioned above, this PhD project is concerned with homicide cases which are tried before the Crown Court and are therefore, with few exceptions, subject to trial by jury. This necessitates a discussion about juries and their position within and influence on the trial proceedings. The main aspect discussed here is the jurors' perception of the events during trial and the information provided to reach a verdict. Some aspects of the theoretical background of research into juries is borrowed from other disciplines such as cognitive psychology and educational research. Researchers in this field appear in constant disagreement over the question whether ordinary members of the public that make up the jury are capable of deciding on such grave judicial matters (Edmond and Mercer 1997). Similarly, there is no agreement on how capable juries are of understanding complex scientific or technical evidence which is often central to homicide trials. Findlay (2001) argues that jurors are not in a position to grasp such evidence, Ward (2009) sees jury as capable but naïve when it comes to believing evidence, and Pikus (2014) considers juries to possess the cognitive skills necessary to evaluated scientific and technological evidence. Edmond (2015a) argues that juries and judges require certain information about the scientific methods employed to help them assess their validity and that it should be the state's responsibility to ensure this information is provided. Similarly, Erastus-Oblio (2009) claims that "the verdict of a jury is only as good as the evidence presented to it" which should be put into practice by striving to produce the best evidence possible and use all available resources (within possible financial limits). Irrespective of their inherent capability, jury understanding can be improved by more effective judicial instructions.

Brewer et al. (2004) compared the comprehension of actual Supreme Court judge's instructions using verbal accounts only, more elaborate verbal accounts, and audio-visual instructions using animations to outline the major arguments. They found that by adding the visual element, participants reached a fairer verdict. This was particularly true for their non-expert group which had no prior legal knowledge thus representing actual jurors more realistically.

Visual aids play a significant role in jury research. Bright and Goodman-Delahunty (2006) found that even neutral photographs are perceived as more compelling evidence than verbal descriptions, following the saying "seeing is believing". However, the viewer might also be "tricked" into believing something untrue, or made believe to remember something they had not actually experienced (Newman and Feigenson 2013). A further problem with images, and gruesome images in particular, is that they frequently evoke an emotional response (Bright and Goodman-Delahunty 2006, Feigensen 2010) leading to less rational decisions and therefore unfair trial outcomes. A study by Battye and Rossner (2017) examined the effect of computer animations on the jury in a re-created terrorist trial. They observed that jurors expected to see graphic images and realistic animations and were disappointed if none were provided, despite earlier studies suggesting a negative influence of these (Edelman 2009). Battye and Rossner (2017) attribute this expectation to the so-called "CSI-effect". The CSI-effect means that much of the jury's expectations regarding forensic evidence is guided by popular crime TV shows, a phenomenon which has been increasingly recognised in studies across the globe (Goodman-Delahunty and Tait 2017). This effect can then lead to a poor judgement of the actual value of the evidence if it does not conform to the juror's expectations, as Goodman-Delahunty and Tait (2017) observed for high-tech visual evidence such as animations. Shelton et al. (2006), however, argue that the CSI-effect is in fact a general technology effect as technology plays an increasingly large part of everyday life. They continue to suggest that it is therefore likely that it is the lack of technological progress in courtrooms which dampens the jurors' confidence in the justice system. With these considerations in mind one can focus on the positive impact visual evidence can have on jury understanding. Audio-visual information is five times more likely to be remembered than audio alone (Fulcher 1996, Lederer and Solomon 1997), thus assisting the jury members in their deliberation. Furthermore, the compelling nature of visual evidence can be employed in a positive manner to explain the facts of the case. For this to be free of bias, the evidence must be presented objectively.

The problem with research in this area is that it relies on different study populations and study designs which makes it difficult to compare the results. Many researchers use students as participants in so-called mock trials where participants are split into groups which then receive differing information on the same (sometimes fictional) case in order to assess which factors influence decision-making (Park and Feigenson 2013). The majority of studies cited above are based on evidence derived from mock trials that can provide some useful insight but lack taking into account the special circumstances under which such a decision is made in a real trial where someone's freedom - or depending on the country their life - is at stake. Research using real jurors is rare, in particular in the UK where the Contempt of Court Act 1981 limits jury research. Few researchers have investigated this prior to the UCL Jury Project which worked with Crown Court juries with the aim of reforming the Contempt of Court Act based on actual evidence (UCL 2018).

2.4 Forensic Science and pathology

Forensic science starts at the crime scene where crime scene personnel are responsible for searching for, recording, and collecting physical evidence. The majority of crime scene departments are attached to the police forces although most staff are civilian. The evidence is then sent to specialist labs, some of which are in-house while others are external paid service providers. However, not all evidence can be analysed due to budgetary limitations - investigators have to prioritise and select items expected to produce the most compelling results. This selection must also include items which potentially exclude a suspect. Failure to do so can lead to one-sided evidence and potential miscarriages of justice (Robertson 2013). If the examined case is a suspected homicide, the deceased is taken to the mortuary where a HO pathologist conducts a forensic postmortem examination of the body with the aim of establishing the cause and manner of death, sometimes with the help of further specialists. The pathologist only visits the scene to examine the body in-situ in complex situations as this would risk deterioration of the body and therefore loss of evidence and would cause costly delays in the investigation. Nevertheless, these scene visits can contribute to the pathologist's understanding and interpretation of the injuries (Saukko and Knight 2004). Autopsy practices have remained fairly unchanged over the past decades although an increasing number of institutions include postmortem imaging techniques in their routine procedures. There is a significant trend towards non-invasive or minimally-invasive postmortem examination as the next chapter will elaborate.

3. The Criminal Justice Process

3.1 From crime to sentence

There is no such thing as a "typical" murder since every case is unique, but the investigation process follows a set routine, starting at the scene of crime where Forensic Scene Investigators[1] (FSIs) search, collect, and document any physical evidence. The role of the plain clothes CID detectives at this stage is mainly to interpret the scene and direct the evidence collection and to conduct witness interviews in order to establish further lines of

[1] FSI is the title used by West Midlands Police, other police units may use different terms to refer to the same job descriptions, such as Forensic Investigator, Crime Scene Examiner, etc. (Williams 2011).

inquiry (Maguire 2011). Once the initial in-situ work is completed, which can take several days, the victim is transferred to the mortuary where a forensic postmortem examination is conducted to establish cause and manner of death and preserve any trace evidence not previously noticed. Occasionally a pathologist or other forensic scientists will attend the scene if it there is a possibility that the standard scene documentation will not suffice to reach an adequate interpretation and that they will profit from an examination of the original context. However, scene visits can be time consuming and costly and are therefore limited to the most complex cases only. This raises the question whether technological advances in crime scene documentation could eliminate the necessity of pathologists' scene visits altogether, thus saving the expenses related to them.

If necessary, evidence and samples from both the scene and the mortuary are sent to specialist laboratories for further analysis - a process that often takes several weeks or months before any results are available. In the meantime detectives begin questioning witnesses and suspects and begin to compile intelligence from a variety of different sources on the latter. Once they have gathered sufficient evidence to charge a suspect they present the relevant data to the CPS who decide whether to charge the individual or whether further evidence is required. From thereon, further investigation is to a certain degree directed by the CPS's view of what is required for a successful trial. If the CPS decide to charge the suspect, an initial court hearing is conducted to settle administrative matters such as setting bail if applicable and to schedule the trial date and duration. Most defendants in homicide cases are denied bail, hence they are taken back to prison where they remain until trial. During this period both sides gather additional evidence to prepare their cases which includes deciding on which experts to call as witnesses. It is important to note that all evidence produced for the prosecution must be disclosed to the defence including unused material and evidence that could undermine the prosecution's case in order to ensure a fair trial (CPS 2008).

The procedure in court follows the standardised routine outlined in section 2.3 which terminates in the judge's sentence. Both parties then have the option to apply for the right to appeal and, if granted, appeal the sentence. Appeals for cases that have been tried before a Crown Court will lie to the Criminal Division of the Court of Appeal whereas appeals from the lower courts lie to the Divisional Court of the High Court or a Crown Court (Malleson and Moules 2010). The sentence becomes valid after this process has concluded and other agencies of the CJS such as prison or probation services take over.

3.2 The stage-gate system

The entire Criminal Justice Process (CJP) can be likened to any other operational process. This realisation is fundamental when looking to improve the process as there are numerous management tools available in fields like product development and manufacturing which can be transferred to public organisations. One such tool is the well-established stage-gate system developed by Cooper (1990). This conceptual approach was designed as a model to reduce wastage when moving a new product from idea to launch by dividing a process into gates and stages. Gates are critical decision points with set deliverables, exit criteria, and output. The deliverables are the input created in the preceding stage, the exit criteria are pre-defined criteria by which the project is judged and which need to be fulfilled in order for it to progress through to the next stage, and the output is the decision reached at the particular gate. The stages are individual workstations or activities which most people would recognise as the actual process. This concept is also applicable to the CJP which progresses through a range of different stages and institutions as outlined above with certain thresholds in between. Cooper (1990) defines five gates and five stages for a standardised process which are immediately applicable to the justice process as summarised in **Table 1**.

Table 1: *Comparison of Cooper's (1990) original stages and gates with those identified for the CJP.*

	Cooper (1990)	**The Criminal Justice Process**
Gate 1	Initial screening	Suspicious death?
Stage 1	Preliminary assessment	Initial investigation
Gate 2	Second screening	Crime yes/no?
Stage 2	Project definition	Full investigation
Gate 3	Business case	Charge?
Stage 3	Product development	Trial preparation
Gate 4	Product review	Evidence admissibility?
Stage 4	Product testing	Trial
Gate 5	Product launch	Verdict
Stage 5	Implementation	Sentence
Post-implementation	Review	Appeal

The product development process commences at gate one where an idea receives an initial screening in order to decide whether it is worth investing resources in its further development. The corresponding checkpoint in the Criminal Justice Process is the initial decision after a callout whether the circumstances are sufficiently suspicious to warrant further investigation which equals Cooper's criterion of committing resources. If the decision at the first gate is to invest further, stage one, the preliminary assessment follows. In product development this involves collecting initial inexpensive data on the market potential of a new product, leading on to gate two (second screen) where the product idea is re-evaluated based on the information gathered in stage one. In criminal justice terms this stage matches the initial investigation aimed at establishing whether a crime was committed where the decision reached at gate two. The following stage two sees the definition of the project including concept and feasibility testing which can justify the further investment. In the justice process this stage is the main investigation where the case takes shape thus setting the scene for the continuation of the case. At gate three the activities from stage two are evaluated again and a business case is made which includes the commitment of serious resources. In the CJS, the gatekeeper of this gate is the Crown Prosecution Service who evaluate the evidence gathered by police and decide whether to charge an individual with an offence or not. The decision to charge mandates committing further resources related to the upcoming trial. Stage three is defined as the development stage with the development and detailed testing of the desired product. This stage can be translated as the trial preparation where both prosecution and defence develop their product – i.e. their line of argumentation for court. Gate four in product development is a further review where the progress made in stage three is assessed. In the justice process gate four is best explained as the judge's pre-trial admissibility decision. The following stage four consists of tests such as field trials or in-house testing with the aim of validating the product. Stage four of the Criminal Justice Process is the trial during which all evidence is validated as it is questioned and cross-examined in court. The final gate in the product development field is the decision to commercialise the product and is the last checkpoint where the project can be killed. The verdict is the corresponding gate in criminal proceedings where the jury decide between guilty and not-guilty. The fifth and final stage is the commercialisation with the implementation of all marketing and operation plans. This stage is the sentencing stage in the CJP where the decision reached at the preceding gate is implemented. Cooper (1990) concludes the process with a post-implementation review which does not qualify as a separate stage but is a stand-alone step. In justice terms this can be seen as the post-conviction appeal process. However, the appeal process is better represented by additional stages since there are distinct processes and decision points. Continuing from stage five the next gate would be the decision to apply to appeal the verdict or the sentence which can be made by either prosecution or defence. Following this decision, the party appealing then needs to present their case to the Court of Appeal which is stage six of the process. Gate seven is the Court of Appeal's decision to grant or reject leave to appeal. If the application is successful, stage seven is the appeal trial which culminates in a verdict - gate eight. The final stage eight is the final sentence and its implementation. The stages and gates of the CJP can be directly mapped onto Cooper's original Cooper's stages and gates as shown in **Figure 2.**

Cooper (1990) sees the benefits of this approach in the reduction of mistakes and the time spent on reworking processes, ensuring in a more successful project delivery with less wasted investment. These are the same objectives set out for the Criminal Justice System commonly referred to by terminology such as more effective and efficient services and a "First-Time-Right" (FTR) approach (Ministry of Justice 2014, Grayling 2014). Applying the stage-gate system to the justice process therefore has the potential to achieve these objectives since the system has been proven to work (Cooper 1990) and the CJP to be a suitably similar process. In product development, despite often being overlooked, the early stages are crucial to the final success and their proper execution can save money further along the process as each consecutive stage is considered to be more expensive than the previous one (Cooper 1990). The Criminal Justice Process similarly benefits from investment into the early stages of the process since the quality of the evidence collected by police affects the prosecution case put before the courts. Weak or flawed evidence might not be admitted nor convince the fact-finder of the case, costing the public money which could have been avoided if the early stages had received more attention.

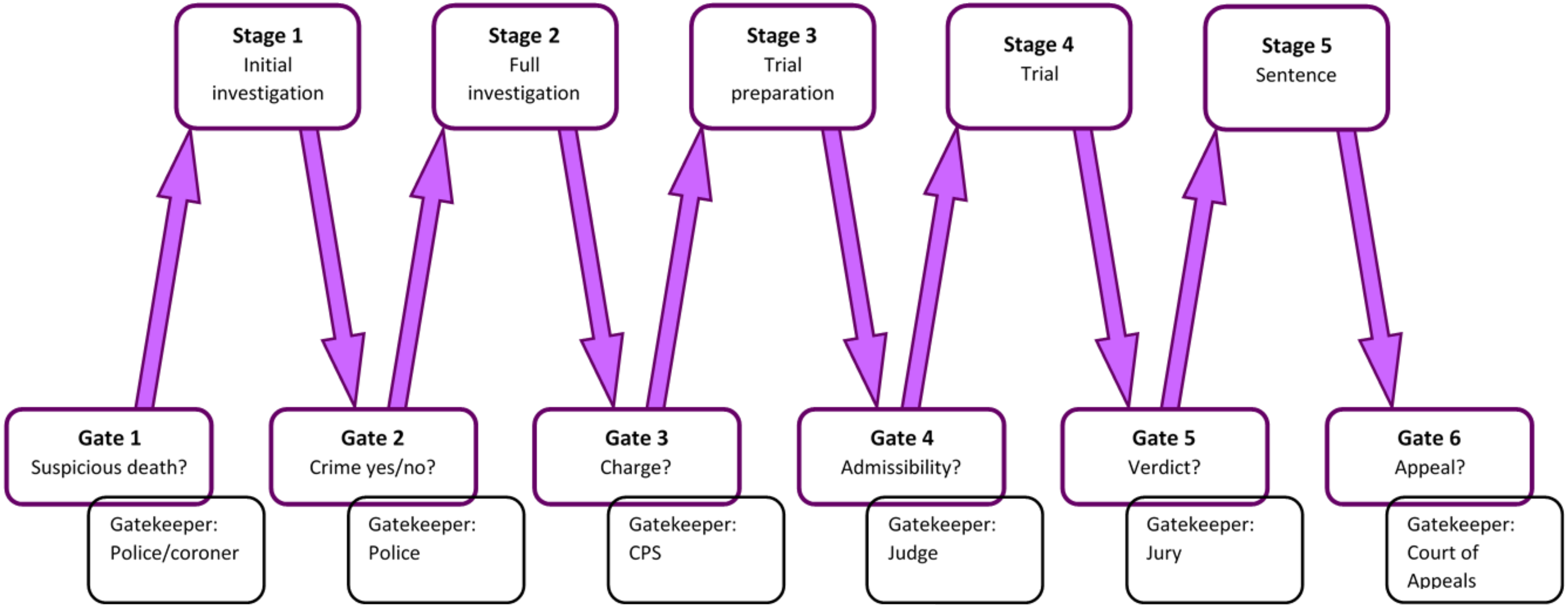


Figure 2: *Schematic representation of the Criminal Justice Process mapped onto the stage-gate system.*

In product innovation projects, it is a senior manager who acts as gatekeeper at every gate, guiding the project through from start to finish. In the CJS the gatekeeper role changes hands at multiple locations; beginning with the police then being handed to the CPS at gate three, the judge at gate four, the jury at gate five, back to the CPS or the defence at gate six in case of an appeal, and finally to the Court of Appeals. This fragmentation could be criticised for being prone to errors and/or poor execution of activities, leading to inefficiency as processes have to be reworked in order to pass the next step. Nevertheless, it is this fragmentation which ensures the independence of the individual agents and prevents concentration of power with a single one of them. An attempt to unify the gatekeeper functions is made by the role of the case progression officer who is responsible for easing the transition of the gatekeeping function between police and CPS.

This roadmap helps to identify weaknesses within the process and to provide suitable entry points for measures to improve individual stages. Each stage has pre-defined activities which are not mandatory but act as a guidance for forward progression of the project. These activities are written down in Standard Operating Procedures (SOPs) for the investigation phase. Including the use of the proposed novel technologies in the SOPs constitutes one investment in the early stages which is expected to pay off in the long-term by improving the evidence quality, thus increasing the chances of success at a later stage.

3.3 Challenges and responses

The criminal justice agencies presented in the first part of this chapter each face different challenges as part of their work. These challenges are related to social, political, or economic changes and evoke a variety of different responses, some of which are shared across the agencies while others are unique to individual agents. Many of the obstacles are either directly or indirectly related to the financial constraints presented in the following, whereas others are more concerned with qualitative factors.

3.3.1 Financial pressure

In the years following the economic crisis of 2008, public spending was cut tremendously first by the coalition and then the conservative government. Two thirds of the overall police budget for England and Wales come from the central government's Police Grant while the remaining third is funded through local taxes. This Police Grant has been subject to a 22% reduction since 2010/11, from £9.6 billion down to £7.4 billion in 2015/16 (House of Commons Home Affairs Committee 2016). No further cuts were announced in the 2015 spending review which was a welcome surprise to many in the profession (House of Commons Home Affairs Committee 2016) but recent changes in the political landscape might bring further changes in the near future. The combination of local and national funding that is distributed according to the Police Funding Formula, has resulted in the individual forces being affected differently by the funding cuts depending on their previous main source of funding (central versus local government) (Garside and Ford 2016). West Midlands Police, who relied heavily on central government grants and only received 12% of their gross revenue expenditure through local funds, were affected severely by budget cuts which amounted to 23%, the highest of any force (House of Commons Home Affairs Committee 2016). It is perhaps this dramatic reduction which has caused West Midlands Police to re-structure their finances and become one of the highest rated forces for efficiency[2] (HM Inspectorate of Constabulary 2016). Their financial strategy includes entering into partnerships with commercial organisations which might be able to provide better specialist services at a lower cost. The present PhD project, although not strictly speaking a service, is an example thereof, providing access to research facilities at a special rate. As further elaborated below, these collaborative projects are frequently cited as the future of policing. Police can no longer operate in isolation if they want to keep up with technological and scientific progress (Ashby et al. 2007). Similar co-operations exist between the Metropolitan Police Service and King's College (King's College London 2017), and between Hampshire Constabulary and the University of Portsmouth (University of Portsmouth 2018).

The need for economisation of processes in the justice system also affects the forensic sciences which experience a high rate of attrition where the forensic evidence produced as part of a case does not reach the court stage. This is perceived as a waste of time and money. Reasons for this attrition include early guilty pleas, inconclusive results, or a lack of confidence in the techniques employed or the results obtained (Walport and Surkovic 2015). While the use of forensic science to encourage early guilty pleas can be considered a successful use of resources, inconclusive or unreliable methods and results are a waste of resources. Further methods designed to reduce this issue should therefore be encouraged even if they require additional input in the early stages as long as they succeed at consolidating a case. This is also argued by Cooper (1990) whose stage-gate system demonstrates that committing resources in the early stages of a project enables savings during the later, costlier stages of the process.

[2] HM Inspectorate of Constabulary introduced a new system of assessing individual police forces across England and Wales in the fields of efficiency, effectiveness, and legitimacy. The PEEL assessment rates them on a four-point scale from inadequate to requiring improvement, to good, to outstanding. This allows a comparison between forces and aims to set a national standard of policing.

Further restructuring was evident in the delivery of forensic examinations as private Forensic Service Providers (FSPs) started to emerge after the dissolution of the Forensic Science Service (FSS) in 2012. The closure of the FSS was criticised by many scientists who anticipated a loss in quality standards for scientific evidence as much of the forensic work was shifted to police in-house labs which was more economical at a time when ISO17025[3] accreditation was only required for external FSPs (House of Commons Science and Technology Committee 2013). This has since been addressed as concerns were raised by the Forensic Science Regulator (FSR) that evidence quality standards must be assured independent of laboratory affiliations and accreditation is gradually introduced for different analytical services (FSR 2016). As indicated in the Home Office's Forensic Science Strategy paper (2016), accreditation is an important step to increase the public's trust in the forensic sciences and the justice system. However, public funding for forensic research is limited across the discipline which has prompted the House of Commons Science and Technology Committee (2013) to issue a warning that the UK may risk falling behind on the exploitation of new scientific and technological developments and to recommend that police and research institutions should work together to prevent this. Cooperation is crucial as the police would be overwhelmed by the demands of research and development which is an expensive and sometimes risky process (Childs and Potter 2014). But following the stage-gate system, input into early stages can lead to a more successful outcome overall.

The financial pressure acting upon the CPS has influenced much of its current situation, especially the efforts to keep court time at a minimum. The CPS Code for Prosecutors explicitly states that prosecutors have to proportionally weigh the cost of prosecuting against the possible penalty and are responsible to ensure a swift and timely processing of cases (CPS 2016). In order to achieve this goal, the evidence needs to be of the highest quality without room for doubt and ideally trigger an early guilty plea wherever possible. Of the 100,000 cases brought before the Crown Courts each year 58% plead guilty which can reduce the sentence by up to a third, depending on the stage at which the plea is made (Malleson and Moules 2010). However, it must be emphasised that the aim is not to trigger a guilty plea for the sake of simplicity; the evidentiary base must be compelling, therefore convincing a guilty defendant to plead and not persuading them to do so. The courts have also suffered under the new regime of austerity and economising the justice system has become necessary as funding for UK courts has been cut from £1.5 billion in

[3] ISO/IEC 17025:2005 General requirements for the competence of testing and calibration laboratories.

2010/11 to £863 million in 2014/15 which has led to the closure of 146 courts as well as to reductions and changes to legal aid which is much criticised by the legal profession (Garside and Ford 2016). While the overall number of recorded crime has fallen from 9,711 in 2010/11 to 7,177 in 2014/15 (Office for National Statistics 2018), the number of complex and therefore costlier cases has increased (Garside and Ford 2016), giving these cuts a potentially harmful impact on the system. Budget cuts in the sector have also led to a restructuring with an even greater focus on early guilty pleas which do not require lengthy, expensive trials. In order to economise trials, new Information and Communication Technology systems were introduced to streamline processes and therefore save time in court, ultimately leading to financial savings (Garside and Ford 2016). This principle applies to the entire Criminal Justice Process where innovative methods can lead to a more effective use of resources, produce results quicker, and thus save time and money.

3.3.2 Miscarriages of justice

Miscarriages of justice have two faces; the wrongful conviction of an innocent person and not convicting a guilty offender. It is the first category that, if discovered, often gets much media attention and is often labelled a scandal. Either way, miscarriages of justice have a grave impact on the public's trust in the system. The police are under enormous pressure if no perpetrator is caught for a crime whereas the courts are generally more in the spotlight if the wrong person has been convicted. For wrongful convictions, blame is quickly shifted to bad forensics and individual scientists as opposed to those system safeguards which should have prevented these from reaching court in the first instance (Garrett and Neufeld 2009, Edmond and San Roque 2012, Ward 2011). By analysing this process failure using the product development approach introduced earlier one might be able to detect where along the process the failure occurred and take measures to avoid this in the future. By looking at some of the most frequently debated miscarriages of justice in the UK (*R v McIllkenny et al.* (the Birmingham Six), *R v George, R v Clark, R v Cannings*) it becomes apparent that frequently the initial fault lies with the forensic evidence produced during the investigative stage and a failure by the gatekeepers of gate four - the decision whether to admit certain evidence or not. The role of forensic sciences is therefore discussed in more detail below.

3.3.2.1 The role of forensic sciences in miscarriages of justice

Forensic science has come under increasing pressure following several high profile miscarriages of justice where forensic evidence has played a central role. The type of forensic evidence in these cases covers a broad spectrum of sciences which raises concerns that there is something inherently wrong with forensics. In the UK, some of the most frequently cited miscarriages are the trials of the Birmingham Six and that of Barry George but there is a long list of similar cases. The Birmingham Six were convicted in 1974 for bombing two pubs in Birmingham based (amongst other evidence) on now highly dubious forensic test results allegedly proving their handling of nitroglycerine used in bomb-making. They were freed in 1991 following several appeals (Edmond 2002). George was convicted (and later freed on appeal) of shooting TV presenter Jill Dando based on a single microscopic particle on his clothing that, as was admitted during the appeal, could have easily been contaminated (Ireland and Beaumont 2015). The poor evidence in other cases covers the fields of blood serology, hair comparison, bite mark analysis, fingerprint examination, and medical examinations (Garrett and Neufeld 2009). The problems are not limited to faulty equipment or technology - more commonly the real issue is the human error in using them and interpreting the results. This latter point is a particular problem when it comes to presenting scientific evidence in court.

Due to their role as experts in their respective field, expert witness testimony is frequently given more weight than it might deserve on a scientific basis (Edmond 2015b). This can become a major issue if the experts themselves claim an over-inflated (statistical) significance for their data which they have no actual evidence for. This was the case in the two trials against Sally Clark and Angela Cannings. Clark was convicted for the murder of her two children, Cannings for that of her three children. The medical expert for the prosecution in both cases claimed that the likelihood of two infants in the same family dying of natural sudden infant death was one in 73million. This was based on a limited scientific evidence base and crudely flawed statistics but the jury, readily believing the expert, considered this sufficient for a conviction (Campbell and Walker 2007). Both women were later freed on appeal but if sufficient resources had been invested at the earlier stages of the process, their wrongful conviction could have been prevented in the first place. At the latest, the gatekeeper at gate four should have ruled the evidence inadmissible but failed to do so. Whilst this is being addressed by the aforementioned more recent changes to evidence admissibility, scholars such as Bernstein (2008) and Adams et al. (2013) have criticised such regulations for having little effect as judges still lack the necessary scientific knowledge to reach an educated decision. They refer to the Daubert standards in the US as example thereof (Daubert v Merrell Dow Pharmaceuticals, Inc, 509 U.S. 579 (1993)). Despite the existence of the Daubert standards, a report by the National Academy of Sciences (NAS) found that judges have a high level of discretion in applying these and rarely exclude forensic science evidence based on them. They therefore call on the forensic science community to address the issue of unreliable science before it reaches court (NAS 2009). The list of wrongful convictions suggests that infant deaths are a particularly contentious area prone to miscarriages due to conflicting expert opinions as the case of Kai-Whitewind demonstrates. The expert evidence regarding the infant's cause of death was at the centre of the defendant's appeal case (Campbell and Walker 2007). Whilst the conviction was upheld, it clearly demonstrates the importance of clear standards in forensic and medical evidence before they reach the courts. The majority of scientists do not act maliciously but there has been instances of experts wilfully altering or misstating their results (Garrett and Neufeld 2009). This is only possible due to the lack of quality control in the system. The Innocence Project in the US helped to exonerate hundreds of innocent prisoners whose convictions frequently featured poor quality or improperly interpreted forensic evidence (Cole 2012). However, this is only possible if suitable evidence has been gathered during the original investigation and then has been retained to allow further examination. In the worst-case scenario the wrongfully convicted individual has been executed for a crime they did not commit, with forensic science to be (partially) responsible for it.

All these wrongful convictions are decided at gate five when the jury determine whether the defendant is guilty but this decision depends on the evidence presented to them, as shown in section 2.3.2 on jury competence. In its original product development context this gate is the last checkpoint at which a new product idea can be killed before it is implemented. In the CJP context this is the final chance (not treating the appeals process as a regular part of the CJP) where a miscarriage of justice through wrongful conviction could be averted. It has become clear that this decision depends on the preceding stages which is where the attention should focus on by improving the quality and objectivity of evidence and presenting it in the best possible way for the jury to reach a well-informed decision.

3.3.3 Evidence admissibility and the Forensic Science Regulator

In order to be admitted evidence must fulfil the criteria of helpfulness, relevance, and reliability without being prejudicial. For forensic science and other expert evidence the admission rules are more specific. DNA evidence tends to be the least contested of the forensic sciences as it has the strongest scientific foundation and is therefore most compelling (Evison 2015) which suggests that other types of evidence produced using scientifically validated technology and methods, such as the ones proposed in this thesis, can reach a similar evidentiary position.

The realisation that poor scientific expert evidence has contributed to a number of wrongful convictions has resulted in several reports across different countries demanding higher quality standards for all sectors of forensic science. In the United States the Daubert standards are frequently cited as having had a major impact on evidence admissibility legislation (Fradella et al. 2003). These standards specify that methods ought to be generally accepted in the scientific community, subjected to peer review, tested with a known error rate, produced independently (Daubert 1993). On a federal level these standards were codified in the Federal Rules of Evidence 702, which demand helpfulness, reliable methods that are based on sufficient scientific data, and methods that were applied appropriately to the facts of the case (Federal Rules of Evidence 2000). The ultimate decision on admissibility is made by a judge who might not have sufficient scientific knowledge to adequately assess the methods and tests presented (Neufeld 2005), despite the existence of these criteria. This was criticised in the National Academy of Science's 2009 report which issued the recommendation that a national body should be created to oversee all forensic case work (NAS 2009), but this has not been implemented to date.

Similarly the Law Commission of England and Wales issued a report in 2011 recommending changes to the admission of forensic evidence in English and Welsh courts. In line with the NAS report and scholars before that (Roberts 1996), their recommendations included an enhanced test for admissibility of expert evidence to be written in primary legislation as opposed to the then case law guidance. These suggestions were implemented by Parliament as the new Criminal Procedure Rules 19 (CrimPR) and Criminal Practice Directions (CPD) 19A which are designed to assist the courts in assessing the reliability and validity of the evidence presented to them and of the methods employed to obtain it. These new practice directions provide a catalogue of criteria against which the methods, interpretations, and conclusions reached by the expert ought to be scrutinised. However, this requires the judge to evaluate the scientific validity of the methods used - a task many judges are not suitably equipped for as they lack the scientific knowledge to make such a decision, a similar dilemma to that of the Daubert standards. In reality this might lead to the changes not having the desired effect as judges might rely on their experience or superficial indicators such as how established a method is. Numerous scholars have criticised this failure regarding the Daubert standards in the US (Neufeld 2005, Bernstein 2008, Mnookin et al. 2011) and similar problems could arise in the UK if not addressed. This highlights the importance of addressing the scientific standards before they reach court by an independent organisation, for example a national supervisory body as suggested in the NAS report (NAS 2009). In England and Wales, this supervisory body is the office of the Forensic Science Regulator. The FSR was established in 2005 as an advisory position to the Government

Science Committee with the role currently held by Dr Gillian Tulley. The FSR's responsibility is to publish quality standards, codes of conduct, and guidance and to ensure that the Forensic Service Providers adhere to these standards. This includes providing proof that the methods used are tested and reliable usually via the route of ISO accreditation. Accreditation to ISO standards 17025 and/or 17020[4] is now required for many fields of forensic science and scene of crime work but the FSR does not currently hold statutory powers[5] which means Forensic Service Providers are under no legal obligation to comply with this. Even accreditation does not completely prevent scientific errors as the enquiry into one service provider's faulty toxicology testing has demonstrated (Tully 2018). Perhaps tougher controls and regular inspections facilitated by statutory powers for the FSR are necessary.

The regulator states that new methods must be tested before being used on casework. If the method as such has been tested and shown to work it will need to be validated for all applications and contexts used. The Criminal Procedure Rules (2015) and the FSR's Code of Conduct (2017) explicitly state that any admissibility test is not designed to prevent novel methods or technologies from getting to court but rather to provide the necessary tools to assess their reliability. One such criterion is whether the method has been sufficiently validated. Conducting validation studies can be a resource-intensive process which some FSPs might perceive as disruption to their regular service provision. Police-attached forensic departments face the additional problem that their budgets are under a greater financial pressure and they might simply lack the capabilities to conduct such studies. Outsourcing this via partnerships with other organisations is one way of tackling the issue and an increasing number of these are being established across the country (Childs and Potter 2014).

Only in late 2017, Supreme Court judge Lord Justice Hughes in collaboration with the Royal Society and the Royal Society of Edinburgh, announced the introduction of scientific primers. These are scientific guidance documents for judges, intended to assist their understanding of the scientific basis of expert evidence. The initial documents summarise the fields of DNA fingerprinting and gait analysis but further publications are planned for statistics, vehicle collisions, and shaken baby syndrome (The Royal Society 2017). These documents include references to validation studies to inform judges on the method's reliability. It is likely that similar guides are to be drafted for the majority of forensic sciences

[4] ISO/IEC 17020:2012 Conformity assessment Requirements for the operation of various types of bodies performing inspection.

[5] At the time of submission consultation regarding the issue of statutory powers was still ongoing.

and methods in the future, including novel ones such as the ones proposed in this PhD, thus increasing the need for a solid scientific foundation and demonstrated reliability. It further illustrates that judges increasingly put pressure on the prosecution to prove the suitability of their evidence and to challenge the laissez-faire approach to admissibility which some researchers have criticised in the past (Redmayne et al. 2011, Edmond et al. 2013, Ireland and Beaumont 2015). Like many other policy measures and reforms this step is also intended to make trials more efficient by providing judges with the uncontested facts of a scientific method, thereby reducing the need for expert witness testimony during the proceedings (Wall 2017). This could be an excellent opportunity for independent research institutions to create meaningful input by conducting such validation studies and contributing to the writing of future primers on their respective expert areas.

Once evidence has been ruled admissible it needs to be presented in an appropriate way at trial. Evidence produced using 3D digital imaging technology for example is less suitable for simple oral presentation which would fail to communicate the visual nature of the details described (Urschler et al. 2014). This encourages the use of specialised visualisation software as frequently employed in engineering disciplines for the preparation of court presentations of complex evidence. The admissibility of three-dimensional evidence is underdeveloped as so far there are few precedents. It is anticipated that not the methods as such will be contested as their validation is rather straightforward. Instead, the traditional criteria of prejudice and helpfulness will be questioned. 3D has an even higher persuasive power than photographs (Campbell et al. 2013), making it susceptible to the prejudice exclusion although there is a lack of studies researching this in a courtroom context (Errickson et al. 2014). A distinction is made between 3D visualisations as substantive evidence and those used as demonstrative or illustrative evidence. The majority of 3D in court (with the exception of simulation data) is used to illustrate a witness's testimony (Campbell et al. 2013) and is therefore employed in a demonstrative way. It has sometimes been argued that demonstrative evidence is subject to less strict regulations (Fulcher 1996). It must nonetheless rely on data generated by validated means and accompanied with sufficient explanation to avoid misinterpretation (Schofield and Fowle 2013). Harston (2008) argues that "real" evidence can become demonstrative evidence and medical images such as X-rays or Computed Tomography scans are examples thereof as they serve as substantive evidence (e.g. trauma detection) and simultaneously as illustrative material of the expert's testimony. Medical images are rarely challenged in court (Kolar 2016) as long as the expert is able to demonstrate the correct operation of the machine used to produce the image (including calibration) and that they are sufficiently qualified to interpret the data. The introduction of 3D objects in English homicide trials has not been reported on often, possibly because it is uncommon due to the sensitive nature of such evidence. One way to sanitise sensitive objects is to create replicas thereof, for example by 3D printing. The use of 3D printed exhibits during trial is more common in the US where numerous companies have specialised in their production (for example Lazarus 3D, Houston, TX, or 3D Printed Evidence, Jacksonville, FL).

4. New Public Management

The strategic changes discussed in the previous section are specific to forensic sciences, other policy changes affect the entire system. Recent government reforms have the aim of creating more effective and efficient public services by changing their management structures. This became known as New Public Management (NPM) which has been discussed in government reforms since the 1970s (Barton and Barton 2011). NPM attempts to transform management in the public sector to become more like the private sector with its more business-focussed approach (Ashby et al. 2007) and has seen the privatisation of some of its services. This includes prisons and probations, and some forensic services which had previously been supplied by the government-owned Forensic Science Service. This business-style transformation emphasises the provision of "services", treating users more like customers and comes with general free market pressures such as reducing cost and delivering quality (Barton and Barton 2011). The implementation of NPM in practice is to streamline processes and to create shared platforms to speed up the transfer of information between agencies in order to accelerate the delivery of justice in general. An emphasis is put on the aspiration to "get things right the first time" (Grayling 2014) which is an objective frequently found in project management texts (Turner 2009) and is also the underlying aim of using the stage-gate system presented in Section 3.2. Similar to the proposed mapping of the CJP onto the stage-gate system, Greasly (2006) used process mapping and business process simulations to analyse police uptake of new technologies. With this emphasis on common market values, new service performance measures were required in order to assess whether justice agencies succeeded with their measures to increase efficiency and effectiveness. However, most performance measurements were initially based on financial indicators and focussed only on outcomes, thus neglecting actual measurements of efficient use of resources (Barton and Barton 2011). The overall increased focus on achieving targets and efficiency have been criticised for neglecting the more qualitative values often associated with the justice system (Diefenbach 2009). However, the strive to improve service delivery has also brought positive changes such as better victim and witness care and has pushed towards better quality of justice provision as organisations are subject to regular audits (HM Inspectorate of Constabulary 2016).

Technology is often envisaged to aid justice agencies reaching their efficiency goals, Greasley's (2006) business process simulation estimated that three hours could be saved on each case by digitising recording processes. However, a lack of acceptance of new technology often inhibits its efficient use (Chan 2001) and police have been shown to be particularly slow at implementing change compared to other public organisations (Barton and Barton 2011) as the next section will show.

5. Police innovation and partnerships

Technology at the scene is usually limited to scene photography and measurements, fingerprinting, and detection of bodily fluids. The latter two are frequently combined with the use of alternative light sources and chemical treatment of surfaces in order to enhance their visibility. This approach relates to the more straightforward cases but since each case is unique it is impossible to describe a standard approach which applies to every single one. Many aspects of the scene examination are still performed using traditional, labour-intensive methods. The best example is Blood Pattern Analysis (BPA) which is conducted by manually attaching strings to blood stains at the scene in order to determine their point of origin (Peschel et al. 2011).

The majority of technology applications in the overall process can be found in the field of lab-based forensic analyses, some exist in the crime scene documentation, but very few in the detectives' investigative work. The most commonly employed lab techniques include fingerprint and DNA analysis and toxicology and histology of tissue samples taken during the postmortem (Williams 2011) and ballistic analysis if firearms are involved. The majority of technology employed by detectives is centred around information technology systems such as databases, although in recent years CCTV image analysis has gained importance and now takes up many hours of an investigation (Evison 2015). Based on the increased use of CCTV footage is the development of new methods of human identification using facial mapping have been developed to add a scientific validation to simple visual recognition (Mallett and Evison 2013). Courts are becoming increasingly digitised following the government's push for more modern courtrooms and many are now able to show audio and video evidence and to share information via ICTs.

The introduction of new technology into the justice system has traditionally been painstakingly slow which results in the novel technology being used inefficiently (Chan 2001). This is partially due to resistance from those whose work it is supposed to facilitate (Barton and Barton 2011). Koper et al. (2014) suggest that acceptance amongst officers will improve if sufficient training is provided, if the technology is sufficiently validated and its benefits are clearly demonstrable. This closes the cycle to police's lack of means to research and validate new technologies which can only be broken by investing in partnerships with academic and research institutions. If these institutions validate and test new methods and demonstrate their benefits, police personnel might be more ready to adopt and support them. Much research has been conducted in the last decade or so examining how police and academics work together and how this cooperation could be improved to achieve more satisfactory results on both sides. Traditionally, police and academics occupy very different spheres with different requirements and expectations and have often treated each other with distrust (Fleming 2010). Academics might be perceived as removed from reality, as sitting in an "ivory tower", while law enforcement might be seen as ignorant towards scientific advancement (Rudes et al. 2014). This view appears to gradually change and more collaborative projects between criminal justice agencies and universities have been established over the last years (Childs and Potter 2014) although a study from the US shows that only one third of partnerships are long-term collaborations (Rojek et al. 2012). This is partly related to the funding cuts experienced by police, causing them to deploy their resources in a more focussed manner and scientific research can help them identifying these areas (Innes 2010, Tillyer et al. 2014). Such collaborations enable scientists to validate their research on real life cases to which they would not normally have access to, while police usually lack the means and resources to conduct research into new technologies and methods (Mennell and Shaw 2006, Ribaux et al. 2010). The UK government has tasked its Centre for Applied Science and Technology (CAST) with the research into new forensic methods, but the high number of niche sciences which contribute to the justice system makes it difficult for CAST to cover all areas due to their lack of experts. Despite the realisation that research is necessary to establish "what works" in policing, there is still a distinct lack of independent research investigating the effectiveness of policy measures (Neyroud 2009). With regards to scientific evidence, the Home Office states in its Forensic Science Strategy paper that "Research into the contribution that forensic evidence makes to the investigation of crime is limited" (HO 2017, p. 15). In this publication they further emphasised the importance of such partnerships for the future of the CJS, citing those between King's College London and the Met, and between Portsmouth University and Hampshire Constabulary as models. The three main objectives for entering such partnerships are: improving the quality of forensic evidence, increasing cost-effectivity, and raising public trust in forensic services. The project presented in this thesis is in accordance with the abovementioned policies and government recommendations and shows some of the signs of successful collaborations as identified by several authors.

6. Summary

This chapter provided an outline of the Criminal Justice System of England and Wales and introduced three of its main agencies: the police, the Crown Prosecution Service, and the Courts. Their roles and responsibilities were outlined with reference to the methods and technologies employed to fulfil them. These technological and methodological choices are shown to be increasingly influenced by the need for more economisation, efficiency, and effectiveness which can be achieved and assessed by applying the management concepts of the stage-gate system, FTR, and the QCD triangle outlined in this chapter. It further opens the field to the introduction of novel digital tools, presented in the following chapter.

Chapter 3: Digital Tools

1. Introduction

After having introduced the field of research and the research problem addressed in this thesis in Chapter 1, and presented the Criminal Justice System with its current procedures and associated problems in Chapter 2, this chapter aims to provide a detailed review of some of the existing digital technologies available to address the gaps previously identified in the fields of crime scene documentation, forensic science, and evidence presentation. The list of available technologies is vast, with this thesis focussing on micro X-ray Computed Tomography (micro-CT, µCT), commonly encountered in industrial settings.

The chapter begins with a presentation of X-ray Computed Tomography in general including the underlying technical principles, its fields of application, and finally potential applications in the Criminal Justice System based on the review in the previous chapter. This section will further focus on how micro-CT differs from medical grade CT and how this could be harnessed in the CJS. The remainder of the chapter will focus on visualisation and how the data created using the technologies presented here could be used to assist improving the delivery of justice.

2. X-ray Computed Tomography and micro X-ray Computed Tomography

The first part of this chapter will take a closer look at the scanning technology used over the course of this project, micro X-ray Computed Tomography. While many readers might be acquainted with standard medical CT, micro-CT is less well-known amongst the general public from personal experience. This section will set the wider technological context for micro-CT by providing an overview of the development of the field of Computed Tomography, detailing the basic physical principles, the similarities and the differences between medical CT and micro-CT, and finally focus on their applications which include the fields of industry, clinical praxis, medical research, and forensics. The latter will be treated in more detail as it lies at the centre of this thesis.

2.1 Evolution of CT

Computed Tomography has its origins in the early 1970s although the foundations were laid almost a century earlier in 1895 when Wilhelm Conrad Roentgen discovered X-rays (Liguori et al. 2015). The year 1972 is often cited as the hour of birth for modern CT, when the first scan results were presented to the public by Godfrey Hounsfield (Fleischmann and Boas 2011) whose prototype CT scanner was installed at the Atkinson-Morley Hospital in London, England, which demonstrates the initial clinical purpose of CT. The method became rapidly established within the medical community, leading to numerous improvements and new fields of application as industry sectors were quick to adopt the technology for quality control and inspection (Hanke et al. 2008, Brunke 2015). Since the initial scan performed on a patient's brain, the technology has significantly advanced, and increased scanning speed and larger possible volumes now enable whole bodies to be scanned (Goldman 2007). These improvements came at the expense of patient radiation doses which rose from 1.3mSv in the 1970s to a peak of 8.8mSv in the 1990s (Kalender 2014). Given the increasing number of CT exams performed in hospitals, 70 million in 2007 in the US alone (Fleischmann and Boas 2011), more recent research efforts focus on the reduction of the dose without compromising image quality.

CT has come a long way since the 1970s which has been facilitated by improvements in computing which finally allowed the implementation of older ideas (Fleischmann and Boas 2011). Current research in the field of CT technology is focused on three main areas: to increase the resolution, to increase scanning speed, and to reduce the dose (Shefer et al. 2013). The improvement of image quality and resolution over the past decades has culminated in the introduction of the now well-established micro-CT and even the first nano-CT systems. However, the radiation dose in these systems is currently too high for clinical use which is driving research into areas of better reconstruction algorithms, X-ray spectrum optimisation, detector technology, and beam collimation in order to reduce the radiation risk and potentially employ it on living patients (Kalender 2014).

As the majority of technologies currently being investigated are not yet ready for commercial use, the future lies in their implementation. With regards to the development of new detector and source technologies one area is of particular interest - the use of CT to distinguish different materials. There are several approaches to the issue: direct photon-counting detectors, dual energy sources, phase contrast, and spectral CT are some of the most promising ones. With increased technical possibilities one might also see a diversification and specialisation in the application of CT.

2.2 Technology overview

2.2.1 Components

The three basic elements that every CT scanner is composed of are an X-ray source, a detector, and a manipulator table or stage for the object to be scanned. However, the arrangement of these three core components varies according to the system's application. Medical CT systems tend to consist of a rotating source/detector unit in which a linear detector is opposed by the source that emits a (usually) fan-shaped X-ray beam. This linked system moves along the patient's long axis on a gantry taking cross-sectional slices at a specified interval and thickness. Alternatively, the patient table is fed through the ring-shaped source-detector unit at a fixed rate. At each slice location the unit rotates around the patient to cover a full 360° view. This translation-rotation movement has been combined in newer systems referred to as spiral or helical CT, which continuously acquires data without having to pause the scanning process (Goldman 2007). More and more modern scanners use multislice scanning where several rows of detectors and X-ray beams are combined to form something akin to a cone beam scanner with a flat panel detector. This reduces image acquisition times. **Figure 3** shows an example of a medical CT machine. In contrast, lab-based micro-CT systems are predominantly designed to incorporate a source and detector which are stationary throughout the scan with a rotating table for the sample between them. Such a setup is enabled by the fact that most lab-based micro-CT applications focus on inert objects which reduces potential image blurring caused by patient movement. This generates the opportunity to use a stationary source where the focal spot remains stable and long exposure times are allowable due to dose becoming unimportant which ultimately contribute to a better resolution (Ritman 2011). Furthermore, the use of inanimate objects allows higher doses which offers further opportunities to improve resolution and increases the range of materials that can be examined.

The advantage of medical CT scanners is the size of the object to be scanned. They can accommodate full bodies while micro-CT scanners are usually limited to objects sized up to 300mm in diameter (Du Plessis et al. 2016). For both types of system the resolution depends on the field of view, the larger the FOV the lower the resolution. The data output created by hospital CT scanners is in DICOM format whereas micro-CT systems produce a range of file formats including DICOM, but also reconstruction software specific ones.

Scan parameters in medical CT scanners are fairly standardised and imaging protocols exist for a wide range of diagnoses. Medical CT images are usually reported in Hounsfield Units (HU) which are a way of standardising the grey values obtained from a CT scan. The grey value of distilled water corresponds to 0HU, that of air to -1000HU and hospital scanners are calibrated regularly using radiology phantoms. Despite being universally used, Lamba et al. (2014) have found that there is some discrepancy in Hounsfield units for the same material scanned on different scanners. Cone beam CT, and therefore most micro-CT scanners, does not directly convert the grey values into HU which makes direct comparisons with medical scans difficult. However, some studies have explored calibrating cone beam grey values using Hounsfield units measured on hospital CT (Hatton et al. 2009, Reeves et al. 2012).

2.2.2 Process

The X-ray source contains an X-ray tube in which a cathode is excited to emit electrons which get accelerated towards the anode by a high power source. The electron beam is focussed by magnetic coils onto a target (typically consisting of molybdenum or tungsten) where it hits the focal spot. The sudden deceleration forces the electrons to convert their energy into X-rays (Bremsstrahlung) under the production of heat (Kruth et al. 2011). The X-ray beam consisting of this Bremsstrahlung and the target's characteristic radiation is then channelled through an aperture in the tube, emitted as a cone beam. The smaller the spot size, the better resolution can be achieved. Depending on the shape of the beam and the aperture, the resulting X-rays can take a linear, fan-shaped, or cone appearance. After leaving the aperture the X-rays pass through the sample where they are attenuated or not. Attenuation is the loss of energy by absorption or scattering whereby the rate of attenuation depends on the material properties of the object (both material and thickness) and the original X-ray energy (Kruth et al. 2011). The overall process is illustrated in **Figure 3.** The non-attenuated proportion of the original X-ray energy is received by the detector which contains a scintillator to convert the incoming photons into a measureable light signal, resulting in greyscale radiographic projections. Highly attenuated X-rays result in darker areas in these projections. This process is called indirect conversion. Direct converters which count every individual photon are currently being developed but their commercial availability is still extremely limited (Holbrook et al. 2018). Their benefit will be in allowing living patients to be subjected to micro-CT exams by lowering the dose to between ten to twenty times below that of current micro-CT as a study by Debarbieux et al. (2010) has shown. In addition, direct converters are better at detecting subtler changes in material allowing examinations of low contrast objects such as different soft tissue structures. Most current micro-CT systems use settings that result in long scans compared to the fast scans conducted on hospital CT scanners (10-20 minutes, NHS 2019). Conducting longer scans could be harmful to the patient, cause image artefacts, and would be highly impractical in a hospital setting due to the high numbers of CT exams performed (Fleischman and Boas 2011).

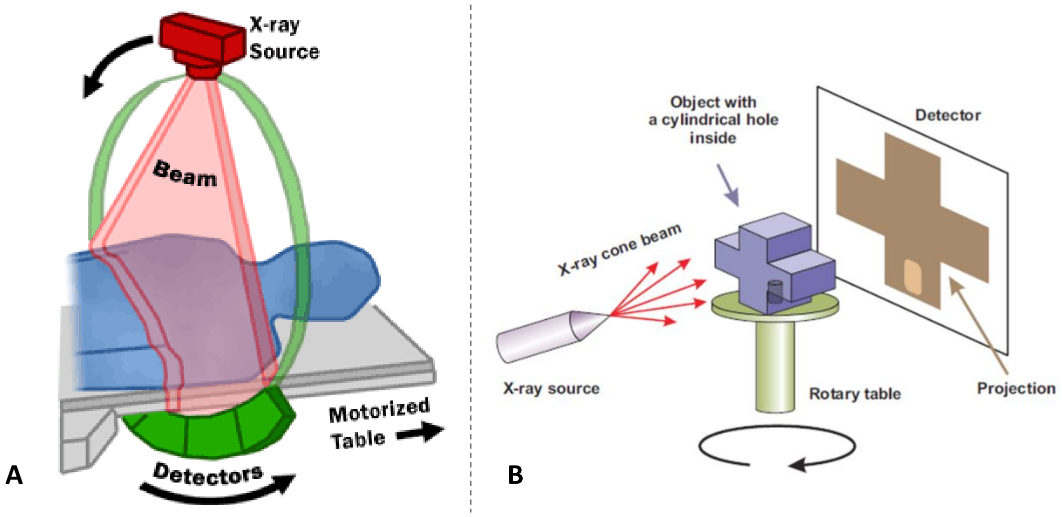


Figure 3: *A: Setup of a medical CT scanner with a ring-shaped source-detector unit, from www.fda.gov; B: Setup of a typical lab-based micro-CT system. The X-ray source on the left and the detector on the right are stationary and the object in the centre is placed on a rotating stage, from Warnett et al. 2016.*

The signal produced by the detector is then reconstructed, typically using a filtered-back-projection algorithm, although other methods such as iterative reconstruction are available. With the algorithm individual projections are reconstructed into 2D images and their 360° views combined into a 3D volume of the object. A high number of projections is necessary for the Feldkamp algorithm as more projections result in a better reconstruction with lower image noise (Feldkamp et al. 1984). Fan-shaped X-ray beams often encountered in hospital settings result in anisotropic voxels (voxel= 3D pixel) which have a pitch-dependant depth which limits direct measurement on the scan volume (Scarfe et al. 2006). The resolution achieved in standard medical CT ranges from 250 µm to 1000µm whereas micro-CT achieves a resolution of between 1µm and 200µm (Kachelrieß 2008). Other differences in parameters include a lower tube current for micro-CT, typically in the order of µA whereas medical CT uses tube currents in the order of mA. Lower current results in better image contrast due to reduced noise but requires longer scan times to match the tissue penetration.

2.2.3. Problems

Each of the different systems has its own inherent difficulties. The most obvious problem in clinical CT is motion as the patient's respiratory, cardiac, or bowel movements can introduce some image blurring, thus rendering any efforts to minimise voxel size below a certain level obsolete. Motion artefacts are seen as blurring, streaking, or shading where the scanned object appears to have a shadow of itself around the edges (Hsieh 2015). The other main concern in a medical context is the radiation dose that the patient is exposed to. A compromise between image quality and the requirements for a diagnosis must therefore be found in order to protect the patient from radiation damage. In lab-based micro-CT scanning radiation exposure can be neglected as predominantly inanimate objects are being scanned. Using such high power leads to new challenges such as increased image artefacts, the most common ones being beam hardening and metal artefacts. While these image artefacts are a problem encountered in medical CT as well, beam hardening is more pronounced in high power micro-CT. Beam hardening is a common problem caused by the polychromaticity of the X-ray beam where lower energy photons get attenuated more rapidly. In the reconstructed image this is visible as dark streaks behind denser objects and in form of cupping artefacts. The hardened X-ray beam artificially lowers the grey values at the centre of an object and makes its edges appear brighter (Dewulf et al. 2012). This is a problem encountered in both micro-CT and medical CT where the dark bands into adjacent tissue could be mistaken for or obscure real pathology. While the grey values can be partially corrected by using filtration both during the scan (Meganck et al. 2009) or during post-processing, care must be taken not to alter the actual dimensions of the reconstructed object (Dewulf et al. 2012).

Metal artefacts are produced when the X-ray beam encounters the dense metal object which absorbs the majority of the energy, thus creating a bright white area and streaking in the scan images which can be frequently observed when scanning multi-material objects including metal. They occur because the metal's density is higher than what the X-ray beam is set to penetrate, leading to an incomplete attenuation profile. In addition to the bright streaks, beam hardening effects can also be observed adjacent to the dense object, adding to the loss of image information. In medical CT, metal artefacts can be caused by metallic prostheses, surgical clips, or dental implants.

A further artefact which can affect dimensional measurements is the partial volume effect. Each pixel of the detector represents the grey value of a material. If there are two materials represented in the pixel the reconstruction algorithm creates an average thereof, thus blurring the edges. A similar problem occurs if the scanned object moves out of view in some projections. This creates streaks in the reconstruction as there is less information available for the algorithm to use. This is less commonly encountered in conventional medical CT where the patient tends to be fully within the field of view. It is a common problem in cone beam CT where a small field of view is selected within a larger sample (e.g. in dental applications). The result is increased noise and brightened edges around the field of view. This can also be seen as the cone beam effect where the areas further towards the edges of the cone, where the cone angle is wider, appear somewhat blurred. This is also apparent to a lesser degree on multidetector CT as the multiple fan shaped X-ray beams are combined into a more conical shape.

