Transfers of gunshot residue (GSR) to hands: an experimental study of mechanisms of transfer and deposition carried out using SEM-EDX, with explorations of the implications for forensic protocol and the application of Bayesian Networks to interpretation

Candidate: James C. French

Institution: University College London (UCL)

Degree: Ph.D Forensic Science

Declaration

I, James French, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated.

Signed…….

November 2013

Acknowledgements

This research was funded by the Engineering and Physical Sciences Research Council of the U.K. through the Security Science Doctoral Research Training Centre (UCL SECReT) based at University College London (EP/G037264/1).

I would like to express my appreciation for the help and support I have received during the completion of my thesis. I would like to acknowledge the supervision of my two supervisors, Dr Ruth Morgan (UCL) and Dr David Lagnado (UCL). This piece of research was made possible by their guidance and academic input. The assistance of the Surrey/Sussex Joint Command Tactical Firearms Unit enabled the completion of the experiments and the support of Oxford Instruments, U.K. facilitated the automated analysis. The assistance provided by Jim Davy (UCL) during the SEM-EDX analysis is gratefully acknowledged. For the support, love and guidance provided by my family and friends, I will always be grateful. To Mum, Dad, Lucy and Lauren: Thank you.

For absent family and friends.

James French, November 2013

Abstract

Gunshot residue (GSR) is produced during a firearm discharge and its recovery from the hands of a suspect may be used to support an inference that the suspect discharged a firearm. Various mechanisms of GSR transfer and deposition involving the hands of subjects were studied through a series of experimental scenarios that were intended to mimic real-world forensic situations. Samples were analysed using SEM-EDX with an automated search and detection package (INCAGSR, Oxford Instruments, U.K.). The results demonstrate the possibility of recovering considerable quantities of GSR from the hands of subjects as a result of a secondary transfer via a handshake with a shooter, or through handling a recently discharged firearm. As many as 129 particles were recovered from a handshake recipient. Additionally, GSR particles were found to undergo tertiary transfer following successive handshakes, while the possibility of GSR deposition on the hands of a bystander was confirmed. Particle size analysis revealed that very large (>50µm and >100µm) particles may undergo secondary transfer. The implications of these findings for forensic investigations are considered, particularly for interpreting the presence of GSR under competing activity level propositions about its deposition and the actions of the suspect. Bayesian Networks are inferential tools that are increasingly being employed in the interpretation of forensic evidence. Using the empirical data derived during the experimentation, the utility of Bayesian Networks for reasoning about mechanisms of GSR deposition is demonstrated. Further research aimed at unlocking the interpretative potential of GSR through empirical research and establishing the use of Bayesian Networks in forensic applications is recommended. It is anticipated that this emphasis on empirical support and probabilistic interpretation, in combination with the findings of this study, will strengthen the scientific basis of inferences made about GSR evidence and contribute to the accurate interpretation of evidence in legal settings.

Keywords: Gunshot residue (GSR), secondary transfer, interpretation, evidence dynamics, Bayesian Networks

Contents

List of tables

Chapter 1 Introduction

Chapter 3 Gunshot residue (GSR)

Chapter 4 The experiments: Materials, methods and procedures

Chapter 5 The experiments: Results, analysis and observations

Chapter 7 The interpretation of GSR evidence using Bayesian Networks

List of figures

Chapter 1 Introduction

Chapter 2 Trace evidence: Evidence dynamics, interpretation and the forensic investigation

Chapter 3 Gunshot residue (GSR)

Chapter 4 The experiments: Materials, methods and procedures

Figure 4.19 INCAGSR screenshot – stage mimic showing sample stub area divided into 335 regular fields. Detected features are shown

Figure 4.20 INCAGSR screenshot – Selecting the recipe and creating and embedding the database under the 'Recipe' tab

Figure 4.21 INCAGSR screenshot – INCAGSR tab navigator

Figure 4.22 INCAGSR screenshot – performing a quant optimisation using the cobalt reference under the 'Quant Optimization' tab

Figure 4.23 (*A)* Side view of backscattered electron calibration stub showing the three reference materials on a horizontal plane relative to an unaltered sample stub ***(B)*** Plan view of backscattered electron calibration stub

Figure 4.24 INCAGSR screenshot – beam compensation and quant optimisation graphs relating to the analysis of a sample stub. 'Stability' tab under 'Review Classes' tab