Ring artefacts are a type of artefact created by hardware faults, either by miscalibrated source-detector units or by faulty detector elements (Kyriakou et al. 2009). Due to the concentric acquisition of images, this results in concentric rings in the reconstructed scan. The majority of these artefacts can be reduced to a certain degree by the scan setup and correction algorithms but only new reconstruction algorithms, such as iterative reconstruction, have a real potential to reduce their effects (Wang et al. 2000). Many of these artefacts are encountered in medical CT as well but it is the cone-shaped X-ray beam used in the majority of micro-CT systems which amplifies their effect.

Knowing these artefacts is crucial if one uses the scan images for defect detection to avoid misinterpreting artefacts as real defects.

2.3 Applications

While standard CT has a vast range of applications predominantly in the medical field, micro-CT is more widely used in industry where it is used for non-destructive testing (De Chiffre et al. 2014), for example to assess new manufacturing processes such as 3D printing (Thompson et al. 2016). It is further used for quantitative analysis of material characteristics such as pores, inclusions, or volume fractions (Maire and Withers 2014). Further quantitative analysis includes dimensional metrology where it adds the possibility to measure internal features as opposed to only the visible surfaces measured by traditional Coordinate Measuring Machines (CMMs). Industry benefits from working with inanimate objects which is the limiting factor for medical applications of micro-CT, as discussed in the previous sections. The majority of the applications in this field are therefore using hospital CT.

2.3.1 Medical practice and research

Having been invented for medical use CT has had sufficient time to become firmly established in both clinical practice and medical research. Due to its huge potential in musculoskeletal imaging it is frequently employed in emergency departments where a rapid injury assessment is crucial (Broder and Warshauer 2006). Although traditional radiographs are still in use, studies have shown that injury detection and assessment greatly profit from CT scanning (De Smet et al. 2015). CT also improves the removal of foreign bodies by displaying them in three dimensions as opposed to the standard 2D radiographs, which assists planning the surgical procedure and increases its success rate. By removing the superimposition of materials which can obscure features on traditional radiographs, CT can assure that all fragments have been removed which might be necessary in cases where debris has entered a wound following an explosion, for example. With terrorist bombings become more frequent this has becomes an increasingly pressing concern in emergency medicine (Hare et al. 2007). CT is further applied in clinical practice as a diagnostic tool to detect tumours and has greatly improved cancer detection, treatment planning, and follow-up care (Simons et al. 2014).

More recent increases in the scanning speed have further enabled doctors to use CT as an intraoperative instrument for guided interventions in poorly accessible areas or for complex operations where accuracy is crucial to avoid complications (Kenngott et al. 2014). Similarly CT can also be used to perform CT-guided needle biopsies of deep lesions which are difficult to perform otherwise (Rimondi et al. 2008). Apart from reducing the risks in the operating theatre using real-time 3D guidance in these scenarios can also reduce surgery times and thus save money.

Another great achievement in the field of medical CT is cardiac CT which is an important tool for the early detection of coronary disease. The difficulty in imaging a living heart is accounting for its constant movement which would normally cause image blurring. The solution is to link the CT to an electrocardiogram in order to complete the scan over several cardiac cycles, only taking an X-ray image at the same heart expansion (Desjardins and Kazerooni 2004).

In clinical practice CT is often used in combination with contrast agents which help to image tissues that would otherwise not be visible. While the administration of these contrast agents in living patients is usually achieved intravenously or by ingestion, staining tissue samples in medical research relies on perfusion which is a time-consuming process (Aslanidi et al. 2013). Some of the substances used in medical research are toxic and therefore unsuitable for clinical practice, but it allows a broader spectrum of tissues to be studied as different contrast agents favour specific tissue types (Lin et al. 2007, Descamps et al. 2014). Tissue staining is a common practice in histological examinations - an area that increasingly employs micro-CT and more recently nano-CT as a minimally invasive alternative (Khoury et al. 2015). Since histology examines tissue samples at the cell level, standard medical grade CT scanners are unsuitable for this due to their lower resolution. Histological examinations are time-consuming, expensive, and destructive, but essential in both clinical and forensic pathology (Lau and Lai 2008, Holme et al. 2014). Future developments might put micro-CT in a position to replace traditional histology which could lead to savings for hospitals as the process is shortened which could also shorten the time until patients are given a diagnosis. Reducing this time also increases chances of healing as treatment can commence earlier. The microscopic level of detail and the possibility to display structures in 3D as enabled by micro-CT has increased the number of biomedical research studies using this technology, predominantly in the area of bone and bone-mineral research (Ritman 2011, Bart and Wallace 2013). Osteoporosis research for example takes advantage of micro-CT's high resolution to quantify bone trabeculae when studying the risk and extent of osteoporosis (Genant et al. 2008). Assessing the structural quality of bone is also at the centre of Kim and Henkin's (2015) micro-CT study of alveolar bone which aimed to improve the success rate of dental implants by understanding the bone micro-architecture. These types of study profit from computer software (BoneJ being the most commonly employed one) which can be used to analyse a range of structural characteristics such as shape, size, orientation, spacing, etc. in all three dimensions (Doube et al. 2010). However, since µCT is not yet clinically available, these studies with the exception of biopsy material, are limited to ex-vivo research. Even living animal studies are rare using this method. Morgan et al. (2009) used µCT to evaluate the effect of different substances on the mineral density of fracture calluses in mice which were harvested at various times as longitudinal in-vivo scans were not ethically allowed. However, current micro-CT technology does not provide absolute densities for the material scanned which makes it difficult to directly compare results to the standard Hounsfield Units used for hospital CT images (Pauwels et al. 2014). Cortical bone has also been the focus of several studies, for example to examine porosity and other age-related changes (Bousson et al. 2000). With the introduction of nano-CT and therefore even higher resolution, scientist are now able to study even the smallest of osseous structures such as osteons, the basic building elements of bone (Cooper et al. 2011).

2.3.2 Other

Other disciplines which have profited from CT include mineral research. It has long been in use to study coal deposits, but more recent advances in micro-CT have enabled geologists to study the mineral composition of rocks. Since the different minerals have different structures and densities, they are visualised as different grey values in the scan (Ketcham and Carlson 2001).

CT also holds an important position in museum and heritage studies. Archaeological artefacts are often in a poor preservation condition and their conservation is a risky process which might cause some damage. Especially metal objects are frequently recovered in a badly corroded state which makes CT an excellent method to study the underlying, undamaged metal, micro-CT being more useful for small intricate artefacts requiring more detailed examination. One can also virtually straighten or unroll bent objects without having to subject the object to additional physical stress. This has led to CT becoming more and more common practice in conservation laboratories (Applbaum and Applbaum 2005). A great project linking such research with the museum display was brought to life by the British Museum in their 2015 "Eight Mummies" exhibition (British Museum 2015). For this project, eight mummies were CT scanned in order to study their mummification practices, associated ritual behaviour, and also the human remains themselves. The museum visitors could then interact with the virtual models, for example digitally unwrap the mummies to see the hidden features. This method of analysis and display is non-destructive but still delivers a maximum of information, possibly making it the future of museum exhibitions. It further eases the pressure associated with the study and exhibition of indigenous remains and objects which often face strong opposition from their communities (Swain 2016). By scanning the specimen or remains and study their virtual image a compromise might be struck to allow scientists to study the object while still respecting the indigenous' wishes and beliefs which might otherwise prohibit this. Other museums have followed this direction and virtual representations of objects are becoming more common in exhibitions (Styliani et al. 2009).

2.3.3 The story so far: CT in Forensics

Over recent years, forensic radiology has emerged as a new sub-discipline of radiology (Aalders et al. 2017) with Computed Tomography as the most commonly employed method followed by Magnetic Resonance Imaging (MRI), conventional radiographs, and ultrasound (Baglivo et al. 2013). Pioneered by the Virtopsy project at the University of Bern, Switzerland, CT has become commonplace during postmortem examinations in a vast number of countries. However, few have a national standardised procedure of when to scan a body and most institutions perform a Postmortem CT (PMCT) examination ad-hoc, using the clinical CT equipment, often outside normal hospital hours (Flach et al. 2014). PMCT is gaining increasing acceptance as many scientists have recognised the potential to gain additional information regarding cause and manner of death from CT scans. Irrespective of the cause for the postmortem exam, a wide range of benefits can be drawn from the 3D images. Apart from the specific applications elucidated further below CT can be useful in determining the victim's underlying conditions which are not immediately linked to their death but which are nonetheless important to record in order to be able to accurately interpret potential injuries.

This applies to certain types of bone pathology which might be mistaken for trauma (Rutty et al. 2013). Although CT might under certain circumstances act as substitute for traditional autopsy a study conducted by Jalalzadeh et al. (2015) highlights the complimentary nature of both methods as each produces superior results in different areas. The non-invasive nature of CT is advantageous in cases where an autopsy cannot be performed due to cultural or religious objections (Flach et al. 2014) or in cases in which a CT scan of the corpse is indispensable because of its fragile condition and the risk of irrevocable, severe damage during autopsy. This can be the case with bodies which have been exposed to fire, desiccation, water, or are in an advanced state of decomposition (Kettner et al. 2014). A CT scan prior to the physical examination does not only preserve a digital record of the original state but might even reveal more detail than the actual dissection.

Practitioners are becoming increasingly aware of the need for validation despite the fact that the technology has been in use for a significant length of time. An increasing number of systematic studies comparing the results achieved with PMCT to traditional autopsies have been published over the last years. One of the areas where CT is superior to dissection is the detection of gas or fluid accumulations within the body cavities (Jalalzadeh et al. 2015). Traditional autopsy methods to recover these are very laborious and complicated and might not succeed in detecting and quantifying them. Different attenuation values depict them clearly in the CT image from which their 3D volume can also be easily and accurately calculated. One specific type of fluid accumulations, haematoma, can be clearly visualised in CT if they are sufficiently large and it is therefore frequently used to detect intracranial haematoma. However, Jalazadeh et al. (2015) have found that small haemorrhages tend to be better detected during autopsy, again emphasising the complimentary value of both methods. MRI would probably the best method for this particular condition but it is more expensive and therefore less available and less commonly employed in postmortem scenarios (Baglivo et al. 2013).

Another less commonly encountered application which forensic practitioners can be confronted with is the estimation of a person's biological age which might be required if an unidentified body is found. Where no personal identification documents exist, age determination is traditionally performed on the basis of skeletal maturation and degeneration. While this is accurate for children and juveniles, determining the age of adults is significantly more challenging and imprecise since the existing methods only categorise the skeletal features into broad age groups (Buikstra and Ubelaker 1994). Wade et al. (2011) have therefore attempted to quantify the age-related changes in trabecular bone using CT.

Their study has not succeeded at assigning an absolute age to certain values but it demonstrates a step in the right direction towards more objective ageing criteria.

Another aspect of human identification where CT might replace traditional methods is the field of facial reconstruction which is sometimes used if an unidentified decomposed or skeletonised body is found but no DNA match is achieved (Wilkinson 2010). The reconstruction aims at publishing a reconstructed face of the unidentified person in the hope that a member of the public might recognise the individual. In practice, the skull is scanned with a laser scanner and then soft tissue is added digitally using population-specific soft tissue indexes. However, these laser scans do not always produce a high-resolution model of the skull and if soft tissue still adheres to it the skull needs to be macerated prior to the scan. CT and micro-CT in particular, have the potential to produce a highly accurate model which might positively influence the final reconstruction and therefore increase the chances of positive identification.

Recently, micro-CT has been used in forensic entomology. The aim of such studies is to establish the postmortem interval of a corpse by studying the developmental stages of insect larvae and pupae. This is traditionally performed using light microscopy but µCT increases the level of detail and objectivity to the process and further allows the study of the insects' internal features (Richards et al. 2012) and therefore a more detailed estimate of time since death.

The aspect which constitutes the majority of 97% of publications in the field of forensic CT is the analysis of trauma (Baglivo et al. 2013) covering all three injury classifications: sharp force, blunt force, and gunshot trauma. CT imaging of gunshot wounds can provide details about the bullet trajectory since the wound channel is often laced with splinters of bone and/or residue that tends to be clearly visible in the scan. Advances in dual-energy CT scanners facilitate the detection of foreign bodies as it offers separate settings for the body and the foreign material to be scanned simultaneously (Persson et al. 2008). The distribution of gunshot residue on micro-CT level can further be analysed to determine the firing range (Rutty et al. 2013).

In the field of Sharp Force Trauma (SFT) predominantly injuries to the skeleton are useful in a forensic analysis since those in soft tissue are too difficult to visualise on CT (Thali et al. 2003). However, those that can be seen hold valuable information about the assault weapon as several studies have successfully demonstrated in examining the correspondence of the kerf features to the weapon involved (Symes et al. 2010). Cases of dismemberment also fall within the broader theme of Sharp Force Trauma even though the cut marks might not have been directly linked to the person’s death. In such scenarios CT scans can be used to identify the weapon used in the process and might also help to virtually match two separated fragments of the same bone to confirm their mutual origin without expensive DNA testing (Seidel and Fulgitini 2014). The ability to take measurements directly on scans has led to research investigating more automated or quantifiable ways of analysing sharp force injuries to reduce human error and subjectivity (Norman et al. 2018b).

The injury category most frequently and successfully examined by CT is Blunt Force Trauma (BFT). Blunt Force Trauma generally manifests as bone fractures where the majority of researchers agree that CT is superior to standard autopsy (Jalalzadeh et al. 2015). Robson-Brown et al. (2011) used micro-CT to examine a victim with multiple cranial fractures and demonstrated the method’s advantages over traditional radiographs and standard autopsy practice. The superimposition on 2D radiographs failed to depict incomplete fractures, some of which were also missed during autopsy. The 3D model resulting from the micro-CT scan helped interpreting the fracture pattern and identifying the impact area which could be matched with a witness account.

A specific example of Blunt Force Trauma is compression to the neck, commonly referred to as strangulation. Fractures of the laryngeal skeleton are frequently encountered in such cases which makes this injury category suitable for an examination using X-ray CT. Flach et al. (2014) have realised this potential and suggest that whenever neck trauma is suspected, a separate laryngeal scan should be performed in addition to standard full-body views. This focus on the neck region is likely to improve the results compared to a standard full body scan, however, the resolution of hospital CT might not be sufficient for the delicate laryngeal structures but could be on a micro-CT scan as Fais et al. (2016) demonstrate. The problem of visualising the soft tissue is particularly challenging as the neck structures only ossify with age, consisting largely of cartilage in earlier life. New developments in CT technology such as spectral CT or phase-contrast scanning and contrast agents could solve this problem in the future.

Another example of blunt force injuries on small structures are cases involving children, in particular where a non-accidental nature of the injuries is suspected. If a suspicious case is admitted most hospitals perform a standard X-ray skeletal survey of any child under the age of two years to document potential fractures on all body parts. These children are generally re-examined at set intervals following initial presentation which makes the cumulative dose of standard CT too dangerous for use, despite the improved diagnostic outcome (Sanchez et al. 2015). CT can be applied to fatal cases and studies have shown that the 3D reconstruction increases the detection of small metaphyseal fractures commonly associated with physical abuse (Kemp et al. 2008). Micro-CT is even better suited for this type of injury due to the small size of the elements in question and the subtlety of the injuries (Tsai et al. 2014).

It has become apparent that the strength of micro-CT as opposed to medical CT lies within the increased level of detail. Critics might argue that this is not enough justification for using such an expensive technology as it does not add new information in the majority of cases. However, the increased resolution does hold the potential that an injury gets discovered that otherwise might be missed as in the example provided by Fais et al. (2016). Even if micro-CT detects additional information in only a fraction of cases, it could be argued that these instances make up for all those where no additional information is found.

Applying micro-CT to criminal cases does not only add more detail to medical grade CT images, it holds the potential for real improvement and change. Isotropic (i.e. with equal dimensions in all three axes) voxels allow direct measurements on the sample which can be performed non-invasively without having to touch and therefore potentially tamper with the evidence. This has two key advantages. First, minimal evidence handling reduces the party's vulnerability towards opposing attacks on grounds of manipulation or damage. Second, the digital data can be easily shared with the other party who can perform their own measurements or assessments without having to invest in their own scans. This is particularly important for evidence created by the prosecution. The state usually has more resources at its disposal than the defence which raises concerns about fairness of the proceedings (Edmond and Roach 2011). Sharing the scan results could therefore re-introduce this fairness as the defence will be provided with the same material at no extra cost.

The non-destructive nature of micro-CT scanning is particularly suited to the process of forensic testing since it allows all further tests which might result in destruction of the sample to be conducted regardless. A study by Walton et al. (2015) shows that micro-CT scanning does not damage the cell or DNA structures respectively, highlighting the importance of such scans at an early stage in the investigation.

3. Visualisation

The final part of this literature review draws on the preceding section as it sheds light on the issue of presenting this new three-dimensional evidence both digitally and physically in a criminal justice context. The main focus lies on the evidence presentation before a court of law. This stage is primarily concerned with visualisation, whereas the analytical benefits are more likely to be incorporated in expert witness statements such as the pathologist's testimony. But even the presentation of the pathology results, which is a generally accepted part of any murder trial, can benefit from enhanced visualisation methods. Pathological and medical evidence in general tends to be very graphic and gruesome making it unsuitable for display. The resulting lack of visual representations makes it more difficult for a jury to understand the testimony and might result in a very dry oral testimony during which jurors might lose attention to the trial (Feigensen 2010). Using medical image data to illustrate the expert's opinion has a long-standing tradition. First X-ray films were used, followed by digital X-ray images, CT and MRI data, and all faced initial opposition but quickly became generally accepted (Golan 2004). The main advantages of these images are that they show the jury images which would otherwise remain hidden and for which they would only have the expert's word for. Additionally, the images tend to be grayscale representations of certain body regions which adds a level of abstraction that reduces the emotional impact and allows the fact-finder a more reasoned decision (Whalen and Blanchard 1982). Saunders et al. (2011) briefly present the approach taken by pathologists in Leicester who were able to show scan data and 3D reconstructed models, run in real time from a laptop. This approach has the benefit that it is interactive and shows both cross-sectional and three-dimensional views and further demonstrates the court-readiness of medical imaging. However, the standard procedure (at WMP) tends to be body mapping where the injuries sustained by the victim are digitally mapped onto a dummy model which can be shown within the crime scene for additional context. The problem with this approach is that it only shows external injuries. Many researchers have explored how this can be achieved more accurately and incorporating medical imaging data to display internal injuries as well (Urschler et al. 2012). This is where digital 3D technologies have demonstrated great promise as different data sets can be aligned for a complete picture. External surfaces can be documented using different laser scanning technologies or photogrammetry for a more photorealistic view. Internal features can be illustrated using CT or MRI data, either as 2D sections or as volume-rendered view. The decision which option to choose depends on the degree of realism intended which reverts back to the issue of jury bias discussed in the previous chapter.

The topic of 3D visualisation in the courtroom has received increasing attention with the introduction of computer simulations and animations, not only for their impact but also for admissibility issues. While it is sometimes argued that visual supplements which are used as demonstrative evidence at trial might be subject to lower admission standards (Campbell et al. 2013), medical imaging often fulfils the purpose of demonstrative as well as substantive evidence (Harston 2008). Both the image acquisition and its visualisation must therefore be validated and well documented. Validation is particularly important for computer animations and simulations. Moving computer graphics can easily be perceived as reality if the underlying principles and data used to generate the simulation have not been explained sufficiently. Jury members might misunderstand the animation or simulation as a depiction of the event rather than an illustration of the expert's opinion thereof or one of the possible explanations (Schofield 2017). As with the depiction of medical evidence, the question is how much realism is necessary to maintain credibility but how much is too much, creating an overly easy-to-believe clip. The latter might be in the interest of the prosecution but goes against the principle of equality of arms as most defendants do not have the means to have such advanced computer graphics produced.

One final consideration is that courtrooms might not be equipped to display images that require specialist viewing software. The previous chapter presented the challenges the courts face and one is the slow adoption of technological innovation even on a basic level. This limitation can bring many ambitious projects to an abrupt end. Tung et al. (2015) present an example of advanced 360 degree spherical photography being shown to jurors which required specialist viewing technology. This arguably improved the evidence presentation but is difficult to implement on a wider scale, simpler solutions such as the one presented by Saunders et al. (2011) are therefore recommended. While their benefits seem widely accepted (Ma et al. 2010, Tung et al. 2015) with excellent examples demonstrating their feasibility, it is likely to take some more time for these tools to become a regular choice in the advocate's toolkit.

4. Summary

This third chapter presented Computed Tomography and more specifically micro-CT which is used in this research project and discussed their advantages and disadvantages. With reference to the gaps identified in the previous chapter, the present chapter demonstrated how the Criminal Justice System could profit from the use of digital tools. Some examples of their application in a forensic context were provided, however, such examples are limited and often based on experimental setups rather than actual case series. Furthermore, none of these cases provide a quantification of the impact created thus highlighting the need for more detailed analyses.

The next chapter will take the information provided in the two review chapters to develop a suitable research methodology based on more refined research questions.

Chapter 4: Methodology

The previous two chapters have provided sufficient background to the field of research to be able to define a more concise research problem and corresponding objectives. The present chapter will detail each step in the research process and provide justification for the methodological choices used to refine and answer the initial research questions stated in Chapter 1. This chapter will commence by setting the scene in which this research project has taken place, thereby briefly outlining the most commonly chosen approaches in criminal justice research. It will continue by presenting some background on how the research came into life and how the research questions crystallised during initial exploration. It will then proceed to set out the case study research design chosen to suit these questions, and present the methods of data collection, data analysis, and dissemination. Throughout this chapter, practical considerations and personal experiences with the implementation of the research design will provide the researcher's perspective which is a common feature in qualitative research texts (Holliday 2007).

1. Research environment

One of the most central pieces of research into criminal justice in the UK is the National Crime Survey which is a quantitative survey of peoples' experience with crime and the justice agencies. The second quantitative study is the Home Office's crime report which serves as the official statistics on reported crimes. Both surveys are important indicators for crime levels and are commonly used by government agencies to inform and justify policy measures (MacDonald 2002). While such quantitative surveys provide useful insights regarding crime trends, they leave a large grey area since they only account for respondents' self-reported experience and reported crime respectively. Complex issues such as the causes and impact of crime or the work of the police, courts, and prisons are more difficult to grasp with such numerical methods. Research in criminal justice therefore relies primarily on qualitative studies, often conducted within the social sciences. Criminal justice spans a wide field with a huge variety of studies covering all agencies and stakeholders although an emphasis lies on defendants and the police. In recent years, researchers increasingly studied policing in action in order to determine "what works". These studies ultimately inform policy-making in what is often referred to as evidence-led policing (Fyve 2017). The present thesis forms an example thereof as it aims to evaluate the effectiveness of certain methods prior to adopting them into policies. This type of research is therefore often conducted with the (financial) support of government bodies. However, the majority of studies research frontline policing as opposed to the investigative departments. Those who do research the CID primarily focus on developments in their intelligence services (Chan 2001, Colvin and Goh 2005). Most researchers in this area employ a combination of interviews, direct observations, and documents research to evaluate strategies and suggest possible improvements. The use of interviews and observations require close cooperation and have increasingly led to partnerships between police and academia (Bales et al. 2014, Burkhardt et al. 2015). These are beneficial to both sides as exemplified by the present PhD project. Such co-operations often take an ethnographic appearance including researcher "ride-alongs" with police staff (Tillyer et al. 2014) or court observations (Cammiss 2004). However, researching the criminal justice agencies is sensitive work as negative press can influence public perception and trust which is an integral aspect in the functioning of the system. Honest cooperation is therefore not guaranteed out of fear of repercussions, especially if the research aims are not fully communicated (Rudes et al. 2014). This was observed in the present project as well but as the knowledge about the project spread, this distrust shrank and information was provided more freely.

2. Developing the research questions

The background to this study was a particular case for which WMP sought help from the University for micro-CT scanning of body parts from a case of dismemberment. One of the Crime Scene Coordinators (CSCs) had heard about the technology available at WMG and initiated contact to explore the possibility of using it in a forensic case. In that particular case, the scan images were successfully employed to visualise saw marks and to plan further steps in the investigation. These results were shown to the jury during trial along with 3D printed evidence (Baier et al. 2017). This case served as a pilot study based on which the PhD project was developed and established Sharp Force Trauma analysis as one of the central research themes. This initial case incorporated all the technology choices available in this project, demonstrating the range of possibilities for future cases and shaping the scope of the PhD Research Agreement. Four cases of suspected strangulations were examined in the aftermath of the dismemberment case and their results informed the decision to add strangulation deaths to SFT analysis as a further emphasis of the research. An initial literature review and informal discussions with detectives led to the inclusion of BFT as a third research focus. This exploratory phase helped refine the broad research topic into the following specific research questions.

1. What stages of the Criminal Justice Process can profit from the introduction of digital visualisation technologies and how?

2. What societal impact can these methods create with regards to shaping police investigations, enabling a higher quality of justice, and changing court experiences?

3. How can the economic impact on the CJS be quantified?

3. Research design

3.1 The process

A guide for drafting a research design was developed by Saunders et al. (2012) and is referred to as the "research onion". It consists of multiple layers of considerations which peel away one after the other to eventually expose the data collection and analysis strategies at its core. The layers, starting with the outer, are:

- Philosophies (Deductive research: positivism, realism, interpretivism, objectivism, subjectivism; Inductive research: pragmatism, functionalism, radical humanism, radical structuralism)
- Approaches
- Strategies (experiments, surveys, case studies, grounded theory, action research, ethnography, archival research)
- Choices (single or mixed methods)
- Time horizons (cross-sectional or longitudinal)
- Techniques and procedures (data collection and analysis tools)

Following this decision making process for the present project, first the appropriate philosophical approach must be selected. Post-positivism was identified as being most likely to lead to the answers sought in this project. Post-positivism is closely associated with positivism but takes a more relativistic perspective. It acknowledges that the actual "truth" can only be studied through subjective knowledge and experience (Groff 2004). This is a similar concept to Maxwell's critical realism which states that the real world cannot be studied directly but only our view of it (Barbour 2014). This is highly applicable to the CJS as the actual facts of a case might never be known, only individuals' accounts of events or their interpretation of the available physical evidence. This philosophical approach is commonly associated with a deductive approach which includes using empirically gathered evidence to test a hypothesis. The most suitable strategy for the research topic and the questions asked was identified as the case study approach for reasons further detailed in the next section. Progressing through the layers of the onion, multiple-method research is more appropriate as it allows triangulation of different data sources and therefore increases the study's validity. Since this study aims to explore how digital technologies can help the justice system, a cross-sectional frame provides a more varied response which is more likely to result in an understanding how they can be implemented. Having chosen a multi-method approach, data was collected using a range of methods such as interviews, documentary research, artefacts, and observations, which were analysed using thematic analysis. Each of the steps outlined here are further discussed below.

3.2 Case study approach

3.2.1 Definition

The overarching research design for this project is the case study research design, closely following Yin's (2014) book as a guideline. According to Yin (2014), case study research is best suited for projects that aim to investigate a contemporary phenomenon within its real-life context whereby phenomenon and context are not necessarily clearly distinguishable. The contemporary phenomenon in this study is technology in homicide investigations within the real-life context of the Criminal Justice System from which they are inseparable. Further features of a case study as defined by Yin (2014) can be observed in the present project. The "technically distinctive situation [with] more variables of interest than data points" (Yin 2014, p.17) is represented by homicide which can be studied from a range of angles, for example the offender's social background or their motives, as well as the mechanisms involved in committing the crime. The second feature defines case study research as reliant on a variety of data sources which in the present study are primary examination results, the police database, and direct observations on the cases. As a third feature Yin (2014) emphasises the theoretical propositions developed at an early stage of the study that subsequently guide data collection and analysis. This is generally found in positivist studies which are more commonly associated with quantitative than with qualitative research methods (Barbour 2014) but Yin (2014) argues that one of the strengths of case study research is the applicability to different epistemological approaches. Theory in Yin's context means a simple theoretical statement acting as guidance for data collection and analysis. Here it is the assumption that there is in fact a benefit in introducing the proposed technologies to the CJS. This hypothesis is based on literature studies and the aforementioned pilot study which confirmed tangible benefits - an essential condition which secured funding from West Midlands Police.

The research questions raised in the previous section further confirm the suitability of the case study research design outlined by Yin (2014) who argues that the method ought to be used for “how” and “what” questions that focus on aspects of a contemporary event over which the researcher has no control. It could be argued that by introducing new technologies the researcher exercises a degree of control over the situation and therefore places the study closer to action research (Yin 2014). However, the researcher only mediated and facilitated the use of technology while the decisions on whether and how to use it were made by the police.

Qualitative research, and case study research in particular, has been frequently criticised for not being rigorous and researchers for being negligent and biased by their personal views (Mays and Pope 1995, Collier and Mahoney 1996). This is not a fault with the method itself but with individual researchers who might have been misled by the flexibility of the approach. The lack of rigour can be counteracted by using data triangulation and multiple cases which also addresses some authors’ concern that it is more challenging to generalise from a single case (Silverman 2010).

3.2.2 Descriptive, exploratory, and explanatory case studies

Yin (2014) distinguishes between three different types of studies irrespective of research method: descriptive, exploratory, and explanatory. Descriptive and exploratory studies are unsuitable for this project as the former do not provide sufficient depth to allow successful changes to the study area and the latter do not rely on pre-formed hypotheses. This leaves the explanatory/causal case study as the best approach since this allows an interpretation of how the new technologies improve forensic evidence which is important to the delivery of criminal justice.

3.2.3 Single versus multiple case study and replication logic

A further distinction is made between case studies involving a single case and those involving multiple cases in a comparative fashion (Yin 2014). This research project relies on the multiple-case study design with the rationale that by increasing the breath of cases a more nuanced picture can be painted. This allows better-informed generalisations and increases the overall robustness of the research design (Yin 2014) which is particularly desirable for research in a sensitive area such as the criminal justice sector. This is achieved by following a replication logic that aims at literal replications to demonstrate that the changes expected are not unique to one scenario but can be translated to a variety of problems. One theoretical replication was added retrospectively as multiple examples were examined over the course of the project which demonstrated some of the technology's limitations.

Based on the literature review in Chapters 2 and 3 and some exploratory work and discussion with stakeholders, three major areas were identified from which suitable homicide cases were included in the analysis: strangulation deaths, toolmarks and SFT, and Blunt Force Trauma. These are suitable not only because of their need for improvement but also because they occur frequently providing sufficient information to draw generalisations from. An additional category was created to accommodate all homicides that did not fit into any of the three categories. They were included as "miscellaneous" since they contributed valuable case diversity and unique examples and acted as a control case with theoretical as opposed to literal replication. In case study research, the number of replications follows a less clearly defined logic than the sampling logic followed in experiments and the exact number of replications depends on the complexity of the higher-level questions (Yin 2014). Three cases and one control case was considered adequate in this study as each was comprised of multiple examples. It was difficult to estimate the number of police cases at the outset of the study since crime is an unpredictable subject. However, the three selected areas cover a large proportion of homicide cases tried before Crown Courts in England and Wales and it was anticipated that they will produce sufficient data. After the first year of data collection, this was reviewed and found to be correct as 19 homicides were examined, the second year saw this figure double, and the third year nearly treble.

3.2.4 Embedded versus holistic cases

Yin (2014) further differentiates between holistic and embedded case studies; the former focusses on the global aspects while the latter focusses on individual sub-units within the case. In this project, each individual homicide case was considered an embedded unit of analysis which could be linked to the overall case i.e. the method of killing. This led to a three-tiered approach with the individual criminal cases at the lowest level providing the raw data for the next higher level which is the forensic understanding of the three homicide methods. The resulting evidence combined feeds the top-tier analysis which seeks to answer the initial, high-level research questions such as the impact at the individual stages of the Criminal Justice Process.

3.2.5 Validity and reliability

There are three aspects to the assessment of quality of case study designs: construct validity, internal validity, and external validity (Yin 2014). Construct validity is concerned with using the right methods to answer the questions. The subsequent sections will demonstrate that the multiple methods chosen for this project allowed the gathering of a breadth of information which covers several perspectives on the impact. Internal validity is achieved if the conclusions drawn are valid and supported by the data and no other explanations are possible. It should be noted that internal validation in this study depends on a degree of speculation and assumption that the "legal truth" encountered in documents and court proceedings corresponds to the factual truth. Without this assumption, all within-case analyses would be rendered inadequate. Lastly, external validity is concerned with the generalisation of one's findings or the theory developed from them to a similar context. By examining three different cases external validity was strengthened in this study.

Reliability is the question whether results can be produced repeatedly and by different researchers. Positivist studies tend to strive for high reliability based on the assumption that if there is only one reality, one must be able to measure it repeatedly. As this study claims to follow a post-positivist logic, it is acknowledged that especially the interview results could be influenced by the researcher's relationship to the interviewees and other researcher's might interpret results with less bias.

3.2.6 The cases

Three research areas were identified from the literature review and some preliminary police work: strangulation, toolmark analysis, and Blunt Force Trauma. The commonality of these cases is their frequent occurrence and the lack of scientific data on their diagnosis or interpretation, thus creating opportunities for improvement. A small number of cases that were examined as part of this project did not fit the criteria for any of the three categories and were summarised as "miscellaneous" cases.

3.2.6.1 Strangulation deaths

Strangulation is a common method of killing, in particular where female victims are concerned as shown in the Office for National Statistics' 2015 crime survey. 18% of female homicide victims in the UK die through some form of asphyxiation making this the second most common method of killing after knife-related deaths. In the US where gunshot injuries account for the majority of homicides, strangulation still accounts for 10% of violent deaths (Armstrong et al. 2016). Despite this high occurrence of strangulation deaths, diagnostic methods have not improved over the past years as the literature review in Chapter 5 shows.

Improving the diagnosis in such cases therefore has a great potential to improve the final case outcome in numerous cases, affecting hundreds of lives.

In the initial phase of the project, one of the detectives or crime scene examiners would suggest a micro-CT scan for suspected strangulations. The further the project advanced, more and more examinations were requested by the pathologist conducting the postmortem examination. The scan data were used to establish a data base with the aim to allow injury classification and characterisation in cases of strangulation. This was cross-referenced with the Home Office Large and Major Enquiries System (HOLMES), a national murder database, to add background information surrounding the case circumstances. Besides the injuries observed the strangulation database contained additional information about the victim (age, sex, height) and sometimes the attack itself. Since the latter aspect is based on witness and suspect accounts, the information is highly subjective and needs to be treated with caution. The ultimate aim of this data comparison was to allow an interpretation of the strangulation process by examining the injuries produced.

In order to understand the injuries one must understand the normal anatomy of the laryngeal complex. The general anatomy is known, but a meaningful comparison depends on the same method being employed. A comparative study was therefore conducted in cooperation with the University Hospital Coventry and Warwickshire (UHCW) examining undamaged larynges from cadavers donated to science. They were scanned using the same micro-CT scanner as the forensic cases to allow the study of the normal anatomical features at a level of detail not previously studied on such a sample size. This step was crucial to avoid misinterpreting the structures seen on the high-resolution forensic scans with pathological features. This formed part of the method validation which is required by the Forensic Science Regulator as discussed in Chapter 2. Ethical approval for this study has been granted by the University's Biomedical Science Research Ethics Council (BSREC)(see Appendix A) and confirmed by the hospital's own ethics committee.

3.2.6.2 Toolmark analysis

Knife-related deaths are the most common form of homicide in the UK, advancing the forensic analysis of such crimes would therefore produce a noticeable improvement of the overall perception of criminal justice agencies. As with strangulation deaths, information from the scans, the pathology reports, and the case background were recorded in an Excel spreadsheet. The information sought from the micro-CT scans included the weapon geometry and sometimes the amount of force used and was requested by investigators and pathologists alike. While there was no dedicated baseline study for toolmark analysis, associated studies which were conducted within the researcher's group can be cited to demonstrate the validity of the method to measure and describe Sharp Force Trauma (Norman et al. 2018a, Norman et al. 2018b).

3.2.6.3 Blunt force injuries/fractures

Blunt force injuries on the skeleton manifest as fractures and can have a wide range of causes including motor vehicle accidents, falls, and violent assault. The pathological identification of fractures is well-developed but individual studies have suggested that an increased level of detail can refine the diagnosis and interpretation even further (Tsai et al. 2014). This is particularly applicable to cases of child abuse where the fracture pattern can be subtle and easily missed and therefore misinterpreted. The high public interest and the emotional stress involved in such cases puts pressure on the CJS to deal with matters swiftly and to the highest possible standards (Pritchard and Wate 2014). Apart from the initial investigation the presentation of evidence in these cases poses further challenges due to their sensitive nature, which lends itself to new digital, more sanitised visualisation methods. Samples submitted in this category were further used for a second validation study comparing micro-CT images to histology (Baier et al. 2019).

3.2.6.4 Miscellaneous

This last category summarises all those cases which demonstrated potentially useful applications of the proposed technologies but which did not fit any of the three previously detailed categories. These are one gunshot wound, one skull for facial reconstruction, one mechanical component from a suspected arson, and one case of food tampering.

The advantage of selecting cases from a wide range of homicide types is that it allows to gain a broad knowledge of the applications of 3D technologies within the Criminal Justice Process, as well as in-depth knowledge of each case.

Despite this project being sponsored by West Midlands Police, some of the cases were examined for other police forces (Warwickshire, Staffordshire, Hertfordshire, Cambridgeshire, West Mercia, Suffolk Constabulary, Metropolitan Police) as awareness of the new methods spread across the forces. The problem with getting these forces involved was that no formal research agreement existed between them and WMG which made access to background information and case updates more challenging. Some cases had to be excluded at the analysis stage as a consequence due to a lack of meaningful data.

3.3 Research methods

As indicated in the previous section, the (post-) positivist theoretical approach is more commonly used in quantitative research, while qualitative research predominantly adopts an interpretivist or constructivist approach where meaning is created directly from the collected evidence (Barbour 2014). While the post-positivist approach best represents this project, qualitative research methods are still better suited as the dominant research method in this project due to the nature of the research aims and the nature of the anticipated evidence. Qualitative research aims to provide explanations as opposed to descriptions of a phenomenon and in doing so provides different perspectives on the same problem (Barbour 2014). The multitude of stakeholders involved in the CJS necessitates the evaluation of different perspectives in order to maintain fairness and a balanced view. Barbour (2014) further argues that qualitative research aims to make a difference within the subject of study which applies to the majority of criminal justice research. The current project is no exception as it involves working closely with the police and pathologists with the intention of improving operational procedures on a long-term basis.

There is a quantitative element to this research project which aims to assess the financial impact. This includes balancing the cost of sponsoring a PhD student with the money saved by technology because of time reduction or discontinuation of an investigation due to new evidence. The problem with trying to quantify these savings is that they rely on estimates provided by those who work within the system which is based on their experience and perhaps somewhat inaccurate. Furthermore, the lack of control cases with the same conditions as the case in question makes it difficult to test the accuracy of these estimates. Nevertheless, they provide an informative insight into the impact created and the estimates provided are assumed to be within the correct scale since the individuals providing the data have been working in their respective fields for several years. The possibility to incorporate these quantitative elements is one of the strengths of mixed-method research which offers flexibility in the methods employed (Barbour 2014).

3.4 Data collection

The primary source of data was the micro-CT scans produced as part of the active police investigations. When a sample was received all appropriate paperwork relating to the transfer of human tissues had to be completed as per internal Standard Operating Procedures. Separate guidelines were followed for setting up the scan. The equipment used was a Nikon 225/320LC (Nikon Metrology, Tring, UK) micro-CT scanner for the majority of cases, and a Zeiss XRadia 520Versa (Carl Zeiss AG, Feldbach, Switzerland) for the remaining ones. Prior to each scan it was ensured that the scanner was within manufacturer's calibration, the sample stage's axes homed, and the X-ray beam sufficiently conditioned (stabilised). The manufacturer's calibration process consists of operational and safety tests (shown in Appendix C) as well as scanning a calibration artefact in order to check the machine is functioning within the manufacturer's specifications. This artefact has been calibrated by a certified calibration laboratory and has known dimensions. If the scan results deviate from these by more than three times the scan's voxel size, the service engineer performs a series of corrective steps such as source and manipulator alignment, filament alignment, and re-centering the rotational axis of the manipulator. Verification of this calibration is performed regularly by the CT operator using the same calibration artefact and the measurement results are recorded. If the results are found to be outside the accepted limit or found to drift gradually over time, the manufacturer is contacted to resolve the issue. Internal research has shown that the manufacturer's calibration results in a scan accuracy of up to, or better than, three times the scan's voxel size without further voxel rescaling. Voxel rescaling is a post-processing step where the voxel size of a scan is corrected using the known dimensions of either a calibration artefact included in the scan, or of accurate measurements of the sample itself taken using an accurate, calibrated and traceable measurement system. According to Lifton et al. (2013), this increases accuracy to the voxel size itself, although internal research has shown that accuracies as good as one third of the voxel size can be achieved.

Once the scanner was confirmed to be in good condition, the sample was then placed centrally on the rotating table to maximise the achievable resolution and to avoid the sample going outside the field of view during the full rotation. The larger the object, the lower the magnification and therefore the resolution of the scan. As a rule of thumb, scan parameters of 120kV, 20W, and 500ms exposure were selected and adjusted as necessary for the sample's material characteristics. Next, a reference image was taken which creates an image at the same settings but without the sample in order to calibrate the grey values received by the detector. Two options were available for image acquisition: continuous scan or stop-and-go scan, which can reduce ring artefacts. The latter option was preferred but it is more time consuming in terms of total scan time. This sometimes caused imaging problems such as blurring due to sample movement were occasionally observed for larynges which predominantly consist of soft tissue. A possible explanation for this is that the soft tissues warmed up and expanded or relaxed over the duration of the scan. Alternatively, the movement might be caused by tissue shrinkage due to dehydration as observed by Du Plessis et al. (2017) for biological museum specimens. Comparison of the first and last radiographs acquired for a scan that had moved did not show any discernible expansion or shrinkage, only overall vertical movement of the specimen. It was found that leaving the sample to acclimatise inside the scanner with the X-rays switched on for approximately 1/2h helped reducing movement during the scan. Aside from the movement during the scan, warming the tissue potentially also affects the resulting scan image as tissue density is known to decrease with increasing temperatures which therefore lowers the grey values (Zech et al. 2014). However, comparison of the first and last projections did not show any visible differences.

Both tissue dehydration and warming should be minimised due to their potential adverse effect on the tissue integrity. It has become clear in the pilot case examined (OP Sanderling, see Chapter 6) that the processes followed in this project do not affect DNA survival. This is supported by research by Hall et al. (2015) who found no DNA degradation in museum specimens following repeated micro-CT scans. However, repeated warming and/or dehydration cycles might degrade the cell structure and thus impair subsequent histological results which rely on the presence and state of certain cell types. Shorter scan times, well-sealed sample containers to limit moisture evaporation (Hall et al. 2015), and quick turnaround times were therefore essential to reduce this risk.

Following the scan completion, the projections were loaded into CTPro, the scanner's proprietary reconstruction software. The first step was to find the centre of rotation for which two slices were selected to detect the correct centre of rotation even towards the sample edges. The next step was to select the strength of the beam hardening filter. Most samples required mild filtration (preset 2 or 3 out of 6 strength options). Following this, the reconstruction volume was adjusted to reduce the overall file size. These settings were then used to reconstruct the volume using the Feldkamp algorithm (Feldkamp et al. 1984). The same steps were followed when using the Zeiss XRadia scanner and its proprietary reconstruction software.

The reconstructed volumes were initially examined visually with regards to the objectives set out by the investigating officer or pathologist and the results were presented in individual case reports. In order to understand the context of each individual investigation, the case files such as the pathology report, autopsy photographs, other specialists' reports, crime scene photographs if applicable, case circumstances, and relevant witness statements were consulted to collate information. These documents were retrieved either through

HOLMES or through direct correspondence with the officer in charge. This was enabled by the researcher's direct access to the force CID and a good working relationship with many of the detectives there. If court presentation material was produced as part of the investigation, an attempt was made to attend court for this evidence presentation and to make direct observations on its perception. Only a small number of enquiries necessitated such presentations and not all court dates could be attended; the evidence in this section is therefore limited. As no two crimes are identical there were some differences in the available documentation material. The large number of police investigations considered for each study case ensured that all sources of evidence could be exploited to their full potential.

In the final phase of the project, semi-structured interviews with key informants provided an insight into the perceived changes the novel technologies have brought about. The key informants were chosen to cover as many different stakeholders as possible and included Crime Scene Coordinators, detectives of different ranks, and pathologists. CPS and barristers were contacted as well but no response was received. Interview questions were adapted to accommodate the different occupations encountered but the overall aim of an impact assessment was pursued in all of them. Only individuals who had been exposed to the work produced as part of this PhD were contacted as they would be able to comment on the actual as opposed to potential or imagined changes introduced by novel technology. Initially it was intended to add another perspective on how the novel evidence is perceived by analysing the court observation and trial transcripts where available. This was envisaged as useful documentation of criticism or concerns voiced by the defence and judge regarding the benefits and problems associated with the technologies. However, due to the inconsistency and delay in the publication of these records it was decided not to include them for analysis. For each case, a separate database was designed which included all examples examined in each category and all associated data from different sources and served as a starting point for the content matrix used in data analysis.

3.5 Approaches to data analysis

As Yin (2004) and Houghton et al. (2015) note, there is no clearly defined way of analysing qualitative case study data. The overarching principle is therefore to link the evidence back to the initial research propositions.

Intra-case data analysis was performed using thematic analysis for both image and text-based information. In addition, the strangulation analysis included the results of a validation study examining the uninjured larynx at micro-CT resolution. Using demographic background information and case evidence for criminal cases, pattern-matching was used to try to establish themes that explain the effects of the newly introduced technologies. Key informant interview results were analysed using thematic analysis in order to identify how the scientific benefits translate into more societal benefits to the justice system and its stakeholders. Analysis of the qualitative data was based on thematic analysis following guidelines by Boyatzis (1998), and more specifically the framework method as described by Gale et al. (2013). The first step in the framework analysis was to manually code the transcribed interviews which assigned conceptual labels to the data. These codes were then grouped into categories of interrelated concepts which served as a starting point for further data abstraction. The data were then reduced based on the analytical framework consisting of codes and categories and entered into a content matrix. This facilitated the identification of themes, commonalities, and differences which were then be compared to the real-life case data in order to validate responses. No attempt was made at statistical analysis due to the non-representative sample size and composition.

As indicated in the literature review of Chapter 2 and illustrated in **Table 1** and **Figure 2**, the Criminal Justice Process can be compared to the stage-gate system used in product development. A further aspect of the cross-case analysis was therefore to identify at what stage/gate the new technology was used and with what result. This enabled identification of the most suitable points of improvement which can form the evidentiary basis for implementing changes to existing standard operating procedures. In order to achieve this each police case was plotted against a schematic representation of the justice process. Information from the interviews was central to this point of analysis.

Analysing the financial impact proved more challenging. A basic tabulation of the cost of the PhD sponsorship against the cost if all case work would have been charged at standard commercial rates could be supportive of the project setup but did not actually demonstrate how much money this technology could save. It was initially anticipated that the key informant interviews would produce estimates of some of the costs involved. However, it soon became obvious that even individuals in highly ranked positions did not possess such knowledge. Estimates were therefore drawn from various reports examining aspects of the overall process that use different methods in their analysis. Informants' estimates were used where they provided information regarding the amount of time saved by using the proposed technologies in specific cases and to assess at what stage in the process these were made.

3.6 Data dissemination

Individual reports were produced for every sample submitted by the police and issued to the examining pathologist as well as the officer in case. These reports included a description of the scanning process, the scan parameters, and the findings as observed on the scan images and were illustrated with relevant images. Two case studies were published in relevant forensic journals (Baier et al. 2017, Baier et al. 2018) to demonstrate the benefits of the technologies as applied to real-life scenarios and to increase awareness of the technologies amongst practitioners.

The histology validation study (Baier et al. 2019) was submitted to the Forensic Science International journal since peer review is an essential requirement set out by the Forensic Science Regulator and is part of the ISO accreditation process that all forensic service providers must achieve. This project aspires to become accredited in the future as part of a long-term cooperation and these validation studies form its foundation.

3.7 Problems/limitations

3.7.1 Bias

The most obvious problem associated with the sampling strategy is the pre-selection bias introduced by the police's decision to submit a sample for micro-CT scanning. This inevitably leads to a focus on more serious and complex cases where investigators expect an improvement by using these novel technologies. There was a distinct lack of cases with no anticipated benefit of using micro-CT that could act as control cases. The few examples for which there was no immediate scanning agenda were included to explore further possible uses.

The other major complication is the fact that much of the documentation like witness statements contain an element of subjectivity. Even after the trial is concluded there is no absolute certainty about the factual truth. Many legal scholars acknowledge that factual truth is distinct from the legal truth which is a probabilistic evaluation of the events in question (see for example Moore 2003). Further problems arise with respect to the impact evaluation as the question of "what" this impact actually is might be perceived differently by different stakeholders. It would therefore be beneficial to hear opinions from all stakeholders and to use these different perspectives to triangulate the evidence, but interviewing CPS and barristers proved difficult and obtaining information from offenders might be limited by ethical constraints or simply willingness to comply. Interviewing jury members is further complicated by the Contempt of Court Act 1981 which states that "*it is a contempt of court to obtain, disclose or solicit any particulars of statements made, opinions* *expressed, arguments advanced or votes cast by members of a jury in the course of their deliberations in any legal proceedings*" which limits any kind of jury research in the UK. This results in a somewhat one-sided view on the issue. As previously mentioned, the collaboration was primarily with West Midlands Police. For cases from other police forces limited background material could be gathered resulting in cases being excluded from a more detailed analysis despite promising results. All the above mentioned professions were expected to use the 3D results produced in this study in a different manner and for a different purpose. For example, the prosecution would use it in court only if it strengthened their case. For the pathologist it was an additional diagnostic tool with the potential to guide and direct further examinations. For the judge (and jury) 3D evidence was expected to constitute a visual aid helping to understand complex situations and scenarios. These different motivations raised the issue whether interview questions should be specifically aimed at certain groups or whether more generalised questions were preferred. Semi-structured interviews accommodate for these different perspectives while still directing the interview in a common overall direction. The numbers in each professional category were expected to be low and therefore not statistically significant but added a further source of evidence for the case study to be triangulated to answer the research questions.

The time frame for a criminal case to be tried in court can be very extensive and several months or even a year could pass between conducting the micro-CT examination and the conclusion of the trial with further delays if the verdict is appealed. For this project this meant that the impact assessment was addressed at a later stage and assessment for cases examined in the later part of the PhD were not included in the final evaluation.

3.7.2 Ethical considerations

The ethical consent for handling human tissue specimens forming part of homicide investigations is granted by the HM Coroner and permission to use associated information in a research context was granted by a formal Research Agreement between West Midlands Police and The University of Warwick. Each human tissue exhibit was accompanied by a Material Transfer Agreement (MTA), signed by the University's Human Tissue Designated Individual in compliance with the University's Human Tissues Licence, and the Designated Individual from the providing organisation. This protocol was also followed for the samples pertaining to the strangulation validation study for which separate ethical approval was granted by the BSREC (see Appendix A) and UHCW's Ethics Committee from where the samples were obtained. A separate ethical approval was gained from the BSREC prior to conducting the impact assessment interviews (see Appendix B). Interviewees were contacted directly where prior contact existed, or via existing contact within the police force where no prior contact was held. Interview data were anonymised - only occupation and experience within the occupational field was retained.

This research inevitably involved access to sensitive personal data of both victim and offender which meant that great care was taken to anonymise such data and to store them in a secure location to which only authorised individuals had access. The sensitivity of the research data also required special security protocols for data storage and secure storage for exhibits while they were within university facilities. These requirements were outlined in the official Research Agreement and were implemented as a password-protected folder on the group’s shared sinology drive for electronic data, a lockable cabinet for hard copies, and a lockable lab fridge for the samples. For publication purposes all information was anonymised and care was taken to avoid the inclusion of any case details which could allow the reader to identify the case. This research provided a unique opportunity for an in-depth experience of the processes of the Criminal Justice System by allowing the researcher direct access to one of its pillars. This bore a great responsibility as the publication of any internal information could potentially harm the system by weakening its credibility and therefore the public’s confidence held in it. All manuscripts intended for publication were therefore reviewed by police personnel who had the final decision on what material could be used. It could be argued that this step compromised the research independence or constituted a form of censorship but no instance was noted where police intervened publication.

Another related potential conflict of interest is the fact that this project was sponsored by West Midlands Police which shifted the focus of research on how these technologies can assist the police, as opposed to the defence or the CJS as a whole. It further introduced the risk of cognitive bias which can unconsciously cause the researcher to evaluate the data produced in a light which is favourable to the funding organisation’s anticipated or hoped for views at the expense of alternative interpretations (Dror 2013). Cognitive bias is a common problem in forensic science (O'Brien et al. 2015) and while being aware of its existence and effect is a crucial first step in addressing the problem, measures should be taken to minimise its risks. The case circumstances were therefore only consulted after the examination of the scan images and every report produced for the police was checked by the project supervisor before being issued.

A further issue that arose from this close relationship with the police/prosecution side was the threat to the concept of equality of arms. This is essential to ensure a fair trial and is the underlying principle for the prosecution's duty of disclosure. While micro-CT images in general serve as an objective representation of the sample, showing injuries in such detail might evoke an emotional response amongst the jurors and the judge which could cause unfair prejudice towards the defendant (Bright and Goodman-Delahunty 2006). This emotional impact is even stronger for 3D prints shown in court as they are similar to the actual object. These considerations were outside the researcher's influence- it was the CPS or the judge who had to carefully evaluate the use of such evidence prior to serving or admitting it and weigh the benefits to the jury's understanding against the potentially prejudicial damage (CPS 2013).

4. Summary

This chapter has refined the research questions and detailed the methodological approach taken for this thesis. The key decisions are:

- Post-positivism as the philosophical approach using empirical data in a deductive manner
- Case study research as the overarching research design using multiple explanatory embedded cases
- Mixed methods were used to incorporate different data sources to allow triangulation and increase validity
- Thematic analysis, pattern-matching, and process-mapping (stage-gate system) were employed for data analysis of qualitative data
- Quantitative data was analysed using published studies interviewees' estimates

Careful planning of the research design included consideration for ethical issues and all effort has been undertaken to minimise these risks as this is crucial in a sensitive area like criminal justice.

The following chapters will present the results of the data analysis with each chapter focussing on one of the homicide types identified as research priorities.

Chapter 5: Strangulation

1. Introduction

As identified in the previous chapters, strangulation deaths are a great challenge for the forensic pathologist or even the coroner before that as the death might appear like a natural one due to a lack of external signs. Clearly, this indicates that the stage at which this particular problem needs to be addressed is the first and second investigative stages of the Criminal Justice Process. This chapter will therefore focus on the scientific contribution of micro-CT in strangulation deaths. The visualisation aspect will feature in the general discussion in Chapter 10. The present chapter will commence by providing a more detailed overview of the problem before presenting the results and discussion thereof. The literature review will commence with a discussion of the term “strangulation”, followed by a description of the basic anatomy and the biomechanical forces involved in causing trauma to the area examined which is crucial in order to interpret the CT data. This review then proceeds to examine the techniques with which these injuries have been studied in the past and then present and the current diagnostic shortcomings, leading on to a discussion of novel technologies, especially micro-CT, and how they might improve the understanding of the subject. The methodology section that follows details how micro-CT was employed in this study and how related case information was utilised to allow meaningful interpretations of the scan data. The subsequent results section is divided into two parts, first the casework results are presented and then the findings from the validation study against which the actual cases are interpreted. This is followed by the discussion to evaluate the real-life findings against the wider context of the CJS and of the problem as presented in the literature.

2. Definitions

Strangulation is often used as a generalising term for a number of similar mechanisms of compression trauma to the neck, causing injuries which are classified as Blunt Force Trauma. In reality the resulting injury pattern is more complex as there are differences in the method of killing and also in the actual cause of death (Hawley et al. 2001). Strangulations are mostly classified according to the method of killing (usually hanging, ligature strangulation, manual strangulation, and positional strangulation) or according to the manner of death (homicide, suicide, accident, or judicial execution) (Iserson 1984). Ligature and manual strangulation are considered exclusively homicidal in nature since suicidal strangulation is not physically possible - the loss of consciousness occurs before the suicide can be completed, forcing the individual to loosen their grip. There have been some unique cases describing suicidal (ligature) strangulations which exhibit complex setups which allow the completion of the suicide after loss of consciousness occurred (Saukko and Knight 2015). The present study will adopt a two-tiered classification combining both aforementioned systems. The first tier is the categorisation by intent as only homicidal cases will be examined while the second tier aims to correlate the different methods, mainly ligature and manual strangulation, to the observations made during this study.

Independent of killing method, death by strangulation is caused by compression of the critical neck structures. However, there are four possible causes of death, each linked to different elements of the neck anatomy. Saukko and Knight (2015) provide descriptions of each, beginning with cardiac arrest which is triggered by applying pressure on the carotid nerve ganglion which is embedded deeply in the neck, close to the internal carotid artery. The next two possible causes are related to the obstruction of vital blood vessels; pressure on the carotid arteries deprives the brain of blood and therefore oxygen, whereas pressure on the jugular veins prevent the deoxygenated blood from returning from the brain. Both lead to a lack of oxygen in the brain resulting in unconsciousness and eventually brain death. The last possible cause of death is by airways obstruction leading to asphyxiation which is probably the mechanism which the general public tend to associate with strangulations.

However, in most cases the actual cause of death is less straightforward and frequently a combination of factors contribute to the eventual death. Interpreting the injury mechanisms employed in strangulation is therefore complicated and poses many challenges. Due to the range of potentially affected structures, the force and duration of pressure required to cause fatal damage varies. Clarot et al. (2005) summarise four factors to be considered: the location, intensity, surface area, and duration of pressure applied to the neck. The effect of these factors also depends on the victim's anatomy which changes the amount of force required (Hawley et al. 2001). A well-developed neck musculature provides some protection since the viable structures are located deeper within the attacked area. The level of force required to cause fatal damage is therefore expected to be higher compared to individuals with less pronounced muscles (Clarot et al. 2005). This complex interplay can prove to be a difficult challenge to any pathologist establishing a diagnosis which is often one based on elimination of other causes (Kolar 2016).

3. Anatomical background: the larynx

Despite the different mechanisms involved, the blunt force involved in all of them tends to produce a similar pattern of injuries which contributes to the difficulty of reconstructing the actual event. Traditionally, damage to the hyoid bone and the larynx are cited as indicators of strangulation (Hänsch 1977, Jaffe 1978) and it is therefore crucial to understand their normal anatomy in order to interpret any potential damage observed within. **Figure 4** shows the anatomy of the larynx and hyoid bone. The hyoid is a delicate bone located on the upper portion of the anterior neck, just inferior to the mandible. It is approximately U-shaped but can vary from V-shaped to horseshoe-shaped and some authors propose even further sub-groups such as boat-shape and asymmetrical (Kumar et al. 2014), although it is unsure whether such subtle differences affect its reaction to external stress. The hyoid serves as anchor for a large proportion of the neck musculature and for the tongue and consists of three to five individual osseous elements which are connected by cartilaginous joints which can fuse with age (Cotter et al. 2015). The elements are the anteriorly placed body, two posteriorly extending greater horns, and two small lesser horns just superior of the body/greater horn junctions. The lesser horns might be unilaterally or bilaterally absent due to natural variation (Advenier et al. 2014). The majority of reported fractures on the hyoid are located on the posterior aspect of the greater horns which are thin and delicate (Kempter et al. 2009, Lebreton-Chakour et al. 2013, Naimo et al. 2015) which leading to researchers to examining the relationship between hyoid shape and fracture susceptibility (Pollanen et al. 1995). They found that the majority of fractures occur at 50˚ curvature which appears to be a weak point in the anatomical structure regardless of the overall hyoid shape. The hyoid is connected to the inferiorly situated thyroid cartilage via the thyro-hyoid membrane. The thyroid cartilage forms part of the larynx which is located at the top of the trachea and which is formed of three unpaired (the thyroid, cricoid, and epiglottis) and three paired (the arytenoid, corniculate, and cuneiform) elements of cartilage. The largest one, the thyroid cartilage, sits at the front of the complex and is sometimes, particularly in men, visible as the Adam's apple. There are numerous muscles and ligaments connecting the larynx to the above hyoid (Marchant 2005, Kutta et al. 2007) and Saternus et al. (2013) suggest that some of the strangulation injuries are in fact created through compression of these connective tissues which in turn create tensile stress on the hyoid and larynx. They should therefore be studied as an entity.

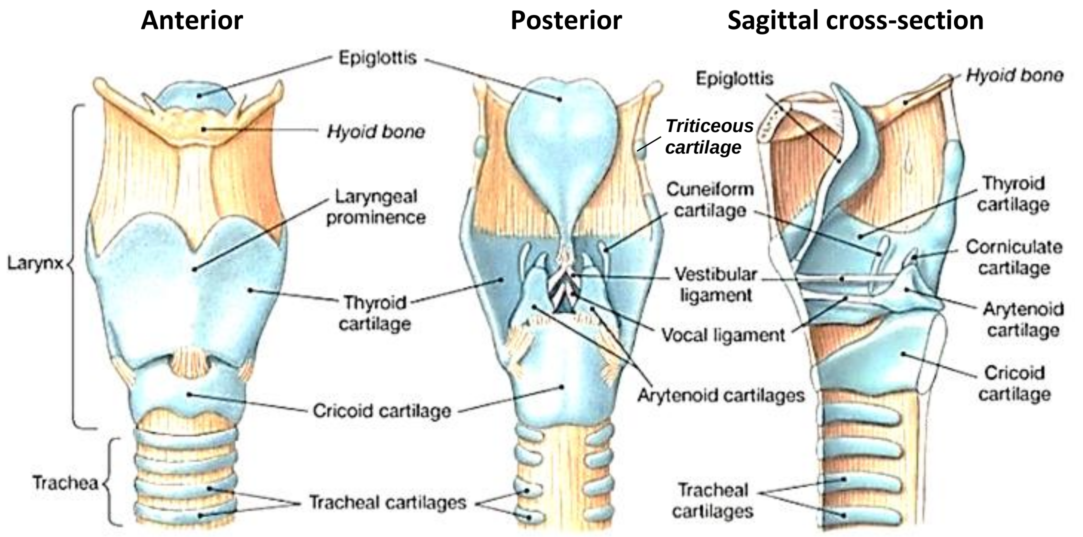


***Figure 4**: Anatomy of the larynx and hyoid bone. Adapted from Bhat 2012.*

The thyroid, cricoid, and arytenoid cartilages are formed of hyaline cartilage which can mineralise over time. Gradually, the mineralised areas get replaced by bone in a process referred to as endochondral ossification (Kutta et al. 2007). No such ossification occurs in the remaining epiglottis, corniculate, and cuneiform cartilages as they are formed of elastic cartilage (Türkmen et al. 2012) which is the same material as in the outer ear for example. The precise cause for this process is not completely understood but a prevalent theory is that ossification is triggered by the mechanical strain at muscle attachment sites (Turk and Hogg 1993, Garvin 2008). Some researchers (Naimo et al. 2013) suggest that with advancing calcification and ossification the material becomes more brittle and thus fractures more easily. This appears plausible for larynges since the more flexible cartilage can mediate some of the load by deformation before it fractures (Carter 1987).

Experiments have shown that fusion at the cartilaginous joints does not increase its fracture potential (Lebreton-Chakour et al. 2013) but there is some indication that age has an effect on the fracture likelihood of both the hyoid and the larynx (Hänsch 1977). However, other studies have found no correlation between age and fracture frequency (Naik and Patil 2005) which demonstrates the complexity of studying strangulation deaths. Traditionally, a fractured hyoid bone was considered proof of strangulation and was thought to be present in the majority of cases (Jaffe 1978). However, more recent studies have produced less clear evidence and only report fractures in up to 1/3 of cases (Hawley et al. 2001, Maxeiner and Bockholdt 2003). Conversely, one has to consider other possible causes for laryngo-hyoid fractures such as falls, sports injuries, and traffic accidents which are frequently cited as examples of injuries that resemble strangulation (Advenier et al. 2014). Laryngeal fractures are therefore not pathognomonic and must be evaluated in conjunction with other signs. This emphasises the challenge of a differential diagnosis but if there is no alternative explanation for the occurrence of such injuries their presence can be crucial evidence. Absolute certainty in the diagnosis of strangulations might still be a long way away but because of its complexity every additional measure to increase confidence of the diagnosis should be considered.

3.1 External signs

Strangulation is often suspected if certain external marks are visible on the deceased. These superficial marks used to diagnose strangulation are sometimes difficult to detect, especially if the victim has subsequently been exposed to conditions which alter or damage the tissues such as fire or water, or simply is in an advanced state of decomposition (Kettner et al. 2014). If the victim is recently deceased without any interference since the point of death, careful examination should produce sufficient evidence for a clear diagnosis. The most prominent superficial sign is petechial bleeding. Petechiae are visible as small pinpoint spots on the skin surface and are the result of bursting capillary blood vessels caused by increased capillary pressure during venous obstruction (Clarot et al. 2005). They can be found on the entire body but if they are encountered in the face or neck area or the eyes they suggest that the obstruction occurred around the neck region. However, they are not specific to strangulation and can occur in cases of drowning, smoke inhalation, smothering, or simply indicate a face-down position (Saukko and Knight 2015). Petechial bleeding is often considered to be related to a high level of force (Plattner et al. 2005) or as evidence of a life-threatening situation if the victim survived (Yen et al. 2007, Christe et al. 2009). This does not suggest that the absence of these marks necessarily indicates a low level of force or disproves strangulation altogether as frequent examples in the literature prove (Strack 2007, Fais et al. 2016). It might be possible that petechiae are more prominent if the actual cause of death is by arterial or venous constriction and less for compression of the nerve ganglion or respiratory organs.

Other visible signs include skin abrasions on the victim's neck and lower jaw which can manifest as scratches, bruises, or simply reddened areas. They can be caused by the assailant's hands directly, by the victim's hands or fingernails in an attempt to loosen the grip around their neck, or by the ligature involved. In the latter case, an impression of the ligature used might form on the victim's neck which provides an indication of the object used which in turn might help linking a suspect to the crime. The problem with skin marks is that they can take some time to develop and might therefore be easily missed which also applies to other subtle injuries which might remain undetected. As with laryngeal fractures, none of the above signs are exclusive to strangulation demonstrating the problems with this homicide method. There is strong evidence in surviving strangulation victims that there are severe long-term injuries which might lead to a delayed death (Laughon et al. 2008, Di Paolo et al. 2009). Carotid artery dissection is amongst the injuries cited which if not detected and treated rapidly can be fatal (Clarot et al. 2005).

3.2 Pathological Diagnosis

If the suspicion of strangulation arises during autopsy the pathologist tends to assess the integrity of the hyoid bone by testing it for hypermobility (Davison and Williams 2012). In practice, increased mobility is established by "wiggling" the dissected bone (i.e. holding the body and moving each greater horn) and if it flexes more than expected it is considered to be damaged and seen as support of the strangulation hypothesis (Kolar 2016). The problem with this approach is the hyoid's inherent flexibility if the synchondroses between body and greater horns are not fused which makes relying on this method very subjective and inaccurate in many cases with potentially devastating consequences if it leads to someone's wrongful conviction based on this evidence. Damage to the larynx is more frequent as it occupies a more exposed position on the anterior neck (Dunsby and Davison 2011) but subtle injuries are particularly difficult to detect. The standard approach during autopsy is to strip away and examine the overlying muscles and ligaments layer by layer (Saukko and Knight 2015). Haematoma within the deep structures of the neck are frequently cited in relation to strangulations and are also categorised as a more severe injury type (Yen et al. 2005, Christe et al. 2009). Once the larynx is exposed it is examined for lacerations and breaks. These are usually only detected if they are associated with haematoma or gross fragment displacement, otherwise there is a high possibility of them being missed during simple visual inspection (Kempter et al. 2009). Therefore, further histological analysis should follow to verify the findings. Histology is the more objective method to demonstrate injuries on the hyoid or larynx but it is a very time consuming and expensive task which ultimately destroys the sample and is therefore not routinely employed (Davison and Williams 2012). It is further limited to one sectioning plane which must be chosen prior to the first cut and adhered to for all following ones. In order to economise histology, slices tend to be taken from areas of macroscopic haematoma or injury or from areas which are known to be affected in comparative cases, increasing the risk of missing damage to less vascular areas of cartilage which produce fewer haematomas.

3.3 Survived strangulation

The forensic assessment of survived strangulations is even more complicated since the internal damage cannot be examined with the same rigorous methods. The primary goal is to treat the victim's injuries, the forensic medical assessment comes second. Medical grade CT or MRI scans and laryngoscopy are often used to assess whether the laryngeal skeleton has been damaged which would require surgical intervention such as fixation. A major challenge for the forensic clinician is to establish the severity of the attack; the more immediate danger the victim was in, the higher the sentence for the perpetrator will be (McClane et al. 2001, Plattner et al. 2005). Hence, the clinician has to interpret how life-threatening the injuries are. Because of the many factors involved in strangulations and the lack of understanding of the forces involved, the assessment largely relies on the victim's and witnesses' accounts which provide a highly subjective view of the incident providing a welcome target for the defence during trial (Laughon et al. 2008).

3.4 The role of forensic imaging

An increasing number of recent studies use clinical Computed Tomography to enhance postmortem examinations in general (Baglivo et al. 2013, Jalalzadeh et al. 2015) with the advantages and disadvantages have been explored in detail in the literature review in Chapter 3. Flach et al. (2014) have realised the need for more detailed scans of smaller structures and suggest performing a separate laryngeal scan in cases of suspected strangulation. Medical CT has also previously been used to study the ossification process of the laryngeal cartilages with the aim of establishing objective criteria that can be used for age determination (Dang-Tran et al. 2010). Micro-CT produces an even higher resolution with the potential to visualise the minute ossified structures of the laryngo-hyoid complex three-dimensionally (Kettner et al. 2013). The method's 3D rendering capability is of particular interest as Becker et al. (2013) note that fracture detection rates are best when the volume-rendered CT image is examined. Micro-CT can improve this further as its high resolution enables the detection of microscopic cracks which standard X-ray or even clinical CT would not be able to visualise. Fais et al. (2016) present such a case where µCT revealed a fracture of the superior thyroid horn which had not been previously detected on clinical CT. The authors then continue to suggest using µCT as a form of virtual histology, an idea that has been implemented by others as a valuable alternative to histology for the study of Haversian systems within cortical bone as it is non-destructive (Cooper et al. 2011). Fais et al. (2016) removed the superior thyroid horns from their sample to be scanned separately due to the size restrictions of their scanner. This appears problematic as these structures are very delicate and extraction might add postmortem artefacts. These are challenging to assess since comparative micro-CT images of the ossified laryngeal structures have not been studied sufficiently yet. Visualising soft tissues can be difficult on CT and damage to the uncalcified laryngeal cartilage might therefore not be sufficiently visualised for a diagnosis, necessitating the administration of a contrast agent. The use of contrast agents in forensic samples might be problematic since some agents are permanent (Aslanidi et al. 2013). This would affect and possibly jeopardize further examinations such as histology. Without contrast agents non-osseous structures such as cartilaginous fractures and haemorrhages are occasionally missed on a CT scan (Kempter et al. 2009) which suggests that while a CT scan increases the detection of certain trauma, it does not replace a physical exam but could serve to guide the pathologist through it. Recent developments in CT technology such as spectral CT, might be the solution to this problem in the future. Another limitation of micro-CT is its high radiation dose which makes it impracticable for clinical use. A high-resolution examination of victims of non-fatal strangulations could provide information about the level of force required to fracture a larynx/ hyoid which could assist the interpretation of fatal cases.

3.5 Summary

Strangulation deaths are one of the less straightforward diagnoses pathologists face. Given the frequent occurrence of homicidal strangulations it is astonishing that the matter is still so poorly understood and so few objective diagnostic methods exist. Any small improvement is therefore expected to be welcomed by pathologists and police alike. New approaches such as micro-CT have shown some promise in isolated cases but are not yet routinely used in forensic pathological practice.

4. Materials and methods

4.1 Case data

Whenever a pathologist suspected strangulation as cause of death they would extract the entire larynx at postmortem and submit it for micro-CT examination. Different dissection methods were used depending on the pathologist on the case. The samples were fixed in formalin to slow down tissue decomposition and were packaged by mortuary staff according to guidelines developed in this project over time. They were positioned horizontally onto a block of foam onto which it was tied with surgical thread and were then placed into a sealable plastic container. Experiments with vertical positioning of the larynx resulted in sample movement during the scan. As indicated in the literature review, the larynx and hyoid form an entity and were therefore extracted as one sample in most cases. However, the dissection process distorts the original relationship between the two elements, their relative location could therefore not be used as assessment criterion. In order to be micro-CT scanned, the sample containers were placed directly onto the scanner's rotating stage, the scanner used for all samples in this study was a Nikon 225/320 LC (Nikon Metrology, Tring, UK). Typical scan parameters were 120kV, 135µA, 500ms exposure, 24dB gain, no filtration, and 3141 projections, although adjustments were made depending on the sample's material properties such as size or degree of mineralisation. Full details of the scan parameters for each case are provided in **Table 2**. The resulting model was examined in VG Studio MAX 2.2 software (Volume Graphics, Heidelberg, Germany) for fractures using the 3D rendering and the 2D sections along multiple planes. An illustrated report was compiled for each case and issued to the police who would then forward it to the pathologist and the histopathologist if a further histological examination was to be conducted. Initially only the preliminary postmortem report and a summary of the case circumstances were available but frequent research visits to the force CID headquarters provided more detailed documentation from the HOLMES database or the investigating officers in person. These documents included the full postmortem reports, radiology reports, histopathology reports, witness statements, and sometimes defence statements.

***Table 2:** Scan parameters used for the forensic specimens in this chapter.*

Case	Voltage (kV)	Current (µA)	Exposure (ms)	Gain (dB)	Filtration	No. of projections	Resolution (µm)
Aberdere	115	78	500	24	None	3141	23.7
Albatross	120	84	500	24	None	3141	23.0
Ampersand	125	77	500	24	None	3141	39.7
Aponi	70	294	1000	24	None	3141	44.5
Aporia	120	92	1000	24	None	3141	34.0
Asgard	150	93	708	24	0.35mm copper	3141	58.3
Ballerine	80	718	708	18	0.35mm copper	3141	57.5
Baudette	120	125	708	24	None	3141	51.7

Bell	90	393	354	24	0.35mm copper	3141	37.0
Bluemist	120	77	1000	24	None	3141	53.7
Bryer	125	85	708	18	None	3141	27.9
Catni	120	60	500	30	0.35mm copper	3141	41.2
Chaucer	100	500	250	24	0.35mm copper	3141	52.2
Helevorn	130	69	500	24	0.35mm copper	3141	42.5
Henge	115	226	500	24	None	3141	70.1
Isengard	150	73	500	24	0.35mm copper	3141	79.7
Market Hill	80	125	500	24	None	3141	55.5
Marshside	130	115	354	24	0.35mm copper	3141	57.6
Note	85	565	354	18	0.35mm copper	3141	49.5
Number	140	218	500	24	None	3141	53.6
Oakwood	100	75	1415	24	0.15mm copper	3135	19.5
Pencil	62	83	2829	24	None	3135	47.6
Platter	85	282	708	24	None	3141	39.7
Sajama	80	100	1000	30	None	3135	50.0
Syringe	80	250	708	24	None	3141	36.4

Data analysis was conducted by comparing the injury descriptions of four different data sets which provided an increasing level of detail, starting with the external description in the postmortem report and the corresponding images, followed by the internal dissection and associated postmortem images, then micro-CT images, and at the most detailed level histology. Not all four categories were present in all cases but as a minimum the postmortem report and the micro-CT images were used. The overall aim was to determine how reliable micro-CT was in identifying injuries and to see how the different levels of analysis correlate. The injuries were also visually overlaid on a schematic representation of the larynx to demonstrate correlations and differences. The following **Table 3** details the criteria that were used to compare the cases and summarises which features were identified with each examination method. The affected area was noted as the approximate region, divided into top, middle, and lower and anterior, left, and right, resulting in nine areas.

The following details about the assault circumstances were added to the overall content matrix from the case files:

- Evidence of a struggle – possible sources of information: witness statements, CCTV, defence injuries
- Demographics – offender- victim relationship, offender sex/age/height/weight, victim sex/age/height/weight
- Mode of strangulation – ligature, manual, chokehold, unknown
- Amount of force used – mild, moderate, severe

Table 3: *Summary of the features commonly observed using different imaging modalities*

	PM external	PM internal	Micro-CT	Histology
Bruising	✓	✓	N/A	N/A
Haematoma	N/A	✓	✗	✓
Cartilage fracture	N/A	✓ Presence - Absence	✓ Presence - Absence	✓ Fresh - Healing
Bone fracture	N/A	✓ Presence - Absence	✓ Fresh - Healing	✓ Fresh - Healing

This complete content matrix of injuries and case circumstances was examined to reveal any trends or patterns which might reveal the causes for certain injuries.

4.2 Validation study

In order to interpret the micro-CT images of real cases, a validation study was conducted with the aim of visualising the normal anatomical appearance of the larynx against which the forensic cases could be compared. These 19 uninjured larynges were obtained from individuals who had donated their bodies to science (age range: 46-94 years; male: 12, female: 7, full details can be found in **Table 4**). The larynges were carefully extracted by a trained anatomist to avoid creating postmortem handling artefacts. They were subsequently scanned using the same equipment at similar settings to the forensic case samples (see **Table 5** for full details) and inspected visually. The features noted from these scans included the presence/absence of anatomical elements, the presence and appearance of fractures, and other features identified as problematic for interpretation in the case examples (triticeous cartilages, circular holes in the ossified cartilage, linear creases, abrupt angles, and fragmentary ossified tissue).

Table 4: *Full demographic details of the samples used for the validation study.*

Sample ID	Age (years)	Sex	Cause of death
S170105	86	F	Cerebrovascular accident
S170163	46	M	Renal disease
S170167	90	M	Pulmonary Fibrosis
S170320	75	M	Cardiopulmonary arrest
S170345	86	M	Myeolodysplastic Syndrome
S170405	87	M	Colon cancer
S170445	80	M	Respiratory failure
S170452	73	M	Lymphoma
S170459	81	F	Lung cancer
S173160	75	F	Neoplasm of lung
S173053	79	M	Lymphoma
S173046	88	M	Coronary Artery Disease
S173045	70	F	Breast cancer
S172982	88	M	Acute Myocardial Infarction
S172809	93	F	OP complications
S171263	67	M	Leukemia
C171288	94	F	Acute Myocardial Infarction
C171258	76	F	Heart failure
L172291	86	M	Adenocarcinoma of lung

Table 5: Scan parameters used for the reference specimens in this chapter.

Case	Voltage (kV)	Current (µA)	Exposure (ms)	Gain (dB)	Filtration	No. of projections	Resolution (µm)
S170105	120	167	500	24	None	3141	38.6
S170163	130	185	500	24	None	3141	38.6
S170167	125	183	500	24	None	3141	41.7
S170320	125	160	500	24	None	3141	42.9
S170345	125	167	500	24	None	3141	43.0
S170405	125	167	500	24	None	3141	42.9
S170445	125	176	500	24	None	3141	38.6
S170452	145	165	500	18	None	3141	37.9
S170459	125	160	500	24	None	3141	39.3
S173160	125	184	708	18	None	3141	41.5
S173053	130	170	708	18	None	3141	40.1
S173046	125	184	708	18	None	3141	44.7
S173045	125	184	708	18	None	3141	40.2
S172982	125	184	708	18	None	3141	42.3
S172809	125	184	708	18	None	3141	39.0
S171263	125	184	708	18	None	3141	44.1
C171288	125	184	708	18	None	3141	44.7
C171258	130	169	708	18	None	3141	39.0
L172291	125	184	708	18	None	3141	44.7

4.3 Impact analysis

The impact of using micro-CT for suspected strangulations was analysed with regards to the stage-gate system and the QCD triangle introduced in Chapter 2. Mapping each strangulation case on the stage-gate process was done directly from the case information. The evaluation of the impact on the QCD assessment criteria largely depended on the interview data presented in Chapter 9 and on personal feedback from collaborators.

5. Results

5.1 Case data

Thirty-three suspected strangulations were examined over the course of this project. Of these, three had to be excluded due to the lack of data pertaining to the case and a further five due to insufficient micro-CT visualisation. The final number of cases used in the analysis was therefore 25. Of these 25, the victim was female in 17 cases and male in eight. The suspects in all cases were male, only in two cases (OP Baudette, OP Asgard) there was no suspect. The majority of offenders were known to the victim, only in two cases (Isengard, Market Hill) the attacker was a complete stranger, the victim in both female. Of the remaining assaults where the victim was female, 10 were committed by a current of former partner, one was committed by an acquaintance, and four were either no crime or no perpetrator identified. Of the assaults where the victim was male, five were committed by an acquaintance and two were identified as no crime. These findings are illustrated in **Figure 5**. The cause of death was ultimately determined as compression of the neck in nine cases. The remaining cases were due to drowning in one case, BFT in two, SFT in two, multiple injuries in one, drug related in three, natural causes in one, and unascertained in the remaining six.

Some general trends could be observed regarding the correlation of the different medical data sets. The diagnosis of strangulation was given in the preliminary autopsy report only when the superficial signs such as petechial bleeding were very prominent or a clear ligature mark visible. When matching the superficial signs to the micro-CT observation it was seen that there was a good overall correspondence regarding the location of both data sets in six of the cases (OPs Aponi, Ampersand, Aberdere, Albatross, Asgard, Bell). OP Aponi showed a direct match at the posterior neck but no superficial marks were visible at the location of the possible micro-CT fracture of the right thyroid lamina.

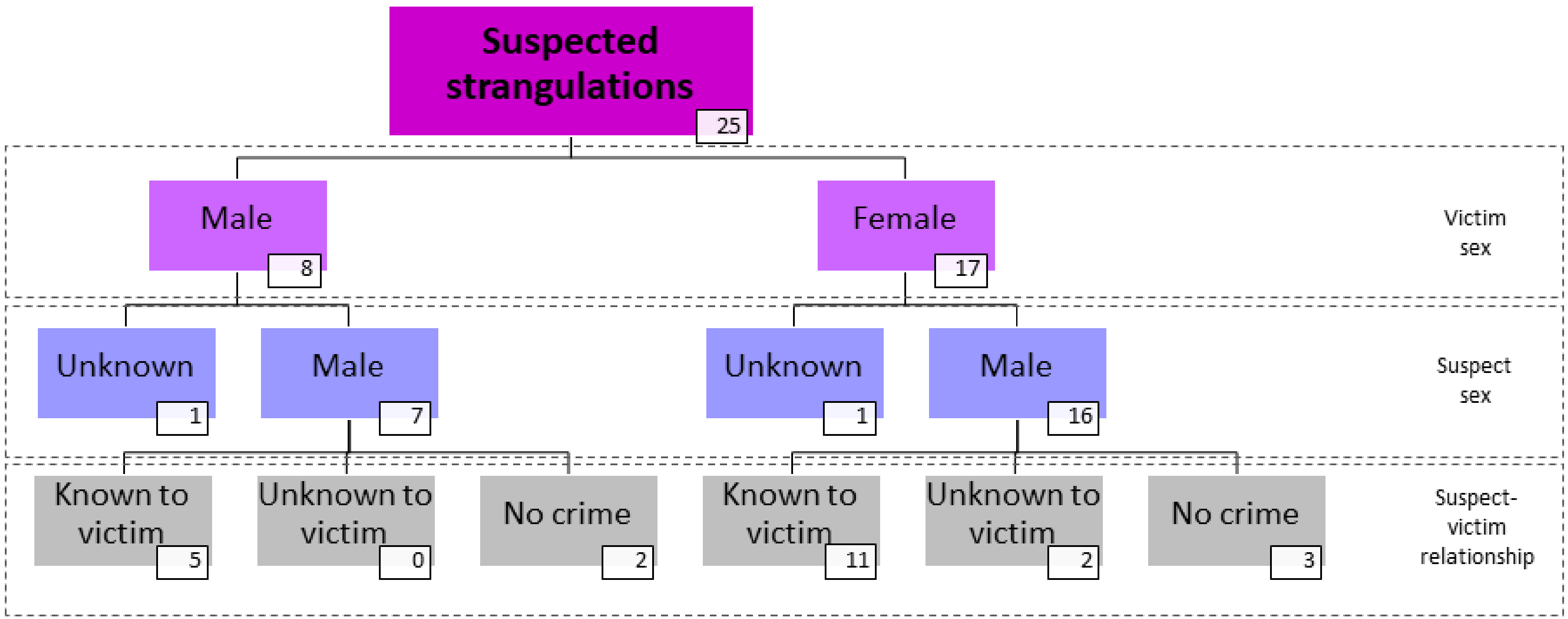


Figure 5: *Diagram representing the victim and suspect information for all suspected strangulation examined in this thesis.*

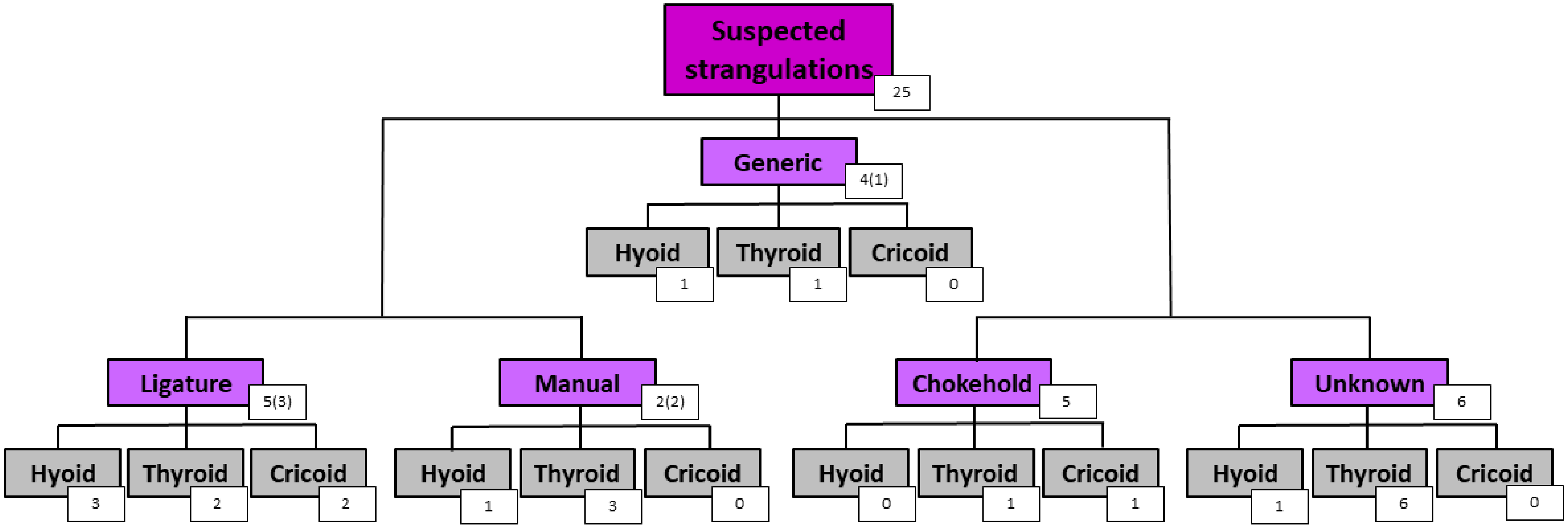


Figure 6*: Summary of the different modes of strangulations and the type of injuries they produce. The numbers in brackets indicate cases where strangulation has contributed to but not caused the death.*

Correspondence between internal postmortem injuries and micro-CT results was observed in 10 cases (OPs Aponi, Ampersand, Albatross, Bryer, Bell, Chaucer, Helevorn, Henge, Isengard, Pencil). Haemorrhages were found to correspond to the location of other injuries in these cases but could not be identified on micro-CT. Correlation of all three levels of detail (external, internal, and micro-CT) was seen in four cases. Combining these data sets was somewhat problematic as the choice of terminology varied between observers and the location of features was difficult to re-align once the larynx was extracted. **Table 6** details how micro-CT compared to autopsy and histology for detecting individual injury types. It becomes obvious that the visualisation of haemorrhages is problematic on micro-CT but fractures are reliably identified.

***Table 6**: Comparison of the performance of micro-CT versus autopsy and histology for haemorrhages, and cartilage and bone fractures. The total number refers to the number of times a particular feature has been identified.*

		Missed on µCT	Confirmed on µCT	Additional on µCT	Total
Haemorrhages	Autopsy	15	0	0	15
	Histology	7	0	0	7
Cartilage fractures	Autopsy	0	8	5	13
	Histology	1	7	3	11
Bone fractures	Autopsy	1	3	1	5
	Histology	0	2	1	3

Fractures of the laryngeal skeleton could be more accurately correlated between the different data sets. In all but one cases where a fracture was described at postmortem it was identified on micro-CT as well, the one exception being OP Sajama which was one of the very early cases. The match was better if the features were described as obvious in the relevant report, injuries described as “possible” matched less frequently. Ligature marks only directly corresponded to micro-CT damage in one case (OP Albatross). Cases with subtle injuries relied more heavily on further examinations for clarity.

Hyoid injuries were observed in five cases at postmortem, three of those were confirmed with micro-CT and two were not scanned. An additional fracture was identified in one case using micro-CT (OP Marshside) which had not been previously observed. Of these six cases, three were subsequently examined histologically which confirmed the fracture in two cases (including the one previously seen only on micro-CT), and discovered a haemorrhage but no fracture in the third (OP Bryer).

Fractures of the laryngeal cartilages were suspected in eight cases at postmortem and confirmed on the micro-CT images. A further five cases displayed a damaged larynx on micro-CT and five displayed possible damage. Histological examination was performed on 15 cases, all of which had displayed some injury or possible injury on the micro-CT scan. The microscopic examination confirmed the scan images in seven cases, in one case injuries were observed where micro-CT revealed none, and in three cases it failed to confirm the micro-CT images.

5.2 Case background

Correlating these results with the case data revealed further patterns relating to the dynamics of the assault. These are illustrated in form of a tree diagram in **Figure 6**. Five cases were ligature strangulations, in a further three ligature strangulation was part of the attack but was not the ultimate cause of death. Two deaths were caused by manual strangulation, in two cases manual strangulation contributed to but did not cause the death. In five cases the manner of death was by chokehold and a further four by not further detailed strangulation which also contributed to one further case. In the remaining six cases, the injuries could not be associated with certainty with any form of strangulation. It further appears that ligature strangulations are more likely to produce fractures of the hyoid or cricoid cartilage (five out of eight ligature cases) although this is not a distinguishing criterion as six further cases displayed damage on hyoid or cricoid which was either due to manual strangulation, chokehold, or unknown mechanisms. It further appears that cases where there is evidence of a struggle display more widespread damage, only six cases included any reference to a struggle within the case file, the exact dynamics of the remaining cases are unknown.

5.3 Validation study

The validation study included a subset (n=9) of the forensic cases analysed in this thesis plus an additional three cases not included in the main analysis of this chapter, resulting in a total of 12 samples. The three additional cases were not included in the main analysis due to the lack of associated information, only preliminary postmortem reports and confessions were available. Only cases where strangulation had been confirmed or ruled out by multiple lines of enquiry were examined. The main feature examined was the presence of fractures. In the control group, three samples displayed a fracture, all at the same location either to the right or left of the anterior midline on the inferior margin of the thyroid laminae as shown in **Figure 7.**

Figure 7: *Anterior view (i.e. seen as if facing the person) of two of the samples from the control group. They both display a vertical feature on the inferior margin of the thyroid lamina, just to one side of the midline (arrows). This feature appears like a fracture but was encountered in several of the control samples.*

This fracture location was observed in four of the forensic samples, and an additional four fracture locations were observed in this group (superior thyroid horns, inferior thyroid horns, cricoid, and posterior greater horns of the hyoid), an example of each is given in **Figure 8**.

Triticeous cartilages were observed frequently - their appearance was similar in both groups with smooth cortical bone and a spherical to oval shape. **Figure 4** shows their position within the thyrohyoid ligament. Abrupt angles are seen along the superior thyroid margins, the superior thyroid horns, and the greater horns of the hyoid in both groups. Circular holes within the ossified cartilage occurred in both groups, they all display clear and regular margins. Linear creases were only observed on the posterior aspect (including superior and inferior horns) of the ossified thyroid cartilage. They predominantly extend vertically along the posterior margin although some are observed on the lateral and medial aspects of the posterior margin. A complete results table can be found in Appendix D.

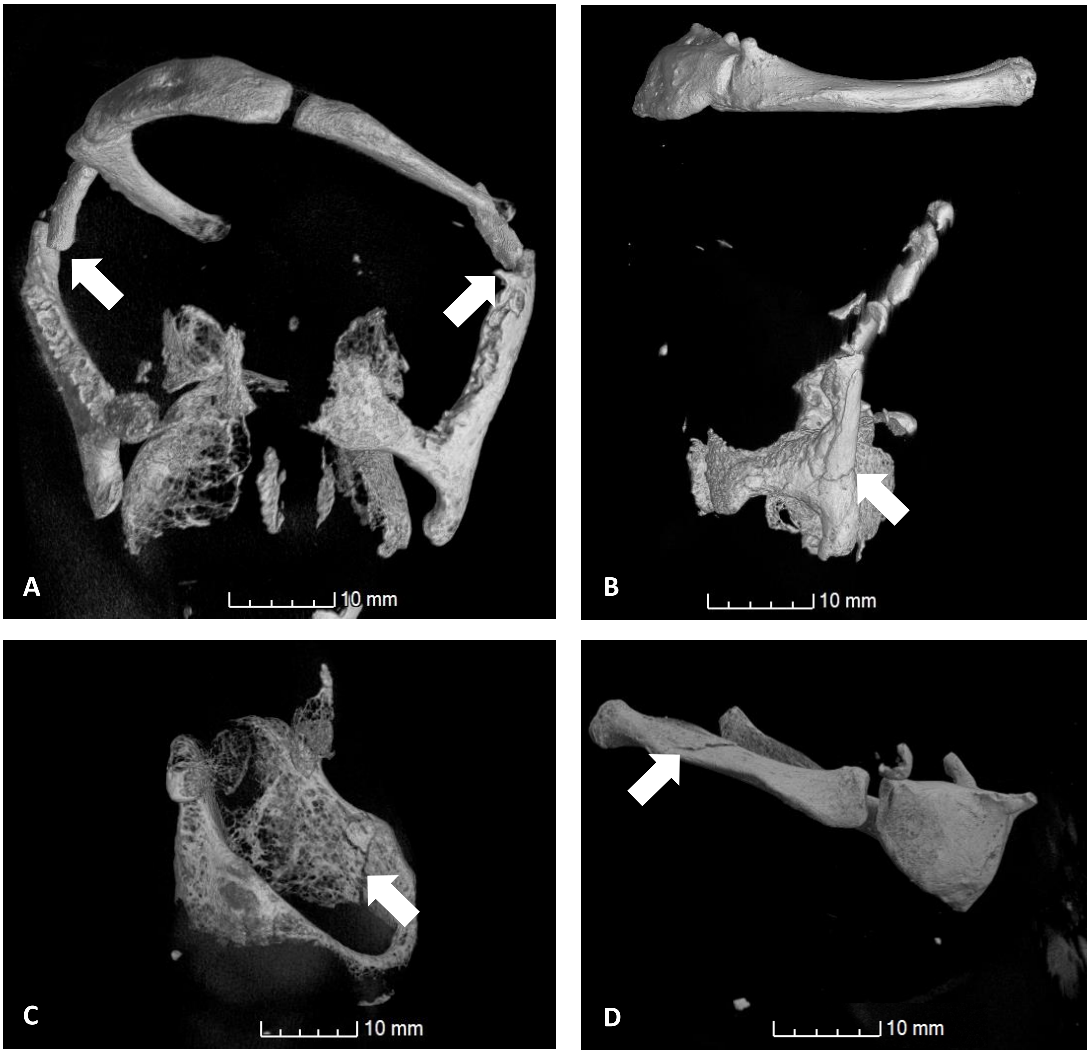


***Figure 8:** Different fracture locations encountered in the forensic group. A: Fracture and medial displacement of both superior thyroid horns, OP Isengard; B: fractured base of the left inferior thyroid horn, OP Bryer; C: fractured cricoid cartilage, OP Asgard; C: oblique fracture of the right greater horn of the hyoid, OP Marshside.*

5.4 Significance of results

Each of the features assessed in the validation study were evaluated against existing literature regarding their significance for the diagnosis of strangulation deaths.

5.4.1 Fractures

The most likely explanation for the fracture-like feature on the inferior thyroid margin is a product of the natural ossification process as it has been observed in both groups. All other fractures occur exclusively in the forensic group and are considered true trauma. All the fractures of the greater horns of the hyoid such as in **Figure 8D** and **Figure 17** occurred in ligature strangulations. This slightly contradicts the summary by Dettmeyer et al. (2014) who observed hyoid fractures more commonly in manual strangulations. The majority of superior thyroid horn fractures such as in **Figure 8A** occurred bilaterally. Only one of those bilateral injuries was not a ligature strangulation. However, there were also cases of ligature strangulation which did not result in bilateral fractures. These overlapping injury patterns pose a recurring dilemma in interpreting strangulation deaths. Many studies have attempted to classify injuries according to the mode of strangulation (Maxeiner and Bockholdt 2003, Naik and Patil 2005, Shaik et al. 2013) and while there are some trends there are also commonalities which make it difficult to draw conclusions based on the fracture pattern alone, for the time being.

5.4.2 Circular holes

Smooth-edged circular holes were only seen in the thyroid cartilage but were not restricted to a specific location (**Figure 9**).

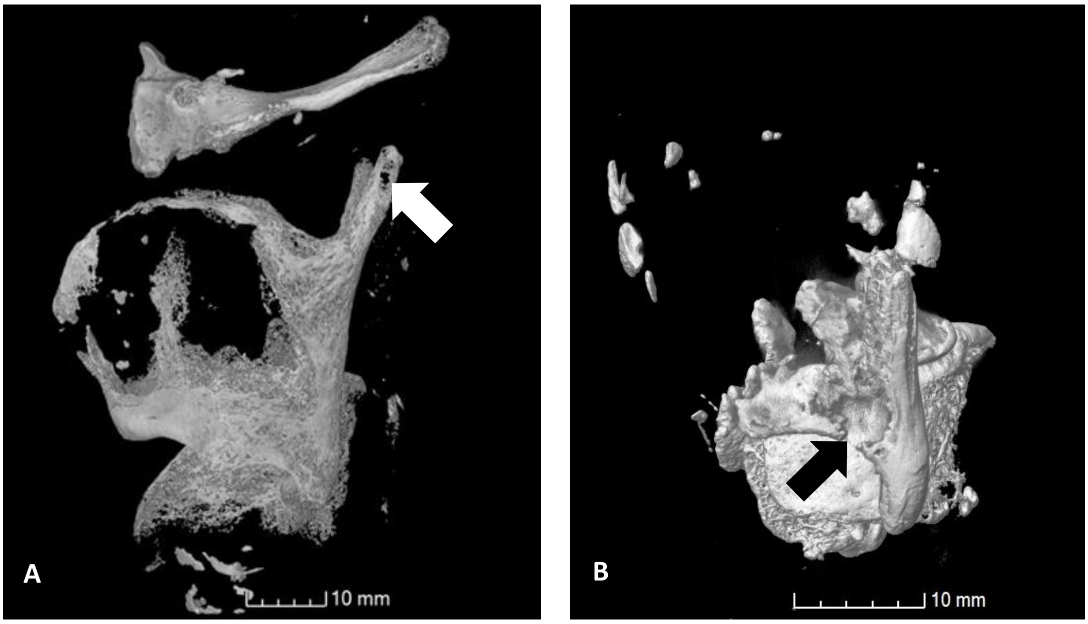


Figure 9: *Circular defects within the ossified cartilage (arrows). A: sample S173046 from the control group showing the defect on the left superior thyroid horn; B: OP Aponi showing the defect at the base of the left inferior thyroid horn.*

Their occurrence within the laminae is a common location for the thyroid foramen which serves as an opening for vessels or nerves (Raikos and Paraskevas 2013). It is possible that the circular openings in other locations fulfil a similar purpose. Alternatively, the cartilage might have ossified around some other anomaly such as a cyst for example which was not imaged in the scan. Their presence in the control group indicates a natural cause and eliminates potential misidentification as damage, for example as caused by fingertip pressure.

5.4.3 Fragmentation

There was an overall higher degree of fragmentation in the forensic group. However, this could be explained by the more advanced age of the donor individuals in the control group which is evident in more advanced stages of ossification. Nonetheless, the appearance of the fragmentary material was similar in both groups (**Figure 10**) with individual ossified "nodules" displaying smooth, rounded edges. While the majority of fragments in the control group are found along the margins of the thyroid laminae and within the cricoid, the case examples display fragments in all locations.

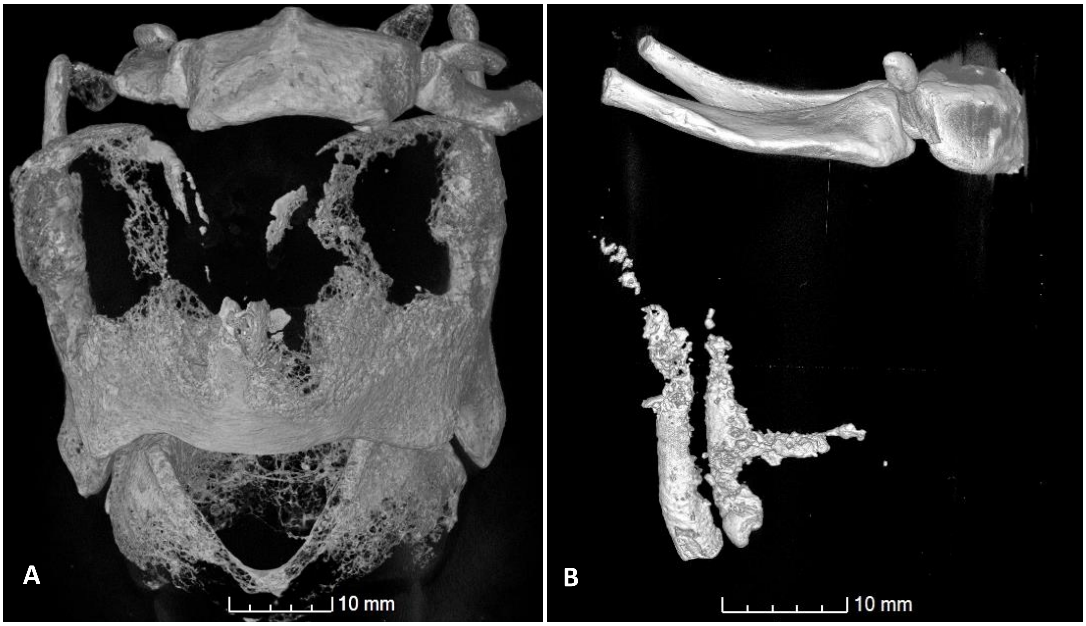


***Figure 10:** Fragmentation of ossified cartilage. A: Sample S170405 from the control group; B: OP Aponi. The naturally occurring fragmentation displays rounded nodules of ossified material.*

As the fragments are similar in appearance in both groups, they are not considered to be compelling evidence of trauma since they have been shown to occur naturally. No other study has ever examined this feature to the author's knowledge, further comparison will therefore depend on a future expansion of this database.

5.4.4 Incomplete fusion

The fusion or non-fusion of the greater horns to the body of the hyoid bone has been a frequently misinterpreted feature. While it is well-established in the literature that these elements can fuse over time (Di Nunno et al. 2004, Naimo et al. 2015), in pathological practice hypermobility is sometimes taken as evidence of a hyoid fracture (Davison and Williams 2012). Depending on the pathologist's sensitivity and experience, a natural non-union might be mistaken for trauma. In radiology, this might also occur if the gap between the body and greater horn is very narrow or the two parts are partially fused. The control group has shown several examples of incomplete fusion with a narrow gap still visible at the body-greater horn junction. Both sides display an uninterrupted cortical bone surface which only begins to disappear after fusion has completed. **Figure 11** shows both the volume rendering and a 2D section through one such hyoid.

__Figure 11__: Control sample S171263 with incomplete fusion of the left greater horn and the body of the hyoid (arrows). A: volume rendering; B: transverse section through the hyoid. This feature could be easily mistaken for a fracture in forensic cases without the control samples.

Hyoid fractures have only been observed in the posterior third of the greater horn where the bone is delicate and thin. This fracture location has been observed as a common injury in several other studies of neck compression (Kempter et al. 2009). This type of hyoid fracture appears to be strong support for compression of the neck.

5.4.5 Abrupt angles

These were encountered frequently in the control group, often on the superior thyroid horns and along the superior margins of the thyroid laminae. In one control sample shown in **Figure 12**, the greater horns of the hyoid were angled upwards in the posterior third. These angles are present in the normal population but from this study it does not become clear whether they are due to normal variation or previous healed trauma. If the latter was the case it would impact the interpretation of fractures in actual cases. It would mean that the superior thyroid horn that has so far only been observed to be fractured in actual strangulations, could be broken naturally as well. This would decrease the significance of damaged superior horns as evidence of strangulation. A study by Maxeiner (1999) found that healed fractures of the hyoid and thyroid cartilage are fairly common, in particular amongst alcoholics who are prone to frequent falls or accidents. However, this study relied on microscopic changes as opposed to macroscopic deformations.

Figure 12: A: Unusual angles observed on the hyoid and superior thyroid horns of control sample S173160. Asymmetry and perceived deformation are ambiguous features in the identification of trauma. B: Sample S171263 for comparison showing straighter superior thyroid horns and greater horns of the hyoid.

5.4.6 Linear creases

These features resemble fine cracks when seen on the 3D volume-rendered scan, an example is shown in **Figure 13**. Using the 2D sections helped identifying them as superficial. They were frequently observed in the control group which is important to avoid misinterpretation as real fractures in the forensic samples.

Figure 13: Posterior view of control sample C171288 showing two linear creases along the posterior margins of the thyroid cartilage (arrows). Knowing they are naturally occurring is essential to avoid misinterpretation as fractures.

The location and orientation of these creases appears fairly unique and rather dissimilar to the actual fractures observed. This feature in particular has only been made possible to study through the increased detail of micro-CT and has not been described previously.

A similar feature was a sharp crest extending in no particular direction, possibly indicating the ossification "front". One side of this crest displays a cortical bone surface whereas the other side displays less solidly ossified material. When examining the volume rendering of a scan, the shadow created by the crest can mimic a fracture line as visualised on **Figure 14**. Having identified this feature in numerous control cases serves as reassurance that this is a natural feature. This was most commonly observed at the base of the superior thyroid horns. The horns displayed more densely ossified material compared to the more loosely structured trabeculae at the base.

Figure 14*: Right lateral view of control sample S170105 showing a crest along and at the base of the superior thyroid horn (arrows). It is likely that this crest is created by contrasting levels of ossification.*

5.4.7 Triticeous cartilages

Triticeous cartilages have occasionally been observed in the literature on normal anatomical variation of the larynx (Di Nunno et al. 2004). These small spherical ossifications are found in the thyrohyoid membrane which connects the superior thyroid horns to the posterior greater horns of the hyoid. The close proximity to the superior thyroid horns poses the risk of misinterpreting them as fragments of the horns, in particular if the soft tissue structures have not been visualised sufficiently to allow a distinction as illustrated in **Figure 15**. The main difference to fragments of the superior thyroid horns is that the triticeous cartilages appear rounded with a smooth cortical surface whereas horn fragments have at least one irregular aspect.

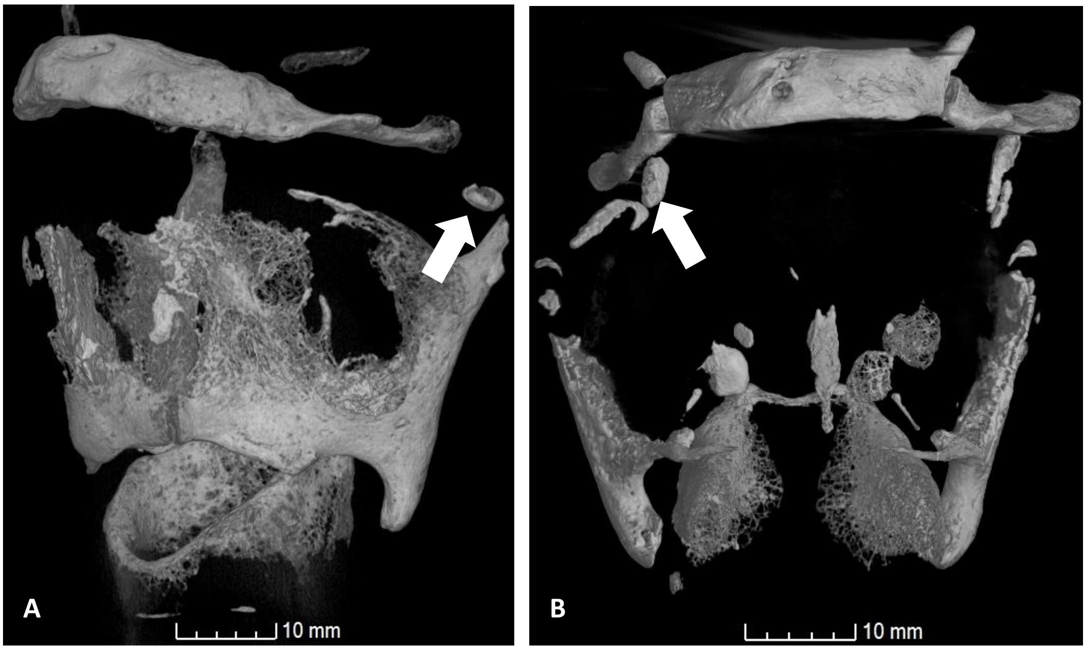


Figure 15: *Two case examples showing triticeous cartilages. Their close proximity to the superior thyroid horns might cause them to be mistaken as fragments of the superior horns. Unlike such fragments, triticeous cartilages are spherical to oval in shape with a closed cortical surface. A: OP Asgard; B: OP Ankara.*

5.5 Validation study 2

A second validation study was conducted to evaluate how micro-CT compares to histology, the current gold standard for assessing laryngeal injuries from forensic contexts (Baier et al. 2019). For this study, two of the larynges (OPs Ballerine and Isengard) and one sample discussed in Chapter 7 were examined by the author and the histologist respectively and results compared collaboratively.

5.5.1 Case one: OP Ballerine

Micro-CT: The analysis of the micro-CT images revealed one possible and two definite injury sites, shown in **Figure 16**. Clear fractures were observed on the posterior right greater horn of the hyoid (area A) and through the ossified cartilage on the inferior border of the thyroid lamina to the left of the anterior midline (area B). The ossified cartilage surrounding the fracture on the left side displayed a thickened region, which was cautiously interpreted as an irregular ossification pattern. An area of possible damage was observed at the base of the left superior horn of the thyroid cartilage (area C) which appeared as a fracture through the ossified cartilage but the overall irregular ossification pattern made a definite diagnosis difficult.

Histology: A fracture was detected involving the right greater horn of the hyoid bone associated with osteocyte necrosis either side of the fracture line, little haemorrhage, and intact periosteum. There was no inflammatory or mesenchymal tissue response. **Figure 17** directly compares the micro-CT and histological appearance of this fracture.

***Figure 16**: Antero-lateral view of the volume-rendered µCT scan of OP Ballerine showing all the injuries identified initially: A= hyoid fracture, B=fracture on left inferior margin of thyroid lamina, C= possible fracture of left superior thyroid horn.*

A displaced fracture was identified on the left superior horn of the thyroid cartilage containing fibrin and showing adjacent osteocyte necrosis, osteoclast activity with osteoblast reaction, and mesenchymal tissue response including an area of intramembranous reaction. The displacement of the superior horn fracture was attributed to the sectioning process (cf. micro-CT appearance).

Inferior to that was a further fracture through the thyroid cartilage on the left posterior part which did not disrupt the perichondrium and contained a limited amount of haematoma with no inflammatory or mesenchymal reaction.

One level below, on the inner surface of the posterior part on the right side of the thyroid cartilage, a small sub-perichondrial haematoma comprising phagocytic inflammatory cells and adjacent necrotic perichondrium was observed. On the outer sub-periosteal bone opposite this haematoma, there was an incomplete fracture through the endochondral ossification showing osteocyte necrosis and medullary haemorrhage and minimal early periosteal reaction. Soft tissue haemorrhage was observed, particularly in the left side associated with fat necrosis and minimal tissue reaction such as the presence of phagocytes and an early mesenchymal reaction.