Figure 4.25 INCAGSR screenshot – run screen showing live analysis of a sample under the 'Run' tab

Figure 4.26 Spectrum and image of the latest feature in the analysis

Figure 4.27 Status of analysis run showing field progress, time to completion and a running total of detected features by category

Figure 4.28 Live stage mimic showing analysis progress. Features are displayed on completed (light green) fields; current field of analysis (orange) is shown, and the remaining fields are shown (grey)

Figure 4.29 INCAGSR screenshot – List of detected features and associated data, image and spectrum for the selected feature. Backscattered image of the selected field is also shown under the 'Review Features' tab

Figure 4.30 INCAGSR screenshot – summary of completed analysis of a sample stub. 'Summary' tab under the 'Review Classes' tab

Figure 4.31 INCAGSR screenshot – summary of detected features for a sample stub by feature classes. 'Classes' tab under the 'Review Classes' tab

Figure 4.32 INCAGSR screenshot – stage mimic showing all detected features on a sample by class. 'Stage mimic' tab under the 'Project' tab

Figure 4.33 INCAGSR screenshot – list of all detected features and corresponding data which was exported to Excel under the 'Review Data' tab

Chapter 5 The experiments: Results, analysis and observations

Chapter 6 A discussion of the experimental findings

Chapter 7 The interpretation of GSR evidence using Bayesian Networks

List of abbreviations

ACB - Auto contrast and brightness

BN – Bayesian Network

BSE – Backscattered electron(s)

CDR – Cartridge discharge residue

DNA – Deoxyribonucleic acid

EAFS – European Academy of Forensic Science

EDX – Energy-dispersive X-ray spectrometry

EPSRC – Engineering and Physical Sciences Research Council

FDR – Firearm discharge residue

FSS – Forensic Science Service

GSR – Gunshot residue

LCN – Low copy number

LR – Likelihood ratio

NAS – National Academy of Sciences

NPT – Node probability table

OGSR – Organic gunshot residue

ONS – Office for National Statistics

PCR – Polymerase chain reaction

SEM – Scanning Electron Microscope

U.K. – United Kingdom

U.S./USA – United States (of America)

Chapter 1 Introduction

1.1 Outline

This chapter introduces the context for undertaking a piece of research in forensic science in general, and in particular, one that seeks to understand mechanisms of gunshot residue (GSR) transfer. This involves a survey of some of the factors that currently influence the practice of forensic science and the undertaking of research in forensic science, in the U.K. and beyond. The commentary addresses legal and scientific issues and the place of this thesis in relation to them. The importance of the forensic reconstruction of firearms offences is demonstrated through an illustration of the nature and rates of firearm offences in England and Wales which are, ultimately, the security issue with which this project is concerned. Indeed, it is the assessment of evidence associated with these offences that the findings of this piece of research are intended to inform. This chapter also previews the issues that currently surround the use of Bayesian and probabilistic reasoning in a forensic and legal context in England and Wales. As a result, it will be demonstrated that research into the application of this approach in forensic science is both valuable and timely.

1.2 The need for research in forensic science: a context

Forensic science, its outputs, the reliability of its methods, the scientific basis of the assumptions which underpin its conclusions, and the body of empirical research available to the support the inferences it makes have all come under scrutiny in recent years. Identifying the reasons for this scrutiny and considering a path forward is currently the focus of much introspection on the part of sections of the forensic science community. A number of legal and scientific forces have been identified as the source of the questions that are being asked of 'traditional' forensic science. The aim of this section is to survey these converging developments and to demonstrate the importance of carrying out empirical research in light of recent and ongoing debates.

According to Saks and Koehler (2005, p.892), the 'traditional forensic identification sciences' are being forced to undergo 'fundamental change'. The authors invoke the

notion of a 'paradigm shift'[1] to describe the process by which these sciences have been forced to adapt by what are termed 'converging legal and scientific forces' (ibid., p.892). Traditionally, the *modus operandi* of these identification sciences has involved comparing patterns, marks and impressions to determine, ultimately, that two marks are indistinguishable from one another and thus, were made by the same object or person. By extension, all other potential sources of the mark are excluded in this process and the assumption is that it is possible to 'individualize' [sic] (ibid., Stoney 1991, Saks and Koehler 2008). Thus, handwriting analysis, toolmark comparison and the comparison of latent finger marks to prints have been considered the reliable 'mainstays' of forensic science which are used in court (Mnookin et al 2011, p.726). This is changing.