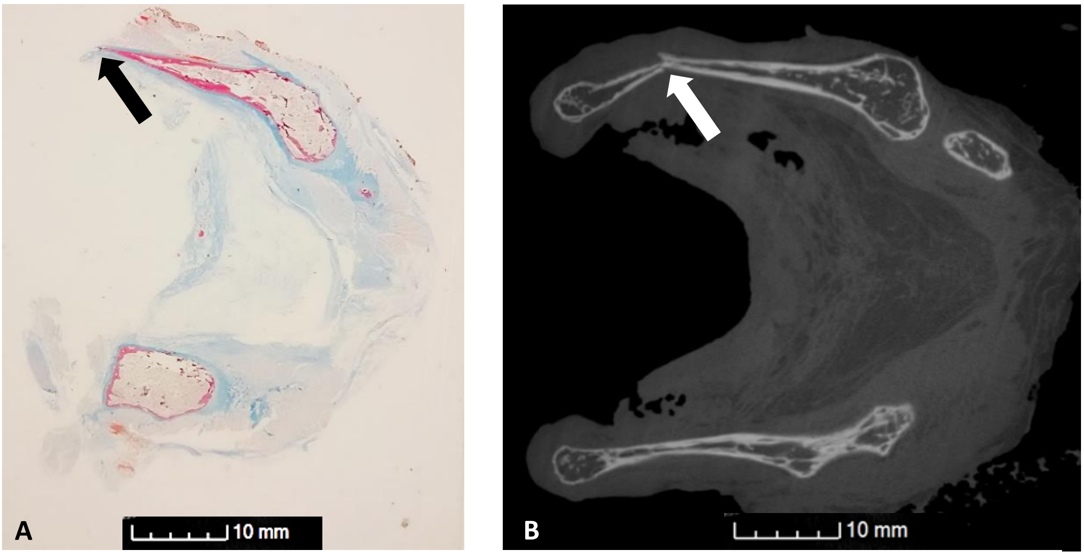


***Figure 17**: Comparison between A: histology slide (MSB stain) and B: micro-CT section (right) through the fracture on the right greater horn (arrow) of OP Ballerine.*

5.5.2 Case two: OP Isengard

The results from all imaging modalities used in this case are compared in **Figure 18 A-F**.

Micro-CT: The scan images showed fractures at the bases of both superior thyroid horns with displacement of the horns anteriorly and medially (***F***). The trachea appeared partially severed approximately 30mm from the top. A small circular cartilage defect was seen on the right thyroid lamina but this was interpreted as a natural feature, possibly a vessel opening.

Histology: Radiographs taken prior to the histological examination showed a discontinuity and displacement of the right superior thyroid horn (***A***). Macroscopic inspection detected haemorrhage into the right sternohyoid and omohyoid muscles (***B-D***) and a postmortem autopsy cut on the trachea. Microscopically, there was extensive fresh haematoma without tissue reaction in the sternohyoid and omohyoid muscles.

A fracture through the cartilage was observed on the left superior horn. The tip of the right superior thyroid horn was seen to be separated from the lower part although the fracture line was not observed in the plane of section. The displacement of the fragments and associated haemorrhages were taken as evidence of a fracture (***E***). The lower sections through the trachea revealed extensive bilateral fresh haemorrhage into the respiratory mucosa and congested vessels.

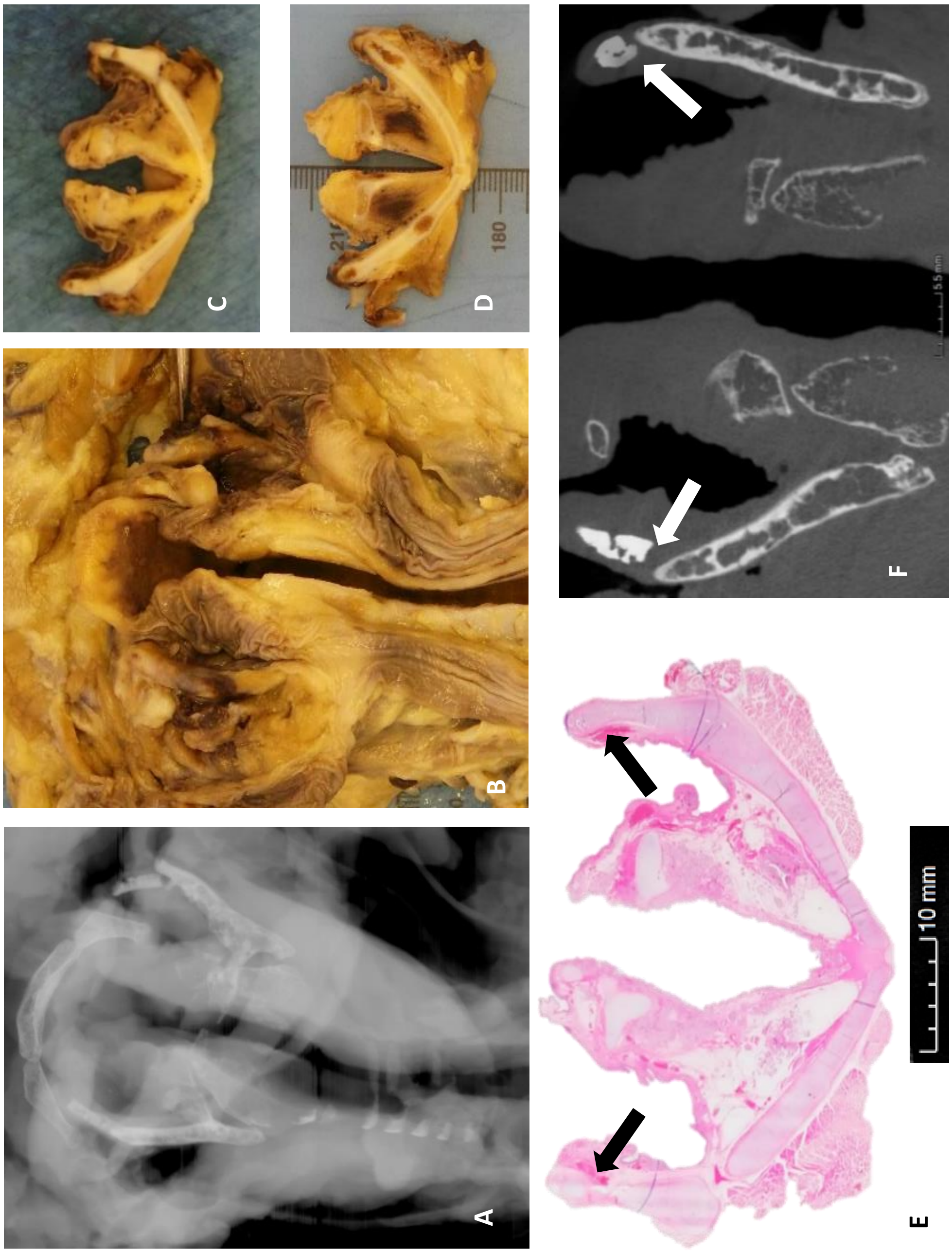


Figure 18: *Comparison between the different levels of examination. A: Radiograph; B: Macroscopic image, seen from posterior. The arrows indicate the areas of haemorrhage; C+D: Transverse sections through the thyroid cartilage, the arrows indicate areas of haemorrhage; E: Histology slide, H&E stain; scale bar=10mm. Areas of haemorrhage are indicated by the arrow heads; F: Micro-CT section, seen from posterior. The arrows indicate the displaced fractured superior thyroid horns.*

6. Discussion

On a more general level, the first validation study helped to become familiar with the normal anatomical variants of the larynx which can range widely in both size, shape, and ossification pattern. It further helped understanding the limitations of the method which are the visualisation of the non-mineralised cartilage and soft tissues due to low image contrast. This means that especially haemorrhages and subtle cartilage fissures are less likely to be successfully imaged which is a major limitation as these are the types of injuries commonly encountered in strangulation cases (Sharma et al. 2008). The study further supplied detailed images of the ossification process. It is useful to know the appearance of this highly variable process as a general background. The reason for this process is still not fully understood but one common theory stipulates that it is caused by the strain acting on the cartilages at muscle attachment sites (Turk and Hogg 1993). Based on the scan images this would suggest that the most stress acts upon the inferior edge of the thyroid cartilage (including the inferior horns), closely followed by the superior thyroid horns. On the cricoid, this theory would imply that the main load rests on the superior aspect - the crico-thyroid joints and on the posterior lamina to either side of the midline. These areas correspond to major muscle attachment sites (see Logan et al. 2017). It appears that attachment sites for ligaments and tendons are affected to a lesser extent and ossify later, which is particularly obvious on the posterior cricoid lamina which anchors the oesophageal tendon and regularly displays low levels of ossification. Those sites which anchor muscles connecting one laryngeal cartilage to another tend to display the densest ossification, for example for the cricothyroid or the cricoarytenoid. This might be a valuable insight for strangulations as well as these areas are potentially more likely to display fractures since Naimo et al. (2013) and Saternus et al. (2013) argue that increasing ossification leads to more fractures. These authors compare larynges of different overall stages but this principle would consequently mean that more densely ossified parts of a single larynx are also more likely to fracture. However, the majority of fractures were observed at the superior thyroid horns and not the inferior horns or posterior margins which generally showed more ossification. On the cricoid, the fractures can be seen on the sides which does not directly correspond to the area of highest ossification. These observations lend strong support to Saternus et al.'s (2013) theory that differences in ossification density create weak links that are then more prone to fracturing. A fracture in these areas would therefore not be unexpected and potentially require less force than other areas. The base of the superior thyroid horns was frequently seen as less densely ossified in the control group and fractured in the strangulation group, supporting this theory.

The good correlation of micro-CT with more established methods shown in **Table 6** supports its use in forensic examinations. The results clearly demonstrate that attacks causing injuries that can be seen at postmortem also result in injuries that can be seen on micro-CT and confirmed histologically. Micro-CT did not only confirm autopsy results, it has clearly been shown that the method can reveal previously unidentified damage. Several authors recommend using CT to examine laryngeal trauma (Becker et al. 2013, Kempter et al. 2009) but findings from this thesis suggest that the resolution might not be sufficient. In two cases (OPs Ballerine and Ampersand), hospital radiology reports were included in the case file and in both cases micro-CT revealed fractures which had not been visible on the standard CT. Over the course of the PhD project an increasing number of samples were submitted for histological examination. This is partly due to the recommendations usually issued in the micro-CT reports to the police, stating that any damage should be validated by other means. This was an essential disclaimer since micro-CT had not been fully validated previously. The validation studies conducted as part of this thesis are therefore a crucial element in the process of method validation. As outlined in the literature review in Chapter 2 the FSR has published guidelines according to which all methods used in forensics need to be fully validated (FSR 2014). The FSR code of practice states that "*The validation shall be carried out using simulated casework material in the first instance and subsequently, where possible, permitted and appropriate, with actual casework material to confirm its robustness*". This study therefore is a partial fulfilment of this first instance of validation. A next step would be to examine experimentally fractured samples but this was outside the scope of this project. Knowing the appearance of the normal larynx has helped identifying some features which otherwise might have been identified as damage. Comparing the micro-CT results to those in the histology report also demonstrates overall good correlation, in particular for fractures. The question arises whether the injuries seen on micro-CT but not under the microscope were false positives or missed in the latter. The results from the second validation study confirm that fractures can be reliably identified on micro-CT (Baier et al. 2019), suggesting that the latter might be the case. The problem with the histological examination is that the analyst is limited to a set plane along which the sample is cut. A further limitation is the restriction to selected 2D sections. These two limitations might lead to some small features being missed. Both methods should therefore be used complimentary to each other. Currently micro-CT is not able to provide an age for any laryngeal fractures due to the resolution required to study the cell level. However, studies by Walton et al. (2015) and Particelli et al. (2012) have shown that by using smaller samples, biological tissue can be studied at this level using micro-CT. This might have future potential for strangulations as it would be faster than histology and provides a 3D view of the area. However, this still warrants further research as the process would involve some destruction to reduce the sample size. On a more practical level micro-CT was easily integrated in the workflow in strangulation investigations and practitioners involved in the project agreed that the duration of the examination did not cause any delays to other lines of enquiry. In fact, the report and the images within could actually reduce the time the histopathologist would spend on planning their procedure, thus helping to fulfil governmental visions for timely delivery of criminal justice and the First-Time-Right approach (Grayling 2014).

The overall correspondence with other data sets (only two out of twenty cartilage and bone fractures discovered during autopsy or histology examination were missed on micro-CT) might cause critical voices to question whether using an expensive method such as micro-CT actually adds any value to the investigation. Even if the increased benefits are minor, they still improve the overall result. It has become clear that the diagnosis of strangulations is surrounded by uncertainty. Using additional technology contributes to increasing certainty and provides the pathologist with more confidence in their conclusions as several of the interviews confirm. The majority of scans in strangulation cases were requested by the pathologists. In many cases the cause of death was given as unascertained or pending as pathologists awaited the results of further testing (micro-CT, histology, toxicology, brain pathology) before forming their final opinion. This suggests that for this particular type of homicide micro-CT is an active component of the investigation, usually in the early stage of the initial inquiry, and not merely a visualisation aid. This is illustrated by OP Bryer where the additional damage observed on the micro-CT scan assisted the pathologist to exclude positional asphyxia as possible diagnosis, or by OP Bluemist where it assisted in ruling out criminal involvement. Reducing uncertainty is also an important aspect of delivering the pathology findings at court as any measure to eliminate the jury's doubt about a matter can be considered a valid effort. The increased visualisation of these structures is a further step to reduce that uncertainty as it makes the issue easier to understand. This demonstrates that whilst initially employed during stage one of the Criminal Justice Process, micro-CT has further reaching implications in the investigation of strangulation deaths through to the fifth gate, the verdict. In turn, this means if micro-CT had not been employed the subsequent process might be deprived of potentially crucial information. In one case (OP Bluemist) the vital piece of the puzzle was contributed by micro-CT - it remains speculation what the outcome would have been in the other ones had it not been used. Adding support to an argument could alter the ultimate decision between guilty and not guilty in the eyes of the jury. If they voted not guilty because of inconclusive evidence and thereby unknowingly freeing an actually guilty person, an extra set of evidence might have prevented this miscarriage of justice. If the jury voted guilty despite inconclusive evidence additional information from a micro-CT scan could prevent the wrongful conviction of an innocent person.

The complexity of strangulation injuries means that the absence of identifiable fractures on the micro-CT scan does not constitute evidence of absence of strangulation. The focus on strangulation injuries from the onset of this project was hoped to lead to new insight about what injuries are caused by what means of strangulation. This cannot be fully answered at the moment as the variety of possible mechanisms and injuries require a larger data set. The types of injuries observed over the course of this project have previously been reported by other researchers using different methods (Maxeiner and Bockholdt 2003, Kempter et al. 2009). Despite these studies, the pathology practice was still to "wiggle" the hyoid to test for hypermobility. This has been changed by the detailed images provided, demonstrating a major impact on work practices.

7. Summary

This chapter has provided an in-depth view of strangulation deaths and outlined the problematic diagnosis of strangulations due to the different mechanisms and methods of the attack. It has further presented the methods employed by pathologists to diagnose this type of homicide which are often insufficient to diagnose with certainty. The proposed method to improve the certainty is micro-CT which has shown to be a reliable method to use in conjunction with histology. The first validation study of this chapter provided a baseline of the normal appearance of the larynx. The most important features observed in this study were a fracture-like anomaly on the thyroid cartilage and a partially fused hyoid. Both could easily be mistaken for real trauma. With this validation, real life cases were examined and the micro-CT scans compared to the pathology and histology reports and the case background. There was an overall good correspondence between the different analytical methods and some injury patterns were identified based on the case data. Micro-CT proved a valuable addition to the CJP from stage two until the end with the main benefit in the decision at gate 2 whether a crime has occurred. Some limitation with imaging soft tissue and ageing fractures were observed and it is strongly recommended that all methods should be used in a complimentary fashion as both histology and micro-CT were able to identify injuries missed by the other – micro-CT does not replace histology. The realisation of the potential of micro-CT has affected pathologists' working practices to include micro-CT as a routine examination for suspected strangulations.

Chapter 6: Toolmark analysis

Toolmark analysis forms the second key research area or study case and covers a large proportion of homicides. While the previous chapter's subject was predominantly concerned with the diagnosis of a cause of death, the main focus in the present chapter is on the circumstances of the attack. Beginning with a short review of the subject area to introduce the problems in toolmark analysis and the methods employed to address these, the chapter will then introduce the samples and methods used in this project, before presenting the results. The results section consists of two parts: the first presents the features observed on the micro-CT scans, the second part details how these observations were used in the three most common applications of SFT analysis in forensic practice. The ensuing discussion will then elaborate on the impact of micro-CT on these applications and on the associated murder inquiries and on forensic toolmark analysis in general.

1. Literature review

1.1 Overview

Toolmark analysis is a wide term describing the interpretation of the physical damage on any surface created by any type of instrument. This includes Sharp Force Trauma (caused by a bladed weapon) in bone or other biological tissue (Banasr et al. 2003), striation marks on spent cartridges (Gambino et al. 2011), and damage resulting from forced entry during burglaries (Petraco and Petraco 2016). Sharp force damage is not exclusive to biological samples. It is also commonly encountered on inanimate objects either on items of clothing worn by the victim or owing to missed blows during an attack. There is some crossover between toolmark analysis and BFT since instruments used in BFT can leave impressions bearing characteristics of their shape, while sharp implements can, if used with great force, cause additional fracture damage such as that observed for machetes or hatchets (Nogueira et al. 2017). Impression marks are a further type of marks which are sometimes considered toolmarks and are created by vehicle tyres or shoes/feet in soft substrate material (Buck et al. 2007). These are more commonly found on non-portable features at the scene of crime and therefore benefit more from mobile scanning technology such as laser scanning since there is less need for internal detail as opposed to the surface of the imprint.

The majority of cases for toolmark analysis come from homicidal stabbings. Knife-related deaths are the most common form of homicide in the United Kingdom at 39% (in the year ending March 2015) with a steep increase reported over the last decade to which the West Midlands are no exception (Office for National Statistics 2018). The perceived "epidemic" of knife crime has become a major topic in British politics as it raised concerns about youth violence and gang crime (Squires 2009). The high prevalence of stabbings does not only pose a threat to public safety but also puts a great financial strain on the public purse through hospital treatment of victims and the ensuing police investigation (Dubourg et al. 2005). Pallett et al. (2014) observed that the fatality rate of all knife-related injuries encountered in an emergency department lies at just over 0.5%, all of which were due to chest injuries at their study site. A broader nationwide five-year study by Christensen et al. (2008) found a mortality rate of stabbing victims at 7.2%. Using hospital data as opposed to police-reported crime statistics might represent a closer to the true prevalence of knife-related injury due to reluctance of reporting an assault (Pallett et al. 2014). The per person cost of hospital treatment of alleged stabbings is calculated as £7,200 which is approximately one third less than that for gunshot injuries (£10,300) (Christensen et al. 2014). It is the high volume of cases that amounts to significant costs. Finding ways to economise any aspect of the investigation could therefore ease the strain on the criminal justice budget tremendously.

The high numbers of knife crime are facilitated by the widespread availability of knives. This availability leads to the problem that it is often difficult to link a specific knife to the crime and therefore the offender which is one of the main objectives of the discipline of toolmark analysis. Sharp force injuries are most frequently observed on the victim's body in both soft and skeletal tissue but also on inanimate objects. These could be the victim's clothing and other items damaged during an assault, but also objects involved in other types of crime, for example arson, damage of property, or burglary. While these were less frequently examined as part of this project, they hold equally valuable information about the assault, illustrated by one example.

1.2 Methods of analysis

Depending on the medium in which the toolmark is created, the available methods for study differ since the physical properties of the mark differ. The methods range from macroscopic inspection to high resolution imaging depending on the nature of the sample and the objectives of the examination. There is a stark difference in the methods employed in routine forensic postmortems and in research studies. The latter often have access to more advanced technology which would not be practical or financially tenable, or simply unnecessary in the majority of cases in forensic practice (Lockyer 2018).

1.2.1 Pathology

The methods employed by pathologists to determine what instrument has caused a particular injury depend on what tissue has been damaged. In general, there are three different types of tissue with three different rigidity levels: bone, cartilage, and other soft tissue such as muscles and fat. Bone, being the hardest, retains any marks well and depicts the weapon geometry accurately provided it has been penetrated enough to display an outline. Cartilage is more elastic than bone which introduces some deformation but still retains the overall shape, especially if the cartilage has begun to calcify due to advancing age. Other soft tissues are unlikely to retain the weapon's geometry as they deform once it has been removed. This limits the analytical possibilities for soft tissue lesions to the depth and angle of penetration and the width of the entry site, which does not accurately represent the original tool dimensions. These measurements are usually obtained using a ruler which, in the case of wound depth, is inserted into the wound track along its long axis (Saukko and Knight 2015). The appearance of the lesion on the skin surface can in some cases provide evidence of the type of blade (single or double-edged and serrated or straight) but often postmortem alterations such as decomposition or heat destroy these marks (Saukko and Knight 2015). This method lacks accuracy but is sufficient for the purpose of describing and documenting the injury. In forensic pathology practice, cartilaginous injuries are rarely examined separately and therefore treated in the same manner (Crowder et al. 2013). Toolmarks in bone offer many more possibilities for analysis including light microscopy, casting, Computed Tomography, and on occasion Scanning Electron Microscopy (SEM) (Capuani et al. 2013). However, in standard pathology these more advanced technologies will be rarely accessible and are predominantly encountered in research studies. The main objectives for many cases is the identification and subsequent matching of a weapon to the injury and an estimate of the force used in the attack. The latter aspect is difficult to quantify due to the many variables involved and pathologists tend to express it in vague terms of weak/mild, moderate, or strong/severe. However, there is little scientific evidence to support these categories (Parmar et al. 2012).

There is a multitude of research studies examining the marks created by different implements using a range of different methods (Sansoni et al. 2009, Gaudio et al. 2014, Pelletti et al. 2017). As mentioned above, these methods are not usually employed in standard pathology but this research forms the underlying scientific foundation for pathology practice and finds application in complex cases where a toolmark expert might be required in addition to the pathologist. The problem with many of these studies is that they rarely replicate the dynamic nature of a stabbing which was found to affect the physical characteristics of the injury. This was found by Norman et al. (2018a) in their experimental study of saw marks which has major implications for the study of dismemberments.

1.2.1.1 Dismemberment

Dismemberment is a specific form of Sharp Force Trauma encountered only occasionally with two to three cases annually in the UK (Rutty and Hainsworth 2014). This rarity results in investigators having little experience with this type of case. When a case of dismemberment occurs, it poses a difficult challenge to the police. The individual body parts are often deposited separately in order to decrease the likelihood of retrieval and to obscure the victim's identity (Seidel and Fulginiti 2014). Nevertheless, cases of dismemberment offer a great wealth of forensic evidence at the dismemberment and deposition sites due to the inherently visceral dismemberment process (Rutty and Hainsworth 2014). The body itself also holds forensic evidence such as characteristic toolmarks which are traditionally analysed by a forensic anthropologist but this examination is sometimes of a destructive nature. In line with general trends in postmortem examination, non-destructive alternatives are increasingly favoured over invasive approaches (Jeffery et al. 2011, Karalis and Denton 2016). Light microscopy and macro-photography are the methods normally employed to study these marks but they do not provide their full three-dimensionality. Rutty et al. (2013) highlight the benefits of micro-CT over traditional optical micrographs for saw marks in bone. They found that the option to adjust lighting, contrast, and depth of view, and to reduce the glare of specular surfaces makes micro-CT highly suitable to study dismemberments. It further allows the visualisation of minute features and micro-fractures which might remain undetected in medical CT (Fais et al. 2016).

1.2.2 Inanimate objects

Studying toolmarks on inanimate objects depends on the type of material examined. Stab marks on textiles, for example, are usually studied under a light microscope to comment on the overall appearance and dimensions and the nature of the edges of the mark (Cowper et al. 2015). In order to identify possible assault weapons the examiner produces experimental stab marks in the same medium against which the original marks are compared visually. It becomes evident that this method relies on the examiner's experience and produces results which are difficult to portray objectively which makes them liable to successful challenges in court (Lock and Morris 2013). On harder surfaces, one aspect of toolmark analysis is the examination of striation marks. These are studied either under a light microscope or a Scanning Electron Microscope (SEM) to identify both the type of blade and its individual characteristics such as damaged areas (Bachrach et al. 2010). Saville et al. (2007) used Environmental SEM and were able to identify different saws based on specific striations left on the kerf walls.

1.2.3 Micro-CT

An increasing number of studies have employed cone beam CT (Gaudio et al. 2014) and micro-CT (Thali et al. 2003) for forensic wound analysis. These studies have demonstrated the benefit of the increased resolution and 3D reconstruction enabled by technology. Further benefits have been demonstrated in studies by Norman et al. (2018a, 2018b) and Pelletti et al. (2017) who use micro-CT images as the basis for quantitative and statistical analysis of toolmark measurements. Using statistics to improve the identification of the culprit weapon offers the potential to reduce the human impact on the interpretation and therefore reduce the human error, making the evidence more objective. However, more studies are needed examining a wider range of weapons.

2. Material and methods

Samples containing sharp force injuries or other types of toolmarks were extracted during autopsy if the pathologist determined that micro-CT scanning could add useful information. The tissue samples were placed (flat where permitted by sample shape) onto a block of foam and packaged in sealed plastic specimen containers. The majority were scanned in a Nikon 225/320 LC scanner with the exception of OP Haweswater as the extracted sections of fabric containing the stab marks were small enough to fit in a Zeiss XRadia 520Versa scanner. Fabric samples in one case were cut from the clothing items under the supervision of one of the FSIs and placed flat onto a foam bed with a second foam frame holding as cover, sparing the actual mark to avoid unnatural flattening of the warped textiles. Both foam sections were then taped together. Care was taken not to stretch the fabric which might have distorted the stab mark. The samples were sealed in police evidence bags in which they remained during the scans. They were mounted on the stage using a clamp holding the foam frame so the stab mark would be positioned vertically. Scan parameters for all samples are provided in **Table 7**. No voxel size correction was performed on the any of the scans which means the uncertainty of any measurements is up to three times the voxel size of the scan. This is ensured through regular machine calibration, as explained in section 3.4 of Chapter 4.

Table 7: Scan parameters used for specimens in this chapter.

Case	Voltage (kV)	Current (µA)	Exposure (ms)	Gain (dB)	Filtration	No. of projections	Resolution (µm)
Casava (hospital CT)	unknown					200	125.0
Cater	135	192	708	24	None	3138	52.4
Haweswater							
T-Shirt	50	60	2000	n/a	0.15mm glass	3201	15.0
Jumper	60	83	2000	n/a	0.15mm glass	3201	22.3
Coat	60	66.7	2000	n/a	0.15mm glass	3201	15.3
Malton	80	73	708	24	None	3141	23.2
Northedge	125	180	500	24	None	3141	58.5
Seminar	65	736	354	18	None	3141	48.9
Piano	110	273	708	24	None	3110	90.6
Sanderling							
Right humerus	200	130	1415	18	None	3142	49.8
Left humerus	200	180	2000	12	None	3142	66.6
Left femur	200	130	1415	18	None	3142	49.8
Skipper	80	313	708	24	None	3141	37.1
Cape	130	215	500	24	None	3141	38.2
Bracelet	140	193	354	24	None	3141	64.9
Needingworth							
Left femur	135	200	708	18	None	3141	72.9
Right humerus	135	200	708	18	None	3141	49.9
Left forearm	125	200	708	18	None	3141	41.5
Neaphouse							
Pelvis	135	187	354	24	None	3141	105.7
Femora	135	208	354	24	None	3141	108.5
Vertebrae	133	207	354	24	None	3141	70.3

Humeri	135	222	354	24	None	3141	87.7
Workshop	135	126	500	24	None	3141	43.1
Compete	130	168	500	24	None	3141	69.9
Literature	120	183	500	24	None	3141	39.4
Northwater	120	160	708	30	None	3141	44.5
Morath	130	154	354	24	None	3141	56.5
Mansriggs	70	542	500	24	0.35mm copper	3141	38.0

All scans were visualised in VG Studio MAX 2.2 (Volume Graphics, Heidelberg, Germany). Width measurements on the toolmarks were taken following the methodology outlined in Norman et al. (2018a; 2018b) which involves fitting a reference plane to the toolmark floor and obtaining cross-sectional images perpendicular to this plane. Some aspects of the methodology were modified to suit the present study as only cross-sectional views were used for analysis. Norman et al. (2018a; 2018b) only consider incision marks in their study, complete stab marks were therefore clipped to fit the reference plane. Width measurements were taken on cross-sections perpendicular to this plane using the calliper tool. For incisions, a further line was fitted to the bone surface on the 2D section and the measurement was taken where this line intersects with the toolmark to avoid falsifying results by taking measurements on the bone wastage which sometimes occurs on the edge of the mark. This process is visualised in ***Figure 19***. For stab marks, the width measurement was taken approximately halfway through the mark. Length measurements were taken on the surface model by selecting the end points (fit point in VG Studio) of the mark and automatically calculating the distance between them. This would produce a direct measurement not taking into consideration any curvature of the sample. Depth measurements were not included as the samples had been removed from their original context. In addition, qualitative features regarding the shape and orientation of the injury were noted with reference to existing literature. No further interpretations were included in the written reports to police as this would be considered outside the researcher's area of expertise. For the purpose of this thesis further analysis was performed, linking the observations to existing literature.

The µCT scan data were compared to the written pathology reports. The initial preliminary reports sometimes indicated the objectives of the micro-CT examinations. The final report described the superficial appearance of the injuries and the internal wound track and interpreted the findings with regards to cause of death, weapon identification and match, and the degree of force used where possible. Further relevant forensic examination reports regarding the injuries or the weapon were compared in the same manner. All this information was entered into a content matrix in form of an Excel spreadsheet. This showed correlations and connections between different methods. Information from the impact interviews (see Chapter 9) was used to determine the influence of the micro-CT images on any subsequent forensic analyses, the police investigation, and also the ensuing court proceedings. It was further used to identify the stages and gates of the Criminal Justice Process where the 3D technologies were employed in toolmark analysis cases.

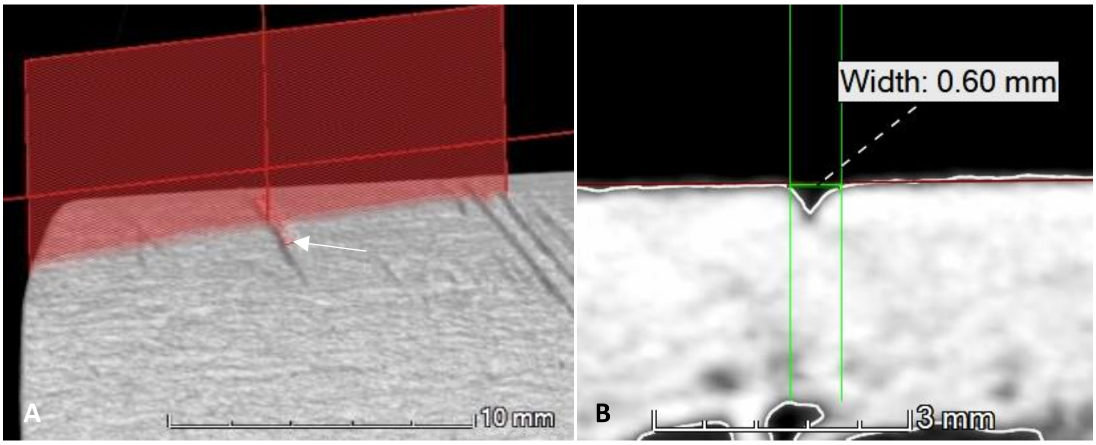


Figure 19: Visualisation of the measurement process for incision marks. A: First a plane was fitted to the floor of the mark (arrow), the sample was aligned to this plane providing cross-sections perpendicular to it. B: Cross-sectional image along the red plane in A. A line was fitted to the bone surface and a measurement taken where the mark and this line intersect.

2.1 Objectives of the examination

In toolmark analysis cases three types of questions (or a sub-set thereof) were put to the examiner:

1. What are the characteristics of the implement causing the injuries/damage?

2. Could a certain suspect implement have caused the mark, i.e. does a specific weapon match the mark?

3. What level of force was used in the creation of the injury?

In order to answer these questions the following characteristics were provided from the micro-CT scans: location and orientation, overall shape, associated damage, and dimensions. The former three categories were given as qualitative descriptions and the latter was measured directly on the scans. Possible weapon matches relied on police information about a certain suspect weapon which was not normally available at the time of the scan. The location first refers to the sample location within the body and then to the location on the sample which can be correlated with the location on the skin surface. It is also important to note what tissue was penetrated as different tissues (e.g. fat, muscle, cartilage, bone) present different levels of resistance against the blade which in turn offers an indication of the force used (see below). The orientation was given as the clock face orientation of the mark in line with the pathology reporting style and might hold information about the dynamics of the attack. Some practical limitations must be mentioned here. In order to keep the specimen size small the sample submitted was often extracted without the overlying skin, preventing direct comparisons of surface and internal features.

Only cases where the injury involved rigid materials such as bone or inanimate materials were considered for dimensional measurements. The dimensions of the injury can be used to gain an indication of the weapon size. Norman et al. (2018a, 2018b) have shown that there is a statistical correlation between the kerf width in bone and the thickness of the weapon’s blade. However, this only applies to bone and possibly other hard materials but not to other biological tissues which retract once the weapon is removed. The other dimension frequently observed is the injury length which, for stab injuries, corresponds to the blade width. It needs to be considered how far the knife penetrated into the tissue as the blade width will be smaller near the tip of the blade. The presence of fractures caused by the sharp force impact can be used as an indication of the degree of force applied. However, the vague terminology used by pathologists only gives an estimation of light/mild, moderate, or severe and depends on the examiner’s experience. All interpretations of the amount of force used reflect the pathologists’ opinion of the case.

3. Results/case data

Nineteen toolmark cases were examined between September 2015 and June 2018. The offender in all but one case was male, the victim was male in all but four cases, although one of the cases with a female victim (OP Piano) does not fit the same pattern as the others since the injuries were caused by a vehicle-pedestrian collision and not by a direct, inter-person attack. In seven cases (all M/M) the victim and attacker were strangers, in the three stabbing cases with female victims the offender was either a current or a former partner, in the remaining five cases victim and attacker knew each other in some capacity. In two cases (Neaphouse, Needingworth) no offender was identified at the time of writing. In one case (OP Cape) the accused, who had admitted stabbing the victim accidentally, was cleared of the murder/manslaughter charges during trial. These findings are summarised in **Figure 19**. Of these 19 cases, six were excluded from more detailed wound analysis as the injuries were located in soft tissue only. **Table 8** shows a comparison of the remaining 13 cases examined, including micro-CT cross-sections, injury outline, postmortem and micro-CT measurements, and assault weapon if known.

3.1 Location and orientation of the injuries

The exact injury orientation was difficult to determine in all cases as the samples were lacking the context of the remaining body against which to register the scan image. In one case (OP Piano), this problem was solved by registering the micro-CT with the hospital postmortem CT scans to obtain the overall orientation of the sample on the victim which proved essential to the further analysis of the case (see discussion). By matching the location of the sample with the full body scan, the exact location of the injury in relation to the victim's standing height was provided. This was then virtually matched with a surface scan model of the van which had hit the pedestrian which demonstrated a perfect match between a sharp fold on the vehicle's bonnet and the damage on the bone. This was taken as evidence that the victim was "impaled" and carried on the vehicle before coming to a halt on the road. However, the hospital CT scan was not normally provided and therefore not regularly compared to the micro-CT results. This holds potential for a future research study comparing hospital CT to micro-CT of the same injury to evaluate the significance of the increased detail.

The overall location of the injuries in six cases was to the front of the chest, frequently on the sternum or the ribs and all of the six cases excluded from injury analysis were in the costal cartilage. None of the examined injuries was located on the posterior side of the body. One case (Casava) had a knife injury on the left temporal bone of the skull, one case (Skipper) displayed an injury on the anterior neck, the part examined for the road traffic collision was the left femur, and three cases (Sanderling, Neaphouse, Needingworth) displayed multiple injury locations on the limbs and neck due to body dismemberment. The samples in one case comprised the victim's clothes (coat, jumper, and T-shirt) which contained multiple stab wounds, two of which were examined with micro-CT. There is a sampling bias since soft tissue injuries, for example on the abdomen, were not submitted due to the limitations of the micro-CT scanner and the anticipated deformation of the wound tract within soft tissue. In two out of twelve cases the injury examined with micro-CT was the only injury - all remaining cases were associated with multiple sharp force injuries. Two cases were complicated by the performance of a thoracotomy by the emergency personnel which obscured the superficial signs at postmortem and affected the measurements taken on the micro-CT since the wound was separated and only approximately re-associated. These cases are marked with an asterisk in **Table 8**.

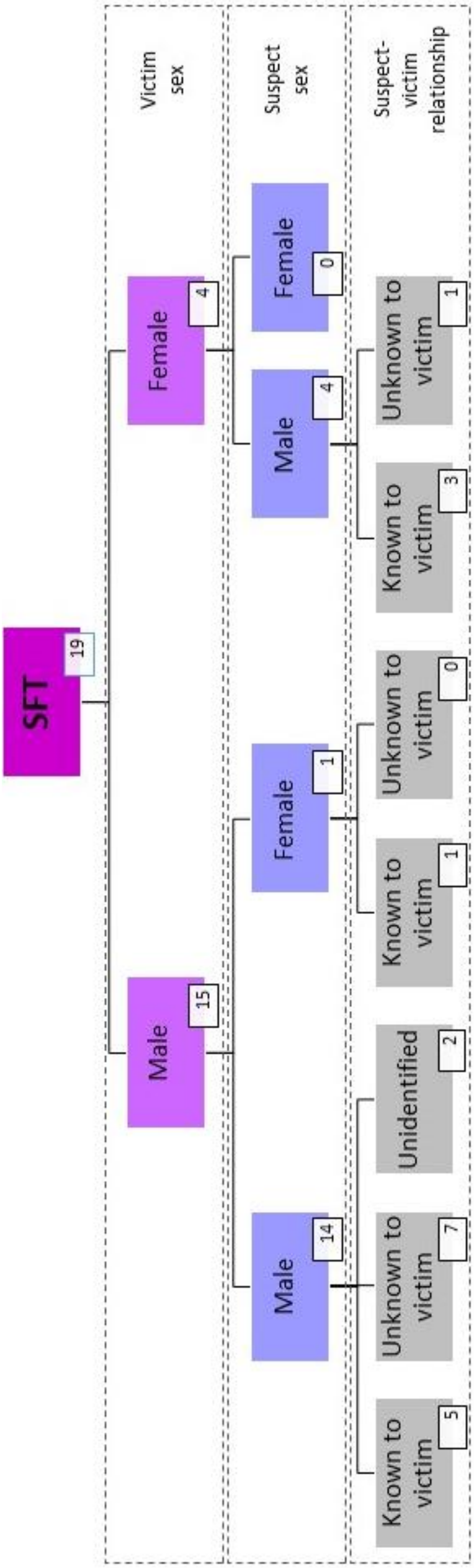
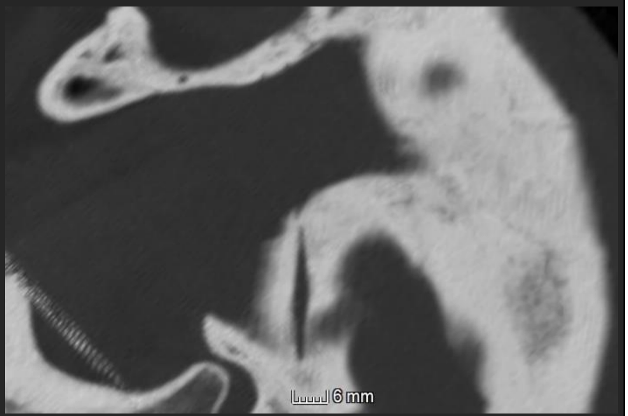
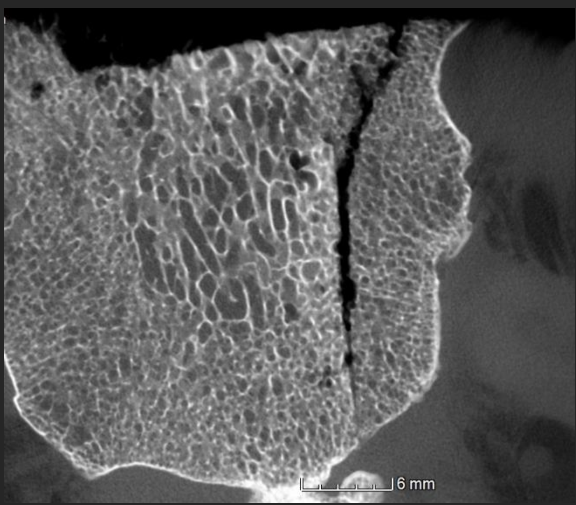
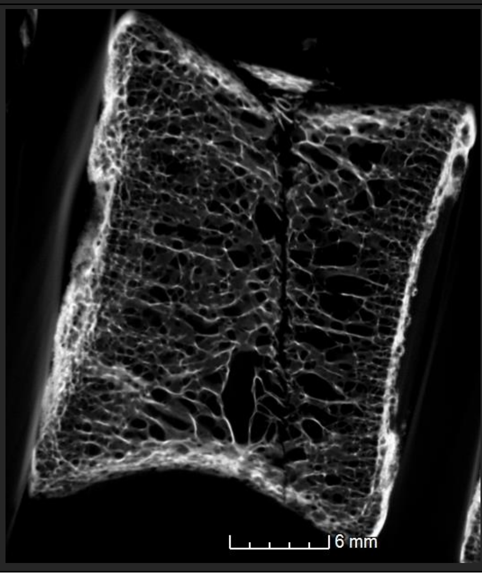
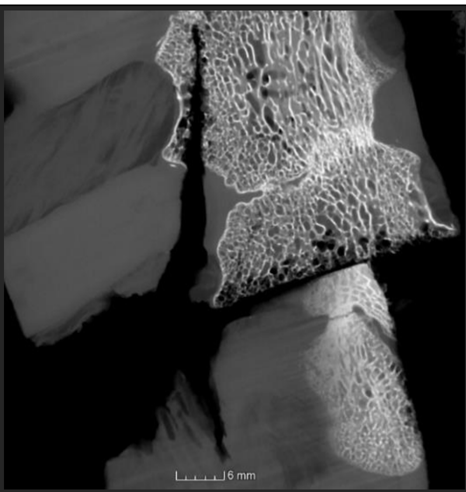
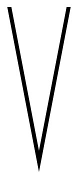
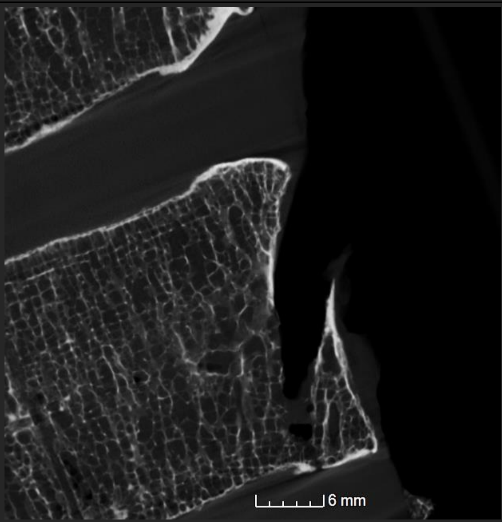
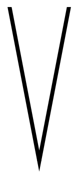
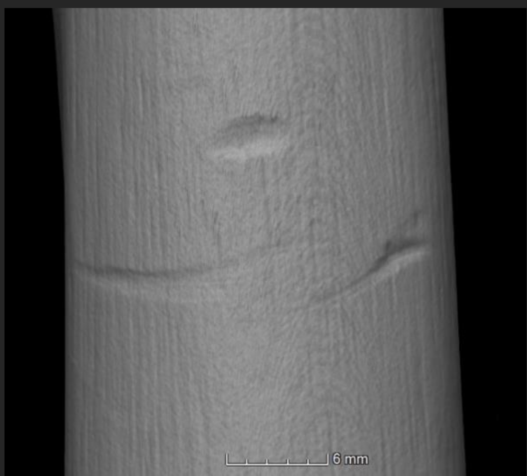
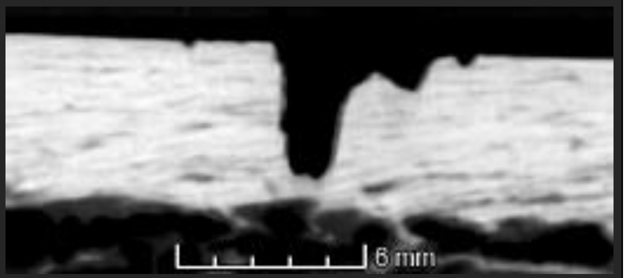
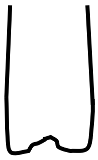
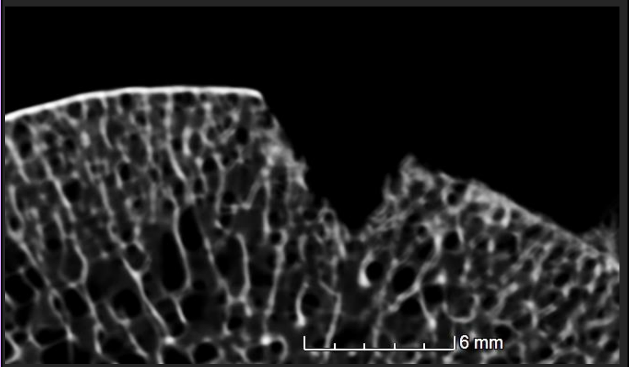
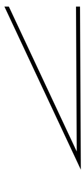
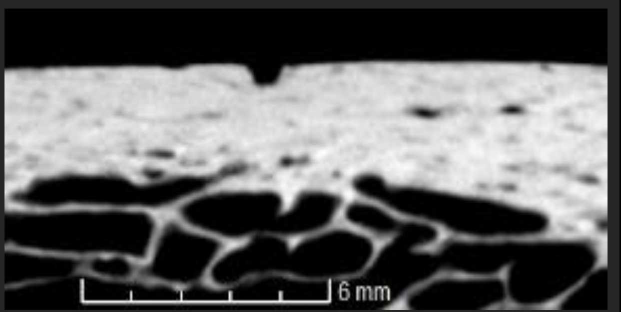
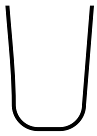
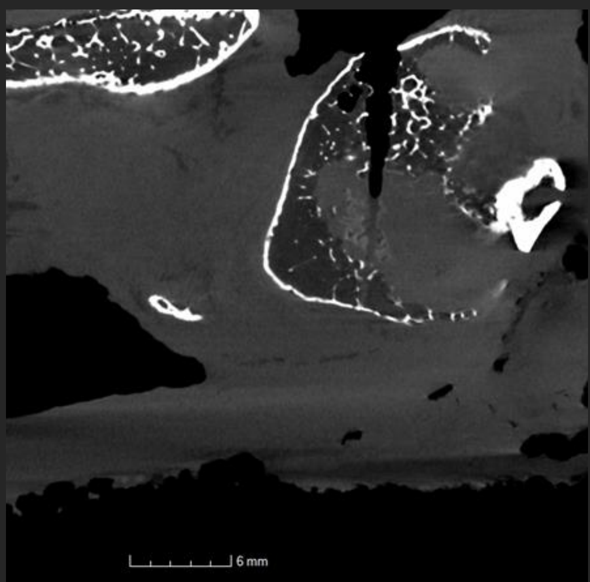
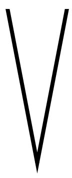


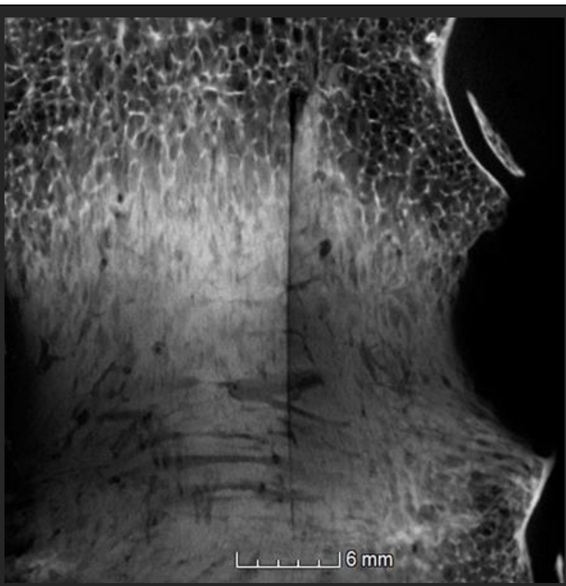
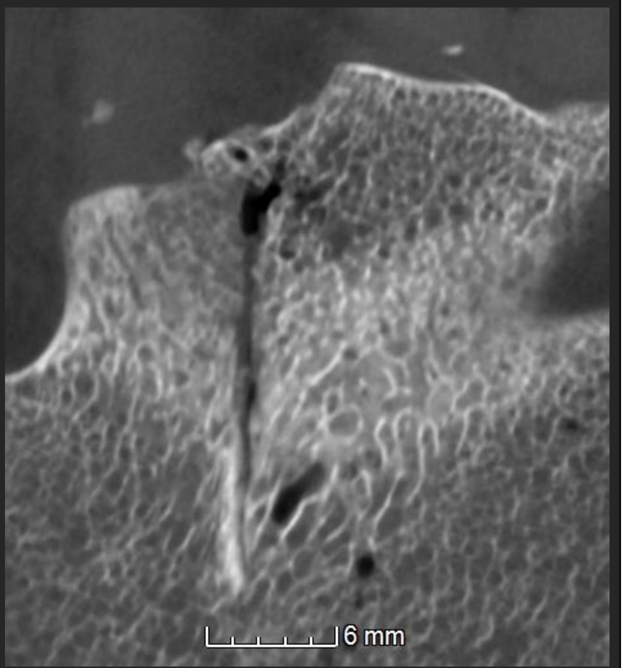
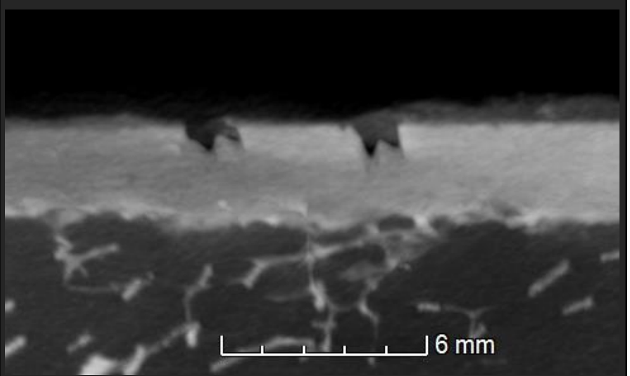
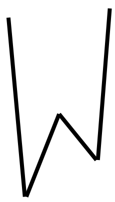
***Figure 20**: Diagram representing the victim and suspect information for all Sharp Force Trauma cases examined in this thesis.*

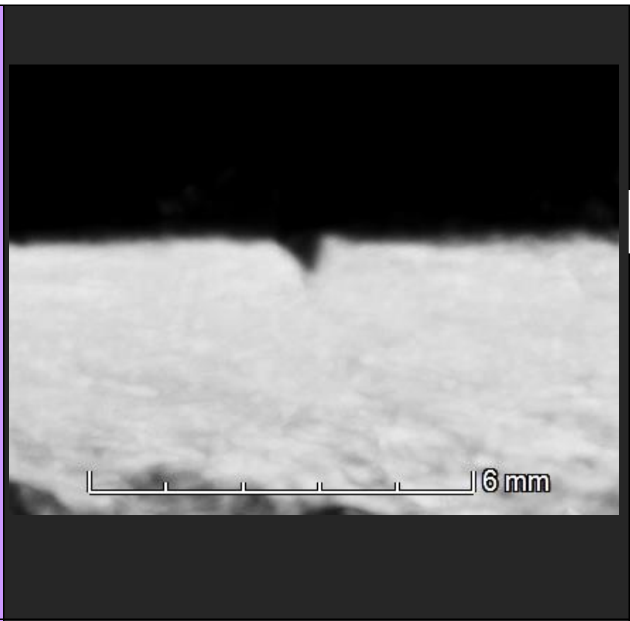
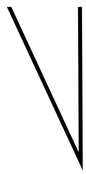
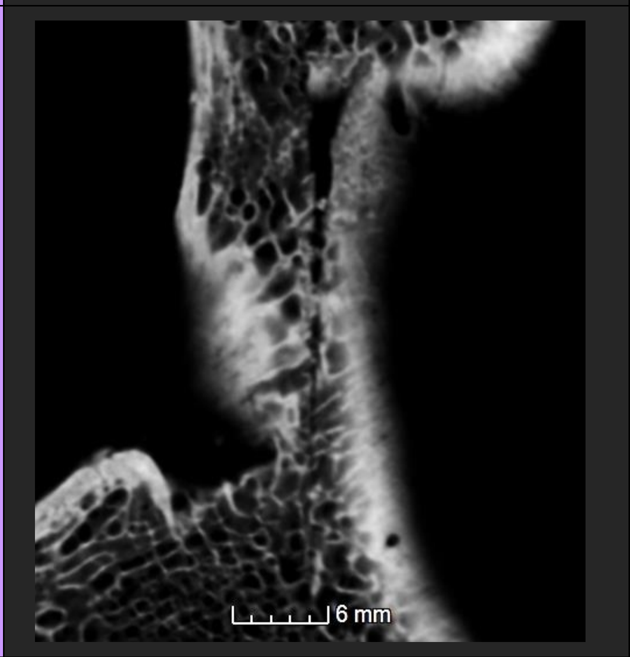
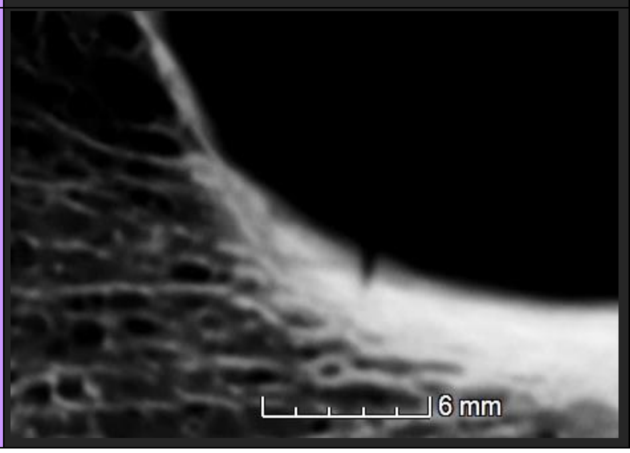
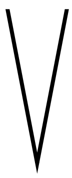
Table 8: Summary of the toolmarks in bone encountered in this study. The second column provides an outline of the injury, open shapes represent incisions and closed shapes stabs. The "Implement used" category in the right hand column is based on information provided in the case files. Cases indicated with an asterisk have had a thoracotomy performed which might have obscured some features of the toolmark.

Case	Cross-section	Outline	Details
Casava			**Location:** skull **Material:** bone **General description:** stab, both ends tapered **PM dimensions:** N/A **CT dimensions:** length: 22mm width: 3mm Error: unknown **Implement used:** 3-4inch blade **CT interpretation:** double-edged blade
Cater*			**Location:** sternum **Material:** bone **General description:** stab, tapered, external bevelling **PM dimensions:** length: 18.0mm max. width: 3.0mm min. depth: 65.0mm **µCT dimensions:** length: 17.0mm width: 2.0mm Error: 157.2µm **Implement used:** Small single-edged kitchen knife **µCT interpretation:** single-edged blade
Malton			**Location:** vertebrae **Material:** bone **General description:** stab, tapered, displaced bone fragment **PM dimensions:** N/A **µCT dimensions:** length: 23.0mm max. width: 1.0mm Error: 69.6µm **Implement used:** Kitchen knife **µCT interpretation:** single-edged blade

Northedge*			**Location:** sternum **Material:** bone **General description:** stab, tapered, fracture **PM dimensions:** length: 40.0mm max. width: 18.0mm **µCT dimensions:** n/a **Implement used:** very large knife or small sword with handle and hilt, minimum 110x45mm **µCT interpretation:** Min. 1 straight edge
Seminar			**Location:** vertebrae **Material:** bone **General description:** incision, severed bone fragment **PM dimensions:** length: 35.0mm max. width: 7.0mm depth: 60.0mm **µCT dimensions:** max. with: 4.0mm Error: 146.7µm **Implement used:** unknown **µCT interpretation:** Straight edged blade
Piano			**Location:** left femur **Material:** bone **General description:** 3 small linear scrapes in cortical bone on anterior surface **PM dimensions:** N/A **µCT dimensions:** N/A **Implement used:** van **µCT interpretation:** N/A

Sanderling			**Location:** femur **Material:** bone **General description:** false start, W shape **PM dimensions:** N/A **µCT dimensions** max. width: 1.8mm Error: 149.4µm **Implement used:** saw **µCT interpretation:** crosscut saw
Sanderling			**Location:** humerus **Material:** bone **General description:** incision, asymmetrical V **PM dimensions:** N/A **µCT dimensions** max. width: 6.0mm Error: 149.4µm **Implement used:** knife **µCT interpretation:** straight-edged blade
Sanderling			**Location:** femur **Material:** bone **General description:** false start, U shape **PM dimensions:** N/A **µCT dimensions** max. width: 0.7mm Error: 149.4µm **Implement used:** saw **µCT interpretation:** saw
Skipper			**Location:** larynx **Material:** bone, cartilage, soft tissue **General description:** incision **PM dimensions:** length (left to right): 125.0mm width: 65.0mm **µCT dimensions:** max. width: 2.0mm (right), 1.0mm (left) Error: 111.3µm **Implement used:** single straight edged kitchen knife blade, dimensions c.120x25mm **µCT interpretation:** Unknown

Cape			**Location:** sternum **Material:** bone **General description:** stab, tapered **PM dimensions:** N/A **µCT dimensions:** length: 24.0mm max. width: 1.0mm Error: 114.6µm **Implement used:** unknown **µCT interpretation:** Single-edged, straight blade
Bracelet			**Location:** sternum **Material:** bone **General description:** stab, tapered, small bone fragment **PM dimensions:** N/A **µCT dimensions:** length: 22.0mm max. width: 2.0mm Error: 194.7µm **Implement used:** unknown **µCT interpretation:** single-edged, straight blade
Needingworth			**Location:** femur **Material:** bone **General description:** false start **PM dimensions:** N/A **µCT dimensions:** max. width: 1.2mm Error: 218.7µm **Implement used:** saw **µCT interpretation:** Crosscut saw

Needingworth			**Location:** femur **Material:** bone **General description:** incision, asymmetrical V **PM dimensions:** N/A **µCT dimensions:** max. width: 0.6mm Error: 218.7µm **Implement used:** unknown **µCT interpretation:** straight edged blade
Neaphouse			**Location:** pelvis **Material:** bone **General description:** stab, tapered **PM dimensions:** N/A **µCT dimensions:** length: 42.0mm max. width: 2.0mm Error: 317.1µm **Implement used:** unknown **µCT interpretation:** single-edged blade, straight blade
Neaphouse			**Location:** humerus **Material:** bone **General description:** incision, symmetrical V **PM dimensions:** N/A **µCT dimensions:** max. width: 0.4-0.9mm Error: 325.5µm **Implement used:** unknown **µCT interpretation:** straight edged blade

3.2 Overall shape

The shape of the marks in bone was analysed in two separate categories: stab marks and incised marks. The one injury resulting from a road traffic collision was treated separately. Stab marks are defined as penetrating the tissue point first, therefore providing the complete weapon cross-section. Incised marks are created with the weapon's cutting edge, providing a profile thereof which is essentially a subsection of the complete stab mark (Bonte 1975). Stab marks were observed in six cases, incised wounds in four, OP Neaphouse displayed both. In OP Northedge the stab wound was bisected by thoracotomy with only the superior half being visible in bone and therefore treated as incision. In all cases of stab wounds, a linear cut was observed. In the majority of cases (n=4), one end was observed to be wider than the other which tapered into a point, creating a wedge-shaped appearance. In one case (OP Casava) the injury seemed to taper towards both ends but only the hospital CT images were available which had a lower resolution. For incised wounds, the kerf cross-section was noted. Two of the three dismemberment cases displayed W-shaped kerfs, sometimes classed as convex (Nogueira et al. 2016). The W in OP Needingworth was asymmetrical with one deeper, narrower trough and one slightly wider, shallower trough. The one in OP Sanderling was somewhat rounded. OP Sanderling also displayed some U-shaped kerfs with a concave kerf floor. All remaining incisions displayed V-shaped kerfs of varying depth and width.

3.3 Dimensions

The longest stab wound in bone measured 42.2mm (OP Neaphouse) but as this is a dismemberment case it is possible that this represents a cutting motion rather than the weapon blade with. A reliable length measurement could be obtained from OP Cape (24.1mm) as the entire blade penetrated the sternum. In OP Cater it was observed that the vertical dimension (corresponding to the blade width) was greater on the external than on the internal surface of the sample, possibly indicating that the weapon had not penetrated further than the curvature of the tip. Alternatively, it was the result of the dynamics of the attack where the blade might have performed an additional cutting motion, thus increasing the length of the mark. Full measurements of injuries in bone are detailed in **Table 8** which also compares measurements taken by the pathologist where available to those taken on the micro-CT scans. The pathologist's wound dimensions were larger for the majority of cases, in particular width measurements. An attempt was made to take measurements from the one case (Haweswater) where the stab marks were produced in clothing. Two stab marks were examined, one in two layers (jumper, T-shirt) and one in three layers of clothing (coat, jumper, T-shirt). The first one measured 20.0mm on both jumper and T-shirt (error: 66.9µm and 45.0µm respectively), the second one 28.0mm in coat and jumper (error: 45.9µm and 66.9µm respectively) and 22.0mm (error: 45.0µm) on the T-shirt. The difficulty with obtaining these measurements was that the fabric was bloodstained which caused some warping as the blood had dried. The different dimensions produced by the same weapon reflects one of the challenges of toolmark analysis in fabric. As work by Kemp et al. (2009) and Cowper et al. (2015) shows, the condition of the fabric (tension, folds and creases, orientation of fibres, assailant sex) can alter the dimensions of a stab mark, thus making measurements unreliable for weapon identification.

3.4 Associated damage

In OP Cater a fine fracture line extended from the superior aspect (the back of the knife) of the injury on the sternum (**Figure 21**). The fact that dense bone had been completely penetrated already indicates strong force, the fracture acts to support this.

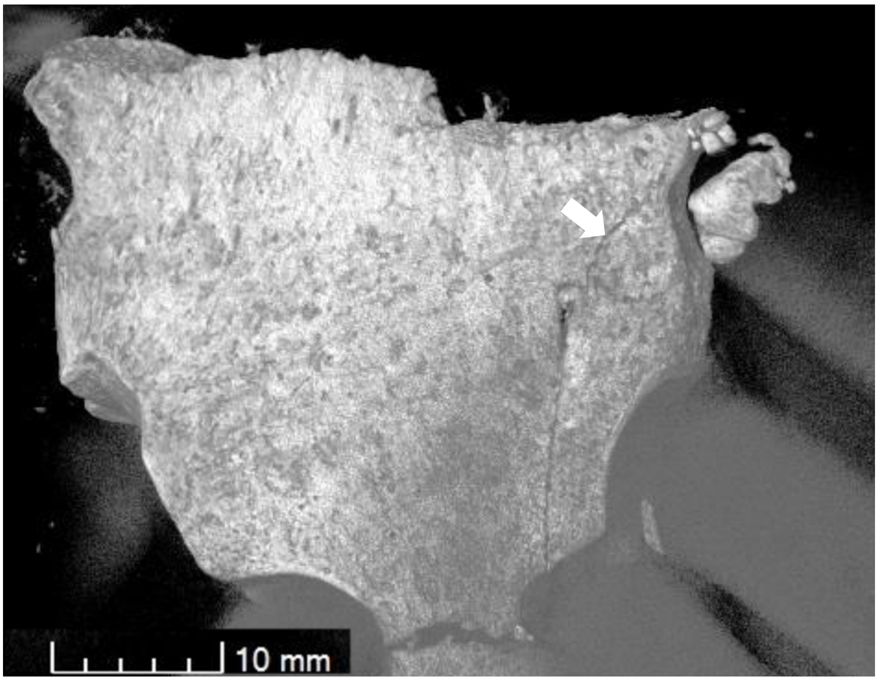


Figure 21: *Anterior view of the sternum of OP Cater. The arrow indicates the fracture line extending from the superior aspect of the stab injury.*

A fracture extending from the stab mark was also observed on the sternum of OP Bracelet. Extensive fracturing and fragmentation was observed around some of the dismemberment sites in OP Sanderling. Small detached bone fragments were associated with the stab mark in OP Malton and OP Bracelet. Associated damage is also a criterion used in the forensic analysis of stab marks in textiles albeit for a different purpose. The margin of the yarn fibres at the stab location appear torn and irregular if caused by a blunt edged implement, whereas a neat, clean planar array is indicative of a sharp-edged implement (Cowper et al. 2015). The micro-CT scans of the textiles in OP Haweswater showed neat, planar margins indicating a sharp-edged blade. This was confirmed by the forensic expert who examined the samples microscopically.

3.5 Application 1- Identifying weapon type

Identifying the type of weapon responsible for causing an injury is the first step in every SFT analysis and a prerequisite for further analysis such as weapon matching. In all 13 cases an assessment was provided by the pathologist or forensic expert, using the characteristics provided on the scan images. Of these 13 cases all but one (OP Piano) were identified as being caused by a bladed weapon such as a knife. In two of these (OPs Sanderling and Needingworth) the use of saws was additionally identified. **Table 9** lists the scan objectives for each scan, including those not further analysed.

***Table 9**: Summary of the cases examined in this chapter. The ticks indicate the information sought by police/pathologists from the micro-CT scans in each case.*

Case	Weapon match	Level of force	Visualisation	Weapon characteristics
Casava			✓	✓
Cater				✓
Compete				✓
Haweswater	✓			✓
Literature				✓
Mansriggs		✓		✓
Northedge				✓
Northwater				✓
Seminar			✓	✓
Skipper				✓
Workshop				✓
Neaphouse	✓			✓
Needingworth	✓			✓
Bracelet	✓			✓
Malton	✓	✓	✓	
Piano	✓	✓		
Sanderling	✓			
Morath				✓
Cape		✓		
Total	**7**	**4**	**3**	**15**

The wedge shape seen in many cases indicates that one side of the weapon is wider than the other which is a commonality of single-edged blades. Double-edged blades are more symmetrical which is reflected in the injury they produce as it would be expected to taper approximately equally on both ends. This distinction can only be made for stab marks, unlike incision marks that only reflect one edge meaning it is impossible to comment on the opposite edge. Possible evidence of a double-edged blade was observed on one of the samples in this study (OP Casava). In five out of the twelve cases of bony injuries the blade was identified as being single-edged, and in the remaining six cases it could not be determined confidently as they were incision marks.

A further criterion used to categorise knives is the morphology of the cutting edge: straight or serrated. This is determined from the cross-section of the kerf which therefore requires the cutting edge of the weapon to have stuck rigid material without completely cutting through its edges. It is easier to determine this feature on cortical bone than in the trabeculae. None of the twelve cases examined displayed evidence of a serrated blade. However, some marks were created in trabecular bone which does not preserve such evidence well.

A further distinction for straight-edged knives is the edge bevel, which can be one sided or symmetrical on both sides of the blade. This is a little studied aspect of toolmark analysis and not normally commented on by pathologists. Crowder et al. (2013) showed that edge bevel can be determined in experimentally produced stab marks as one of the arms of the V shaped kerf will be longer than the other for asymmetrical bevel. Unfortunately, out of the three recovered murder weapons of which an image could be obtained, two had only damaged cartilage (OP Northwater, OP Mansriggs) and one cartilage and trabecular bone (OP Skipper) which disallowed examining the cut mark for this criterion. The available description of the remaining recovered weapons did not include any reference to the edge bevel.

OP Haweswater presented the full outline of numerous stab mark on several items of clothing. They were also analysed by a forensic scientist who concluded that they were produced by a single-edged blade, although their report did not comment on whether the edge was straight or serrated.

The only two cases where different weapons were used were two of the dismemberment cases which showed evidence of sawing implements. OP Needingworth displayed two types of kerf shape, an asymmetrical W-shape with one deeper, narrower trough, and a more superficial V-shaped kerf. W shapes are indicative of crosscut saws (Symes 1992, Love et al. 2015, Hainsworth 2017) and the V shape of a straight-edged knife. OP Sanderling displayed a more varied pattern, including U, W and V-shaped kerf cross-sections. The latter is indicative of a knife while the former two are indicative of saws. U shapes have been associated with a variety of different saws (Symes et al. 2010, Love et al. 2015, Hainsworth 2017, Norman et al. 2018a) and more detailed analysis would be necessary for further distinction. However, the scan resolution was not sufficient to study aspects such as striation marks on the kerf walls which is best performed using SEM (Saville et al. 2007) or digital microscopy (Love et al. 2015).

3.6 Application 2- Weapon matching

An assault weapon was recovered in only six cases (OPs Bracelet, Malton, Sanderling, Mansriggs, Skipper, Northwater), a description by the defendant was available in one case (Haweswater), and visual evidence in form of photographs or CCTV footage was available in two cases (Casava, Northedge). In the remaining nine cases (excluding OP Piano) there was no indication of the assault weapon. In the six cases where a weapon was available for comparison, multiple weapons were available as possible culprit weapons initially. Multiple weapons were actually involved in OP Sanderling, in the other five cases only one of the ones available was found to be the actual assault weapon. For OP Northwater, the pathologist was shown the potential assault weapon. Their opinion was that based on the knife's characteristics it was possible on pathological grounds (mainly considering blade size and single edge) but had to be confirmed by DNA. An image of the recovered weapon could be obtained in only four cases, they are shown with their corresponding toolmark in **Figure 23**. Two of these (OPs Mansriggs and Northwater) did not injure any bone and were therefore not matched to the toolmark, one (OP Skipper) corresponded to the mark identification of a straight blade, and the fourth one (OP Sanderling) was correctly identified as a saw but the saw type could not be determined in more detail.

The case where the suspect's description of the assault weapon (hairdresser's scissors, six inch blades) was compared to the damage inflicted on the victim's clothing it was ruled out as possible weapon, leaving the actual one in question. This conclusion was based on an experiment which a forensic scientist from a private FSP conducted for the police as part of the forensic examination of the stab marks. This scientist therefore produced experimental stab marks on the exhibits using a range of different weapons (including scissors matching the description) and then visually compared the results to the original marks using a light microscope. This report was included in the case file and concluded that the damage was caused by a bladed weapon such as a knife. This interpretation was based on the planar array of the cut fibres which could also be observed on the micro-CT images as shown in **Figure 22**.

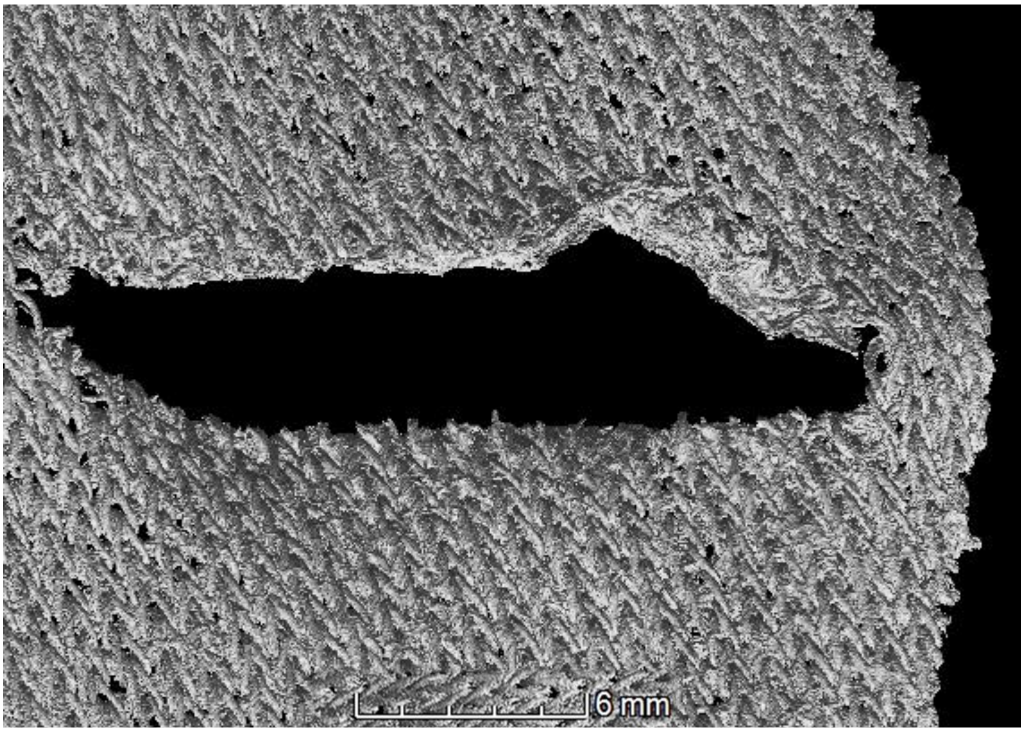


Figure 22: *Stab mark on the victim's T-shirt, OP Haweswater. The forensic scientist took the planar array of the cut fibres as indication of the use of a bladed instrument such as a knife. The fabric surrounding the stab shows some warping due to dried blood.*

In the two cases where the injury was compared to an image of the weapon it was found that an instrument of the type the defendant was seen with could have been the assault weapon. It would not, however, identify a specific one as responsible.

3.7 Application 3- Level of force

Given the absence of bone injuries and resistant clothing and the presence of a sharp tapered knife as assault weapon, the degree of force in OP Mansriggs was judged as at least moderate. The micro-CT images were explicitly mentioned in the pathology report in support of this evaluation (no skeletal injuries). A similar finding (no bony injury, no associated BFT) was made in OP Northedge despite the large dimensions of the injury. In OP Cater where the stab injury had penetrated the sternum, the level of force was also evaluated as at least moderate. The level of force in OP Morath was also considered moderate rather than severe since the knife had not injured the ribs, only the costal cartilage as the micro-CT scans revealed. In contrast, a bony injury was observed on the lumbar vertebra of OP Seminar and in the thoracic vertebra of OP Malton indicating the use of severe force. There was no instance where the degree of force was described as light.

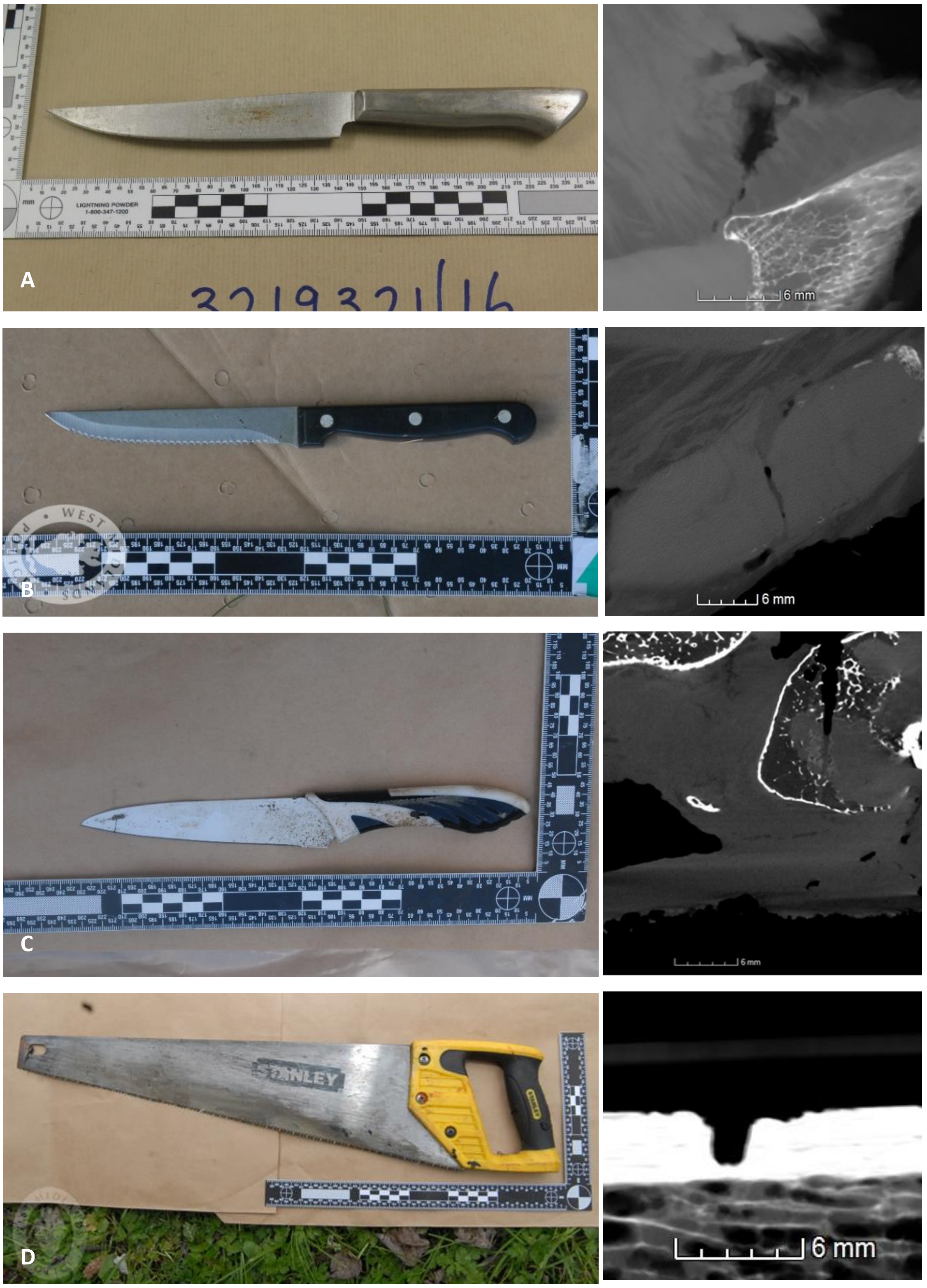


__Figure 23__: Comparison between the assault weapons (left, A: images courtesy of Metropolitan Police Service; B-D: images courtesy of West Midlands Police) and the micro-CT image of the corresponding injury (right). A: OP Mansriggs; B: OP Northwater; C: OP Skipper; D: OP Sanderling.

4. Case detail

4.1 Application 1

The different kerf shapes noted in OP Needingworth are likely to represent two different weapons. The information regarding the injury shape was given to the police/anthropologist with only a broad weapon class. For the purpose of this thesis the marks were interpreted in more detail against existing literature on forensic toolmark analysis, including an experiment conducted at WMG in conjunction with UHCW (Norman et al. 2018a). The W-shape was identified as being caused by a saw, most likely a crosscut saw (Symes 1992, Symes et al. 2010, Norman et al. 2018a). Crosscut saws have teeth filed at an angle to cut through the material which creates the characteristic W shape. The V shape is likely to represent a different weapon such as a knife - perhaps a straight blade as no evidence of a serrated blade was observed. The use of multiple implements has been observed in cases of dismemberment (Morild and Lilleng 2012, Seidel and Fulginiti 2014) and was confirmed by OP Sanderling as well. The W shape indicates a similar saw class as in OP Needingworth. The U-shaped grooves were initially suspected to be caused by a power saw; however, studies have shown these could have been caused by a range of different saw types (Symes et al. 2010, Norman et al. 2018a). V-shaped kerfs indicate the additional use of a knife and the extensive fracturing at the dismemberment sites suggests the use of blunt force to separate the body elements. This suggested that the assailant experienced some difficulties with the dismemberment process, trying multiple different tools and eventually blunt force. It is not uncommon to observe different tools being used in dismemberments as the process of sawing or cutting through the different layers of tissue is less straightforward than anticipated by the perpetrator who in response will try different implements (Rutty and Hainsworth 2014). **Figure 24** visualises the results of this struggle.

This contrasts with OP Neaphouse where the dismemberment signs were all caused by a single instrument, most likely a single-edged knife as the stab mark on the os coxa suggests. It was further assumed that the knife must have been very sharp since it penetrated the entire hip joint which consists of solid cortical bone, severing the femoral head. The pattern of knife marks in this case was reminiscent of professional butchery marks as they were located around the joints (**Figure 25**), cutting through the softer cartilaginous parts (Rainwater 2015, Seidel and Fulgitini 2014).

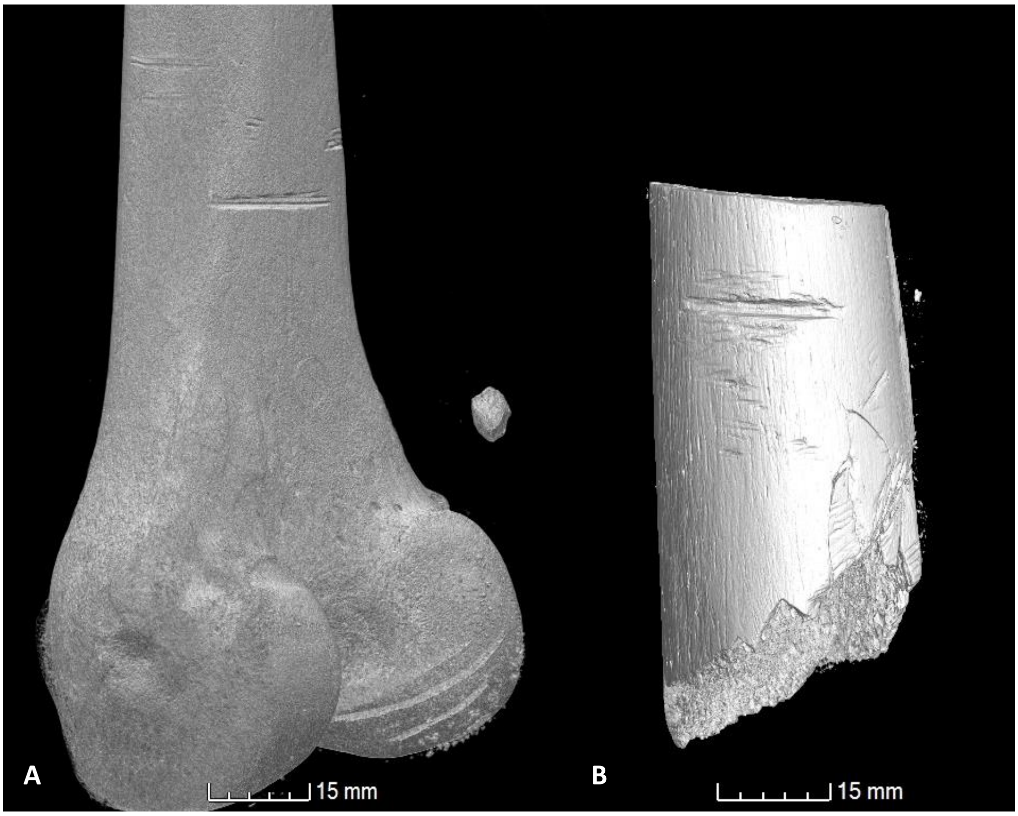


Figure 24: Numerous false starts on the skeletal elements indicate some difficulty in the dismemberment process. A: Distal femur from OP Needingworth, multiple false starts from the same weapon are found all over the sample; B: femoral shaft fragment from OP Sanderling showing multiple false starts with different tool characteristics and bone shattering.

They strongly resemble the pattern of knife marks observed by Porta et al. (2016) who reached a similar conclusion that the perpetrator had some understanding of anatomy and possessed good knife skills. This insight might steer the investigation and thus directly influence later stages of the process. Police in this case did in fact suspect the perpetrator to be found in the halal butchery scene. However, no further evidence was available at the time of writing.

In the remaining cases, being able to identify the weapon as single-edged blade with approximate dimensions was not always central to the overall case. However, it was crucial for investigators to demonstrate that they know as much as possible of the case circumstances to give their investigation credibility. Having an early description of the likely assault weapon can narrow down investigators' search for the actual weapon, thus making the investigative process more time/resource efficient. If the search then leads to the recovery of a weapon, a match can be justified more convincingly if it corresponds to a prior prediction rather than an injury description being completed retrospectively, introducing potential bias.

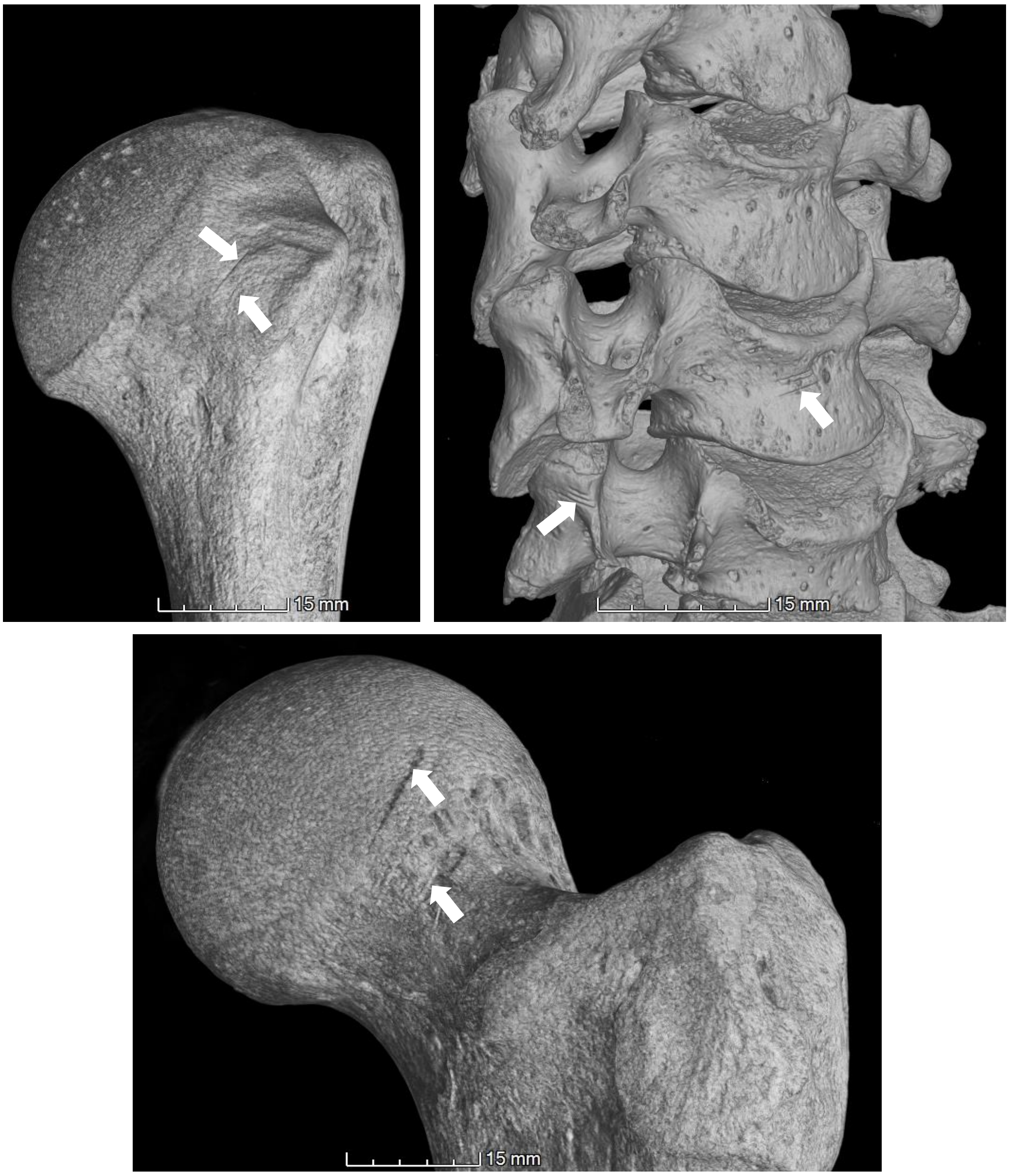


Figure 25: *Three skeletal elements from OP Neaphouse which all display the same type of subtle incised marks located around the joint ends (arrows). A: proximal left humerus; B: cervical vertebrae; C: proximal left femur.*

Studies have shown that dimensional measurements on micro-CT can be further improved by using voxel scaling (Kruth et al. 2011, Lifton et al. 2013) which has been exploited by Norman et al. (2018a, 2018b) who employ statistical models to predict the weapon type used to create incised toolmarks in bone. This experimental study has great potential to add quantitative methods to the analysis of SFT which could in future be used on case data to test the models. This is an important learning point for the continuation of this project as future cases of SFT will be scanned with a calibration artefact in order to enable voxel scaling and therefore allow the use of such statistical models.

4.2 Application 2

Having identified the type of weapon causing an injury, the next step is then to compare the suspect weapon if recovered and to make an assessment whether it matches the injuries. The challenge is that with the sheer quantity of knives in circulation, having a possible match does not rule out other weapons (Saks and Koehler 2008). The availability of knives makes it difficult to directly match a certain weapon even if using statistical methods since there are multiple copies of the same knife in circulation. Positive identification is only achievable with DNA or perhaps fingerprints. The reliance on DNA, illustrated in for example OP Northwater, clearly shows the limitations of toolmark analysis. It is not possible to positively identify the correct weapon purely based on its and the wound's physical shape, but in the absence of DNA, it can provide strong circumstantial evidence.

In OP Sanderling a collection of tools was recovered from the same location as the victim's body which included a hand saw, a kitchen knife, a chisel, and a hammer. In addition, an electric carving knife was found to have been disposed of by the perpetrator. The saw shared class characteristics with the W-shaped kerfs seen on some of the scanned samples, the knife with the V-shaped kerfs. The hammer and chisel could both have caused the BFT but there is no evidence to confirm this with certainty. It remains to be speculated whether the electric knife produces similar cuts to other power saws and whether it could have produced the U shape (Norman et al. 2018a). The different injuries are shown in **Table 8**. The tools were confirmed to have belonged to the perpetrator by other means and it would have been a rare opportunity to scan the tools to attempt a virtual match with the injuries but unfortunately this was not possible.

A negative weapon match was achieved in OP Haweswater. Having established that hairdresser's scissors could not have produced the marks seen on the victim's clothes contradicted the defendant's account of the events which influenced the entire court proceedings. The defence claimed that the attacker, provoked by the victim, fell into a blind rage and grabbed the first implement they found in their bag which happened to be a pair of hairdresser's scissors as they were on route to a friend's for a haircut. The forensic conclusion that the injuries were not caused by such scissors suggested that the defendant had actually carried a dangerous weapon in a public place which demonstrated some form of premeditation and intent (CPS 2018). From a legal perspective this constituted the difference between manslaughter and murder, the latter of which the defendant was convicted at trial. Had it not been for the forensic science evidence, the offender would have got away with the lighter sentence of manslaughter. While this was not the achievement of the micro-CT scans since the final opinion was that of the forensic scientist, the characteristics used to identify the weapon type were visible on the scans as well. In the future, this aspect of the forensic toolmark analysis could be performed on micro-CT scans instead of under the microscope. However, like for strangulations, a baseline or validation study will be required to add a solid foundation to this particular application.

The one case where the examined toolmarks were not caused by a cutting or sawing implement was OP Piano. The demonstrated fit of the vehicle damage to the bone injury (**Figure 26**) was central to the prosecution's argument in court which argued that the driver of the vehicle had caused the crash due to excessive speed. The scan data was therefore part of the CJP from the first stage (initial investigation) until the sentencing at gate five because of the information they contributed.

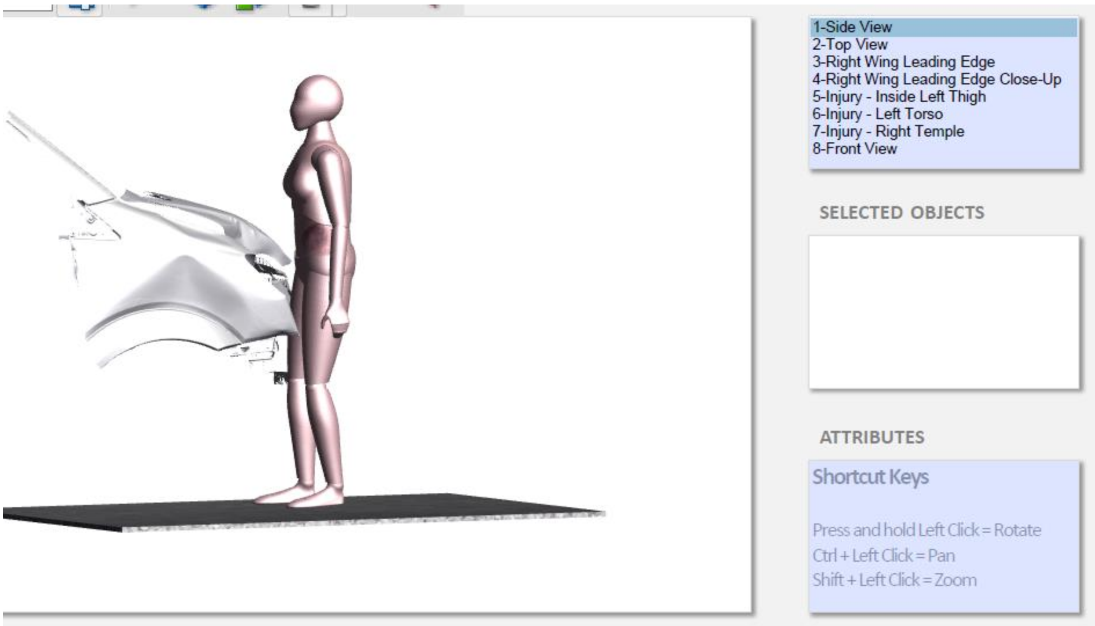


Figure 26: *Interactive 3D model of the vehicle scan which was matched with a scaled model of the victim. The victim's injuries were mapped onto the dummy, the one on the left thigh corresponds to the height of a sharp metal fold on the vehicle's bonnet. Model created by Mike Donnelly in Geomagic (3D Systems, Morrisville, US) and exported as 3D PDF.*

It was used in stage one to distinguish between accidental death and driver fault. The investigation was influenced heavily by the newly discovered injuries, shown in **Figure 27**, indicating that the victim had been carried on the vehicle before being projected forward where they landed on the road. This enabled the collision investigation team to select the appropriate formula to calculate the vehicle's speed at the time of impact, reaching the conclusion that the driver was speeding. The scan models on which this was based were requested to be prepared for court. The solution was to create a 3D PDF document which could be shown using court technology and to which there was no objection. At trial, this model was shown to visualise the match.

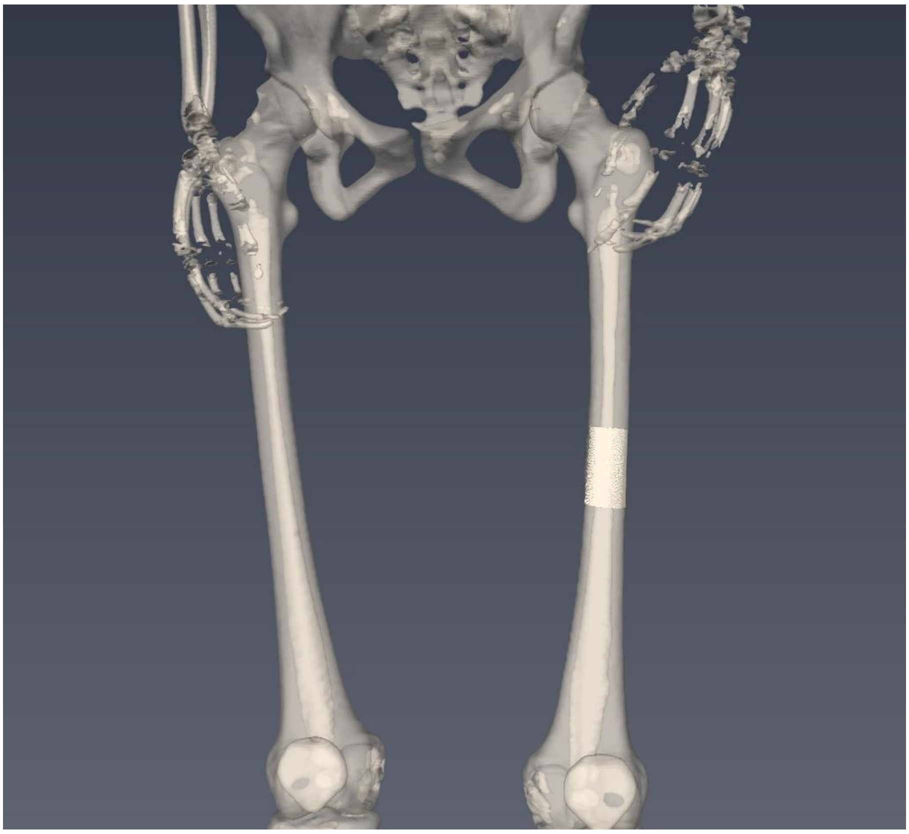


Figure 27: *Overlay of the micro-CT scanned section of the left femur on the hospital CT scan. This gave a precise location of the injuries on the victim.*

4.3 Application 3

Some samples were submitted to inspect whether any bone had been damaged or whether the weapon had only struck cartilage as subtle bone injuries are difficult to detect with the naked eye. This occurred predominantly within the ribcage where the injury was close to the costochondral junction. This would then be used by the pathologist in the determination of the level of force. The absence of cases where the amount of force used was described as light is likely to be due to the sample focus on homicide cases as light force is less likely to result in fatal injuries. At the other end of the scale it appears that there is some reluctance amongst pathologists to use the term severe force even if there is a significant skeletal injury. This devaluates this particular aspect of the forensic toolmark analysis as the majority of cases will be assessed similarly regardless of actual force used. The use of this three point scale is based on the pathologist's subjective interpretations which has been criticised by Nolan et al. (2018). Based on their experiments using a novel force plate dynamometer they recommend four factors when establishing the amount of force used. These are the weapon tip radius, assailant sex, minimum force required to penetrate the tissue, and whether the latter is greater than the force that can be generated by the attacker. The importance of the knife and tissue properties have also been highlighted in earlier studies by McCarthy et al. (2007) and Nolan et al. (2013). This demonstrates that the weapon and material characteristics of the area penetrated are more relevant to the assessment of force than the injury itself which calls for more studies being conducted in this field. Combining experimental data with computer simulations based on 3D models created during the present study could be used to generate a knowledge base for different weapons and tissue types. The problem with such experiments is the disparity between experimental setup and real-life dynamics. Experiments can recreate the attacker's action but rarely take into consideration those of the victim. If the victim moves forward at the same time as the attacker, the force of the impact and the associated damage would be greater but it would be wrong to say the attacker had used a higher level of force. This could contribute to the pathologist's hesitation in attesting severe force.

5. Discussion

In the Criminal Justice Process most toolmark analyses are performed during the full investigation (stage two) as the initial question of whether the death is suspicious is solved easily due to the presence of an injury which is rarely caused by accidental means. In some cases the process terminates at gate three, for example if the injury is suicidal in nature, but the majority of cases will eventually lead to a charge. In cases of Sharp Force Trauma, answering the first objective is critical in the process of the investigation as this could lead to the assault weapon which in turn could lead to the perpetrator. The second question is often posed if one or more weapons have been retrieved from a suspect but cannot be directly linked to the crime due to a lack of DNA evidence. In practice, it was noted that the first type of question is the more common one as it seems that most criminals knowingly dispose of their weapon after an attack. The third question was occasionally added to the objectives of the inquiry although the answer thereof proved difficult from the scan alone. The severity of the attack is important at the later stages of the CJP, in particular the sentencing at stage five. Higher force could result in a longer sentence as the attack is perceived as more violent. OP Haweswater has shown that the choice of weapon can influence the CJP all the way through the process and micro-CT can be used to analyse this. In OP Seminar and OP Malton the pathologist requested the micro-CT with the court proceedings in mind. In both cases the knife had been struck from the front and penetrated the entire thorax into the spinal column. As this would be difficult to show to the jury the pathologist decided to use the micro-CT images to visualise the extent of the damage to enable the jury to imagine the level of force required. The most pronounced impact was created by OP Piano where the results of the micro-CT actively influenced the entire process as outlined above. This impact is difficult to quantify as it is of a purely societal nature, consolidating the quality of justice and satisfying the social responsibility police/CPS have towards the victim and their families.

In cases where the characteristics of the assault weapon are sought, the forensic expert is usually limited to the appearance of the injury superficially and the depth of the wound canal which is determined by simply inserting a ruler or similar object into the injury. The problem with this approach is that the superficial injury might not represent the weapon characteristics clearly as soft tissue deforms easily, as illustrated by the comparison of postmortem and micro-CT measurements. However, these measurements are difficult to compare directly as the pathologists would take them on the skin surface which was usually removed from the sample before the micro-CT scan. Other issues which might complicate the external wound analysis are decomposition and evidence of emergency procedures such as thoracotomy which can destroy the wound tract. The wound dimensions given from the micro-CT scans sometimes differed somewhat from those given by the pathologist as soft tissue would obstruct the pathologist's view. Measuring the internal dimension by inserting an object only gives the depth until the weapon strikes bone, the damage within bone is usually too thin to let a ruler etc. pass through. Hospital CT can provide an indication of the injury but mostly the resolution is insufficient to allow precise measurements. This can be achieved with micro-CT, however a few limitations, which were observed over the course of this project, must be mentioned. These are the obvious visualisation issues with soft tissue, the loss of a detailed outline where the blade penetrates trabecular bone, and the removal of the sample from its original context.

From the interviews it has transpired that pathologists have different views of their role in SFT analysis. Some submitted a sample with other forensic examiners' benefit in mind whereas others considered it their responsibility to comment on the general weapon characteristics and how to present them at court. However, they all had in common that they realised the improvement that micro-CT can bring to the examination of stab marks. None of the cases, except the dismemberments, actually involved a toolmark expert. This is probably due to the individual cases and the overall body of evidence but also due to the pathologist being able to provide a sufficient assessment assisted by the micro-CT images.

Despite having been applied to SFT for the first time fifteen years ago (Thali et al. 2003), micro-CT is still not commonly employed in everyday forensic pathology practice but with increasing availability it might become firmly established within the discipline in the future.

6. Summary

The high volume of homicidal stabbings enabled a thorough comparison of the sharp force injuries produced. In addition, three dismemberment cases added further examples of less common toolmarks. The advantages of using micro-CT for toolmark analysis are:

- Clear outline of marks in bone and cartilage.
- Increased detail allowing more accurate measurements.
- Increased detail showing previously non-identified injuries.
- Detailed 3D models for court presentation.

Some limitations have become apparent which are:

- Limited soft tissue visualisation.
- Level of force cannot be directly estimated from the micro-CT scan but future research can use the digital models for more detailed simulations.

Micro-CT in toolmark analysis is usually performed during the second stage of the CJP but has a strong impact on subsequent processes and decisions in selected cases. In some cases the detail enabled by micro-CT has proven to be crucial to the entire process. Overall, using micro-CT for Sharp Force Trauma analysis has proven to be a useful addition for a more detailed injury depiction for investigators and the courts. The next chapter will take a closer look at injuries caused by blunt force and how they profit from the new technology.

Chapter 7: Blunt Force Trauma

1. Introduction

Strangulations and stabbings cover a large proportion of homicides encountered in the UK. The third key area examined in this thesis is Blunt Force Trauma which accounts for nearly a quarter of homicides (Office for National Statistics 2018). BFT can have different causes ranging from falls, to sports injuries and motor vehicle collisions but only homicidal BFT will be considered in this chapter. Homicidal BFT can be caused with a blunt instrument or without a weapon. The former has been shown to overlap with toolmark analysis in the previous chapter and the latter with strangulation in the chapter before that. The forensic examination of such injuries is well established, it was therefore uncertain at the beginning of the project what micro-CT could add to the field. Following the examination of some initial pilot cases it soon emerged that in adult cases the added benefit was sometimes limited, but in juvenile cases the added value was immediately obvious. The main proportion of this chapter will therefore be dedicated to infant deaths where the examination of BFT is a highly sensitive subject due to the potential implication of child abuse. Like the previous chapters, this one begins with a literature review to introduce current practices and challenges, followed by the methodology applied to actual cases and the results thereof. The subsequent discussion will then evaluate these results with regards to the overall research questions and position BFT within the Criminal Justice Process.

2. Literature review

Blunt Force Trauma covers a wide range of injuries and causes and is frequently encountered in criminal but also in accidental cases as vehicle collisions and falls comprise the majority of serious cases (Le Blanc-Louvry et al. 2013). The manifestation of Blunt Force Trauma ranges from bruises to skeletal fractures with the main focus in this chapter being on the skeletal damage as observation of soft tissue detail with micro-CT is limited. Bone fractures are a fairly well researched area of forensic anthropology, it is the context which often makes them controversial. The most common issue is the intent behind injuries caused by a third party whether they result from an accident or were caused intentionally (Bilo et al. 2010). This is a particularly pressing concern if the victim is a child as it raises the issue of child abuse. As often when a crime involves vulnerable individuals such as children, the elderly, or the mentally ill, there is a lot of pressure on the investigators to produce rapid results (Elks 2008). This pressure has sometimes been held responsible for the mistakes made during such an investigation resulting in the miscarriages of justice detailed in the literature review. Forensic science evidence has had a particularly grave impact on some of these miscarriages of justice (Robertson 2013), perhaps because investigators and prosecutors accepted this evidence too readily to deliver the results expected by the public. It has been recognised since that the investigation of suspicious infant deaths and diagnosis of child abuse is highly dependent on the medical professional conducting the examination and that there is much controversy and difference in opinion (Betts 2013). Any additional evidence that could improve this type of investigation is therefore a valuable contribution to both science and society. If a suspicious case is presented to a hospital, a radiological skeletal survey is standard protocol although more and more institutions now routinely perform a full-body CT scan to improve injury detection. The advantage of CT over standard X-ray for this application has been demonstrated in a study by Arthurs et al. (2017). It is the distribution pattern of skeletal trauma which indicates child abuse and injuries like posterior rib fractures, metaphyseal fractures, and spiral fractures of the long bones are generally associated with non-accidental injuries (NAIs) (Kemp et al. 2008). A common defence strategy where rib fractures are concerned is that they were caused during Cardiopulmonary Resuscitation (CPR) attempts (Bilo et al. 2010). The timing and location of these injuries becomes central to the case and the consensus amongst practitioners is that CPR related injuries are found on the anterior ribcage (Arthurs et al. 2017). The age of the fractures can further provide information regarding the treatment of the victim after the injuries had been inflicted and whether they received any medical attention or whether they were neglected and whether the age of the fractures matches the account of resuscitation. Neglect can be inferred if the injury begins to show healing without proper fixation or re-alignment of the bone, potentially causing long-term problems had the child survived. These healing signs increase the support for a non-accidental nature for the injuries.

BFT analysis can also overlap with toolmark analysis. It is not uncommon to encounter cases where a blunt instrument has left an imprint on the victim's skeleton. The pathologist would then be asked to comment on the shape of the instrument in order to identify the assault weapon (Sulaiman et al. 2014). As with NAI, the interpretation of the trauma relies on the fracture pattern - in this case the shape and progression of individual fracture lines at the impact area. Intersecting lines often indicate multiple impacts as the force of the repeated impact dissipates into the existing ones (Viel et al. 2009). Often one can see impressions of the implement used and they tend to be more readily visible on the bone compared to the soft tissue due to the presence of blood and soft tissue mass. Medical CT has been proven to be of particular use for visualising impact fracture patterns as the scan records the injury with any loose fragment in situ whereas autopsy risks losing that spatial relationship (Ebert et al. 2011). Postmortem CT has become a firmly established imaging technique in BFT at many institutions worldwide (Aalders et al. 2017). It also helps to visualise the injuries in areas otherwise inaccessible with standard autopsy methods and provides a more complete description of every single fracture line.

As a final aspect of BFT analysis there is the question of the level of force used in the attack. This is a recurrent question put to the pathologist since it carries much weight at trial and can influence the length of the sentence if found guilty (Parmar et al. 2012). As with sharp force injuries, determining how much force was used is challenging as it depends on a multitude of factors including the victim's underlying health and potential medical conditions which influence the inherent bone stability, for example osteoporosis. There is some clear potential for this aspect of skeletal analysis and a number of studies have used micro-CT based quantitative image analysis for bone quality studies (Djuric et al. 2013, Vasilić et al. 2009). In accordance with SFT analysis, the level of force is given as mild, moderate or severe. The most used criterion is the skeletal element showing the damage. The biomechanical properties of individual bones are reasonably well understood which makes this the starting point for further interpretation. The extent of the damage, for example fragmentation and displacement, is another criterion often cited in pathology reports. Regular hospital CT has been used to improve the interpretation of all these features (Le Blanc-Louvry et al. 2013) and based on these results it was anticipated that the increased resolution of micro-CT will be helpful to further refine such diagnoses. It was further anticipated that the images created with micro-CT could improve the visualisation of subtle injuries, perhaps making this the method's most significant contribution to BFT cases.

3. Materials and method

The following are the four main issues in BFT analysis as identified from the literature:

- Identifying injury mechanisms and instrument if applicable
- Estimating amount of force used

- Determine the timing of an injury in relation to time of death
- Distinguishing accidental from non-accidental trauma

A further objective was to investigate how the increased detail and the visualisation technologies could be used to present the evidence in court.

In order to analyse these, micro-CT scans of the skeletal element in question were conducted on a Nikon 225/320 LC micro-CT scanner using the settings detailed in **Table 10**. Samples were secured onto a foam bed which was then placed into a sealable plastic container by mortuary staff. The position of the sample was determined by mortuary staff and depended on practical considerations such as availability of suitably sized containers. The sample size also determined the final scan resolution with larger samples resulting in lower resolutions. The scans were visually examined in VG Studio MAX 2.2. The volume rendering was used to describe the overall appearance of the fracture and to take measurements of individual features such as obvious shapes and overall fracture length. No voxel size correction was performed which means the uncertainty of any measurements is three times the voxel size of the scan. The 2D sections were used to examine the fracture propagation through the bone and to identify and characterise callus structures where applicable as they were easier to see in the sections due to the visualisation of a wider spectrum of grey values. A qualitative description of the injury was provided in an illustrated report which was issued to police, pathologists, and bone expert. Quantitative measurements were included if they added benefit for example if a weapon was expected to be involved. If advanced visualisation was requested during trial preparation, the animation tool in VG Studio was used. The animations were kept as simple as possible, showing different perspectives of the injured part and detailed views of the area of interest. No change to the original data was performed other than visualisation effects such as adjusting the greyscale. If required, 3D prints were created by extracting a surface model and printing the object on either a Form 2 (Formlab Inc., Somerville, MA, USA) or a Stratasys J750 (Stratasys, Eden Prairie, MN, USA) printer. For one of the cases the scan images were segmented according to grey values to separate the bone shaft and the callus that had formed around it. This was visualised by printing the callus in a transparent material through which the white bone was visible.

***Table 10**: Scan parameters and approximate sample size of the specimens scanned for BFT analysis.*

Sample	Voltage (kV)	Beam current (µA)	Exposure (ms)	Gain (dB)	Filtration	No. of projections	Resolution (µm)	Sample size
Argon skull	125	680	354	12	0.35mm copper	3141	84.4	147x 130x 73mm
Bagon skull	140	143	708	24	0.35mm copper	3141	34.0	66x 60x 18mm
Vault ribs	125	160	354	24	None	3141	45.0	83x 71x 160mm
Mansergh ribs	75	587	354	18	None	3141	44.0	88x 30x 62mm
Picture ribcage	125	208	354	24	None	3141	77.1	132x 130x 93mm
Picture L arm	125	200	354	24	None	3141	58.6	90x 107x 55mm
Picture R arm	125	200	354	24	None	3141	47.8	75x 92x 90mm
Picture L leg	125	200	354	24	None	3141	57.7	113x 102x 85mm
Picture R leg	125	208	354	24	None	3141	62.9	110x 119x 71mm
Picture skull	135	187	354	24	None	3141	44.7	81x 78x 37mm
Picture R clavicle	125	208	354	24	None	3141	23.9	41x 33x 29mm
Pitch ribcage	125	208	354	24	None	3141	79.8	147x 128x 98mm
Eldamar skull	125	40	708	24	0.35mm copper	3141	45.9	81x 48x 84mm
Rococo ribcage	120	330	250	30	None	2500	99.9	171x 168 130mm

Rococo femurs	120	82	1000	24	None	2172	95.1	103x 61x 185mm
Rococo pelvis	120	92	1000	24	None	3135	47.5	80x 92x 69mm
Rococo phalanx	125	87	708	24	None	3135	9.0	9x 9x 9mm
Hotel posterior ribcage	79	759	500	18	None	3141	69.5	139x 103x 52mm
Coal ribs	120	141	500	24	None	3141	73.7	106x 118x 67mm
Melba ribcage	140	65	500	24	0.125mm tin	3141	81.8	145x 150x 90mm
Sarsar ribcage	150	213	354	24	None	3141	95.0	190x 169x 123mm

As for the previous two types of homicides a content matrix was compiled consisting of the case background for each case including the suspect-victim relationship, information about potential weapons, and about the attack where available. Pathological findings were noted to allow comparison of the different methods used and further forensic examination results were added to the content matrix where available, for example for the fracture age provided in the histopathology report.