The advent and development of DNA as a forensic tool has resulted in a number of exonerations in cases which it was not originally utilised. In a number of these exonerations, forensic evidence had been presented by the prosecution (Garrett 2008) and moreover, this evidence was subsequently found to be misdirected and to have had its probative value overstated (Garrett and Neufeld 2009). Concurrently, a number of errors and scandals have emerged that have cast doubt on the accuracy and reliability of forensic comparisons. For example, in the U.S., Brandon Mayfield was erroneously linked to the 2005 Madrid train bombings via a fingerprint comparison. Meanwhile the central issue in the protracted case of Shirley McKie in Scotland was whether a fingerprint examiner was capable of making an error when comparing marks (The Fingerprint Inquiry Scotland, 2011).

Simultaneously, critical scholarship and research has begun to examine the claims and underlying assumptions inherent in the comparison sciences (Saks 1998, Pretty and Sweet 2001, Faigman et al 2002, Epstein 2002, Saks and Koehler 2008). The assumption of 'uniqueness' (Osterburg 1969) – that no two objects will generate the same mark, pattern or impression – which permits unconditional identification of an individual or object, has been questioned. Saks and Koehler (2005, 2008) argue that when invoked, this assumption serves to apparently negate the need for population data or empirical research into the common attributes of two different objects. Crucially, these assumptions are often theoretically and empirically unfounded.

[1] After Kuhn (1962)

Such critique and scrutiny stems, at least in part, from the apparent differences between identification sciences and the scientific paradigm associated with the emergence, development and practice of DNA analysis for forensic purposes (ibid., Broeders 2006). DNA science represents a different model to which the criticisms aimed at traditional identification sciences appear not to apply. DNA science exhibits a theoretical, statistical and empirical underpinning. DNA typing and identifications made using DNA involve a statistical, probabilistic approach founded on population genetics and empirical research into the occurrence of genetic characteristics within populations (Saks and Keohler 2005). Saks and Keohler (2005) observe that DNA science can demonstrate probabilistic conclusions based on databases, established standards, known error rates, empirically determined random match probabilities and a body of empirical research which can be used to support inferences. By comparison these elements, it is argued, are conspicuous in their absence with respect to non-DNA forensic science, particularly in those fields that involve mark, pattern or impression comparison.

Scientific developments and pressures have been accompanied by legal developments regarding the admissibility of forensic evidence. This is a response to (as well as a source of) the criticisms that have been mentioned. In the U.S., the admissibility of expertise and of scientific evidence was addressed in *Frye v U.S.* (293 F.1013 D.C. Cir [1923]) and in *Daubert v Merrell Dow Pharmaceuticals* (509 U.S. 579 [1993]), with the latter giving its name to a set of rules and standards which scientific evidence must satisfy if it is to be admitted to the courtroom in over half of U.S. states. Among these is the requirement to demonstrate the scientific foundation and to provide supporting data, as well as to indicate the error rate of the forensic technique. The courts in the U.S. have heard a number of challenges to forensic evidence on these grounds which further emphasise the apparent shortcomings of traditional forensic science.

The 2009 report by the National Academy of Sciences, 'Strengthening forensic science in the United States: A path forward' (NAS 2009), was considered by many to represent a damaging critique of the state of forensic science. The report targeted the way forensic science is practiced, the research which underpins it, the reliability of its techniques and conclusions, and ultimately, the probative value of its outputs. For Mnookin et al (2011, p.731), the report represents a 'watershed' for forensic science;

highlighting, in accordance with Bono et al (2011), that what was once accepted as good enough can no longer be considered sufficient. It is important to stress that, while the report, and indeed the subsequent commentaries on it (see Mnookin et al 2011, Bono et al 2011, Linacre 2013 Margot 2011), focus on pattern and impression comparison evidence, '…pattern evidence areas are not alone in generating the [expressed] concerns' (Mnookin et al 2011, p.733). Rather, the deficiencies and subsequent recommendations reverberate within all fields of forensic science, including trace evidence analysis and the domain of DNA analysis. Furthermore, while primarily an evaluation of the state of forensic science in the U.S., its observations and implications are 'global in their reach' as they 'are intended to apply to forensic science as a whole' (ibid., p.733). The consultation report prepared by the Law Commission (2009) on the admissibility of expert evidence concerns similar issues within the legal context of England and Wales.