4. Results and analysis

4.1 General numbers

Twelve blunt force cases were examined over the course of this project as summarised in **Figure 28**. In eight cases the deceased was an infant or toddler of less than two years of age, in the remaining four cases the deceased was an adult. Three of the children were male and five female, three of the four adults were male and one was female. The suspect in all child cases was a parent or legal guardian, in the adult cases suspects were acquaintances in two cases, the victim's son in one, and not identified in the last. Ribs were the most commonly examined part of the body in nine cases, followed by skull sections in five cases, and limb bones in two. In all but three cases only one sample was examined and those three with multiple samples were all suspected child abuse cases. For two cases more than two samples were examined which displayed a complex pattern of fracture distribution with fractures of different ages. Of the nine cases involving ribs, five consisted of the complete ribcage and all were child cases. One of the eight child cases (OP Hotel) was established as no crime due to a non-diagnostic injury pattern.

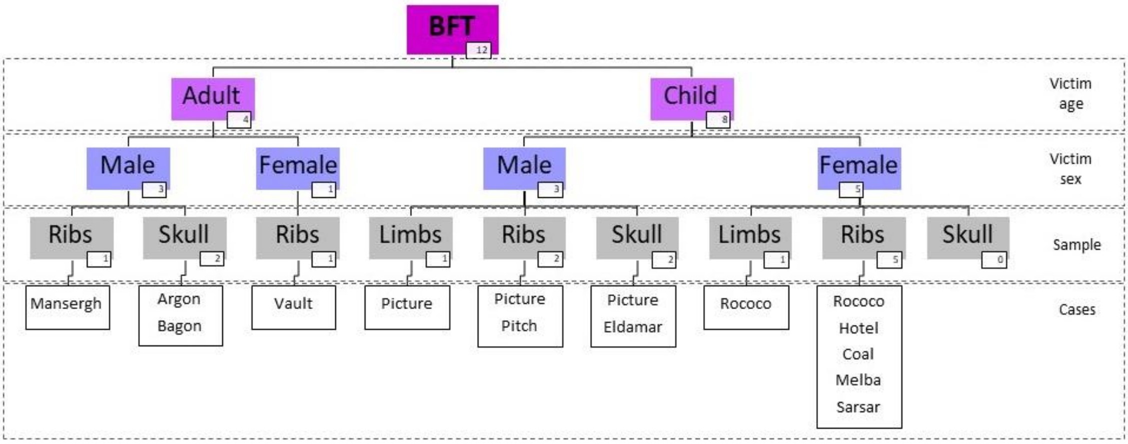


Figure 28: *Tree diagram of the distribution of BFT cases.*

All cases were examined as part of the first two stages of the Criminal Justice Process, the initial and full investigation. Two cases (OP Argon, OP Rococo) were involved at stages three and four as the micro-CT images or visual presentations derived from them were used to support the pathology expert witness testimony. The further use of the micro-CT reports in three cases (OPs Picture, Coal, and Pitch) remained unknown at the time of writing since they were submitted by a police force with which there was no formal research agreement. However, it remains somewhat uncertain to what extent the micro-CT reports were used as part of the juror packs during trial since this would not require police to contact the researcher for additional information and therefore often went unnoticed.

4.2 Injury mechanism

One of the objectives of conducting micro-CT scans of fractures was to provide information about the injury mechanism, for example whether a blunt instrument was used as was the case in two cases (OP Argon, OP Bagon). These two cases were both skull sections from adult male individuals. In OP Argon there were two distinct injury shapes observed, one was an approximately square shape with rounded edges, the other a longer, slender boat shape with a fracture line along the long axis. This indicated that the injuries were caused either by two different implements or by one implement with different sides. While micro-CT could not provide a definite answer without any contextual information, the analyst was able to provide a description and visualisation of the geometry causing the injuries. In light of the case circumstances the prosecution considered this evidence as support for their argument that both defendants were involved in the attack using the claw hammer and spanner found at the scene. These tools were also surface scanned and precise measurements were provided to the pathologist for comparison with the wounds. The surface models created by these scans could potentially be used to allow virtual matching to the pathology model to provide a best fit and to illustrate the possible angles at which the tools could have impacted the bone. Two possible matches are shown in **Figure 29**.

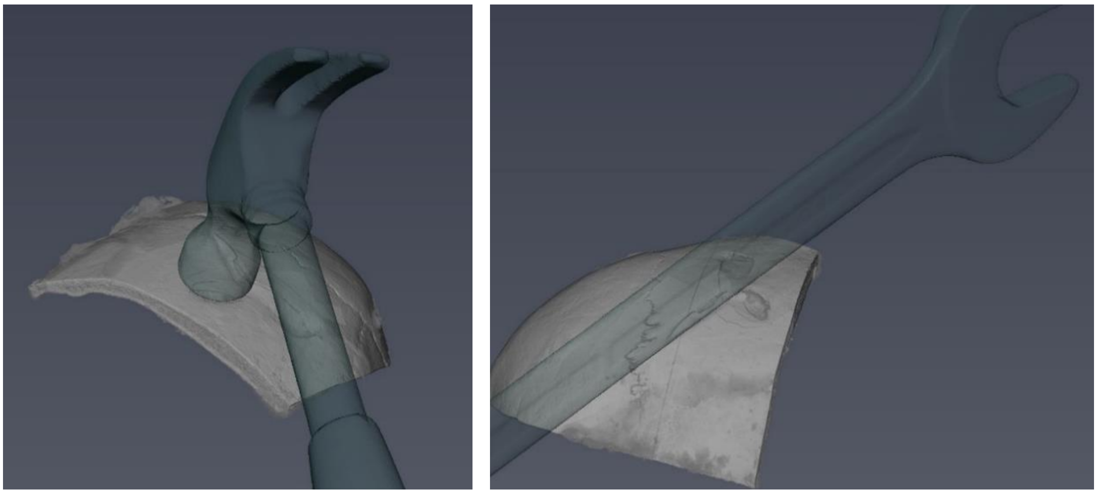


Figure 29: *Two possible weapon matches overlaying surface scans of the hammer and spanner onto the micro-CT scan of the injured skull fragment in OP Argon. The matches shown here are only illustrative and represent a small proportion of the range of possible matches.*

This option was not used during the investigation or trial as it lacks a scientific foundation which is one of the main concerns relating to many of the 3D and virtual reality "gimmicks" in forensic science (Campbell et al. 2013). The skull sample from OP Argon was 3D printed and presented in court along with the illustrated report. This was the third case where evidence produced at WMG was presented as major evidence during trial and the first case where the project supervisor was summoned to testify as expert witness in court. The importance of this is discussed in Chapter 9 where investigators share their views on the case.

The second case where a weapon match was sought was OP Bagon. This case also involved a skull fragment with a patterned fracture. The defendant admitted striking the victim only once with a metal rod of approximately 0.5m length in self-defence. The pathologist confirmed the implement as a possible weapon but could not confirm the number of blows despite the presence of multiple lacerations on the scalp. The blood pattern expert who examined the scene suggested that there were two impact points at different levels. On the micro-CT images the fracture showed as long and oval-shaped and was identified as being caused by a long straight implement which corresponds to the pathologist's opinion. There were further fracture lines indicating a possible second impact which is supported by the BPA. This case demonstrates the additional benefit of the microscopic detail added by micro-CT since the fracture lines from the second impact were very subtle. It further illustrates the importance of integrating all possible lines of evidence for the best possible interpretation and increased confidence in the results. Both cases are shown in **Figure 30**.

There was no distinct pattern to the injuries in the remaining two adult cases. One remained unidentified and one was caused by kicking. In two of the suspected child abuse cases the injuries were attributed to CPR, based on the anterior location of the rib fractures. Injuries in confirmed child abuse cases were due to compression (ribcages) and shaking/twisting while holding on to limbs tightly (long bones) as identified by the pathologist and histologist based on existing research in this area.

4.3 Degree of force

Investigators frequently ask pathologists to comment on the level of force used to cause certain injuries. This usually informs the prosecution about the perceived violence of the attack which can affect the length of the sentence received if found guilty. It is near impossible for pathologists to put an absolute number on the amount of force used and they tend to categorise it into low, moderate, or severe, which is primarily based on experience and subjective interpretation. Putting absolute numbers on the CT scan is equally difficult. If the material properties of individual samples were known, future research could conduct Finite Element (FE) analysis or simulations could be performed based on the micro-CT scan in order to obtain closer estimates.

In one of the cases, OP Vault, the victim's bones were osteoporotic due to advanced age which informed the bone pathologist's opinion that the amount of force required to cause the fractures was only mild. The micro-CT images did not show any obvious bone changes and the fractures had the same appearance as those on non-osteoporotic bone. No further reports contained an assessment of the amount of force and the full postmortem report was unavailable in six cases.

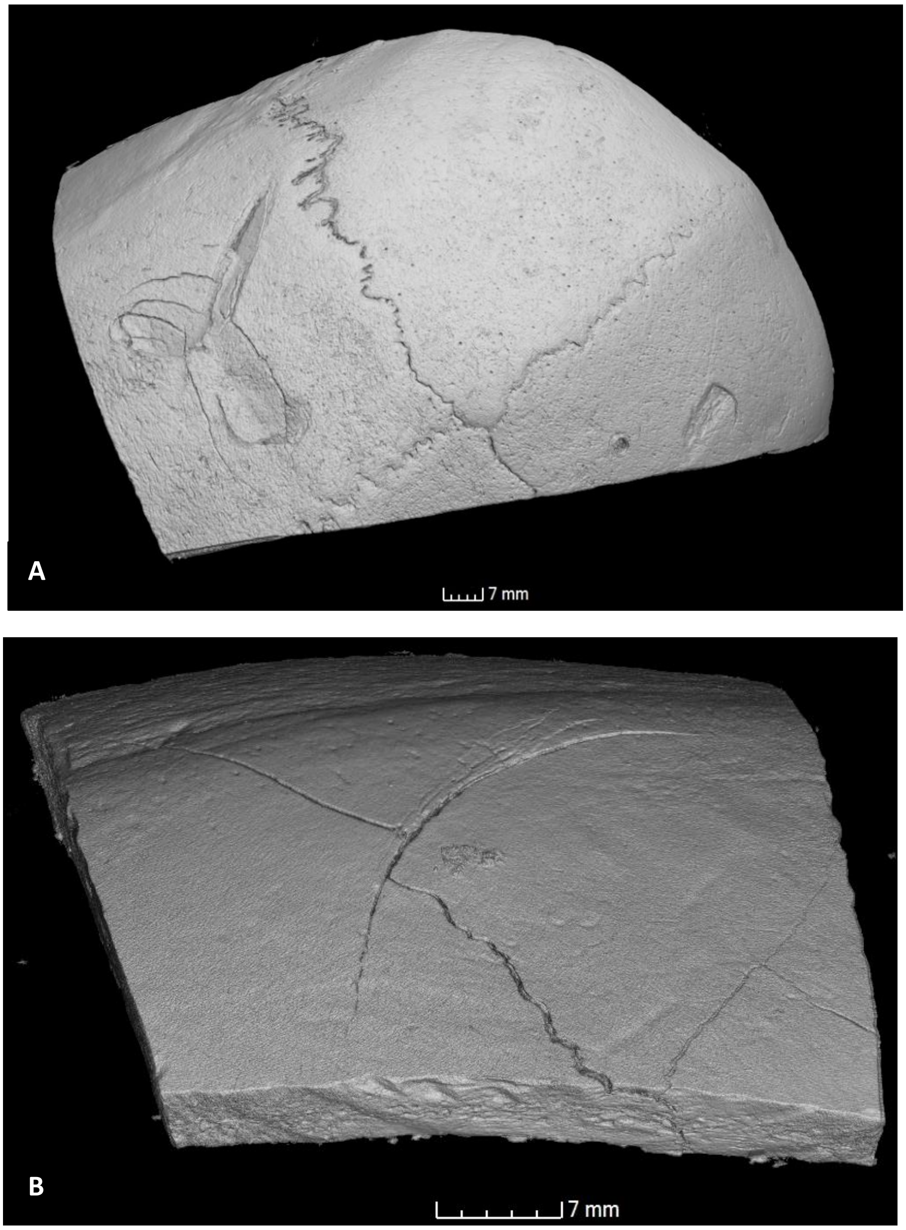


Figure 30: *The two adult skull fragments examined for evidence of a blunt instrument being used in the attack. A: OP Argon, showing two different shapes of injuries, one squared depression, and one oval shaped one. B: OP Bagon: the main injury consists of two opposing curved fracture lines. Further fracture lines intersect with the main injury, possibly indicating a second impact.*

The micro-CT images showed fracture displacement in three of the child ribcages of which one also displayed a displaced femoral fracture and one a humeral fracture. This would suggest that in relative terms the applied force was more severe in those two cases.

4.4 Fracture timing

Estimating the timing of a fracture is a crucial prerequisite for determining whether a crime has been committed or not. Pathologists distinguish between antemortem, perimortem, and postmortem trauma (i.e. before death, around the time of death, and after death). Antemortem trauma usually is not directly associated with the cause of death but can have other implications for the assessment of the deceased's medical history. This can include evidence of torture or, as encountered in two cases examined (OPs Rococo and Picture), evidence of longer lasting child abuse and neglect. The deceased 18-months-old toddler in OP Rococo showed signs of recent and past injuries at autopsy, thus prompting micro-CT scans of the femurs, the right hemi-pelvis, the ribcage and the distal phalanx of the right little finger. Two samples, the ribcage and the right femur, stood out in terms of injury timing. Both displayed evidence of antemortem fractures, recognisable as such due to the formation of unstructured new bone (Malone et al. 2011, Morgan et al. 2009) which had lower grey values indicating lower mineralisation and therefore more immature tissue. The ribcage showed this type of bone reaction on multiple ribs, predominantly on the posterior aspects. The appearance thereof differed between individual ribs, some displayed unstructured, loosely woven new bone deposits while others displayed a denser, well-structured callus with beginning cortical bone formation. The right femur displayed a displaced fracture surrounded by a gross callus which displayed a range of grey values indicating different levels of bone maturity. This was clear evidence that the traumatic events had occurred some weeks before death. Within these calluses there were different levels of grey values which might give the relative timing of the individual injuries. It was concluded based on histopathology that: the oldest fracture dated to approximately three months prior to death, the femoral fracture dated to six weeks prior, another episode occurred at approximately between one and three weeks prior to death, one several days prior and one just before or around death. The right pelvis also showed some damage on the micro-CT scan which had not been seen on the hospital radiographs and which the histopathologist did not observe either. There was a clear fracture through the ischium with a disruption of the cortical bone which also displayed small amounts of callus. **Figure 31** shows the 3D view and a 2D section thereof. It seems plausible that the impact which had caused the femoral damage also impacted the pelvis. This additional discovery emphasises the benefit of the additional three-dimensional detail provided by micro-CT and the complimentary nature of these methods. A possible explanation for this injury being missed during histology is the limitation of the histologist to one cutting plane which might have not included this particular area. The micro-CT report was not available yet when the pathologist conducted their exam, otherwise they might have adapted their cutting plane.

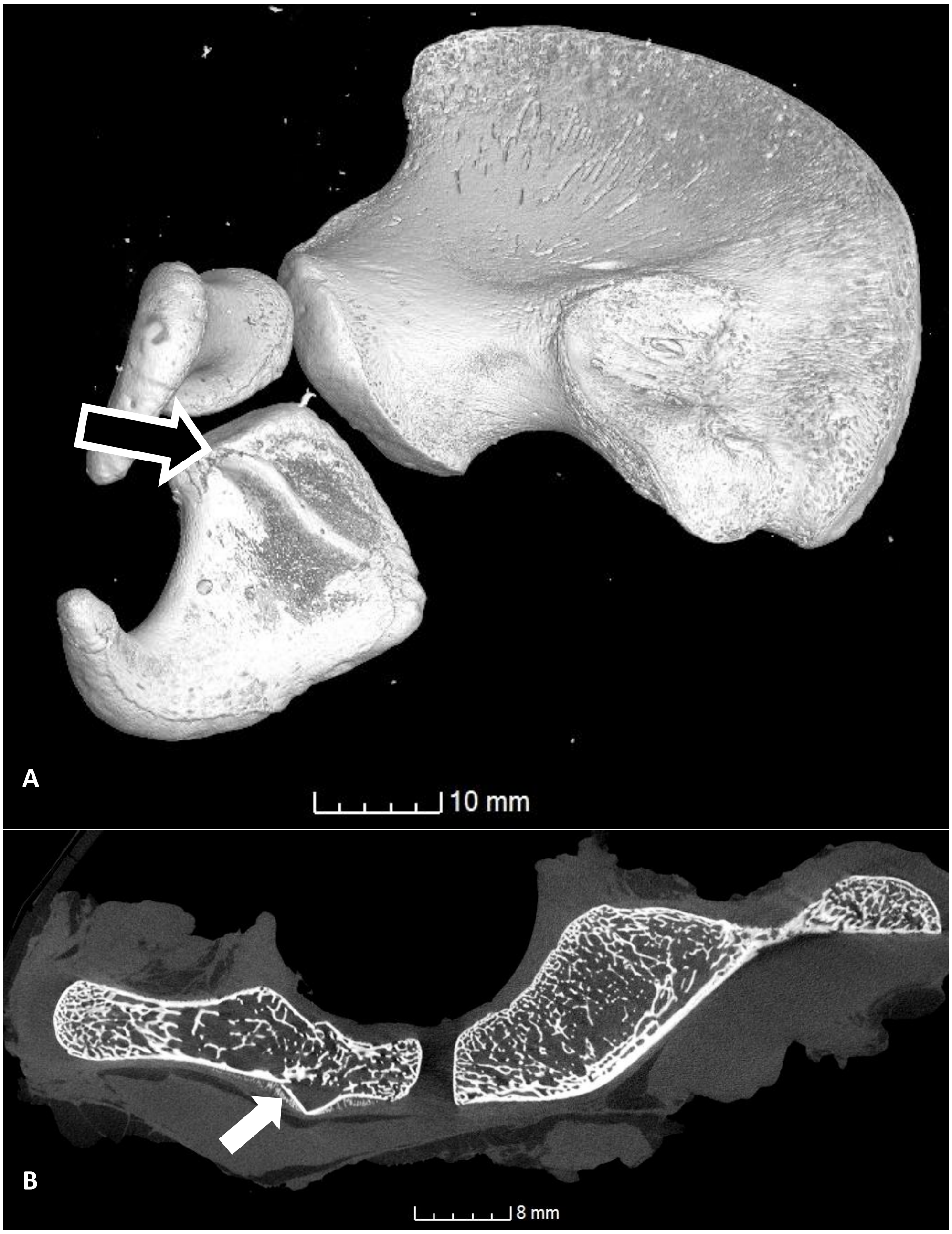


Figure 31: A: 3D model of the right pelvis of OP Rococo showing an anomaly on the internal side of the ischium (arrow). B: Cross-section through the anomaly showing early callus formation as fuzzy light material (arrow).

A similar case was that of a one-month-old male infant (OP Picture). Numerous fractures were encountered on the radiographic skeletal survey and at autopsy, instigating the micro-CT examination. These scans revealed multiple metaphyseal fractures, a spiral fracture of the left humerus, fractures through the right humerus and clavicle, the sternum, and the parietal. The ribcage displayed both anterior and posterior fractures. The majority of the injuries, except on the anterior ribs and on the parietal, exhibited new bone formation associated with fracture healing. The callus on the ribs was less mature than some of those observed in OP Rococo and took the appearance of a light, fuzzy halo around the sample, similar to the two to five days old ones in OP Rococo. This suggested an injury age of less than a week prior to death, or even more recent as it has been suggested that younger bones are known to heal more quickly, although the evidence base for this is somewhat unclear (Kraft 2011, Malone et al. 2011, Pickett 2015). The histology report in this case was not available for comparison. Different callus appearances from three of the cases are illustrated in **Figure 32**.

The possibility of a postmortem date for the fractures was raised in OP Vault. Rib fractures were noted at postmortem but the body of the victim was partly decomposed, meaning it had been left exposed to the environment for some time thereby increasing the chance of the fractures being a postmortem artefact. On the micro-CT images the fractures had the same appearance as perimortem fractures in other cases as they appeared to have occurred in fresh bone without signs of healing. Because of the decomposition, histology could only narrow this down to anywhere between 12h prior to death and few days thereafter. In this case, the context and the defendant's account were the most informative pieces of evidence.

All remaining cases were instances of perimortem trauma where the timing was not the disputed aspect.

4.5 Accidental v non-accidental

The distinction between accidental and non-accidental causes is crucial from the very first stage of the Criminal Justice Process which leads to the decision whether a crime has taken place at all. This usually depends on the circumstances and witness accounts which are often sufficient to decide whether the case is treated as suspicious. Examining the injury is therefore not required to form this decision. In other cases the suspicion cannot be sufficiently confirmed or ruled out necessitating detailed analysis. A specific type of injury frequently examined at this stage is rib fractures. These are particularly contentious as they are often observed in cases of child abuse where it is frequently claimed that they were caused by resuscitation attempts (Bilo et al. 2010). Complete ribcages were scanned for five separate cases and individual excised ribs in one (OP Coal). The deceased in all six was a toddler of less than two years age.

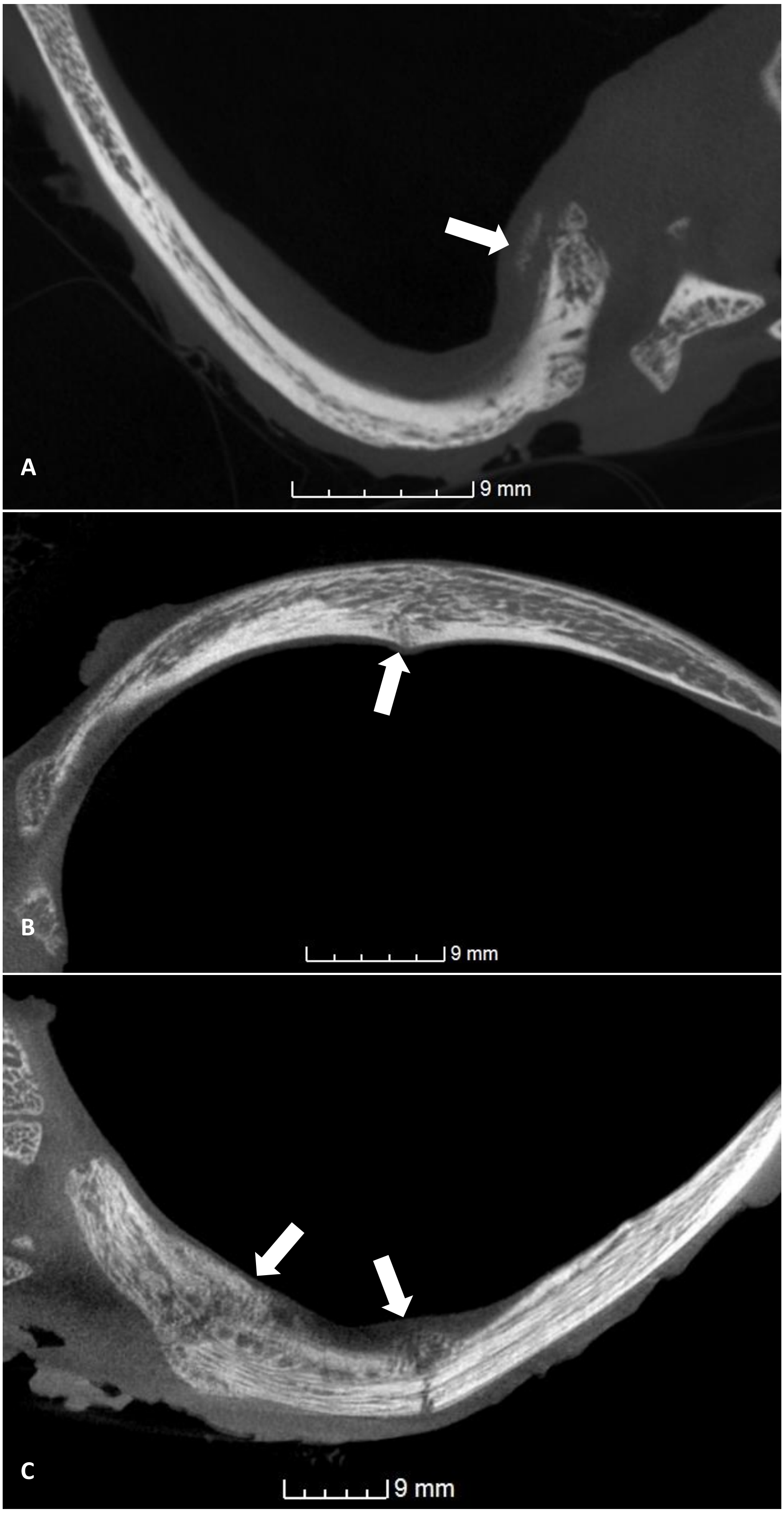


***Figure 32**: Different appearances of calluses around rib fractures of three different cases. A: OP Picture, no fracture age provided; B: OP Melba, no fracture age provided; C: OP Rococo, the fracture closer to the rib head dates to 1-2 weeks before death, the other one to 2-5 days before death.*

In one case (OP Hotel), the decision at gate two was that no crime was committed and that the rib fractures were likely to be caused by CPR following a natural death. This decision was reached based on histology data regarding their timing and the distribution of the fractures as interpreted by the pathologist. This case was submitted for micro-CT scanning due to the discovery of anterior rib fractures at autopsy. However, only the posterior half of the ribcage was scanned, the anterior injuries were therefore not imaged. No damage was seen on the sample and the histopathologist, who examined the entire ribcage found the anterior fractures likely to be caused by CPR. In all other cases the suspicion was upheld.

In OP Coal only the right second to fifth ribs were scanned. They all displayed subtle fractures on the rib heads with small detached fragments of bone. In OP Melba the thorax was micro-CT scanned as the skeletal survey performed in hospital was believed to show a minimum of one healed posterior rib fracture and recent fractures on the anterior ribcage. The healed fracture was confirmed on the micro-CT scan but no evidence of the possible further antemortem ones was found. A symmetrical pattern of anterior fractures was seen on the left and right second to fifth ribs.

In OP Pitch fractures were identified on the anterior ribs (left second to seventh ribs and right first to seventh ribs) and on the posterior rib heads (left first to ninth ribs and right first to eighth ribs). None showed any evidence of healing. Further information regarding histopathology results and case outcome could not be obtained.

For OP Sarsar the entire ribcage was examined because of subdural haematoma found during autopsy, along with “damage on the ribcage” described by the pathologist in the preliminary postmortem report. Two subtle fractures through the costochondral junction of the left sixth and seventh ribs were initially observed on the micro-CT images. Further suspicious areas were identified but they could not confidently be interpreted as fractures. They were confirmed as fractures during the second examination after the histology results had been consulted. **Figure 33** shows an example of these anomalies illustrating their subtlety.

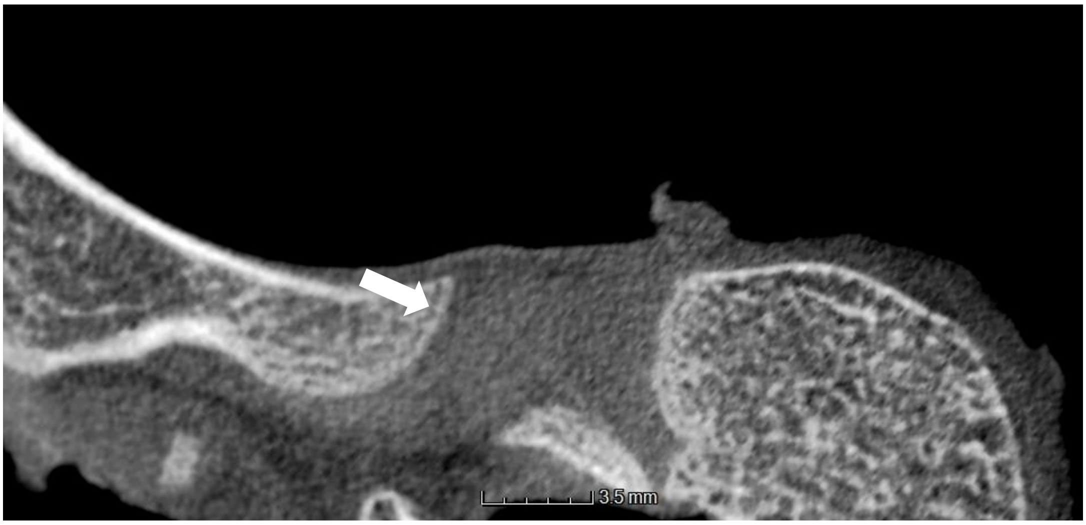


__Figure 33__: 2D section through the head of the left fifth rib of OP Sarsar. The arrow indicates the subtle anomaly which was confirmed as a fracture with histology.

The specimen was further examined by the histopathologist who provided an age of 12h-2days before death for the previously identified fractures. However, further fractures were discovered on the posterior rib heads as well as additional ones on the anterior aspect. The posterior fractures dated to between one and three days prior to death which indicates that there could have been one episode of trauma or two separate ones. When reviewing the original micro-CT scans based on this information, all but one of these fractures could be identified. They were not initially interpreted as such due to their subtle appearance combined with interpreter confidence/lack of medical training. It is further possible that higher resolution could increase the correct identification of fractures. All cases examining complete ribcages were limited as the sample would occupy almost the maximum possible object size (28cm diameter). A focus on individual ribs would allow a resolution closer to that of the histology examination. The timing of the fractures ruled out CPR as a cause (the child had been on life support for less than a day) and maintained the suspicion of child abuse. No healing process could be observed on the micro-CT images. This case was used as an example to validate micro-CT as a method for forensic fracture analysis by comparing it to the current gold standard of histology (**Figure 34**) (Baier et al. 2019). The pattern of rib fractures was consistently symmetrical for all complete ribcages examined with left and right sides generally showing the same number of fractures at the same level. This applied to the anterior as well as the posterior fractures.

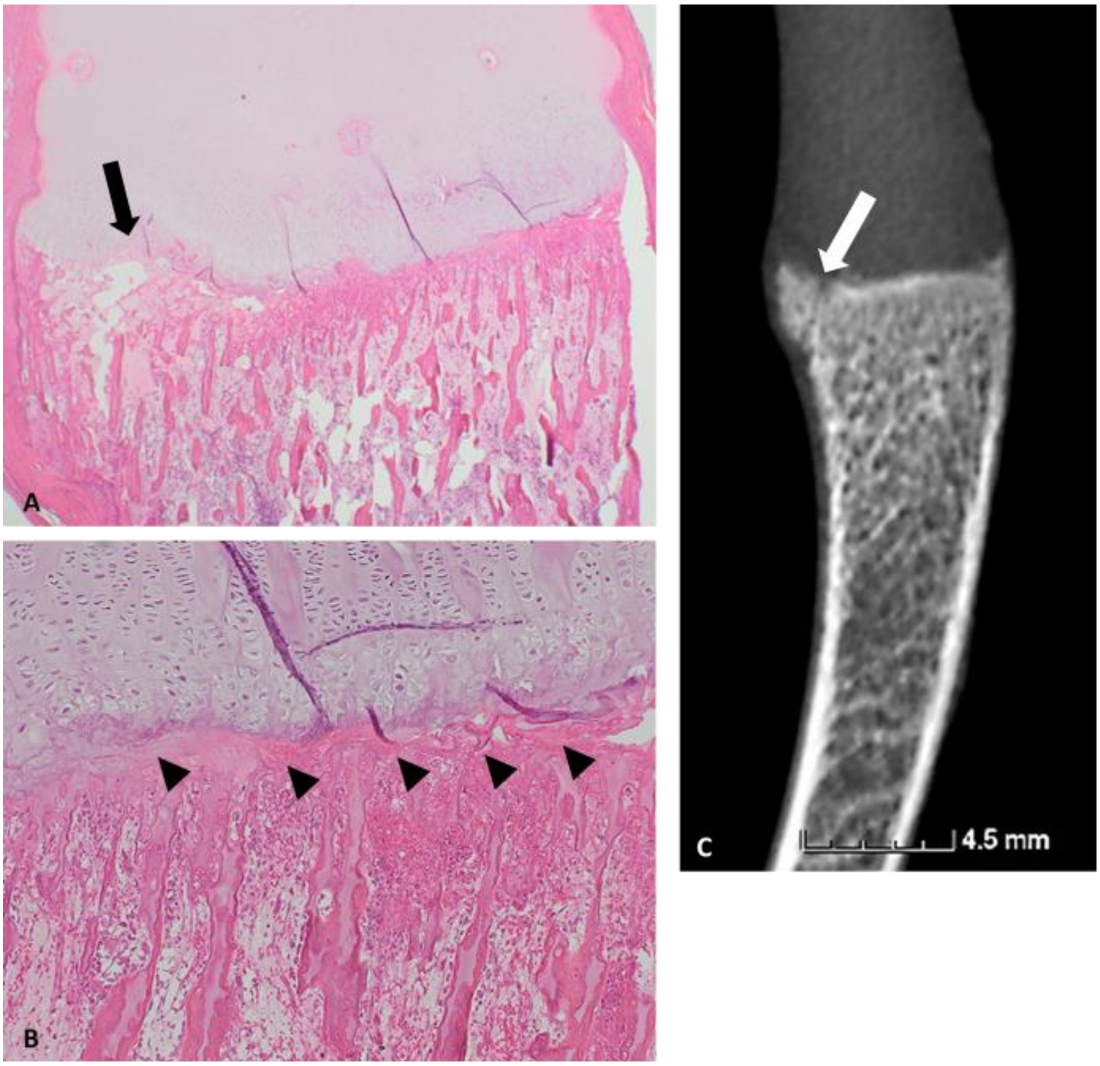


Figure 34: Histology slide showing the anterior fracture of the left 6th rib. A: x2 objective, B: x10 objective; H&E stain. Through the x10 objective the fracture can be clearly seen to run along the costochondral junction (arrow heads). C: Micro-CT image of the injury (arrow). From Baier et al. (2019).

The above mentioned cases OP Rococo and OP Picture revealed more distinct evidence of child abuse as seen in the injury pattern spread over multiple skeletal elements. The presence of posterior rib fractures, spiral fractures of the longbones, and metaphyseal fractures are often considered diagnostic of child abuse (Kemp et al. 2008). The fracture in OP Rococo is shown in **Figure 35**. In addition, both cases showed evidence of neglect since many of the fractures did not receive any medical intervention such as immobilisation, causing repeated re-fracture and excessive callus formation. No other explanation for these injuries were given by the defendants.

***Figure 35**: Volume rendering and coronal section through the right femur of OP Rococo. The excessive callus formed around the misaligned, untreated fracture shows evidence of re-fracturing and areas of different callus maturity.*

4.6 Visualisation

A visual representation of blunt force injuries was used in every report written for the investigators and pathologist showing both 3D and 2D representations of the fractures. The 3D view in particular was thought to improve people's understanding of where in the body the injury is located based on existing research in the field (Urschler et al. 2014, March et al. 2004). For one case[6] (OP Twist), the author was asked by the pathologist to visualise an existing hospital CT scan of a head injury in 3D in order to better understand the fracture propagation as the hospital CT issued to the pathologist did not contain the 3D rendering. This demonstrates the benefit of the 3D view which pathologists clearly value in their line of work. Three-dimensional views were also used in OP Rococo to create a court presentation featuring video clips of the volume-rendered scans. Different stages of healing were coloured differently to make the results immediately visible and comprehensible as demonstrated in **Figure 38**. In two cases (OP Argon, OP Rococo) the scan was further visualised by creating a

[6] This case was not included in the overall BFT analysis as no associated case information was included and the sample was not actually micro-CT scanned. It is in addition to the twelve main cases.

3D print which was then used in court as a visual prop in OP Argon (Baier et al. 2018). For OP Rococo it was mainly used as a visual aid during the investigative phase but did not end up being shown in court as defence counsel objected to its presentation. From the interviews it was extremely powerful in understanding the extent of the damage and giving a “feel” for the became clear that the 3D prints, the one of the leg being shown in **Figure 36**, were considered force applied. The process from initial scan to final print is illustrated in **Figure 37*.***

Figure 36: *3D print of the femur scanned for OP Rococo. The callus was printed in semi-transparent to show the displacement of the two shaft fragments which were printed in white.*

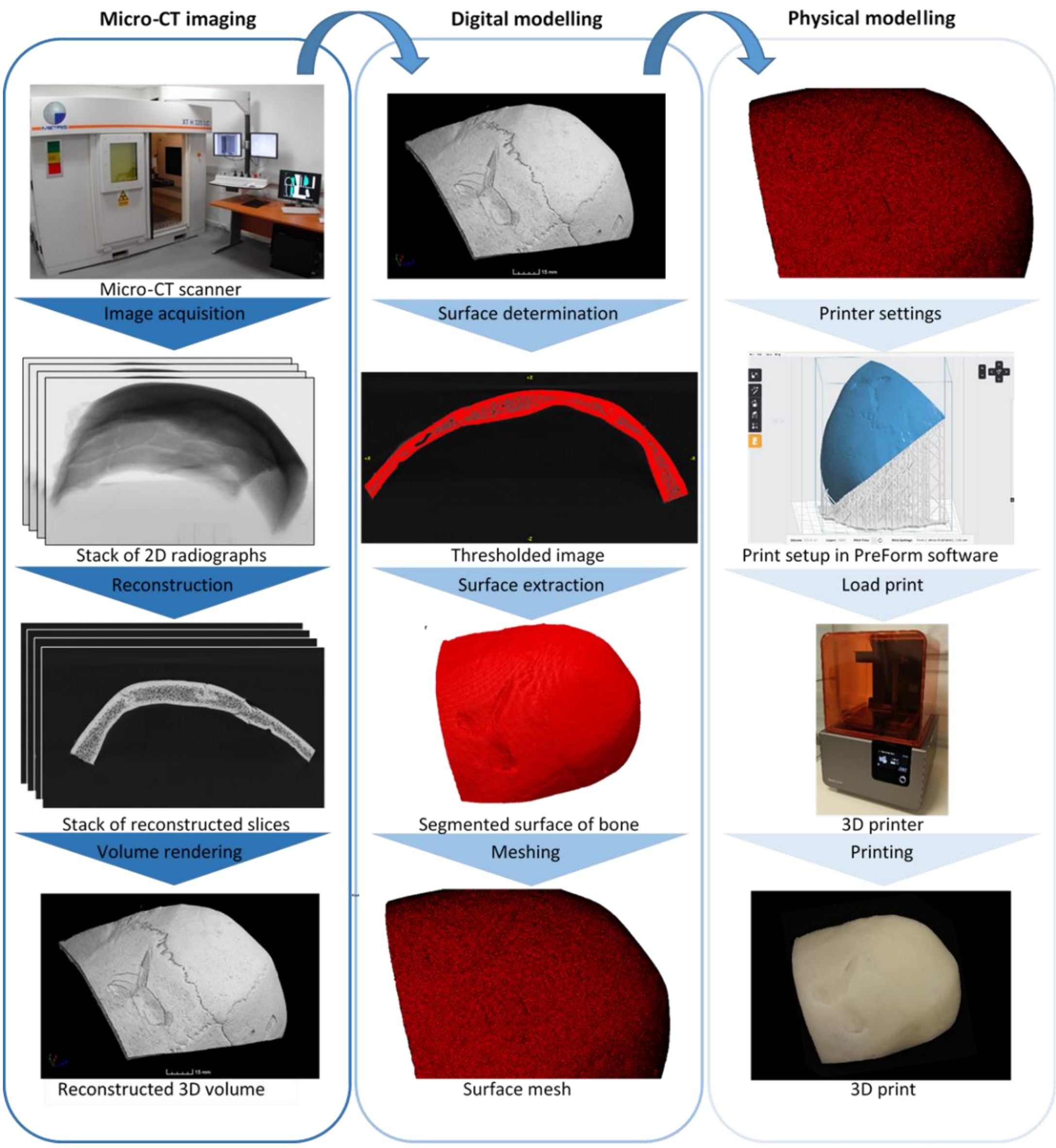


Figure 37: *Complete work process involved in creating the 3D print for OP Argon which was shown in court to illustrate the complex injury pattern seen on the skull fragment. From Baier et al. (2018).*

3D printing is a generalising term for Additive Manufacturing (AM) technologies of which there exist a plethora (Vaezi et al. 2013). AM was originally thought of as a rapid prototyping method in industry but has since evolved into a standalone manufacturing tool (Gibson et al. 2015). The possibility to create any freeform shape has also been realised by the medical community who use it for patient-specific implants (Jardini et al. 2014) or treatment planning and education (Bagaria et al. 2011). In a forensic context, 3D prints have been used in court, for example to visualise trauma (Kettner et al. 2011).

5. Discussion

5.1 Micro-CT v medical CT in BFT analysis

Hospital CT has frequently been used in cases of Blunt Force Trauma in both clinical (Grassberger et al. 2011) and forensic settings (De Bakker et al. 2016). Numerous studies have been conducted to compare medical grade CT to conventional autopsies and these highlight its benefit for BFT analysis (Krentz et al. 2016, Le Blanc-Louvry et al. 2013, Leth et al. 2012). Its main advantages are cited as detecting trauma in inaccessible regions and to a more complete extent without losing the spatial relationship of loose fragments (Kettner et al. 2011). Medical grade CT has the further advantage that the whole body can be scanned which is particularly useful if there is multiple trauma. The question therefore is whether micro-CT adds any benefit to the existing CT technology. The answer to this question lies with the increased detail of micro-CT scanning which has been demonstrated to be a great asset to forensic fracture analysis in certain cases. While hospital CT is less restricted by the sample size, micro-CT can then be used to examine selected trauma in more detail, as for example done by Brown et al. (2011). This was particularly useful in the two cases involving weapons where the tool imprint was seen more clearly with micro-CT. While many cases can be sufficiently imaged using regular postmortem CT, it is the subtle injuries and smaller, more delicate samples where micro-CT has proven to be essential. De Smet et al. (2015) have demonstrated how cone beam CT improves the detection of small bone and joint fractures and the cases presented in this thesis have highlighted how micro-CT has a similar or even more pronounced effect. This bears the most significance for the juvenile cases which involve smaller elements and often fractures which only involve a small section of the joint ends. While gross injuries and calluses are generally detected on both radiographic and CT skeletal surveys, incomplete or subtle fractures are not. This problem has been reported in the literature; plain 2D radiographs in particular have been criticised for not showing enough detail due to superimposition (Arthurs et al. 2017, Hong et al. 2011). This has become apparent in the present study as some of the ribcages were micro-CT scanned following the detection of injuries in hospital. The number of injuries counted on the micro-CT models often exceeded those identified earlier. However, it has also been noted in OP Sarsar that while the injuries were visualised on micro-CT, they were not always interpreted as such during the initial examination, especially if the scan resolution had been affected by the sample's larger size. This raises the question of whom should inspect the original scans. The researcher in this project has no formal training in radiology/postmortem CT interpretation which might have caused them to exclude some anomalies as fractures in this particular case due to low confidence in identifying small features. It would be beneficial to such cases if the examining pathologist would inspect the original scan data as opposed to only the prepared report. This was not practical as the data could not readily be transferred to them due to file size and required specialist viewing software and pathologists have very busy schedules which prevented them from coming to WMG to inspect scans here. The same applies to the histopathologist who frequently examined samples following the micro-CT scans. After the first few cases it became standard practice for them to ask for the reports before commencing their own work, especially in cases of suspected Non-Accidental Injuries. The benefits of this arrangement will be discussed in more detail below and in the interviews in Chapter 9.

5.2 Validation

Working closely with other experts led to the realisation that an ideal work process would be to conduct the micro-CT scan, process the scans, and then analyse the images together in order to allow the histopathologist to plan their procedures accordingly. This would improve the correlation between the two methods which has the potential to further validate micro-CT as a method and develop its use further, possibly allowing fracture ageing at some point in the future. Few studies have examined fracture age using micro-CT as it is a difficult experimental set-up (Shefelbine et al. 2005, Morgan et al. 2009). A validation study was therefore conducted as part of this PhD project comparing the micro-CT manifestation of fractures to that of histology, albeit not focussing on the fracture age but rather on the presence/absence. This study found a good correlation in the detection of bone fractures but recommends further research on a wider range of samples. The complimentary nature of histology and micro-CT is most pronounced for fracture dating. Calluses of varying degree of maturation have been observed on the micro-CT scans but little research has been done in this field and there are many factors which influence the callus appearance, thus making it difficult to provide precise timings for an injury. In the context of suspicious rib fractures one needs to be aware of the effects of CPR which can sometimes cause the ribs to fracture. While these fractures tend to be found on the anterior aspects of the ribs (Stöver 2007, Weber et al. 2009), a precise timing can only be provided by histopathology. Validation studies are an essential requirement in forensic contexts as previously discussed for strangulation injuries in Chapter 5. In sensitive areas such as child deaths they add an important level of certainty which these cases often lack (Lynøe et al. 2017). The literature review in Chapter 2 has outlined how forensic science evidence has contributed to many miscarriages of justice to which child cases seem to be particularly prone. The problem with the forensic evidence in child cases is often the reliance on opinion evidence (Betts 2013) and a lack of empirical data which is the issue addressed by validation studies. Improving the correct diagnosis of such cases even minutely has the potential to prevent miscarriages of justice from happening and thereby contributing to improve the quality of forensic evidence enabling fairer trials which benefits the whole of society.

The final societal benefit affecting child cases is the public perception of the investigation process. The public and all other stakeholders want to see progress being made but this public pressure to convict a culprit has been partially responsible for investigators' readiness to accept flawed expert testimony in the past (Findley and Scott 2006). Demonstrating that all available resources and technological advances are being exploited can reassure them that police have left nothing untried and raise confidence in their work.

5.3 Visualisation

The visual output of the micro-CT scans of blunt force injuries is a further benefit observed irrespective of the type of case examined. 3D models, both virtual and physical, can increase the comprehension of the fact finder as several studies indicate (Urschler et al. 2014, Petersson et al. 2009) and which multiple interview respondents confirmed (see Chapter 9). Any visualisation of traditional autopsy evidence, especially from child deaths, in court is problematic as it is considered too emotionally upsetting for the jury (Errickson et al. 2014). However, the micro-CT models were perceived as sufficiently abstract since they only showed selected elements that were less reminiscent of an actual individual. A selection of images shown during the trial of OP Rococo is provided in **Figure 38**. Displaying these models digitally in larger-than-life further reduced the perception of the sample as being an actual human infant body part. 3D prints were more contentious to introduce as evidence as they were printed on a 1:1 scale, reminding people again of the reality and the vulnerability of such a small human being. The researcher observed this effect on themselves as well. Despite having scanned and examined the original samples of OP Rococo it was not until holding the 3D prints that they became fully aware of the size and fragility of the victim. This sparked feelings of disbelief how someone could cause such injuries to a child and also anger towards the perpetrator(s). This effect has also been noted by Bright and Goodman-Delahunty (2006) who studied the effect of graphic images on a mock jury. They found that by showing them such images their rational decision-making decreased while the likelihood of a guilty verdict rose. Forensic scientists are not immune to these effects. Subconscious bias can, as shown in Chapter 2, cause the forensic scientist to draw rash or incorrect conclusions based on the circumstantial information they received prior to their examination (Bernstein 2008). The dilemma in practice is that on the one hand some information is necessary to adequately interpret the findings, on the other hand too much information might lead to the scientist seeing what they expect based on the information. The dangers of cognitive bias is becoming increasingly recognised in forensic science and careful case management is required to mitigate the effects (FSR 2015).

5.4 BFT analysis in the CJP

Relating these findings back to the management concepts introduced in Chapter 2 demonstrates their applicability to the investigation of Blunt Force Trauma. For infant deaths, micro-CT demonstrated value from stage one onwards. Because of the plethora of possible causes for sudden infant deaths (Athanasakis et al. 2011), the initial phase of the investigation is critical as it needs to be established whether a suspicious case could reasonably be due to natural causes. This decision affects everyone related to the case. From an emotional point of view, this is the most difficult part for the child's parents or carers who might see themselves facing charges for child abuse and/or murder. This means that investigators in this particular stage are under enormous pressure to make this decision as swiftly as possible to avoid unnecessary emotional distress. At the same time, the First-Time-Right principle is even more imperative than anywhere else in the system as mistakes at this stage can result in the miscarriages of justice described in Chapter 2. The experience of being wrongfully accused of murdering one's child can be life-changing and traumatic. This confirms Baxter's (1995) observation that resources invested into the early stages of the process help reducing the risk of failure or even more expensive measures further along the process. As Cooper (1990) notes, every step in the stage-gate system is more expensive than the previous one. While this refers to financial costs in management texts, it is also accurate in terms of social costs in the CJP. Having concluded that a death is suspicious, micro-CT has been involved in stage two as well. Using OP Rococo as an example, this investment into creating 3D printed models during the investigation stage paid off during the trial preparation. The emotional value attached to the model of the fragile leg bone caused defence counsel to object its admission. According to the investigators involved the defence were in an unwinnable situation. If they admitted the object it might have such an impact on the jury that they would be more ready to convict but not admitting it just demonstrated the weak position they were in already (see Chapter 9 for more detail). While this might be a desirable effect from the prosecution's perspective, it opens the use of 3D prints to criticism. This emotional power of persuasion is exactly what scholars have cautioned against (Kassin and Dunn 1997, Fowle and Schofield 2011) and rightly so it seems from the above comment. The defence is the first safeguard, followed by the judge's decision to admit or reject the evidence although evidence is rarely rejected if none of the parties object (Dixon and Gill 2001). However, in this particular instance it seems as if the traditional trial safeguards had fulfilled their role.

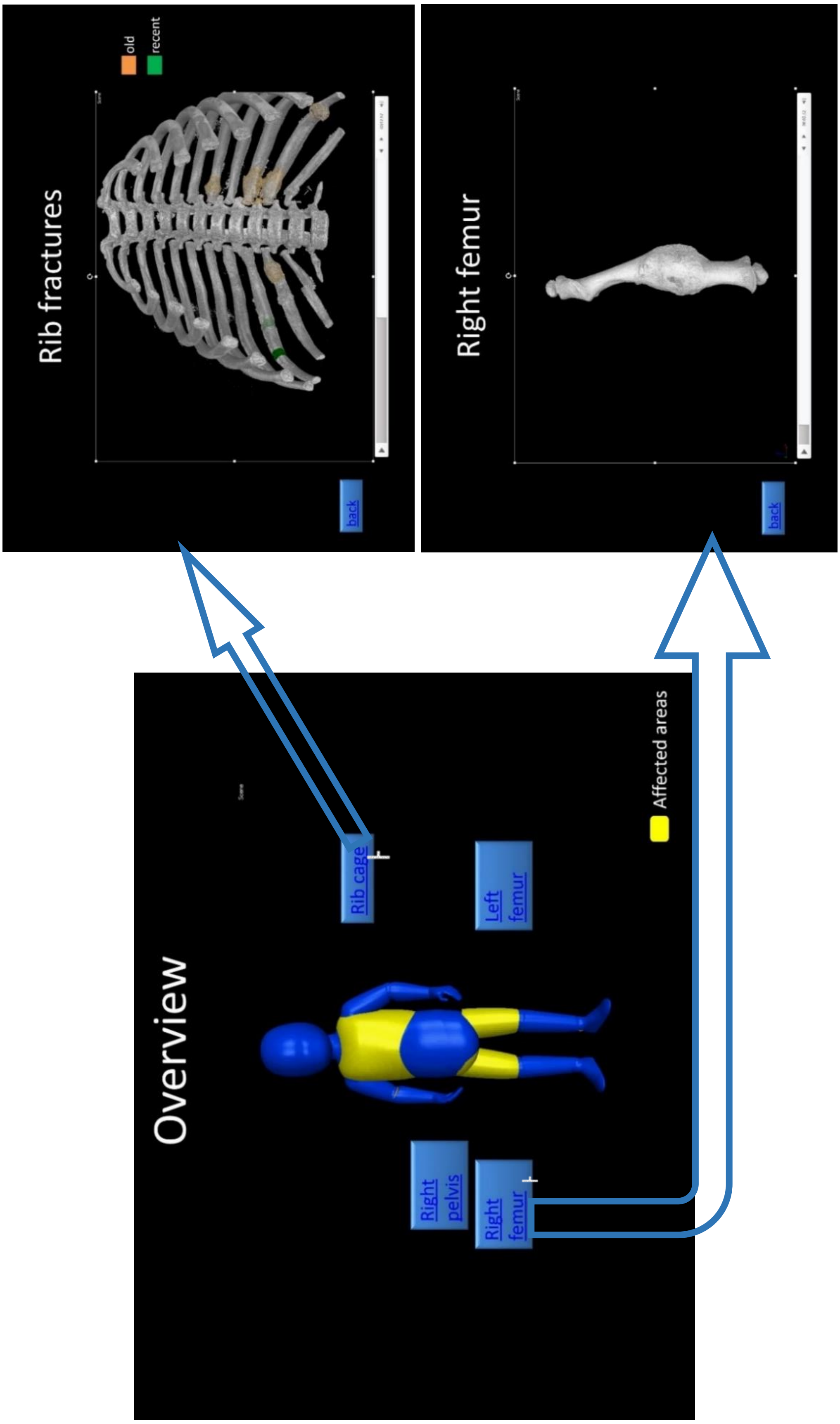


***Figure 38**: Slides from the court presentation prepared for OP Rococo. The left slide is the opening slide showing in yellow an overview of the body elements that were micro-CT scanned. Each button would open a hyperlink to a video animation of the relevant part, seen on the right.*

Overall, micro-CT has contributed to the quality aspect of deliverables, although this only affected limited number of homicidal BFT cases encountered by pathologists as hospital CT is sufficient for the majority. The main contribution is to the delivery component and in selected cases perhaps the cost element that is often related to the delivery. However, it is not possible to clearly distinguish these three components as they are all inter-related. Taking OP Rococo as an example the quality of evidence was improved by the images which at the same time constitute the delivery before the court. In OP Rococo it was postulated by several individuals who had been involved in the case that using these images and animations the trial could be reduced by approximately three to four weeks, thus also saving resources.

6. Summary

This chapter has presented the objectives for conducting BFT analysis of forensic cases, which are the determination of the injury mechanism, the amount of force used, the timing of the injuries in relation to the time of death, and whether a fracture has been caused by accidental or non-accidental means. It has become evident that the main benefit of micro-CT can be found in the examination of suspicious infant deaths due to the increased detail required in such cases. This has been particularly crucial to one case where micro-CT detected additional injuries not identified by the current gold standard histology.

Different stages of callus formation were observed but precise fracture timing relied on histology. Some of the cases examined in this category also served as part of a method validation study which compared the micro-CT findings with the histology and which found overall good correlation of these methods.

The chapter has further discussed the use of visualisation techniques to relay this information to a range of audiences, both lay and professional. Animations and 3D renderings provided powerful visual support, especially in court, while 3D prints were treated more cautiously due to the potential prejudicial value. The added benefit was such that pathologists requested 3D representations to improve their understanding of individual fractures.

These points demonstrate how micro-CT can be used during all stages of the CJP. Initially to determine whether a crime has occurred, then to support the medico-legal death investigation and then to prepare and present court material. The images can even affect the final gate – the verdict.

Blunt Force Trauma is the third and final major case study of this thesis, the following chapter provides an overview of cases that did not fit in any of the three previous categories but which are nonetheless important to mention.

Chapter 8: Miscellaneous cases

1. Introduction

The previous three chapters have focussed on frequently encountered types of homicide covering the majority of cases investigated by WMP. Some of the cases examined over the course of this project do not fit these three categories but they nonetheless deserve to be discussed to demonstrate the range of applications of micro-CT. They can further be used to illustrate some of the method's limitations. Many of these samples were scanned as exploratory cases without a dedicated agenda for the scan resulting in a varying degree of helpfulness. This chapter presents four such cases: two of which involved human remains and two which involved inanimate objects. Each will be presented with some case background, a description of the sample and how the scan was used, followed by a discussion of their relevance within the overall project and the wider forensic literature.

2. OP Western

Police contacted WMG with the request to scan a skull which was found alongside the rest of the individual's skeletonised remains near a motorway slip road. The anticipated outcome was a 3D model which could be used as the basis for facial reconstruction in order to identify the individual. The sample occupied the maximum volume of the Nikon 225/320LC micro-CT scanner (28cm diameter) but was successfully scanned using the following settings: 170kV, 174µA, 708ms exposure, 24dB gain, 119.5µm resolution, and 3141 projections. The scan was reconstructed into a 3D model (**Figure 39**), which was then converted into an STL file for the facial reconstruction expert to use. However, this was not necessary in the end since the individual was identified through DNA in the meantime. The reason for choosing to base the facial reconstruction on a micro-CT scan as opposed to the usually employed laser scanner was the increased level of detail that can be achieved with the former. More detail on the original data might lead to a more accurate representation of the individual's face, thus increasing the chances of identification. Investigators were shown the skull model in 3D in WMG's visualisation suite to which the general impression was that the 3D visualisation allowed to imagine the deceased's facial features. While this has no scientific backing, it still demonstrates the power of three-dimensional outputs.

Figure 39: *Volume rendering of the skull scanned for OP Western. The detail could have been used for facial reconstruction if necessary.*

3. OP Crescendo

The sample examined for OP Crescendo was a neck block which was extracted from an individual who had been fatally shot in the neck. Gun-related deaths are becoming more frequent (Office for National Statistics 2018) but this was the only scanning request brought to WMG. The pathologist in this case decided to submit the sample for scanning as a trial case to explore the applications of micro-CT to other fields of investigation but there was no real anticipated benefit to the police investigation by performing the scan. The equipment used was the Nikon 225/320LC scanner at 138kV, 609µA, 354ms exposure, 30dB gain, 108.4µm resolution, acquiring 2750 projections. While more projections result in a better reconstruction it was decided to reduce the number of projections in order to reduce scanning time. This was necessary because the sample consisted almost entirely of soft tissue which has been observed to cause motion artefacts when the tissue warms up. This might be due to tissue expansion or decomposition processes. Conducting the scan of the sample proved to be less straight forward than previously scanned samples because of the gunshot residue contained within which caused metal star artefacts shown in **Figure 40**.

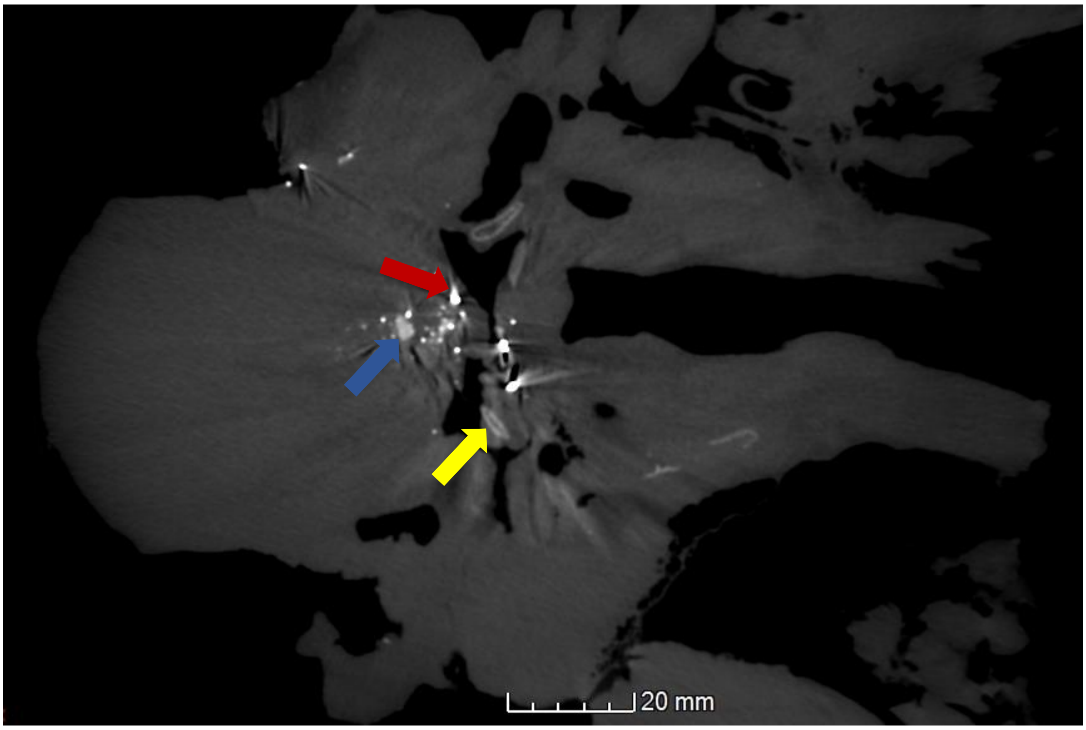


***Figure 40**: 2D section through the throat sample in OP Crescendo. The different types of material (metal- red arrow, possibly glass- blue arrow, bone-yellow arrow, soft tissue- surrounding matrix) can be seen in the scan. The star-shaped bright streaks are artefacts caused by the metal.*

The scan images showed the approximate wound track along which particles of different sizes and densities were scattered. The bullet itself was deformed and lodged in the soft tissues of the neck as shown in **Figure 41**. The different particle densities were interpreted as actual shot, bone fragments from the damaged mandible, and glass fragments (**Figure 40**). The latter was based on the case information that the victim had been shot through a car window, demonstrating the importance of some context for the interpretation of the scan images. While the scan data produced interesting images of the distribution of fragments, they were not essential evidence as it was clear from the forensic postmortem how the victim had died.

__Figure 41:__ Volume rendering of the neck structures of OP Crescendo. The dense white particles are gunshot residue and debris, the hazy grey areas the soft tissues of the neck. The difference in material densities limited the scan quality.

4. OP Bowie

The first case involving inanimate objects was not related to a homicide investigation. The sample in question was a pack of beans from a big supermarket that was scanned as part of a food tampering investigation. Sharp metal objects such as pins and needles had been discovered in other bags of the same batch and metal scanning by the supplier had identified the exhibit as containing metal. The pack was carefully wedged into a block of floral foam to hold the beans upright during the scan as in this position the maximum diameter was lowest. The foam has a very low density and therefore does not show in the scan. The sample was scanned on a Nikon 225/320LC micro-CT scanner at 115kV, 95µA, 708ms exposure, 30dB gain, 0.5mm copper filtration, 98.6µm resolution, and 3141 projections. The scan image in **Figure 42** shows the beans containing the foreign objects. Investigators were put in contact with WMG by one of the CSCs hoping that the scan would answer the question of where in the production chain the tampering occurred.

The scan showed a higher than expected number of foreign objects including pins with heads, pins without heads, and a larger sewing needle. A total of 25 objects were encountered, one per bean except for the sewing needle which was accompanied by another pin. The types of pins were similar to those recovered previously by customers. However, the foil wrapping of the beans included small perforations which had a diameter larger than the pins. The metal objects could therefore have been introduced before or after packaging by using the existing perforation thus not damaging the packaging. It could not be established from the scans whether the beans were contaminated prior to packaging or thereafter, therefore not answering the scan objectives.

***Figure 42**: Volume rendering of the bag of beans scanned for OP Bowie. The pins and needles can be seen as dense white material at the top of the bag. The plastic foil of the packaging could not be sufficiently visualised.*

5. OP Bullfinch

The final case in this section was related to a homicide inquiry although the exhibit in question is the valve of a gas cooker. The offender had started a fire in an attempt to conceal the traces of the homicide. The fire was put out swiftly and the gas cooker was examined to determine if the offender had planned to cause even more damage. The external switch had no markings which made it impossible to determine whether it was in an open or closed position. A scan of the valve was hoped to answer this question non-destructively. The valve was scanned using a Nikon 225/320LC micro-CT scanner at 215kV, 28µA, 1000ms exposure, 24dB gain, 0.5mm copper filtration, 100.5µm resolution, and 3141 projections. The sample in its evidence bag was placed on the stage so that the majority of its cylindrical components were in line with the rotation axis. The scan images were clear enough to see the internal structures of the valve but an assessment of its actual position required more mechanical knowledge than the examiner had. The outside and the internal mechanism are shown in **Figure 43**. The CSC who had submitted the job contacted the fire investigators to have them examine the scans but no action followed, presumably because this was not a central argument to the homicide investigation.

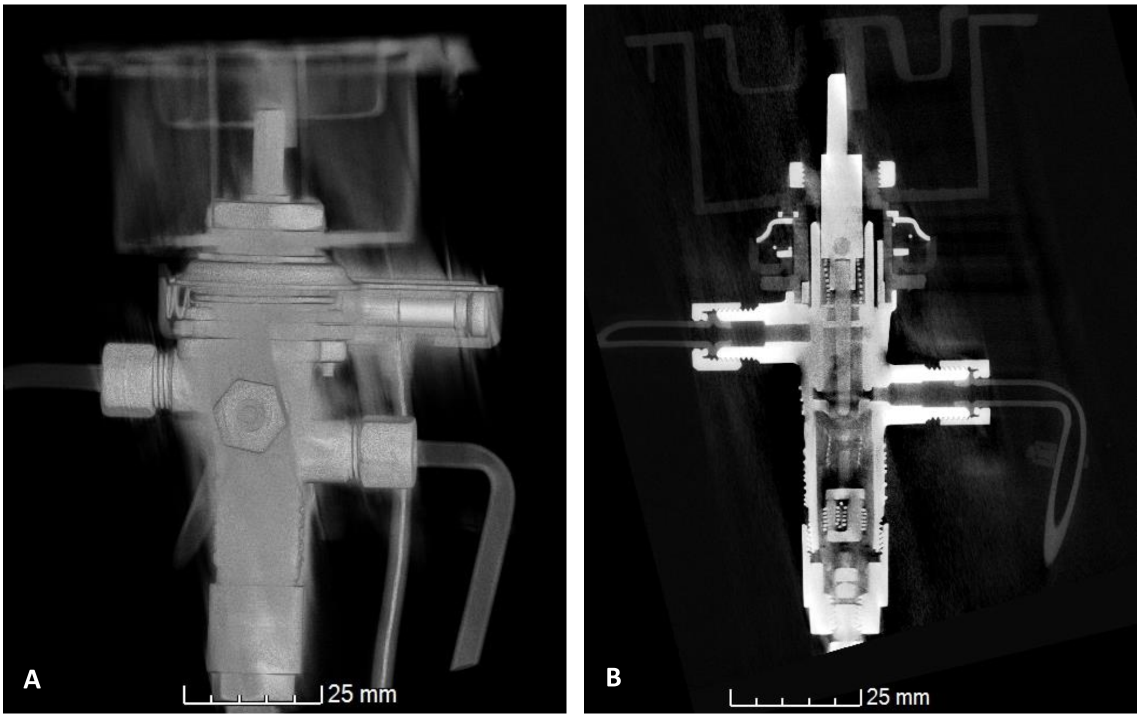


Figure 43: *A: volume rendering and B: 2D vertical section through the gas valve scanned as part of the investigation of OP Bullfinch. The section shows the internal mechanism in a non-destructive way.*

6. Discussion

The literature review in Chapter 3 has presented a range of potential forensic applications for micro-CT but few were based on actual cases. Only a few of these examples were examined, possibly due to the rarity of some or due to the fact that investigators were unaware that micro-CT could be useful in a particular case. This demonstrates the importance of involving police staff in the research side of the project so they become aware of the range of possibilities. The opportunity to test these often experimental applications on actual cases is one of the project's main benefits as it transforms theoretical research into applied research.

6.1 Stage-gate system evaluation

All the cases presented in this chapter contributed interesting facts about the application of micro-CT to a range of cases which are not exclusively homicides. Due to the nature of the investigations the full potential of the micro-CT scans was not used and it was limited to stages one and two of the stage-gate system. In the first case, it would have been interesting to see if the CT-based facial reconstruction produced different results to the standard method and how it would be rated by the practitioner. Another chance for that was provided in OP Neaphouse as the dismembered remains in this case had not been identified and a facial reconstruction was hoped to shed light on their identity. However, no evidence could be obtained at the time of writing. Facial reconstruction is an essential part of the initial investigation as the identification of the deceased is often the first step towards establishing whether a crime has taken place at all (Cattaneo et al. 2010). This in turn affects all subsequent stages.

The examination of gunshot wounds can in some cases contribute to the second stage of the process since the case would be considered suspicious upon discovery of the injury, thereby skipping the first stage. Fais et al. (2015) have demonstrated that in an experimental setup micro-CT can be used to determine the firing range which might affect some cases. It could further be used to examine striation marks on the bullet in order to identify the gun that fired it (Banno et al. 2004), demonstrating some overlap with toolmark analysis.

In OP Bowie the scans were used in the second stage as it was clear that this amount of well-placed hazardous objects could not be an accident. Similarly, the scan of the gas valve was only part of stage two as it had already been established that the perpetrator had committed arson. Had the gas valve been a central piece of evidence then it might have been used during trial showing the original position of the switch without having to destroy the exhibit. This would have been a suitable case for a 3D print which could have been shown in court to explain the mechanics of the sample.

6.3 Forensic opportunities

In OP Crescendo a study of the particles within the wound track could have provided insight into the behaviour of a bullet after entering the body. A brief analysis showed the dispersal of fragments according to size but does not take into consideration the fragment material. In emergency care CT is used to direct the surgeon removing the foreign particles (De Lucas et al. 2004). In forensics the use of PMCT has been used to visualise the general wound tract. However, as the soft tissue retracts there is no clearly visible path (Jeffery et al. 2011). While micro-CT has limited potential for the wound examination of gunshot injuries its strength in this field might be the examination of the bullet. A study by Banno et al. (2004) has revealed the characteristic striation on bullet cases used to link them to the firing weapon. They used confocal microscopy to achieve a three-dimensional view but micro-CT would be expected to produce similar results with the added benefit of allowing automated comparisons.

OP Bowie had great potential but the pre-existing perforation of the plastic bag and the difficulty of imaging this thin foil meant that the scans did not contribute to the overall investigation.

The gas valve examined for OP Bullfinch would have carried more weight if the arson was a central element of the case. It would also have been an excellent opportunity to expand the research network to work with the fire services which would have been useful as there is potential for collaboration in fire investigations, in particular for the laser scene scanning.

6.4 Diversification

These cases also demonstrate the importance of an agenda for the micro-CT scanning. If there is no objective for conducting the scan, the result is only a new way of illustration with varying degree of usefulness. However, it also allowed to explore scanning different materials and the limitations of micro-CT in a forensic context. It could therefore be considered a feasibility study for further investigations. The diversity of cases demonstrates the learning process taking place amongst police staff which is an essential outcome of the project and secures its future continuation. Some of the samples were submitted by scene investigators, while others were submitted by the pathologist which shows how awareness of the technology spread and led to a willingness to help develop its use. Both inanimate objects were submitted by a CSC whose involvement is crucial for non-homicide cases as they attend scenes of all types of crimes and are therefore best suited to expand the use of micro-CT for other issues in the CJS. By establishing contacts between crime scene personnel and detectives from departments other than the CID technology awareness is spread beyond the current scope. Involving different police departments can be useful as staff, and therefore knowledge, move between departments and might work for the CID at some stage in their career. It further opens more potential research areas. As Custers and Vergouw (2015) argue, police are more willing to adopt new technology if its usefulness has been sufficiently demonstrated. This statement has been supported by several interview participants (see Chapter 9) who also agree that seeing a range of stakeholders submitting samples can therefore be considered a sign of acceptance of micro-CT.

7. Summary

This chapter has broadened the spectrum of micro-CT applications in criminal investigations to include non-homicide cases and inanimate samples. This has demonstrated the method's use in forensic engineering cases but has also demonstrated its limitations, in particular in samples containing multiple materials of very different densities. The main learning point from this chapter was the benefit of this particular collaboration which facilitated the exploration of more unusual or uncommon cases. The present and the previous three chapters have presented the scientific impact created by micro-CT, the following chapter will present the overall impact as perceived by different stakeholders through open-ended interviews.

Chapter 9: Interview results

1. Introduction

One of the main research objectives was to investigate the impact created by using micro-CT in homicide investigations. The scientific contribution has been discussed in the previous chapters whereas the present chapter examines the impact on different stakeholders as perceived by them. Some aspects of the impact could be observed from the outside, for example how the images were used in some cases. The impact as perceived by different stakeholders is best assessed through open-ended semi-structured interviews that were conducted with key informants from different sectors of the CJS which had been exposed to the technology. Allowing informants to comment freely on the project further provided the reasoning behind the observable impact which will ultimately help refining and improving how the technology is being used. These interviews were also intended as the predominant source for first-hand information regarding the general processes involved in homicide investigation and for the resources put into it to enable the financial analysis envisaged at the onset of this study. As the results will demonstrate this proved to be more challenging than anticipated. Qualitative methods supported by some statistical information are commonly employed in criminal justice research to evaluate the success of certain measures or to inform future policies (Reiner and Newburn 2008) and give useful insight into the functioning of the CJS. Using key informants as a source of evidence holds the promise of gaining more accurate information than by simple observational or statistical data as it provides in-depth explanations of individuals' motivation and personal views which might differ from the "official" stance. That is assuming that interviewees tell the truth and not some sanitised version thereof. This chapter details the interview process and the analytical methods before presenting the results and finally a discussion of their relevance.

2. Methods and materials

A total of 14 individuals were interviewed for this study, seven from the police CID, three pathologists, and four CSCs. One each from the police and the forensic department occupied high-ranked managerial roles. All participants were selected based on their prior involvement in the cases examined over the course of the PhD project and their contact details were taken from the case files for each case or through personal contacts. The prerequisites to be selected were either involvement in multiple cases or involvement in a particularly high profile case. In addition, the two high-ranked individuals were interviewed to gain further information on the project's impact at policy level. An invitation email was sent to potential respondents detailing the background and aims of the study. Prior to the first interview, the interview plan was trialled on two individuals who also had inside knowledge of the cases. This pilot testing served to refine the questions in order to maximise information output and generally practice interviewing skills and the use of the recording equipment. They were transcribed to allow planning time requirements for the future interviews. Each interviewee was sent a list of cases they had been involved in after agreeing to partake in the study in order. Interviewees were met at their workplaces and interviews took approximately 30 minutes (shortest 23min, longest 52min). All interviews were audio recorded using a Zoom H4n Pro recording device and written notes were taken as a backup in case of technical problems with the recording. The audio files were completely transcribed at the earliest opportunity. Interviews were conducted following guidelines by Arksey and Knight (1999) who provide helpful advice on interviewing technique and preparation.

The question topics were:

1. In relation to this stage-gate diagram, can you describe your work process [investigation/postmortem examination/crime scene examination] and what resources are involved?
2. Where on this diagram would you place the cases you have been involved in where micro-CT scanning was used? How were the scans used?
3. Can you describe your attitude towards micro-CT both at the start of this cooperation and towards the end?
4. Where do you see the main benefits of micro-CT and why?
5. Has the availability of micro-CT affected your line of work [investigation/ postmortem examination/crime scene examination]?

2.1 Analysis

The interviews were analysed using thematic analysis, following the general approach outlined by Boyatzis (1998) and more specifically framework analysis as outlined by Gale et al. (2013). Framework analysis is a form of thematic analysis commonly used to analyse semi-structured interview data (Gale et al. 2013) and has been employed in qualitative research since the 1990s (Ritchie and Lewis 2003). It has proven particularly valuable for organisational policy research (Srivastava and Thomson 2009) which is where the current project fits in as well. It is so popular as it is not restricted to a single philosophical or epistemological approach and offers flexibility in the coding process. Closed coding is associated with deductive research where codes are created based on previous literature or the research questions. Inductive research tends to use open coding where the codes are directly driven by the collected data, but a combination of these two can also be employed. Gale et al.'s (2013) guide is particularly suitable due to their focus on multidisciplinary mixed-method research and the clearly structured protocol. The first stage of analysis requires transcribing the audio recordings into text documents. This also helps to become familiar with the data which is stage two of the analysis process although further readings of the transcripts are required. The third stage is the actual coding where each transcript is read line by line while labels are assigned to bits of information. In the present study a combination of pre-defined (closed) and unrestricted (open) coding was used. The pre-defined codes were based on the research questions and were concerned with aspects of the project impact such as quality, cost, and delivery (time) of outputs. Further pre-defined codes related to the before and after perceptions of the novel technologies. Few open codes were applied as the pre-defined ones covered the majority of the interview content since the interviews were designed to answer these particular questions in the first place. These open codes were mainly used for applications of the micro-CT scans which had not been mentioned in associated case files, for example their use at trial. A total of 67 codes were identified initially. The codes and their descriptions and an example excerpt were examined by a second researcher who would then apply them to five transcripts in order to evaluate their appropriateness and to develop further open codes if necessary. Gale et al. (2013) recommend that a minimum of two researchers should independently code a subset of transcripts as each will bring their own perspective to the codes. Due to the high number of closed codes in the present study it was considered sufficient to use this second opinion as an optimisation for the existing framework. The reviewed codes (n=74) were then applied to all transcripts. In the fourth stage, the codes were then grouped into categories or clusters of similar or related concepts forming the working analytical framework. Twelve categories were identified with between three and 13 codes each (see Appendix E). The categories were: Background on general resources, Background on processes, Background on finances, Financial considerations, Use of micro-CT in investigation, Use of micro-CT in court, Effect of micro-CT on other processes, Pre-micro-CT attitudes, Post-micro-CT attitudes, Police-academia relationship, Applications, and Management concepts. The full list of codes, their descriptions and one illustrative example are illustrated as a word cloud in **Figure 44** to illustrate the most common concepts and frequently used terms.

Figure 44: *Word cloud of the codes used to analyse the interviews. The larger the word, the more frequently it was mentioned in the codes, their descriptions, and examples. Produced in NVIVO (QSR International, Melbourne, Australia).*

This framework was then applied to all transcripts in stage six of the process. This was achieved by using abbreviated identifiers for easier use. The next step involved charting the condensed data into a framework matrix in the form of an Excel spreadsheet showing the individual interviews in rows and the codes in columns. This visualised how certain codes repeat or differ across the interviewees without losing each respondent's context. This led to the final stage, the data interpretation which included identifying patterns, connections, and explanations. As the codes were compared analytical memos were composed once a pattern emerged (Gale et al. 2013). The case-specific information provided regarding the stage-gate system was added to the diagram of the process as a visual aid.

3. Results

None of the respondents objected to the initial representation of the stage-gate system or its appropriateness to the CJP. Furthermore, the respondents mapped the majority of cases in the middle stages of the process, only two were plotted at stage one but none past the fifth stage (see **Figure 49**). However, not all cases were discussed in detail in the interviews as respondents had only been involved in some. Results are first summarised as overall observations before providing a more nuanced view dividing them according to occupational group.

The main information on the background of homicide investigations was the unpredictability of cases and the near impossibility to plan such an investigation. This variability was also cited as one of the reasons why budgeting for this type of work is a major challenge. None of the respondents, regardless of their occupation or rank, could provide absolute figures for any aspect of their work. Some vague estimates were given for the hours of overtime worked. Detective 4 estimated approximately 500h of overtime for straightforward cases, increasing to 1,500h for more complex ones. This corresponds to Detective 2's estimate that category A murders are approximately three times more expensive than category C ones but at the rate of £20 per hour these estimates add to a lower amount than those provided by Manager 2 (£50,000 for a category C murder). No estimates were given for the overall cost of the police investigation. The range of possible costs for forensic services was estimated as between £3,000 and £50,000 although individual experts could charge as much as £80,000. In addition, Pathologist 1 estimated the cost of the postmortem and associated tests to be well into five figures, but could not be more specific. Similar uncertainties surrounded estimates for the time requirements of this process. Despite this lack of knowledge regarding the precise resource requirements, there was a general agreement that micro-CT helped to reduce both time and money spent, based on experiences with individual cases.

On the use of micro-CT there were three main themes that emerged from the data. These were the use of technology to direct or influence other processes of the investigation, its cost-saving benefit, and the use of scan data for visualisation in court. The first two are closely linked as the most frequently mentioned influence was a more targeted and therefore efficient investigation. Court visualisation was considered important to enable a better understanding of medical evidence and to maintain the jury's attention during trial. Many of the respondents agreed that the crucial difference to existing visualisation options was the detail and the clinical, sanitised appearance of the scan data. The compelling nature of the objective scan images was cited as the main cause for reductions in trial time as observed in two case examples. Only one detective had some prior knowledge about micro-CT, the remaining participants approached the project open-minded, being "*blissfully ignorant*" (Detective 2, p.2, l.76) about the potential uses. Comparing reported attitudes prior to the project with those after three years reveals how initial concerns and reluctance were quickly dispelled as the benefits became more apparent with each case. None of the prior concerns appear to have slowed the use of micro-CT. The only real concern was the evidentiary status of micro-CT but since the technology was used as an addition rather than a replacement for other evidence this concern did not influence respondents' decision to use it. Post-micro-CT attitudes where unanimously positive and often superseded initial expectations and the overall arrangement of the cooperation received approval from all sides. This might relate to the fact that all areas which interviewees identified as most important had been examined over the course of the project, demonstrating the real-life application of this research. In relation to initial concerns, respondents often mentioned the police's general adversity towards new technology and change due to the potential risk it carries. The demonstration of benefits was an important factor for technology acceptance across all occupations. Another factor in the overall technology acceptance was the spread of awareness which was frequently cited as crucial to the project's success. The spread of awareness within the police was facilitated by a few key individuals whose names were repeatedly mentioned in the interviews. These key individuals were located in the forensics department, the CID, and amongst pathologists.

3.1 Results by occupation group

The above results were shared between the different stakeholders interviewed for this study. There were some minor differences between each occupational group, often related to their motivations for certain actions or the importance assigned to individual aspects of micro-CT. In interviews with the four CSCs the respondents often talked more about scene scanning[7] than micro-CT and their involvement with the latter was less well-established than other professions. They provided less case-specific information as they were not usually closely involved in the case despite having suggested micro-CT scanning at the onset. Some CSCs also had an exaggerated expectation of the results that micro-CT could deliver; CSC 3 for example described the potential for toolmarks as follows: "*It's amazing what's available*

[7] Laser scanning of crime scenes was occasionally performed as part of the cooperation but is not discussed in this thesis as it is outside its scope.

and what you can tell us. With SFT it's the angle, force, blade comparison" (p.2, l.70-71). The results in Chapter 6 clearly show that this is more difficult in reality.

Pathologists were more focussed on the improvement of micro-CT to specific causes of death and also showed more concern for validation studies to provide them with more scientific data to rest their interpretations on. One aspect where pathologists' opinions varied was their role in Sharp Force Trauma analysis. One respondent considered it further experts' role to analyse the micro-CT images whereas another respondent stated to have requested the scans for their own benefit and that the detail provided equipped them with the necessary information to make an assessment.

The informants in managerial roles confirmed the project's compatibility with strategic policies such as professionalisation of police work through academic partnerships, the creation of a more efficient service that makes best use of the available resources, and to employ research to determine whether the proposed changes actually have the desired effect (evidence-based policing).

4. Discussion

The overall impression gained from the interviews was a positive attitude towards the project across the entire spectrum of CJS professions examined. The strong agreement with the schematic representation of the justice process supported the use of the stage-gate system as a management tool applied to the CJP, thereby justifying basing the analysis of the project's success on this concept in the overall cross-case analysis in the next chapter.

4.1 Justification for investment

Some further similarities have crystallised during the interviews, such as the importance of the initial phase of the process in both product development and criminal investigations. In operations management this is known as the concept of the fuzzy front end (Kim and Wilemon 2002). This is the idea that investing in the early stages of the process helps focussing the later stages and thereby reducing the costs which increase with each stage. As the interviews with informants in managerial roles show, this was recognised early on and constituted an influential consideration when setting the project up. The initial expectation was to "*invest to save*" (Manager 2, p.1, l.41). It was shown that even within the stages (e.g. the full investigation) it is worthwhile committing resources in the early phases as the longer the investigation lasts, the more expensive the required processes and the higher the chance that crucial evidence vanishes. The search for the offender is an excellent example thereof given by an investigating detective. If no one has been held responsible during the first week or two following the assault the search radius and cost of manpower and resources grow almost exponentially up to a large-scale DNA search (Detective 1). For the court stages, the accumulation of costs is linear as the longer a trial lasts the more expensive it is as it takes up the time of many senior employees, administrative staff, and requires the use of the court facilities. In addition, it is time lost for the jury members and their employers, although this would be more difficult to quantify. It becomes evident that the assessment criteria used to evaluate the success of a project (Quality- Cost- Delivery (QCD) triangle) can be applied to the CJP as well.

4.2 Public perception

It has further transpired that even in cases where the use of the digital technologies has not had a significant effect on the overall investigation it was still an important factor of showing that all available resources had been exhausted and nothing left untried. As one detective put it, making use of all available resources is important to ethical conduct and what police morally owe the victim and their family. This is an important social aspect as it instils public confidence and trust in police work. One case where this was specifically mentioned was OP Platter. While in this particular case micro-CT did not shed any light on the cause of death its use nonetheless demonstrated that all possibilities have been exhausted. Investigators confirmed that they would use it again in similar cases simply to minimise the risk of missing evidence. Cases involving children are particularly affected by this due to the emotional strain it puts on the parents, who are often the prime suspects, and society as a whole. Thinking back three years ago, micro-CT would not have been part of this process. This shows how deeply engrained the technology has become into homicide investigations, it is now expected that it is employed in situations such as OP Platter, "*we can't go back*" as Manager 2 (p.2, l.73) phrased it.

4.3 Case information

The majority of cases did not rely on the 3D technologies exclusively but rather used it as an additional method to increase confidence in the pathological findings for example. This falls in the category of quality improvement which was most frequently mentioned in relation to pathological evidence. Situations where this was of particular importance is where standard postmortem was complicated by decomposition and was acknowledged by detectives and pathologists alike. The more sources of information support a certain fact the closer the judicial truth comes to the factual truth. A further aspect of quality improvement is the evidence presentation frequently commended in the interviews. Many interviewees agreed that the images and 3D prints created using micro-CT or laser scanning facilitated the understanding of medical and pathological evidence. However, the informants' opinion about jury understanding of the evidence is based on speculation and inference from their experiences as they are not allowed to speak to jury members either. This was lamented by some interviewees who consider this a missed opportunity to evaluate their own evidence.

4.4 Police-academia relationship

While the general attitude was positive, the level of enthusiasm differed much between the interviewees. Those who had been less closely involved, in particular on a personal level, showed more moderation or restraint in praising the project. This is not to say they had any negative feedback but they often did portray the use of micro-CT as helpful but not essential and emphasised the limitation posed by the type of case. Those with more personal relationships with the project and its participants strongly advocated its benefits, often describing it as the future. This seems natural as individuals convinced of a technology's benefits would strive to be more closely involved (Allen and Wilson 2004). It remains to be seen if individuals become more outspoken advocates as their involvement continues to grow. Many respondents confirmed the common sense interpretation that the fact that nearly all investigators were involved in more than one case meant that the research must have struck the right chord otherwise they would not have requested micro-CT scans for subsequent cases.

Whilst many samples were scanned following the pathologist's request, an interesting finding was the reasoning with which pathologists decided whether to submit a sample for micro-CT scanning or not. It was initially assumed that all submissions were made to directly assist them in their work, i.e. establish the cause and manner of death. Through the interviews it became clear that this was only the case in the suspected strangulation cases.

In SFT cases, some pathologists requested the scans with the investigators' work in mind. For BFT cases, the motivation varied as some cases served purely to visualise the injuries while others served to detect damage invisible to the naked eye. Another interesting finding was the early involvement of the forensic CSCs. Many scans at the beginning of the project were requested by them. An explanation for this is the personal involvement of one of them who was one of the first proponents of the project and whose engagement was fundamental to its creation. **Figure 45** shows a distribution of the originators of the scan request divided by type of case.

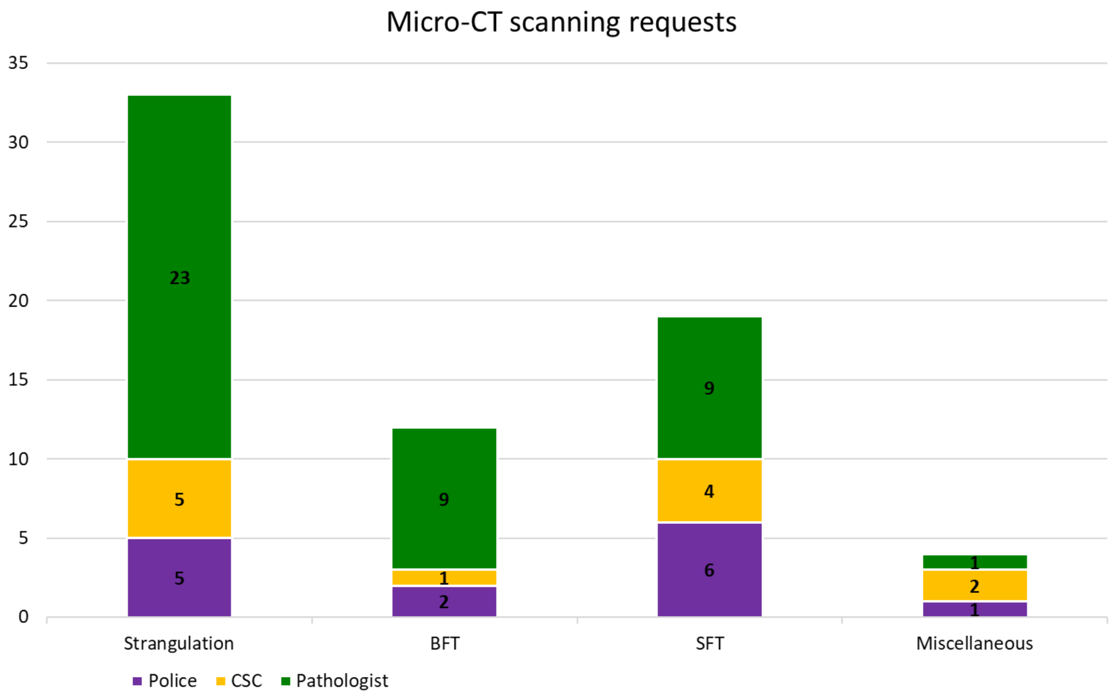


Figure 45: *Graph showing who requested the micro-CT scans according to case type.*

Once the micro-CT scanning had proven helpful, more requests came from the pathologists. The pathologists' involvement might have affected the technology acceptance amongst police, especially as it was observed that the hierarchical structure of the police force meant they are very willing to listen to a scientist's opinion. Many researchers have written about police reluctance to embrace new technology (Ashby et al. 2007). This was not observed over the duration of this project and the main argument amongst interviewees was that through the initial case (OP Sanderling) and subsequent early cases, the benefits of the technology had been demonstrated and any concerns had been dispelled. This correlates with Custers and Vergouw (2015) whose interview study found that police are more likely to adopt new technology if its usefulness has been sufficiently proven. The fact that police did not need to learn to use the technology is also likely to have contributed to the uptake. However, there were the usual concerns amongst certain individuals within the organisation that the new technology would replace their jobs. This is also a common observation not just within police organisations but across industries (Vieitez et al. 2001).

From the interviews it seems as if this projects had chosen a successful strategy for incorporating micro-CT into everyday detective work. This was acknowledged by most of the interviewees who saw no problem with the integration of the micro-CT scanning in the overall workflow, thus no inconvenience was caused. Had the use of micro-CT added time delays to any aspect of the process, the support for it might have been more limited. The nature of the cooperation had a major impact on its success. Many interview participants agreed that they only submitted such a large number of items from a variety of cases because there was no direct cost associated with a submission. They agreed that if it was a paid for service they would have been more selective in their submissions and only have those scanned where a positive outcome was expected. This would have affected the overall research base of the project and would have limited the exploration of possible applications. It is important to have these cases where the outcome was unpredictable as they served as kind of control cases and to strengthen both internal and external validity of the research design (Yin 2014).

4.5 Strategic policy

From the interviews at policy level it became clear that the project fits well within overall government strategies in policing. From the forensic perspective collaborations are strongly encouraged. After the demise of the Forensic Science Service in 2012, the forensic landscape had become fragmented and inconsistent (House of Commons Science and Technology Committee 2013) but more recent strategy papers highlight the need for a national agenda with internal and external co-operations and resource-sharing at its heart (HM Inspectorate of Constabulary 2016). The present cooperation between WMP and WMG is intended to evolve into a specialist hub onto which police forces across the country can draw for assistance, thus putting WMP at the forefront of technological innovation. It has become apparent that this is in the interest of those decision-makers as this development will reflect positively on them in future performance evaluations in which effectiveness and efficiency of investigations are essential criteria (HM Inspectorate of Constabulary 2016). This could have implications for stakeholders' future careers with a successful project outcome possibly contributing to individuals' promotion. Due to these possible career implications, it can be considered a high commendation that they would take such a risk by supporting this project and one can be sure that they would not support it if they were not genuinely convinced of the positive outcome.

5. Summary

The key informant interviews provided a unique insight into the workings of the criminal justice sector. It has become clear that the overall attitude towards the new technology is positive across all organisational roles and that it fits in well with existing approaches. An interesting finding was that CSCs were responsible for the submission of the earlier samples and that pathologists gradually became more involved and spread the knowledge about micro-CT to other police forces. Their motivation behind the submissions was not limited to the pathological diagnosis but also included court presentations and assisting investigators.

The technology aversion that some scholars attribute to the police was not observed in this study. On the contrary, all interviewees expressed their support for micro-CT, especially after having demonstrated its benefits which dissolved any initial evidentiary concerns. The validation studies conducted as part of this PhD further increased confidence in the technology and promoted its use.

Further evidence has emerged regarding research areas which hold promise for future research and which is directly in line with police/CJS needs and policies. While this interview study offers a somewhat prosecution-centred view, it nonetheless demonstrates how micro-CT has been perceived.

Chapter 10: Discussion

1. Introduction

The previous chapters have each focussed on the scientific contribution of micro-CT to a specific type of homicide, and individual stakeholders' evaluation of the impact on specific case examples. The present chapter will now draw on these to examine the overall impact on the Criminal Justice System in an extensive cross-case synthesis. Aspects discussed in this synthesis are the QCD triangle and how the themes that emerged from the previous chapters can be assigned to each of the triangle's sides. The QCD stands for Quality-Cost-Delivery which are three aspects commonly used to assess the success of a project (Department of Trade and Industry 2005). The quality side is influenced by the main themes of objectivity and clarity and by external admissibility and validation requirements. The delivery side of the triangle consists of the time saving influence of the new technologies on other processes within the CJP which immediately affects the third side, the costs. The discussion of how overall costs were reduced leads to the final part of the cross-case comparison which is the assessment of the remaining operations management concepts such as the stage-gate system and the First-Time-Right approach and how they fit in with the general New Public Management principles.

The second half of the discussion will focus on the societal impact of the project. This includes the practical outcomes which were outlined in the Research Agreement between WMG and West Midlands Police and which have a direct impact on everyday detective work. It will also discuss the organisational issues encountered over the course of this project and how they could be addressed to ease future collaborations. A central aspect to this is the general acceptance of novel technology which is discussed in the final section of this discussion.

2. Cross-case synthesis

This first part of the discussion chapter aims to answer the overarching research question: how can these 3D technologies benefit the CJS. All aspects of the answer are covered by using the QCD triangle.

2.1 The QCD Triangle

2.1.1 Quality

The main factor that applies to all types of homicide is that micro-CT constituted an additional source of objective evidence. In an area where the interpretation of events depends much on expert opinion, these objective images are a welcome source to increase the expert's confidence in them. The objective images were not only available to police and experts, they were also included in jury information packs, regardless of the manner of homicide of the case in trial. These images constituted an unbiased illustration of expert evidence and allowed the jury to form a more educated view of the evidence. Objectivity is important to maintain a fair trial, especially in a situation where the defendant does not readily have access to the same technology.

The objective nature of the images leads to increased clarity. This applied to all types of injuries and is therefore related to the general complexity of medical evidence. Having three-dimensional images adding to or replacing the more commonplace two-dimensional images used in the past appears to be received positively amongst all stakeholders of the CJS suggesting that this is an objectively positive contribution. This reverts back to the research into improved understanding of medical evidence through three-dimensional supporting images introduced in Chapter 2. The evidence from all cases suggests that the experiments conducted as part of studies such as those by Kassin and Dunn (1997), Brewer et al. (2004), or Park and Feigenson (2013) produce valid results that are applicable to real-life contexts as well. It is known that different people prefer different learning styles and that a combination of multiple sensory channels increases the information retention (Shams and Seitz 2008). Ultimately, the process the jury undergoes during trial is a learning process and the better they understand the facts and interpretations, the more just the verdict is. It could be argued that a just verdict is the ultimate quality criterion in the justice system.

Irrespective of the nature of the homicide, the objectivity and clarity of the evidence are taken into consideration when assessing the evidence admissibility during the trial preparation stage along with considerations of fairness, helpfulness, and relevance (Roberts and Zuckerman 2010). Generally, no problems with admissibility were encountered. OP Sanderling, which was the first case to go to court featured the micro-CT evidence heavily without being challenged. A slide of the court presentation is shown in **Figure 46**.

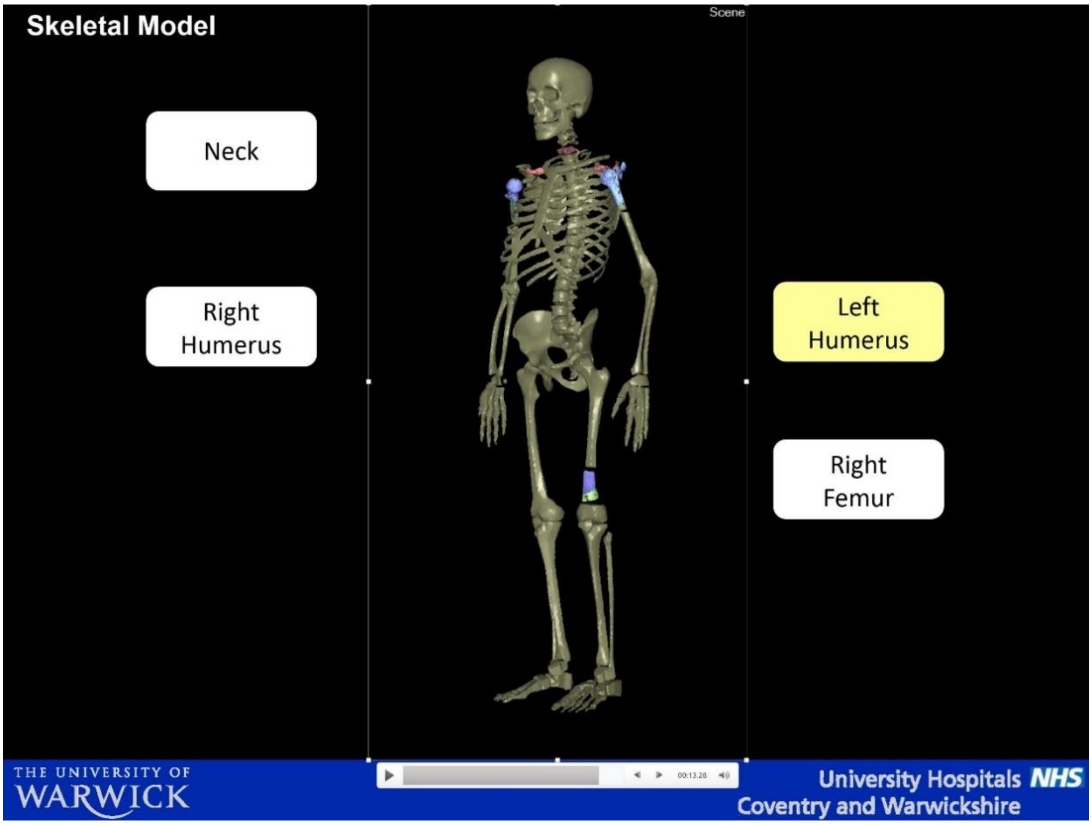


Figure 46: *Slide from the court presentation produced for OP Sanderling. The skeleton model featured the micro-CT samples highlighted in colour and hyperlinks to detailed views of each element. This helped understanding the anatomical context of the dismemberment.*

The only example where the novel evidence was faced with objections was in OP Rococo. While the images and video clips were accepted, defence counsel objected to a 3D print being shown. Their argument was that the prints were too emotionally upsetting whilst not adding new information or additional clarification that could not be shown by the scan images alone. This shows the importance of evaluating such new evidence before admitting it in order to maintain the equality of arms of a fair trial. In OP Argon the 3D print was admitted without any objection, suggesting that personal preferences and distastes might influence evidence admission. During the trial preparation for OP Argon the question arose how realistic a 3D printed model should be. It was a fine balance between accurately representing the sample and providing sufficient abstraction to reduce potential emotional distress and bias by being too realistic. The final print resembled the colour of bone but had a clearly plastic appearance but one of the investigators later commented that the light colour made it difficult to see the injuries. Using different colours might highlight these as shown on the digital models for OP Sanderling (**Figure 46**) and OP Rococo (**Figure 38**). However, colours must be chosen carefully as they can evoke negative emotional responses as well (Gao and Xin 2006).

Some of the respondents voiced the initial concern that scan images might not be admitted as the technology was so new and they feared it could be ruled too complicated and therefore inadmissible. This concern was quickly dispelled as the benefits demonstrated outweighing of any possible confusion. In light of the often liberal admission of new technologies (O'Brien et al. 2015) this concern was unlikely to become reality. Despite the new Criminal Procedure Rules which aim to regulate the admission of forensic evidence, courts in England and Wales still have a track record of liberally admitting all forms of evidence (Edmond 2016). This, as several interviewees confirmed, is particularly true for novel evidence of which there is little knowledge at court. Defence barristers might lack knowledge about its specifics and choose not to attack the evidence as they do not know its weaknesses. This novelty will eventually wear off and barristers and judges might subject this evidence to scrutiny as outlined in the CrimPR (2015) with the main criterion being method validation. The two validation studies discussed in the earlier chapters are therefore essential for the acceptance of micro-CT in court. Further validation studies will be necessary to study different applications and to allow an estimate of error rates which is a critical component of method validation set out by the FSR (2014).

2.1.2 Delivery

The delivery aspect of the QCD triangle is often also referred to as the time aspect and assesses the timely delivery or completion of a project or process (Turner 2009). The process here is the entire CJP from the crime until sentencing. At a first glance it would appear that by introducing an additional forensic examination the overall length of an investigation will increase which would contradict the CJS's principle of timely delivery of justice. This was true to a degree in some of the early cases as the practical integration of the micro-CT examination and the reporting format had not been firmly established yet, leading to minor delays in turnover times. Writing the report did take longer each time a new type of injury was examined for the first time. However, initially the pathologists completed their findings without waiting for the micro-CT results as they were not yet attributed with much weight. As the project advanced it became easier to incorporate the technology in the overall workflow and to conduct the examination and the time delay did not affect the overall process any more. Many of the interviewed detectives stated their satisfaction with the turnaround times for micro-CT scan reports which was typically to be much faster than other forensic experts' results. As stakeholders became more familiar with the technology they realised how it could be used to facilitate their own work. Interview participants emphasised how the micro-CT results were used to narrow down possible lines of inquiry, for example by narrowing down the type of weapon to search for, thus saving time otherwise spent on unnecessary or futile actions. Focussing processes has also benefitted further forensic examinations like histology. The histopathologist used the scans as an aide to plan their examination, thereby making it more efficient and perhaps reducing the time required for it. While in the interview they could not confirm this, detectives shared the opinion that the turnaround times for histopathology reports had improved since the introduction of micro-CT. This cannot be accredited to micro-CT entirely as the histopathologist might have improved their routine as well, but it is one possible contributory factor. Further reductions in time have been demonstrated to occur during trial of a variety of cases as the increased clarity and compelling nature make the evidence presentation easier and therefore faster to understand. The only requirement seemed to be the complexity of the case at trial, not the type of homicide. The more complex the case the more can be achieved with additional evidence. This potential to accelerate the delivery of justice is fully in line with several government publications. The CPS Code of Practice for Prosecutors puts prosecutors under responsibility to ensure this process runs quickly and smoothly (CPS 2013), using micro-CT evidence should therefore be in their best interest.

Some of these time reductions such as the influence on the histopathology are difficult to quantify whereas others such as shortened trial times can be directly translated into cost reductions. This is endeavoured in the next section.

2.1.3 Cost

It is difficult to assign a number to potential costs or savings of micro-CT in an individual case. Few scholars or government publications have addressed the issue and the studies that have been conducted often rely on different data sources or use different methodologies which makes comparison difficult. A major study was undertaken by the Home Office in 2000 (Brand and Price 2000) and updated in 2005 (Dubourg et al. 2005) and 2018 (Heeks et al. 2018) which aimed to provide a total estimate of the cost of crime including long-term costs such as lost work output, victim services and prison costs. Brand and Price (2000) addressed the distinction between social and economic cost of crime which, in their opinion, is a false one. While their argument for this is compelling, this chapter only aims to put a value on the direct economic savings, whilst still acknowledging the social impact.

The aspect considered here arises as a consequence of crime, which is only a fraction of the cost of crime since much of the overall cost is derived from the anticipation and prevention of crime such as burglar alarms, insurance, or social work programs. Knowing the cost of crime is an essential prerequisite for assessing policies and measures designed to reduce these costs. Brand and Price (2000) estimate the average total cost for homicide to a minimum of £ 1million, a figure exceeded by Dubourg et al.'s (2005) estimates of nearly £1.4million and the latest 2018 figures of £2million (Heeks et al. 2018), the highest amount for any type of crime. While violence against a person only comprises 5% of crime, it amounts to 53% of the overall costs due to the high per-case cost of homicide shown in **Figure 47**. Around a tenth of this sum occurs for the Criminal Justice System (see **Figure 48**) and while this aspect of the costs of crime is easier to grasp than for example the emotional cost, it is still under-researched (Wickramasekera et al. 2015).

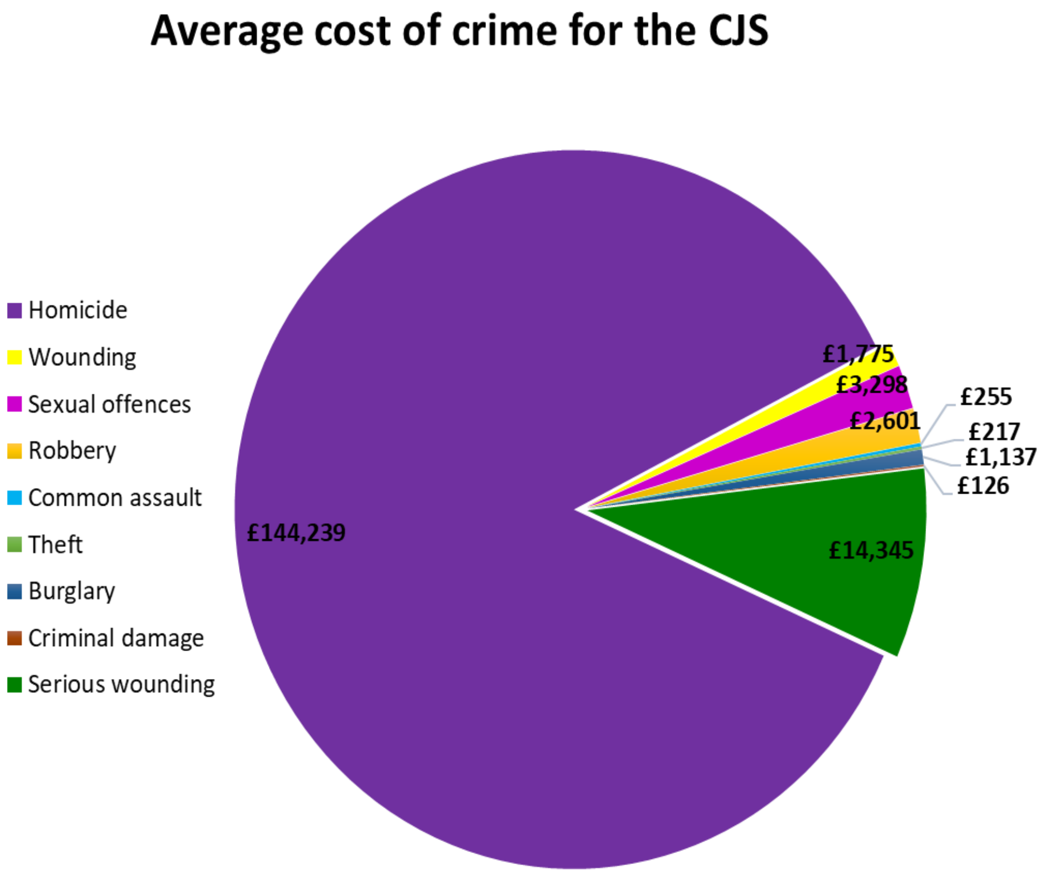


Figure 47: *Average cost per type of crime for the CJS. Homicide is clearly shown as the most expensive per-case crime.*

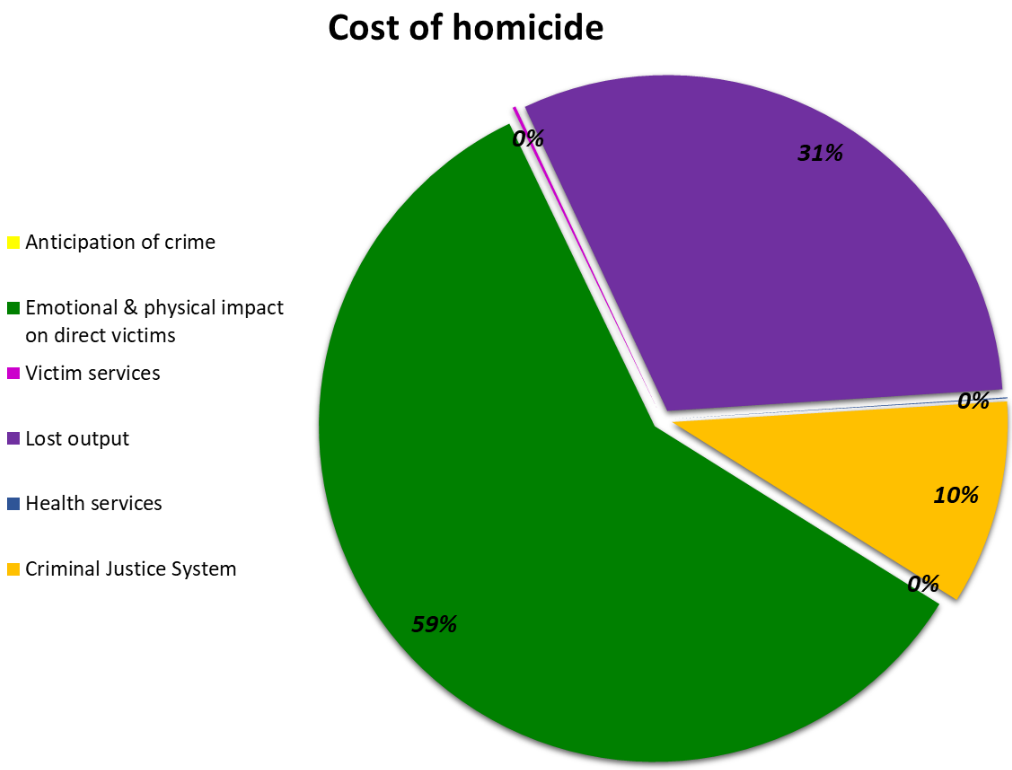


Figure 48: Distribution chart of the cost of homicide for different stakeholders. The total cost is estimated at nearly £1.4million. Adapted from Dubourg et al. (2005).