The NAS and Law Commission reports consolidate, reflect and reinforce many of the debates and much of the scrutiny surrounding the practice of forensic science referred to in this chapter. Critically, on the scientific basis and empirical research underpinning forensic science, the NAS report concludes:

> *'The simple reality is that the interpretation of forensic evidence is not always based on scientific studies to determine its validity. This is a serious problem. Although research has been done in some disciplines, there is a notable dearth of peer-reviewed, published studies establishing the scientific bases and validity of many forensic methods.'* (NAS 2009, p.8)

A number of commentators within the forensic science community have recognised the need to look hard at forensic science in light of the report and other legal and scientific developments. Change is clearly necessary and some have attempted to consider what the post-NAS report world of forensic science – or new 'paradigm' of forensic science (Saks and Koehler 2005, p.892) – should look like.

Subsequent commentaries have been unanimous in highlighting the need for empirical research. While this call is not novel, the urgency with which it is made has increased. Mnookin et al (2011) argue that simply engaging in research is not enough but rather, what is required, is the creation of a research culture which is institutionalised and into which the practice forensic science is firmly embedded. Their review considers why this culture is currently lacking and considers what a research culture in forensic

science should look like. At its heart, they argue, should be the question of the 'relationship' between 'research-based knowledge' and practices (in the laboratory and in the field). Consequently, in different domains of forensic science the following questions should become commonplace: *What do we know? How do we know it? How reliable is that knowledge?* Mnookin et al (2011), among others, argue that these questions are only answered by reference to empirical scientific data and cannot be presumed or concluded with reference to notions such as 'experience' or 'competence'. In short, a new paradigm is called for in which claims and assumptions which lack empirical foundations are replaced by inferences and conclusions which are made with reference to an empirical and theoretical knowledge base. This necessitates a commitment to generating and testing hypotheses regarding, for instance, the behavior of evidence under certain conditions; to deriving error rates and carrying out blind testing for comparison and analytical tests, and to collecting data on environmental ('background') rates of traces or the occurrence of patterns within populations.

1.2.1 The current investigation and the need for a research culture

The aims and objectives of this piece of research into the transfer and deposition of GSR resonate strongly with calls for the provision of a research basis in forensic science (see section 1.4.1). Its nature and undertaking also reflect the values of the research culture that Mnookin et al (2011) discuss. The authors consider a 'respect' for empirical support (ibid., p.742) to be essential; that bodies of data are desirable and that attention should be paid to the degree of support they can provide for a claim. The authors distinguish conclusions based on rigorous data from those based on 'hunches' (ibid., p.742) and highlight the connection that should be made between the results of research, the claim or proposition that is proffered and the degree of confidence or reliability that can be assigned to it. While it is desirable that robust research will inform practices, reports and testimonies, the authors add the caveat that care should be taken not to cite data as support for propositions or hypotheses that 'extend beyond the reach of the research design' (ibid., p.742). The importance of making data sets, as well as the practices and procedures employed in producing

them, available for others is identified. In so doing, further research should be actively encouraged and avenues for its undertaking should be highlighted. In addition, a 'critical perspective' should be at the core of attempts to design, review and guide research. In order to eschew dogma the findings of research should be considered provisional claims that can be modified, altered and improved with further study. It is acknowledged that this rationale to answering questions which constantly and incrementally improves and builds knowledge may not satisfy the definitive questions which are asked in the courtroom and means that judge and jury may have to make use of the 'best available answers to scientific questions at that given moment in time' (ibid., p.744). Finally, Mnookin et al (2011) advocate the open exploration of research problems rather than seeking to legitimise and vindicate current practices or to reproduce certain results or hypotheses.