These figures apply to the average costs. However, the general consensus amongst practitioners involved in the present project was that especially complex cases benefit from the new technology. This would suggest that micro-CT has the potential to reduce costs in fewer cases but by a higher amount in any single one of those. This cost-benefit appraisal was expected to impact the future of this project but despite the lack of actual numbers police were eager to extend the collaboration due to the overall perception of usefulness and improvement. Further financial impact assessment was initially intended to be based on key informants' estimates. However, while all interviewees were asked questions regarding the resources required for their line of work, they rarely produced any specific numbers and often not even rough estimates. This was rather surprising as the general consensus seemed that money was definitively saved with micro-CT, implying some knowledge of the finances involved. Some estimates could be obtained for time savings based on detectives' experience of trial duration for numerous cases. For OP Rococo, several informants suggested that the compelling nature and clarity of the images contributed significantly to reduce the trial length from the scheduled five weeks to two weeks. A day in Crown Court is estimated at close to £2,000 in staff, judicial, and juror costs, not including expert witnesses (Morse 2016). A reduction in trial time by three weeks therefore constitutes cost savings of a minimum of £30,000. Extremely difficult cases such as OP Rococo are rare but tend to require more resources such as experts witnesses. A similar case of complex Non-Accidental Injuries was examined in OP Picture. Assuming similar trial benefits this would have saved the Criminal Justice System a further estimated £30,000. The two further child death cases examined were less complex in terms of the injury pattern, any reduction in trial time would probably have been less pronounced, perhaps in the region of one week, i.e. £10,000 but this is purely speculative. For OP Sanderling, the estimated reduction in trial time was approximately three weeks as well, adding another £30,000 in savings. An even bigger saving was achieved in OP Bluemist, eliminating the cost for a full-blown investigation and a court trial. Using only the overtime budget estimates for a category C murder provided by one detective, this would be £10,000 (500 hours at £20) on top of staff salary. Another detective estimated overtime budget for a category C murder at £50,000 (£200,000 for a category B) but the lower estimate was used to provide a minimum saving. Assuming two weeks trial time, a further £20,000 were saved. This adds up to a minimum of £140,000 in confirmed savings based on only six of the cases examined over the course of the project. Further savings are assumed but no actual data could be obtained from the interview participants.

Balancing the overall costs of the PhD against the theoretical cost of charging standard commercial rates is more straight forward. For commercial projects, micro-CT scanning time at WMG is charged at £1,000 per day and analysis at £500 per day. For the 42 cases examined for WMP completed at the time of writing (including those not considered for analysis and excluding cases from other police forces) a total of 52 days of scanning and 80 days of analysis (including writing reports) was recorded, adding up to £108,000 (£52,000 for scanning, £56,000 for work hours). The PhD was funded with a total of £75,000 which is £33,000 less than the commercial rate. Comparing the financial input to the confirmed actual savings results in net savings of £65,000 for the Criminal Justice System.

The fact that in effect there was no service charge for the scanning work influenced the decision whether to use it or not. Detectives and forensic examiners were more willing to submit a sample for scanning despite uncertain outcome and usefulness. This contributed to the broad research base accumulated over the course of the project which added knowledge about the type of samples and injuries suited for the technology. This would probably not be the case if each submission would have been charged at commercial rates.

It has become clear that all three assessment criteria are closely linked as quality can come at increased costs and time (leading to higher costs), reductions in time lead to reductions in costs, and increased quality can lead to reduced time requirements and therefore again lower costs.

2.2 Operations management in the CJP

The above section presented the QCD triangle used in operations management to evaluate the success of a project and demonstrated how they have been applied to evaluate the success of the Criminal Justice Process. The second major concept introduced in Chapter 2 is the stage-gate system which is used to answer a major component of the initial research question, being which individual stages of the CJP benefit from micro-CT. For this, the CJP was broken down into individual processes and thresholds as suggested by Cooper (1990). Interviewees who were shown the diagrammatic representation presented in Chapter 2 generally agreed with this representation and were able to indicate the points of entry for micro-CT and digital visualisation for individual cases, resulting in the updated diagram in **Figure 49***.* This showed that the strength of micro-CT lies mainly within three stages, the initial investigation, the full investigation, and the court stage. While micro-CT did not actually reach the court stage in many cases, its impact here was more pronounced. The early stage involves determining the cause of death which is crucial for the police, charging a suspect with murder is significantly more challenging if one cannot determine the cause of death. This was the case in OP Platter and OP Vault as decomposition had obliterated this. The results from the initial investigation obviously effect all subsequent stages, thus placing micro-CT in the next stages as well. For one type of homicide, stabbings, the main entry point was during the full investigation. In these cases, the cause of death was rather obvious and the pathologist did not require further scanning to be confident in their opinion. The purpose of the scans was to help investigators identifying the murder weapon, usually after a suspect had been arrested. Stage three only saw the scan images being used if requested by the barrister. Depending on their personal preferences they might make more or less use of it. Usually, if micro-CT was used at this stage there was the intention of showing it in court. This was sometimes made redundant by the offender’s guilty plea. The most note-worthy case here is OP Sanderling where, according to investigators, the images produced with micro-CT caused the defence to change their argument. Overall, only three cases involved the production of images specifically for court.

The entire purpose of the stage-gate system is to optimise the process. This led to the realisation that investment in the early stages will save resources being wasted later on (Cooper 1990). One of the senior police detectives understood this concept early on, using the same argument to justify the spending on this PhD project, stating that “We need to invest to save" (Manager 2, p. 1, l.41). Experience with this project proved this to be directly applicable to homicide investigations. The most frequently mentioned case was OP Bluemist. Interviewees agreed that had it not been for the micro-CT scans providing additional support for the absence of external trauma, a full homicide investigation would have ensued. Due to the evidence, the death was no longer treated as a crime and handed to the Coroner, thus saving substantial costs. This focus on the early stages closely links to the Right-First-Time approach which originates in manufacturing operation management (Department for Trade and Industry 2005) but has been adopted by government to define the principles of best practice in justice (Grayling 2014). This concept is now firmly established in NPM and is a recurrent term in government publications on criminal justice. In criminal justice terms, RFT has two motivations. One is to avoid miscarriages of justice and the second one is to use resources more efficiently. The National Audit Office published a report in 2016 where it found that the CJS has failed to achieve the latter so far (Morse 2016). By following the stage-gate approach these objectives can be achieved. While it appears like common sense that justice should be right the first time, the emphasis here is that by doing things right at the first attempt eliminates the need to re-visit earlier processes, thus making the overall process more efficient. In the stage-gate system this is the task of the gate keepers as careful review before continuing to the next stage prevents having to re-do previous work. The FTR concept is closely linked to the QCD triangle. Better evidence quality increases the likelihood of making the right decisions the first time, this in turn reduces time and therefore cost spent on the process. This indicates that some of the ideas brought about by NPM have an actual positive impact on the delivery of justice, despite the criticism voiced by its opponents (Fleming and Lafferty 2000). Critics of NPM often argue that the focus on the financial savings puts justice in second place. However, using the concepts presented in this study enables policy makers to find a better balance between these apparently contrasting aims and spend resources more targeted where they can maximise the justice outcome.

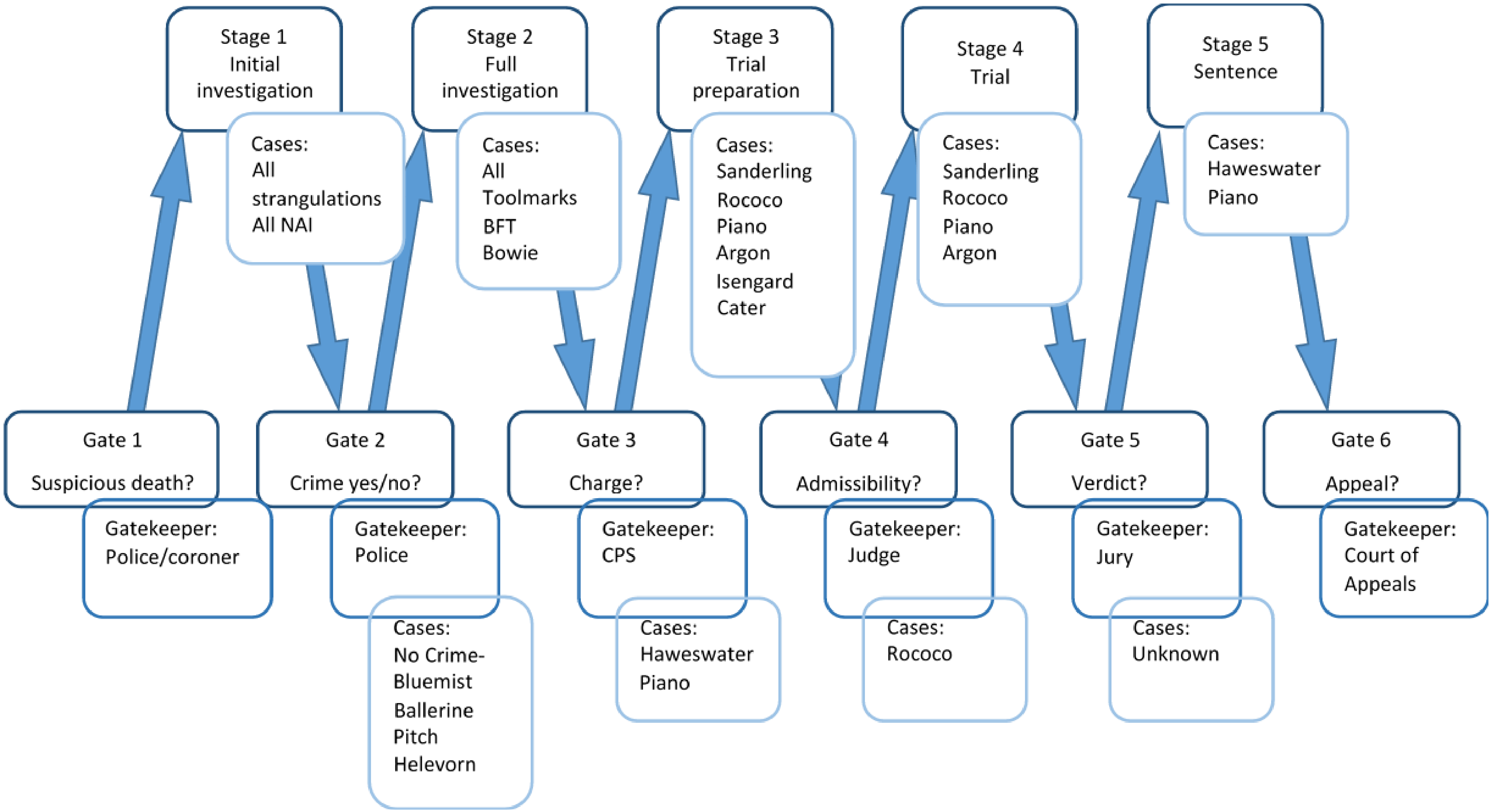


Figure 49: *Schematic representation of the stage-gate system from Chapter 2 with the addition of the cases discussed in the interviews.*

From the interviews it further transpired that those involved in bringing justice, i.e. police, care foremost about doing what is needed before worrying about financial concerns ("*At my level I'm not overly concerned with budget, my job is it to bring justice to the person responsible for the crime*", Detective 4, p.1, l. 20/21). Fleming and Lafferty (2000) argue that private sector management strategies cannot directly be implemented in public organisations as these are more complexly structured. The concepts here seem to contradict this view. However, the intertwined nature of the three concepts applied in this project suggests that success is more likely if measures are used in conjunction with others and not in isolation.

3. Societal impact

This section aims to answer the question of the societal impact created by using digital 3D technologies in the CJS. It will focus first on police and academia as two specific institutions of society before looking at society as a whole.

3.1 Changing police practice

One of the original project outcomes defined in the Research Agreement between WMP and WMG was the establishment of new Standard Operating Procedures (SOPs). These were thought to specify how micro-CT should be incorporated into homicide investigations and increase the awareness amongst all officers. The current procedures developed over the course of the project during which they changed and improved frequently as both sides gained in practical experience. No SOPs have yet been written into actual documentation but the majority of detectives revealed in the interviews that in reality the practices have become engrained in investigators' approach to a murder investigation. The police murder investigation manual provides a "checklist" of actions to consider at the crime scene (National Centre for Policing Excellence 2006) and ideally micro-CT will feature in this list in the future. Educating officers in training about the uses of micro-CT maximises the spread of knowledge, possibly even to a national level which would help establishing micro-CT in future policing. As the future of the collaboration moves into the forensic department, it is likely that the SOPs will also become part of the forensic strategy which is discussed at the onset of each investigation. Education is also important for the judiciary to enable best possible use of the novel evidence. This could be achieved in the form of a micro-CT "Primer for Court" as presented in Chapter 2. Such a document would summarise the method's underpinnings, its applications, relevant validation studies, and limitations. This could equip judges with sufficient knowledge to replace the researcher having to testify in court, thus saving further resources on the system.

This collaboration brought about organisational changes for both sides. One of the main issues for the police at the beginning of the project was the correct packaging of the sample for micro-CT scanning. Since the technology was new to the majority of officers, they did not realise the need to minimise the potential sample movement. Inviting them and the mortuary personnel who would perform sample packaging to view and learn about WMG facilities increased their understanding of the technology and led to a streamlined packaging method which proved to be successful. Similar issues were encountered each time external police forces were involved that used a different mortuary. In these cases they were referred to the UHCW team who provided their guidance. The coordination between police and WMG regarding sample transport was initially somewhat difficult as neither side was sure whom to contact. Over time these issues dissolved as personal contacts were established thus facilitating communication. Bales et al. (2014) have also found that such personal relationships between academics and police are vital for successful cooperations as it builds trust between both sides. Trust is particularly important for police as any external links are a potential risk (Burkhardt et al. 2015). The communication problems persisted for external police forces where limited prior contact existed which resulted in samples being delivered to the wrong location, insufficient information accompanying the sample, or incorrect sample packaging. This highlights the importance of SOPs which can be referred to and shared amongst forces.

For the university the main difficulty was the security level required to store both the physical evidence and the ensuing data. Previous work with industry had included confidentiality agreements but the forensic project required additional compliance with FSR standards. In practical terms this warranted access controlled storage facilities for samples and additional encryption for data storage which were swiftly implemented. The most important new adaptation was the (unofficial) SOP for reporting the results of an examination. In the beginning, the existing report template for industrial examination was used to describe the micro-CT findings. Over time it became clear that this was not the most suitable style as it did not include a section on the case background. Case background is important for the overall interpretation of potential injuries and it is important to disclose what information the examiner had prior to the examination to prevent accusations of unconscious bias. The Criminal Procedure Rules explicitly state that expert reports must include this section. They further demand that expert witness statements warrant a statement of the expert's qualifications and a declaration of their duty to the court which again changed the reporting format.

3.2 Technology acceptance

The success of this novel technology is not a given. Researchers frequently draw attention to police's adverse attitude towards new technologies and change in general (Barton and Barton 2011) which results in them lacking behind the private sector in terms of technological progress. This reluctance stems from a number of reasons, the main one being the risk that a new technology brings into an investigation. If investigators are unfamiliar with the principles of the technology with which the evidence is gathered, they are less likely to employ it (Bouwman and Van de Wijngaert 2009). How would they be able to defend its use in court? This attitude was confirmed in the interviews with potential risk being a common pre-micro-CT concern. However, one of the interviewees argued the opposite. They speculated that as the defence barristers know so little about the technology they lack a basis on which they can attack it. Whichever side prevails, this is likely to change in the future as the majority of barristers act for both prosecution and defence at some point, taking knowledge about micro-CT with them.

Custers and Vergouw (2015) found in a survey amongst police personnel that once the usefulness of a newly introduced technology has been demonstrated it is accepted more readily. This finding is supported by the interview results in this project. Several participants from forensics, police, and pathology admitted initial concerns regarding the evidentiary status of micro-CT but agreed in unison that after seeing the first results these concerns were quickly dispersed. Not having to use the technology themselves certainly facilitated the acceptance of micro-CT further as Bouwman and Van de Wijngaert (2009) found that ease of use is often a limiting factor in the introduction of new police technology. The micro-CT scans were easily integrated in the overall workflow through the aforementioned SOPs which meant little procedural change and no time delay for the investigation. The main difference between this study and the majority of research on police technology acceptance is that in the present case police were not the technology users, they were merely presented with the results. Any reservations are therefore due to the evidentiary concerns. This is why validation is important as it disperses these evidentiary concerns and proves that the method is reliable. However, not being actually involved with the technology caused many investigators to perceive the project more as a service rather than a research study.

4. Summary

This chapter has highlighted the project's overall contribution to the CJS over the past three years, thereby creating a supportive argument for the future use of micro-CT in forensic investigations. Reviewing all three case categories showed that the QCD triangle is applicable to the CJS as well. Evidence quality such as clarity and objectivity are a major benefit irrespective of type of case. This is demonstrated by the position visualisation options held by different stakeholders within the cases. Admission of the image data was generally unproblematic and the validation studies conducted as part of the research were perceived as additional means to ease the path in the future. The only controversial issue was the admission of 3D prints which suggests further research into the perception and influence of these.

A financial estimate showed the potential to save money by using micro-CT but this estimate is likely to be somewhat inaccurate due to the difficulty of obtaining absolute numbers for each element of the process. The overall estimated minimum saving of this project was £65,000 in public money resulting from reductions in trial time in several cases and the early termination of the police investigation in another.

Chapter 11: Conclusions and outlook

1. Key points

The key findings of this thesis can be divided into two categories: scientific or pathology knowledge, and contributions to the administration of justice.

The first literature review has revealed how the different justice agencies work together to form the Criminal Justice System. By understanding their respective roles and functions one can better understand how financial pressures and strategic policy changes affect these agencies. This literature review has also highlighted the catastrophic consequences of miscarriages of justice to which flawed forensic testimony often contribute significantly, thus justifying research efforts such as this thesis which aim to improve certain aspects of forensic science. The literature review also introduced the stage-gate system, the QCD triangle, and the First-Time-Right approach which were used throughout the data analysis and discussion chapters to demonstrate how these management principles can be used to evaluate the introduced changes and ultimately create a more effective and efficient Criminal Justice Process.

The second literature review presented the background to micro-CT which has been used in industry for some time but only recently found applications in forensics, for example for entomology, Sharp Force Trauma analysis, or gunshot wound examination. It further suggested that the use of 3D images or even objects improves the understanding of complex evidence in court. Based on these findings it became obvious that more research was required using more extensive series of actual case examples.

Three main areas (strangulation, toolmarks, and Blunt Force Trauma) were identified as bearing the highest potential for micro-CT and which were treated as individual study cases within the overall research design of multiple-case study research. Due to the nature of the data created during this project, qualitative research methods were chosen as the predominant methods to compare visual and textual information from a variety of data sources.

The largest study area was strangulation deaths. Micro-CT proved to be well suited to imaging the small structures of the larynx and the subtle fractures within. These images added objectivity and clarity, which contributed to increasing the pathologists' confidence in their diagnoses. In addition, the digital 3D models assisted the histopathologist in planning their procedure, micro-CT has thus further improved and streamlined parts of the CJP. Because of the high number of strangulation cases and the potential impact of micro-CT, a validation study was inevitable. This study showed the normal appearance of the laryngeal skeleton at micron resolution against which those from suspected strangulations could be compared. This study proved to be essential as some features which mimic trauma were identified as being part of the natural ossification process.

The second major area, toolmark analysis, was improved by providing more detailed views and dimensions of the injuries, in particular those in bone. This assisted identifying the weapon or type of weapon in several cases. No direct validation study was conducted for this thesis, but a large-scale experiment using micro-CT to statistically quantify saw marks in bone supported using micro-CT in forensic cases.

The usefulness of micro-CT in Blunt Force Trauma cases was initially regarded with some scepticism as it was unsure whether it could add much information that hospital CT could not produce. It soon became obvious that micro-CT could become a game-changer for the field of paediatric Non-Accidental Injuries. This, similar to the strangulation research, led to another validation study. This one was of a more general scope, comparing the micro-CT scans of three cases, including one of child abuse, to histology which is the current gold standard in forensic wound analysis. The strong correlation further justified the new method, improving the likelihood of its admissibility before a court of law.

These three areas covered the majority of homicides encountered in day-to-day police work. Some cases, including scans of non-biological tissues, did not fit in these categories but nonetheless deserved to be mentioned to illustrate further applications of the new technology. This included scans of a bag of beans and a switch from a gas cooker that had been tampered with, scanning a human skull for facial reconstruction, and a gunshot wound. Micro-CT had mixed benefits for these cases, they therefore also served to illustrate some limitations.

Apart from the anatomical knowledge, this thesis also wanted to investigate stakeholders' perceived impact of having introduced micro-CT. The response from the interviews conducted for this purposes was overwhelmingly positive. The practical arrangement of the collaboration plus the improvements in quality, time, and visual output was acknowledged by nearly all respondents. It further became clear that this research project is perfectly in line with government policies which was a priority for respondents in managerial roles. One of these government aims was the reduction of costs, the interviews therefore also provided some background on police/forensic spending used to assess potential savings brought by micro-CT.

The previous discussion chapter then finally brought together the results from all results chapters for a cross-case synthesis. This demonstrated the usefulness of micro-CT for visualisation, regardless of type of case or sample. It further supported the applicability of the stage-gate system across the entire spectrum as different types of cases occupied different stages of the process. Their main commonality was the importance of the early stages, perfectly summed up by the phrase "invest to save" used by one of the respondents. Drawing on all cases also clearly demonstrated how other management concepts such as the QCD triangle can be used to determine the success of the present project. The extra detail has improved the quality of evidence, the three-dimensional visualisation options improved the delivery of the evidence by increasing understanding, and together the technology succeeded in reducing time and therefore cost of the investigation and/or trial.

2. Evaluation against the research objectives

The research questions raised in Chapter 4 were:

I. What stages of the Criminal Justice Process can profit from the introduction of digital visualisation technologies and how?
II. What societal impact can these methods create with regards to shaping police investigations, enabling a higher quality of justice, and changing court experiences?
III. How can the economic impact on the CJS be quantified?

These have been answered as follows:

I. All stages of the CJP profit from the introduction of micro-CT scanning although the case-by-case impact depends on the type of homicide and the complexity of the case. Strangulations and BFT analysis predominantly affect the first stage where it is determined whether a crime as taken place. This decision then affects the remainder of the process. Micro-CT in SFT is mostly used during the full investigation in stage two. The most pronounced benefit for the pre-trial and trial from micro-CT visualisation occurred in SFT and BFT cases where it led to an increased understanding of medical evidence.

II. Police and pathology practices were demonstrably shaped by the incorporation of micro-CT. Awareness of the technology put micro-CT on police officers' mental checklist of actions to consider at the crime scene. Pathologists became aware of the subtlety of certain strangulation injuries which changed their autopsy practice in such cases to become less invasive. Adding micro-CT to the existing pathology toolkit improved the detection of injuries and increases confidence in the pathological evidence. It further demonstrated how police exploit all available resources and do everything in their power to investigate a crime. This has become invaluable especially in cases involving children where public pressure is high.
III. The increased detail and the visual output thereof provided new tools for evidence presentations in court which can increase jury comprehension and has shown to reduce trial times by increasing the clarity and objectivity of argument.

This thesis has demonstrated that by investing in sponsoring a PhD project police were able to save a minimum of £65,000 in taxpayers' money. This estimate is based on government publications on CJS costs and stakeholder approximations of time savings.

3. Limitations and further research

3.1 Limitations

The financial impact analysis planned in the beginning of the project emerged as less straight-forward than anticipated. Obtaining actual numbers from any of the interview respondents proved to be difficult, even from those in managerial roles. Using published studies gave an indication but none were broken down in a way to allow distinguishing the elements or processes which could be affected by using micro-CT. Data on the cost of court trials were particularly difficult to obtain. This resulted in very vague estimates as opposed to the initially intended detailed breakdown.

The implementation of the interview study design also proved to be more challenging than anticipated. The low response rate from individuals working for the prosecution, barrister's chambers, or the courts limited the overall strength of the resulting analysis and shifted the focus towards the pre-trial stages of the CJP. The timeframe of the interview study was limited by the fact that it had to be conducted at a point within the project when sufficient cases had been examined and concluded in court, towards the end of the project. With the continuation of this partnership, more opportunities will arise to speak to these stakeholders as more and more cases will have come to their attention.

One of the major technical limitations that have become apparent during this project is the poor visualisation of soft tissue. This applies to strangulations where the larynx has not ossified, and to SFT in cartilage. Future technological developments such as spectral CT are likely to address this issue, in the meantime trials with staining agents might alleviate the situation. However, using staining agents on forensic samples raises new concerns of reversibility as they might affect further work such as histology.

These limitations open new opportunities for further research.

3.2 Further research

Two validation studies were conducted as part of this project but many more applications need to be verified before using micro-CT as a stand-alone method.

This project has generated a wealth of data which could be analysed in a multitude of additional ways but would have exceeded the bounds of the present thesis. One further research area would be a more extensive comparison between micro-CT and hospital CT. This was only performed in one case (OP Piano) where the difference was central to the case outcome. Such a comparison would be useful as a guide for radiologists and pathologists to be more targeted in their selection of samples for micro-CT scanning.

The high numbers of stab wounds examined over the course of this project illustrated the need but also the challenge of providing a detailed description of the inflicting weapon based on the wound geometry. The saw mark experiment conducted in association with the forensic partnership with WMP produced a large set of saw marks which is rare in the literature. Nevertheless, more research is needed looking at stab marks, intra-class differences, and individual weapon characteristics. With the vast number of knife classes and differences within these classes, this could amass to a substantial research project in its own right.

From the interviews it has become evident that research in the field of Non-Accidental Injuries in infants remains a major concern in forensics. This includes research into fracture healing to age the fracture. Different stages of healing were observed within and between cases and were confirmed histologically. More detailed and controlled studies would be helpful but are difficult to conduct.

A further topic discussed following the interviews is the collaboration between an academic department and the police with all its benefits and challenges. This offers unique opportunities to study the success factors of such a working relationship in more detail than in the interviews in the present thesis which lack perspectives from the judiciary, CPS, and defence. They could potentially contribute more information on the impact of the novel evidence on the courts and the jury. Studying this impact in more detail could benefit from further collaborations with the social sciences, legal studies, and psychology. Close collaboration will further be required to develop written Standard Operating Procedures as both sides need to be involved in the process to ensure proper implementation. These SOPs will be necessary for the development of the university department into a major centre for forensic research and case work as ISO accreditation will become inevitable.

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Appendix A

BSREC Ethical approval- Larynx validation study

WARWICK

MEDICAL SCHOOL

PRIVATE
Ms Waltraud Baier
Warwick Manufacturing Group
International Manufacturing Centre
University of Warwick
Coventry
CV4 7AL

16th March 2016

Dear Ms Baier

Study Title and BSREC Reference: *Using micro-CT to study calcification processes in the human larynx* REGO-2016 1761

Thank you for submitting your revisions to the above-named study to the University of Warwick's Biomedical and Scientific Research Ethics Sub-Committee for approval.

I am pleased to confirm that approval is granted and that your study may commence.

In undertaking your study, you are required to comply with the University of Warwick's *Research Data Management Policy*, details of which may be found on the Research and Impact Services' webpages, under "Codes of Practice & Policies" » "Research Code of Practice" » "Data & Records" » "Research Data Management Policy", at:
http://www2.warwick.ac.uk/services/ris/research_integrity/code_of_practice_and_policies/research_code_of_practice/datacollection_retention/research_data_mgt_policy

You are also required to comply with the University of Warwick's *Information Classification and Handling Procedure*, details of which may be found on the University's Governance webpages, under "Governance" » "Information Security" » "Information Classification and Handling Procedure", at:
http://www2.warwick.ac.uk/services/gov/informationsecurity/handling.
Investigators should familiarise themselves with the classifications of information defined therein, and the requirements for the storage and transportation of information within the different classifications:

Information Classifications:
http://www2.warwick.ac.uk/services/gov/informationsecurity/handling/classifications
Handling Electronic Information:
http://www2.warwick.ac.uk/services/gov/informationsecurity/handling/electronic/
Handling Paper or other media
http://www2.warwick.ac.uk/services/gov/informationsecurity/handling/paper/.

www.warwick.ac.uk

Appendix B

BSREC ethical approval- Interview study

WARWICK
THE UNIVERSITY OF WARWICK

PRIVATE
Ms Val Baier
WMG
University of Warwick
Coventry
CV4 7AL

12 February 2018

Dear Ms Baier

Study Title and BSREC Reference: *Assessing the impact of digital 3D technologies on criminal investigations* REGO-2018-2147

Thank you for submitting the revisions to the above-named study to the University of Warwick's Biomedical and Scientific Research Ethics Sub-Committee for approval.

I am pleased to confirm that approval is granted and that your study may commence.

In undertaking your study, you are required to comply with the University of Warwick's *Research Data Management Policy*, details of which may be found on the Research and Impact Services' webpages, under "Codes of Practice & Policies" » "Research Code of Practice" » "Data & Records" » "Research Data Management Policy", at: http://www2.warwick.ac.uk/services/ris/research_integrity/code_of_practice_and_policies/research_code_of_practice/datacollection_retention/research_data_mgt_policy

You are also required to comply with the University of Warwick's *Information Classification and Handling Procedure*, details of which may be found on the University's Governance webpages, under "Governance" » "Information Security" » "Information Classification and Handling Procedure", at:
http://www2.warwick.ac.uk/services/gov/informationsecurity/handling.
Investigators should familiarise themselves with the classifications of information defined therein, and the requirements for the storage and transportation of information within the different classifications:

> *Information Classifications:*
> http://www2.warwick.ac.uk/services/gov/informationsecurity/handling/classifications
> *Handling Electronic Information:*
> http://www2.warwick.ac.uk/services/gov/informationsecurity/handling/electronic/
> *Handling Paper or other media*
> http://www2.warwick.ac.uk/services/gov/informationsecurity/handling/paper/.

Please also be aware that BSREC grants **ethical approval for studies. The seeking and obtaining of *all* other necessary approvals is the responsibility of the investigator.**

These other approvals may include, but are not limited to:

www.warwick.ac.uk

WARWICK
THE UNIVERSITY OF WARWICK

BIOMEDICAL AND SCIENTIFIC RESEARCH ETHICS COMMITTEE
CONSENT FORM

Study Number: REGO-2017-2147
Participant Identification Number for this study:
Title of Project: Assessing the impact of digital 3D technologies on criminal investigations
Name of Researcher(s): Ms Waltraud Baier, Prof. Mark Williams

Please initial all boxes

1. I confirm that I have read and understand the information sheet dated 25/10/2017 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason. ☐
3. I understand that relevant sections of the data collected during the study, may be looked at by individuals from The University of Warwick, or from regulatory authorities where it is relevant to my taking part in this study. I give permission for these individuals to have access to my records. ☐
4. I agree to take part in the above study. ☐
5. I agree that the interview will be audio recorded. ☐
6. I agree to the researcher getting in contact with me (via email:________________________________) after study completion to disseminate the findings of this study in form of a PhD thesis or journal article. ☐

________________	________________	________________
Name of Participant	Date	Signature
Waltraud Baier	________________	________________
Name of Person taking consent	Date	Signature

31/01/2018 Revision 1

1

WARWICK
THE UNIVERSITY OF WARWICK

PARTICIPANT INFORMATION LEAFLET

Study Title: **Assessing the impact of digital 3D technologies on criminal investigations**

Investigator(s): **Waltraud Baier, Prof. Mark Williams**

Introduction

You are invited to take part in a study. Before you decide, you need to understand why the study is being done and what it would involve for you. Please take the time to read the following information carefully. Talk to others about the study if you wish.

(Part 1 tells you the purpose of the study and what will happen to you if you take part. Part 2 gives you more detailed information about the conduct of the study)

Please ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

PART 1

What is the study about?

The proposed study aims to assess the impact of using digital 3D technologies such as micro-CT, laser scanning, and 3D printing as part of criminal investigations. The novel technologies examined were introduced as part of a PhD project working alongside West Midlands Police on live homicide cases.
Using qualitative interviews with key informants from different criminal justice agencies, the study will evaluate if and how these technologies affect standard procedures, whether they bring about improvements for the investigation and the trial, what challenges they might face, and what people's subjective experience with them is. Information provided in these interviews is further used to assess whether the introduction of technology has the potential for financial savings.

Do I have to take part?

It is entirely up to you to decide. We will describe the study and go through this information sheet, which we will give you to keep. If you choose to participate, we will ask you to sign a consent form to confirm that you have agreed to take part. You will be free to withdraw at any time, without giving a reason and this will not affect you or your circumstances in any way.

What will happen to me if I take part?

If you decide to take part, you will then be sent a list of cases in which aforementioned 3D technologies were used and in which you were involved in as some aspects of these will be discussed in the interview. The researcher will then arrange a suitable time/place with you to conduct a face-to face interview. This can either be the researcher's office at Warwick University or your own workplace, whichever you prefer. You will have an opportunity to discuss any remaining issues with the researcher and if you are still happy to participate, both you and the researcher will sign the consent form. The interview will then commence and the researcher will ask you open-ended questions to which there is no right or wrong answer, your personal opinion is desired. This will take approximately one to one and a half hours. The interview will be audio recorded unless you opt out. Following the interview, the researcher will transcribe the recording, at this point the interview will be anonymised. The recording will be deleted after complete transcription.

What are the possible disadvantages, side effects, risks, and/or discomforts of taking part in this study?

You might be asked questions to which your personal opinion answer might not conform to your organisation's official stance. All answers will be anonymised so they cannot be traced back to you. If you still prefer not to reply you are under no obligation to do so.

Dealing with the criminal justice sector involves handling sensitive data. We would like to reassure you that the process of anonymization will remove any connection between individuals and specific cases.

We are aware that you have a busy schedule, committing to this interview might interfere with your regular work. To reduce this interference, we aim to be as flexible as possible when scheduling an interview.

What are the possible benefits of taking part in this study?

Participation in this study will give you an opportunity to make your voice heard and share your experiences with the technologies studied which can ultimately contribute to a better use thereof and possibly improve the delivery of criminal justice.

Expenses and payments

Unfortunately, we cannot reimburse you for any expenses but in order to keep these at a minimum, the researcher is willing to visit you at your workplace so you won't have any travel expenses.

What will happen when the study ends?

The audio recorded interviews will be transcribed and the recording deleted after the study ends. The transcript, along with the signed consent forms will be kept according to University guidelines for 10 years after the project finishes.
Any information obtained during this study will be reviewed by a senior detective from West Midlands Police prior to submission as PhD thesis.

Will my taking part be kept confidential?

Yes. We follow strict ethical and legal practice and all information about you is handled in confidence. Further details are included in Part 2.
We might use verbatim quotes to illustrate important issues in the final document. These quotes will be anonymised and only state the respondent's profession and years of experience.

What if there is a problem?

Any complaint about the way you have been dealt with during the study or any possible harm that you might suffer will be addressed. Detailed information is given in Part 2.

This concludes Part 1.

If the information in Part 1 has interested you and you are considering participation, please read the additional information in Part 2 before making any decision.

PART 2

Who is organising and funding the study?

This study forms part of a PhD project, funded by West Midlands Police, which aims to examine the role of digital 3D technologies in the criminal justice process.

What will happen if I don't want to carry on being part of the study?

Participation in this study is entirely voluntary. Refusal to participate will not affect you in any way. If you decide to take part in the study, you will need to sign a consent form, which states that you have given your consent to participate.

If you agree to participate, you may nevertheless withdraw from the study at any time without affecting you in any way.

You have the right to withdraw from the study completely and decline any further contact by study staff after you withdraw.

If you wish to withdraw from the study, please contact the researcher stating the interview number shown on your Consent Form.

What if there is a problem?

This study is covered by the University of Warwick's insurance and indemnity cover. If you have an issue, please contact the Chief Investigator of the study:

Waltraud Baier, email: [redacted] mobile: [redacted]

Who should I contact if I wish to make a complaint?

Any complaint about the way you have been dealt with during the study or any possible harm you might have suffered will be addressed. Please address your complaint to the person below, who is a senior University of Warwick official entirely independent of this study:

Head of Research Governance
Research & Impact Services
University House
University of Warwick
Coventry
CV4 8UW
Tel: 024 76 522746
Email: researchgovernance@warwick.ac.uk

Will my taking part be kept confidential?

The data collected as part of this study will be anonymous, no identifiable demographic information will be collected from participants and each will be assigned a unique respondent number. The only information gathered will be their job role and time spent in this role (in time ranges of <2years, 2-5 years, 6-10 years, 10+years). No specific connection to a particular case will be made which could identify the respondent based on information publicly available about the case.

What will happen to the results of the study?

The results of this study will constitute a substantial part of the researcher's PhD thesis and will additionally be published in a peer-reviewed journal. If you wish to receive a copy, please indicate so on the consent form.

Who has reviewed the study?

This study has been reviewed and given favourable opinion by the University of Warwick's Biomedical and Scientific Research Ethics Committee (BSREC): REGO-2017-2147

What if I want more information about the study?

If you have any questions about any aspect of the study, or your participation in it, not answered by this participant information leaflet, please contact:

Waltraud Baier, email: [redacted] mobile: [redacted]
Prof. Mark Williams (supervisor), email: [redacted]

Thank you for taking the time to read this participant information leaflet.

Appendix C

Example calibration certificate

Business Management System	XTF53-02
General Business Process	12th December 2014
Local Rules – Radiation Protection	Form Page 1 of 1
Critical Examination Certificate	

Cabinet type	**XTH 320 LC**	**Serial No.**	**JN1657**
Target 1	**320 Reflection**	**Target 2**	**225 Reflection**

Reason for test: New installation ☐ Modification Annual check ✓ Other (specify)

	Target Type	Maximum kV	Maximum µA
X-RAY SOURCE	320 Reflection	320	1000
	225 Reflection	225	1000

[A] DETAILED INSPECTION PRIOR TO SWITCH ON

1. Visual Checks		
LEAD FINISH	(check for damage/holes etc.)	✓
LEAD CAPS	(fitted on all relevant screws)	✓
LABYRINTH & CABLE SHIELDS		✓
TOP HAT, GUN BOX & II BOX		✓
DOOR & WINDOW		✓

2. Operational Checks		
INTERLOCKS:	Door, Key Switch, E. Stop	✓
CONTROLS:	X-Rays, On/Off	✓
SIGNALS:	X-Ray On, Pre-Warning	✓
X-RAY GUN:	Position, Alignment	✓
LABELS:	Radiation, Lead Glass, Other	✓

1 If Pass mark with a (✓) If Fail mark with a (✗)

Description of source position and any other relevant comments:

[B] FULL POWER RADIATION CHECK

Measurements are taken on all external surfaces of the cabinet with all panels attached, both with direct beam and with an aluminum scatter block, located in the direct beam.

This is repeated with all the targets listed and the highest measured value of leakage is recorded below.

CPS Radiation Monitor Details	
SERIAL NO:	19737-19775
Calibration Due:	30/05/19
MONITOR:	Mini 900
PROBE:	44A
µSv Radiation Monitor Details	
SERIAL NO:	09151
Calibration Due:	30/05/19
MONITOR:	MINI 900
PROBE:	900D

	Location	Maximum Reading.	
1	Door Frame & Seals	<0.5	µSv/hr
2	Window	<0.5	µSv/hr
3	Door Wall	<0.5	µSv/hr
4	L.H Wall	<0.5	µSv/hr
5	R.H Wall, Imaging Box	<0.5	µSv/hr
6	Back Wall	<0.5	µSv/hr
7	Roof, Top Hat	<0.5	µSv/hr
8	Base, Gun Box	<0.5	µSv/hr
9	Other	na	µSv/hr

The above enclosure meets current standards for operation by non-classified personnel as required by the Ionising Radiation Regulations 1999.

Inspection carried out using a Mini Monitor Type 900D with ZP1490 gamma compensated GM tube.

Tested for a maximum of 1 µSv/hr		User manuals and relevant customer information supplied (initial installation only)	
Test Date:	03/12/18	**Name:**	Jas Gill
Next Test Date Due*:	03/12/19	**Signed:**	[redacted]

* If this date has elapsed, please inform the RPS immediately

Completed certificate to be copied and supplied to the customer.

Original to be retained by Nikon for at least two years (Pass Original to Nikon RPS)

Appendix D

Results table strangulation validation study

Case	**Sex**	**Age**	**Location of feature**	**Type of feature**	**Superficial marks**	**Internal marks**	**(Mode of) strangulation**
Aponi	F	35	R sup horn	Complete fracture	Some	Yes	Unknown
			L + R inf thyroid horns	Circular hole			
			Sup thyroid margins	Fragmentary ossification			
Aberdere	F	35	R of ant midline inf thyroid margin	Incomplete fracture	Yes	Yes	None
			L of ant midline inf thyroid margin	Incomplete fracture			
			L + R	Triticeous cartilages			
			Sup thyroid margins	Fragmentary ossification			
Albatross	M	32	L sup horn	Displaced fracture	Yes	Yes	Ligature
			R sup horn	Complete fracture			
			R of ant midline inf thyroid margin	Incomplete fracture			
			L of ant midline inf thyroid margin	Incomplete fracture			
			Laminae	Fragmentary ossification			
Bulblet	M	71	L greater horn	Complete fracture			Possibly ligature

			R sup horn	Incomplete fracture			
			R greater horn	Abrupt angle			
Catni	F	61	R of ant midline inf thyroid margin	Complete fracture	Yes	No	Unknown
Chaucer	M	20	L inf horn	Complete fracture	Yes	Yes	Chokehold
			R inf horn	Complete fracture			
			Post thyroid margins	Fragmentary ossification			
Isengard	F	37	L sup horn	Displaced fracture	Yes	Yes	Unknown
			R sup horn	Displaced fracture			
Holborn	F		R greater horn	Displaced fracture	n/a	n/a	n/a
			L sup thyroid horn	Fragmentary ossification			
Marshside	F	51	R greater horn	Complete fracture	Yes	No	Ligature
			R inf horn	Incomplete fracture			
Pencil	M	59	R greater horn	Complete fracture	Yes	Yes	Possibly ligature
			L greater horn	Complete fracture			
			R of ant midline inf thyroid margin	Incomplete fracture			
			R sup horn	Incomplete fracture			
			L sup horn	Incomplete fracture			
			Sup thyroid laminae	Fragmentary ossification			

			L + R	Triticeous cartilages			
Platte	F	68	L sup horn	Displaced fracture	Yes	Yes	Ligature
			R sup horn	Displaced fracture			
			L sup horn	Complete fracture			
			L of ant midline inf thyroid margin	Complete fracture			
			Laminae	Fragmentary ossification			
Ankara	F	48	R sup horn	Displaced fracture		Yes	Manual and ligature
			L sup horn	Displaced fracture			
			R	Triticeous cartilage			
			L + R sup thyroid horns	Fragmentary ossification			

Control					
S170459	F	81	R of ant midline inf thyroid margin	Complete fracture	n/a
S173045	F	70	R of ant midline inf thyroid margin	Complete fracture	
			L + R	Triticeous cartilages	
			Laminae	Fragmentary ossification	
			L lamina	Circular hole	
S172809	F	93	L of ant midline inf thyroid margin	Complete fracture	

S170452	M	73	L + R	Triticeous cartilages	
			Sup margins laminae	Fragmentary ossification	
S170445	M	80	L + R	Triticeous cartilages	
S170320	M	75	L + R	Triticeous cartilages	
S170167	M	90	L + R	Triticeous cartilages	
			Posterior thyroid margins	Abrupt angles	
S170163	M	46	Sup margins laminae	Fragmentary ossification	
			Sup thyroid horns	Fragmentary ossification	
			L + R	Triticeous cartilages	
S170105	F	86	Ant midline	Fragmentary ossification	
S173160	F	75	Sup thyroid horns	Abrupt angles	
			Greater horns	Abrupt angles	
			Ant and sup laminae	Fragmentary ossification	
S173053	M	79	L sup thyroid horn	Abrupt angle	
			L and R ant laminae	Circular hole	
S173046	M	88	L sup thyroid horn	Circular hole	
			Laminae	Fragmentary ossification	
S172982	M	88	Sup thyroid margins	Fragmentary ossification	

			Sup thyroid margins	Abrupt angles	
C171288	F	94	Sup thyroid margins	Abrupt angles	
C171258	F	76	Laminae	Fragmentary ossification	
			R	Triticeous cartilage	
L172291	M	86	L + R	Triticeous cartilages	
S170405	M	87	L + R	Triticeous cartilages	
			Sup margin ant laminae	Fragmentary ossification	

Appendix E

Qualitative codes for interview analysis

Code		Description	Example
1	**Background on general resources**		
1A	General staff numbers	Estimate of staff numbers involved in the overall investigation	"There's me, 4 sergeants and about 16 DCs in an ideal scenario."
1B	Staff numbers at scene	Estimate of staff numbers attending the scene of crime	"Initially, there'd be me, a sergeant and a couple of DCs"
1C	Case example: staff numbers	Reference to specific case and how many staff were involved in certain tasks	"In OP Argon I think 8"
1D	Staff pressure/workload	Evaluation of whether staffing levels are appropriate for investigative tasks	"We've had further staff sent to us to help out, so easily 16 DCs and it's still not enough but the department is under a lot of pressures"
2	**Background on processes**		
2A	Investigation	Description of tasks and issues involved in investigation	"Then when it's confirmed that there's a deceased person in there, then they'd contact their supervisor to come down have a look, so then there's a third person there"
2B	Forensic strategy	Description of the forensic work in an investigation and how it is organised	"They will then hold on to any samples that are gained and then we'll have a forensic strategy meeting"
2C	Forensic Imaging	Description/discussion of how forensic imaging techniques are used in the investigation or during autopsy	"When I get the phone call of a case coming in if there's any evidence of trauma, especially to the head, I ask for a [hospital CT] scan. But we don't automatically do it"
2D	Specialist scene visit	Explanation of specialist's (e.g. pathologist, BPA expert,…) role at the scene	"We would like to allocate a dedicated coordinator to a case who will be the principal holder and FSI to assist them and get those initial jobs done, get the pathologist out to a scene"
2E	Unpredictability of investigations	Explanation of the uniqueness of every murder and associated difficulty in planning/predicting the investigation	"You can't plan to investigate a murder."
2F	Challenge of uncertainty in early stages	Importance of early stages of investigation and challenge of unknowns at this stage	"The more clarity you can get at the early stage of the investigation the more you can narrow it down."

2G	Duration of processes	Time requirements for individual tasks or overall processes	“After you’ve made that initial assessment which could be an hour or all day depending on how big the job is”
2H	Case example: Duration of investigation	Reference to specific case and how long aspects thereof took	“I think it [OP Platter] came to our attention on 4/5/17 and trial concluded January 2018”
3	**Background on finances**		
3A	Investigative budget	Estimate of the budget available for the investigation	“This depends mostly on the investigative teams and what they come up with.”
3B	Forensic budget	Cost of the overall forensic budget of an investigation and cost of specific forensic examinations	“One murder might cost £3000 in forensics […] Others might take up to and beyond £50000”
3C	Overtime budget	Explanation and estimate of overtime budget available for a case	“What we do at the beginning of an investigation is to ask for a budget which is primarily to cover overtime […]and it could be anything from a couple of hundred hours in a fairly straightforward case to thousands”
3D	Financial limitation/pressure	Financial strain and how it affects different organisations within the CJS	“The main thrust was that we as a police force have less money than we had 20 years ago”
3E	Increase of costs with time	Description of rising costs of investigations the longer they go on for	“So essentially the longer something drags on, the cost almost increases exponentially?- R: Yeah, can do.”
3F	Reduction of costs	Need to reduce spending and measures taken to do so	“The smaller the fishing net can be, the quicker and cheaper it is to investigate.”
4	**Financial considerations**		
4A	Cost for gain consideration	Weighing spending on certain examination against the expected outcome, getting value for money	“It’s more of a case of whether it’s worth the investment.”
4B	Invest to save	Investing in innovation to reduce spending longterm	“Like here, we invested some precious police money but by investing we were actually able to save more money on the investigations”
4C	Putting justice before budget	Doing what’s considered necessary to deliver justice as primary concern for investigators when deciding an action	“At my level I’m not overly concerned with budget, my job is it to brig justice to the person responsible for the crime”
4D	Social responsibility	Having a social/moral obligation to solve a crime as primary concern	“It also demonstrates to the defence we’re doing this ethically”

4E	Best possible evidence	Investigators being charged with collecting the best available evidence	“We are told to provide the best evidence possible for the court, the best evidence is with the micro-CT scanning.”
4F	Do everything possible	Demonstrating that all resources have been exploited in an investigation.	“Because we didn’t have a cause of death we had to explore everything, all possibilities.”
5	**Use of micro-CT in investigation**		
5A	Micro-CT to direct investigation	Using the micro-CT results to follow certain investigative leads	“from your work […] that would give us a huge steer in what outstanding weapon we’re looking for”
5B	Micro-CT for additional detail/evidence	Obtaining evidence not otherwise obtainable	“But if you’re looking at kind of generic stab wounds, any additional information from the work that you do is going to narrow down the search from maybe millions of possibilities to maybe a few”
5C	Micro-CT to increase confidence in other evidence	Using micro-CT to support interpretations based on other evidence	“I thought other experts are going to love this cause it’s going to support their opinions and theories”
5D	General importance/benefit of micro-CT	Other benefits of micro-CT described by respondents	“sometimes it can stop a crime investigation, or it can really progress he investigation in one way or another”
5E	Micro-CT to be more efficient	Using micro-CT to narrow down investigative leads/prioritise actions	“Historically, we just did things to death. If we could use some science we can eliminate that”
5F	Micro-CT to reduce trial time	Using micro-CT based evidence to shorten the court trial	“It’s kind of in a way in that one it saved court time, it could’ve easily be a 6 week trial as opposed to the 2-3 weeks it took.”
5G	Micro-CT to create permanent record	Using micro-CT to create a permanent digital record of the victim’s injuries	“My hope was that with the scanning we would create a permanent record without having to keep the bodies”
5H	Case example: disproving defence argument	Reference to specific case and how micro-CT was used to disprove the offender’s defence argument	“His [offender in OP Sajama] explanation was that he had only touched her neck for only a split second but the scans clearly showed damage to the hyoid thereby contradicting his statement”
5I	Case example: outcome without micro-CT	Reference to specific case and its possible outcome had micro-CT not been used	“If we couldn’t have said it couldn’t have been a pair of scissors that person might have gotten away with a manslaughter”
5J	Case example: Micro-CT to confirm initial suspicion	Reference to specific case and how micro-CT confirmed initial suspicion	“So your scan then showed some internal damage, confirming the initial suspicions.“

5K	Case example: Level of force	Reference to specific case and how micro-CT was used to interpret the level of force used in the assault	"I hope that in the future we can add more science to the degree of force involved, rather than just the pathologist's scale"
5L	Case example: non-destructiveness	Reference to specific case and how micro-CT's non-destructiveness assisted the case	"But by having the scans and getting a good picture and the 3D model without any destruction of the bone, it was the perfect technology for the perfect job [OP Sanderling] really.
5M	Case example: general benefits	Reference to specific case and how micro-CT generally benefitted it	"Sanderling was a proof of concept that micro-CT works."
6	**Use of micro-CT in court**		
6A	Visualisation for court/jury	Description of how micro-CT can be and was used to visualise evidence for court	"If you take an inanimate object like a bone or a weapon and can produce it such detail to a jury is a consequence I didn't realise at the start"
6B	Case example: visualisation	Reference to specific case and how micro-CT images were shown in court	"I n a case like this, it's the presentation to the jury to show the knife fits"
6C	Micro-CT to improve evidence presentation	Explanation how micro-CT can improve evidence presentation in court	"It's much easier to provide a clean clinical view with the settings you're producing"
6D	Medical evidence in court	Description of how medical evidence is delivered in court	"From having sat in court cases, the hardest bit of evidence to get your head around is medical pathology evidence"
6E	Improved understanding of medical evidence in court	Description of how micro-CT can and has improved the understanding of medical evidence in court/by the jury	"We can do that with our computerised models but having that object to compare against the description of something really complicated it adds a thousand words"
6F	Jury use	Description of jurors' attitude during trial and how micro-CT can be used to affect this	"If you create confusion amongst the jury, if they don't understand something or are unsure of something, they will go with not guilty"
6G	Handling 3D print	Description of impact of having a 3D printed object in court/during investigation	"Actually having the item in 3D and handling it gave another perspective on the evidence, that was very important"
7	**Effect of micro-CT on other processes**		
7A	Effect on police practice	How the availability of micro-CT scanning has changed the way in which investigators approach a crime	"[…] that now has got to be included in the checklist, can we use Warwick University for scanning?"

7B	Effect on pathology practice	How the availability of micro-CT scanning has changed the way in which pathologists approach their work	"It's just re-writing the way pathology looks at things."
7C	Practical integration micro-CT with police work	Evaluation of how micro-CT fits in the overall investigation workflow	"importance of getting the items scanned at an early stage so then you can do your work in parallel to our investigation and tie it up later on"
7D	Practical integration of micro-CT with pathology	Evaluation of how micro-CT fits in the pathologist's workflow	"I think the system is well in position. It doesn't delay things"
7E	Complimentary nature of micro-CT and postmortem autopsy	Details how traditional autopsy and micro-CT each add value to the other	"What was interesting in that was that there was a difference in findings between pathology, micro-CT and histology"
7F	Increasing speed of histopathology	Using micro-CT to guide and therefore speed up histopathological examination	"it probably speeds things up as the bone pathologist can target areas"
8	**Pre-micro-CT attitudes**		
8A	Pre-micro-CT expectations	Respondent's expectations of possible outcomes of micro-CT	"Theoretically it sounded like a very good idea"
8B	Pre-micro-CT experience	Respondent's exposure to micro-CT prior to this project	"I had no contact with it, but I was aware of it through life in general"
8C	Pre-micro-CT concern	Respondent's concerns regarding the introduction of micro-CT	"A little bit concerned. It was new technology and it might have been rejected by the defence or prosecutors as being too complicated"
8D	First contact	Account of how respondent first came into contact with micro-CT	"I've obviously always known about the project even before I came on this role, I was always aware of its existence from Paul Tebbutt"
9	**Post-micro-CT attitudes**		
9A	Positive post-micro-CT evaluation	Positive evaluation of micro-CT based on outcomes of this project	"I don't think anyone would have envisaged that it would have such an impact on investigations."
9B	Negative post-micro-CT evaluation	Negative or highly cautious evaluation of micro-CT based on outcomes of this project	None found
9C	Neutral post-micro-CT evaluation	Respondent shows reserved opinion of usefulness of micro-CT, neither extremely positive nor negative.	"I think it wasn't critical but useful."
9D	Limitations of micro-CT	Limitation and shortcomings of micro-CT technology	"The only downside is the size-limitation"

9E	Dependency on micro-CT	Details how police cannot go back to not using micro-CT	“The only other thing would be if the project was to end, where are we going to recreate that? We can’t go back”
10	**Police-academia relationship**		
10A	Nature of collaboration	Description of how WMP and WMG have worked together	“having this full-fledged partnership between the university and police, is just unique.”
10B	Successful police-academia collaboration	Description and criteria of what makes a police-academia collaboration successful	“But if you get that mutual understanding right from the beginning of what we’re trying to achieve and maintain that regular contact, then things get done”
10C	Knowledge sharing/spread of awareness	Importance of spreading awareness of the project and educating people about its benefit	“Perhaps a road show to advertise the results because you do have some good cases here. And it really is to let them think about it and realise the technology is there”
10D	Police adversity towards technology/change	Description of how and why police are slow/reluctant to change or adopt new technologies/practices	“The police are resistant to change because it carries a risk, they are absolutely risk adverse.”
10E	Technological advance to assist police	Description of how new technologies benefit everyday policing	“A large part of investigations now are solved by CCTV, telecoms, and the advancement of forensic science and I include you in that.”
10F	Technology acceptance	Conditions for police to embrace new technologies/practices	“if it wasn’t that successful it wouldn’t feature so heavily across the jobs”
10F	Validation	Importance of method validation as required by the Forensic Science Regulator and associated issues	“If you scanned normal individuals we might find small areas of trauma through normal living. We need the control cases”
10G	Evidentiary concerns	Potential issues arising from using micro-CT for evidence	“we thought as a number of fractures didn’t show on the scan […] it might confuse the jury”
11	**Applications**		
11A	Types of cases examined	Different types of homicides investigated using micro-CT	“Half the cases are from infants, the other from adults, but hardly any in between”
11B	Frequency of micro-CT	How often a micro-CT scan was conducted with regards to overall case load	“I’m now getting well over 100 cases a year and I’m getting micro-CT reports on maybe 20%.”
11C	Case example: reason for micro-CT scan	Reference to specific case and why a micro-CT scan was requested and by whom	“We didn’t have the murder weapon at the time of the post-mortem so we discussed that a scan of the ribs which were

			nicked on either side of the injury could help us finding the murder weapon.”
11D	Research area	Evaluation of which type(s) of homicide benefit most from micro-CT, both currently and in the future	“I’d say cases where you don’t have a cause of death, decomposed bodies for example, dismemberments”
12	**Management concepts**		
12A	Stage-gate system	Mention of the stage-gate system or individual sections thereof and reference to specific cases and their place within the SGS	“That really came in at stage 1 the initial investigation”
12B	Objectivity/quality	Explanation of how micro-CT improves evidence quality	“It’s presenting the facts accurately in a more objective way”
12C	Service delivery	Explanation of how micro-CT has been delivered as a service	“ It [the reporting format]’s exactly what the courts would want, they don’t want to deal with huge amounts of technical information”