The principles that are integral to this new research culture are well served by this thesis. Crucially, this piece of research seeks to generate an empirical understanding of the transfer of GSR which can be referred to when making inferences regarding the presence of GSR. Meanwhile, in drawing conclusions and considering the implications for forensic practice and interpretation, the scope and limitations of the research design are acknowledged. Publishing and presentation of results and methods represent an inherent element of this research process, while particular consideration is given to suggesting and encouraging complementary and further work. This thesis is concerned with various mechanisms of GSR deposition, a relatively under-researched topic. It tests and explores the assumption that the potential for GSR secondary transfer is likely to be minimal in casework situations. In doing so, this thesis considers novel reconstructive and probative potential of GSR in a way that supplements the current capacity to utilise GSR evidence in casework. An open, exploratory approach that follows the findings derived is required, so as to expand our understanding and consider the potential implications for forensic protocol. Finally, the latter phase of this piece of work reflects recent research in forensic science in its exploration of a Bayesian approach to interpreting GSR evidence under competing hypotheses about its transfer and deposition.

In illustrating the potential value of research, Linacre (2013) provides an example that resonates with the subject matter of this thesis. An instance is referred to when the

possibility that a secondary transfer mechanism was responsible for a transfer of bodily fluids and the subsequent recovery of a DNA profile in a case. When cross-examined, the expert in question was able to refer to research publications regarding the likelihood of a secondary transfer. For Linacre (2013), the provision of an opinion informed and supported by recent empirical research in this example represents a perfect illustration of the connection that can and should exist between forensic research and practice. In essence it is this connection that this thesis is concerned with making with regard to the transfer of GSR. By empirically deriving data concerning the potential for transfers of GSR, inferences that are made regarding the likelihood of a secondary transfer, for example, can be supported by reference to published empirical data. Furthermore, by exploring the potential for employing an interpretative framework based on Bayesian Networks in the assessment of transfer problems involving GSR, this investigation will also consider the application of empirical research in forensic practice.

1.2.2 The path towards a research culture

While it is desirable that the need for research in various fields of forensic science will be met by work motivated by the same concerns as those which stimulate this thesis, there are several difficulties. The limited resources for funding, particularly in the current economic climate, are in danger of stymieing the potential for research where it is needed (ibid., Robertson 2011, Linacre 2013). In the U.K., the recent closure of the Forensic Science Service (FSS), which has been met with disapproval by many internationally (ibid.), has dramatically changed the landscape of forensic science provision. A number of questions are raised by this development and of particular concern are the potential implications for the development and undertaking of research programs in forensic science. The research arm of the FSS had previously provided valuable, high quality research in many areas of forensic science including DNA and evidence interpretation (see, for example, Evett et al 1998, 2002). While the responsibility of carrying out research cannot be assigned to one body, Linacre (2013, among others[2]) has identified the research 'vacuum' that will be left to fill. In the U.K.

[2] Ian Evett echoed this sentiment at the 6th European Academy of Forensic Science Conference (EAFS 2012) and at 'Forensic Horizons 2012' hosted by the Forensic Science Society. Evett was also critical of the ruling of the Court of Appeal in *R. v. T* (2010)(see Chapter Seven)

it remains to be seen whether the need for rigorous scientific research can be reconciled with the requirements of the police services; namely, cost effectiveness, rapid delivery and outputs which are error free, all within the wider economic context of financial constraints and budget cuts.

There are a number of further dilemmas regarding the undertaking of research. Many forensic practitioners are not trained researchers and moreover, the financial implications of carrying out research may mean that commercial laboratories do not do so (Mnookin et al 2011, Linacre 2013). Accordingly, it seems that universities must be at the centre of attempts to establish research programs and projects (Linacre 2013). Funding, however, is limited and that which is made available to carry out research in forensic science may continue to represent an impasse. Universities are, notwithstanding, free from other constraints such as law enforcement balance sheets or "provider-customer" dynamics. Crucially, however, this must not mean that the scientific research becomes disconnected from practice (Linacre 2013). Rather, its relevance, value and practical application should be demonstrable, and its aims and objectives need to be informed by an understanding of knowledge gaps, police needs, the legal context and operational problems. Ensuring the applicability and wider benefit of research will involve careful research design and attention to the practical consequences of research in writing up. Also crucial are effective reporting and dissemination of research and results in the relevant spheres (Mnookin et al 2011). For research in this field, these will include the scientific and forensic research communities, as well as legal and practitioner audiences.

The features of a relevant piece of research have been central to the formulation and execution of this thesis. Given the source of its funding[3], the *Raison d'être* of this thesis is the motivation for the use of science and techniques from different disciplines to address security problems. Therefore, this thesis is well placed to further the forensic science knowledge base whilst contributing to operational practices, specifically in the investigation and detection process following incidents involving firearms. It will also contribute to the scientific underpinning of claims made in court, in the pursuit of safe and reliable justice. Cooperation and engagement with, and

[3] EPSRC funding was acknowledged in the 'acknowledgements' section on page 3 of this thesis

presentation to, the relevant user communities, as well as consideration of the relevance and benefit of the research are central tenets of this research project.

1.3 Firearms offences in England and Wales: underlining the importance of firearms forensics

Section three of The Office for National Statistics' bulletin entitled 'Focus on: Violent Crime and Sexual Offences, 2011/12' (ONS 2013) presents figures relating to offences involving the use of firearms in England and Wales. These offences include any recorded crime in which a firearm has been used; when it has been fired, or used either as a blunt instrument, or to make a threat. Importantly, this category of offences does not include possession offences (in which the firearm was not 'used').

A firearm was used in 9,555 recorded offences in 2011/12 in England and Wales. A 60% decrease in the number of firearms offences recorded since 2004, is however, largely attributable to the reduction in recorded offences involving air weapons (which tend to have less serious consequences) by 74% since 2004.

	Firearms offences in England and Wales 2011/12
Air weapon offences	3554
Non-air weapon offences	6001
Total	9555

Table 1.1 Air weapon and non-air weapon firearms offences in England and Wales 2011/12 (ONS 2013)

While offences involving the use of firearms represent a relatively small proportion of all recorded crimes in England and Wales (0.2%), they tend to be associated with serious crimes such as homicide or aggravated robbery (especially when the firearm is not an air weapon). A firearm was used in 42 of the 540 homicides that are currently recorded for 2011/2012 in England and Wales, and in all of these cases, the firearm was fired. Meanwhile, around 3% of robberies in 2011/12 involved the use of a

firearm and 282 serious injuries were caused by firearms during the same period. Taking all firearms offences for 2011/12 into consideration, 35% were for violence against the person (homicide being the most severe), while 27% were for robbery. From 2009 (incorporating 2009/10, 2010/11 and 2011/12), 8% (141) homicides have resulted from the shooting of a gun.

Offences involving non-air weapon firearms numbered 6001 in 2011/12, compared to 7040 in 2010/11. It is these offences that tend to be associated with the most serious crimes and that are more likely to result in serious injury or fatality, as demonstrated by figure 1.1. While 46 % of the 6001 recorded offences involving a non-air weapon were instances of violence against the person offences only 6% were for criminal damage. On the other hand, 77% of all air weapon offences were for criminal damage offences, while only 16% involved violence against the person, underlining the less serious nature of most air-weapon offences.

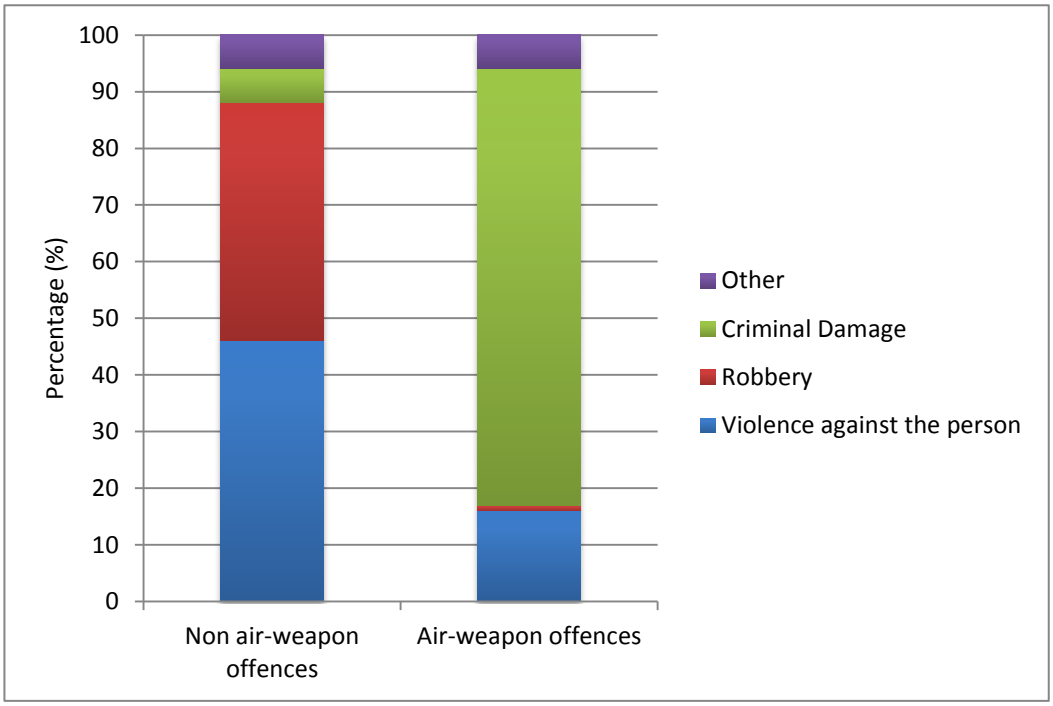


Figure 1.1 Comparison of non-air weapon and air weapon offences by offence type in England and Wales 2011/12 (ONS 2013)

In terms of the type of firearm used in offences, 2651 of the 6001 non-air weapon firearms offences involved the use of handguns. Of these handgun offences, firing of the weapon took place in 13% of cases and a fatal or serious injury was the result in 36% of offences in which a handgun was discharged. The prevalence of the use of

handguns in the most serious of offences involving firearms is illustrated by the fact that, of the 42 homicides caused by shooting in 2011/12, 18 (43%) involved the use of a handgun. Meanwhile, the prevalence of handguns compared to long-arms and other firearms is also evident in figure 1.2 with regard to the robberies that involved firearms in 2011/12; handguns were used in 64% of cases.

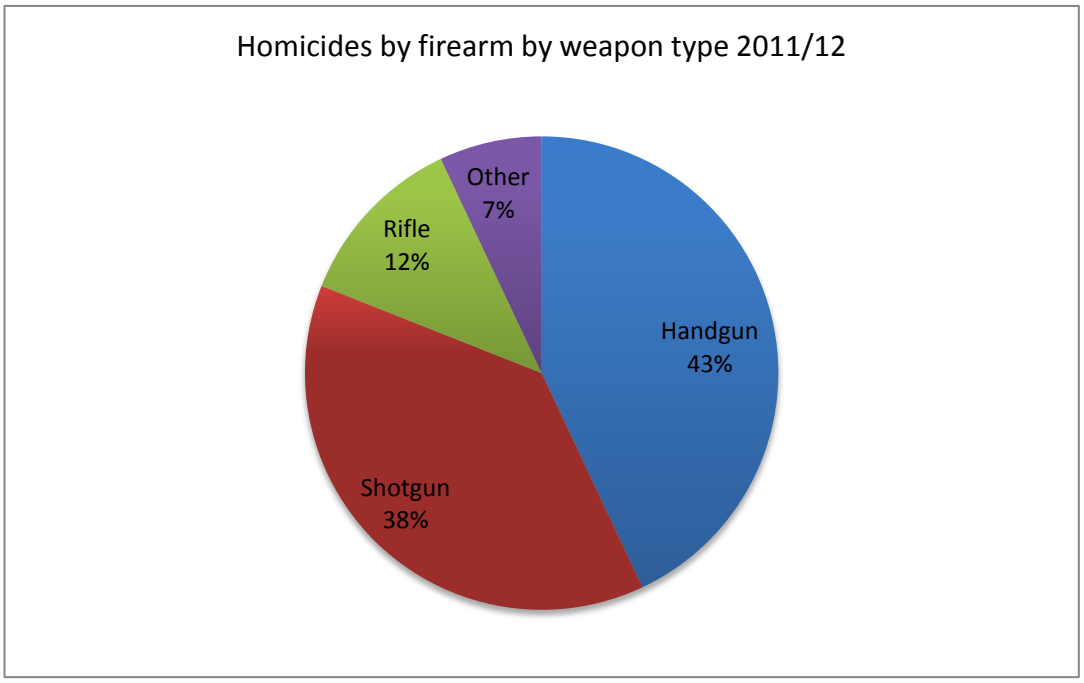


Figure 1.2 Homicides caused by a firearm in England and Wales 2011/12 by weapon type (ONS 2013)

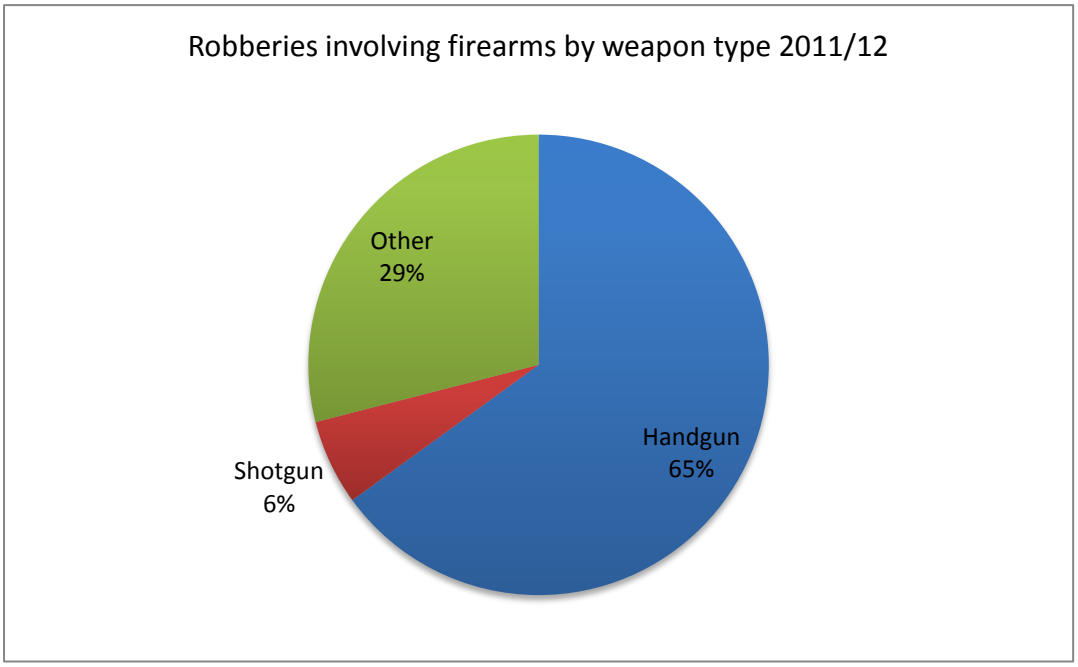


Figure 1.2 Robberies involving a firearm in England and Wales 2011/12 by weapon type (ONS 2013)

Offences involving the use of firearms represent a significant contribution to the number of serious crimes in England and Wales. Moreover, within these offences, the prevalence of handguns is notable. Whether the gun is fired or merely handled, the capacity for forensic scientists to employ trace evidence analysis in making inferences about the identity of the perpetrator(s) and to reconstruct the crime scene is vital if public safety is to be assured through the identification and safe conviction of offenders. Research which enhances the use of forensic methods and techniques which assist the process of investigation and detection with regard to such firearms offences is, therefore, valuable. Conceivably, the present piece research could assist in investigation and detection when it is necessary to distinguish between a number of suspects, perhaps in a case in which a gang or group of individuals were present and it is necessary to determine their respective roles in the commission of the offence.

1.4 Thesis overview

This section presents the aims and objectives of this thesis. An outline of each of the eight chapters is then provided.

1.4.1 Aims and objectives

Aims:

- The aim of this piece of research is to investigate the nature of the transfer and deposition of GSR and the implications of these mechanisms for the interpretation of GSR evidence and for the forensic investigation of incidents involving firearms

Objectives:

- To experimentally simulate transfer and deposition scenarios involving GSR
- To use SEM-EDX to quantify the GSR presence on samples taken during the experiments in order to generate a body of data on GSR transfer and deposition
- To consider the importance of the experimental findings for our understanding of the dynamics and behaviour of GSR under different scenarios

- To consider the implications of the experimental findings for the collection, analysis, interpretation and presentation stages of a forensic investigation that involves GSR evidence
- To explore the utility of using Bayesian Networks to facilitate the interpretation of GSR evidence, particularly for scenarios that involve multiple suspects
- Using case examples, to incorporate the empirical findings generated during the experimental phase within a Bayesian Network framework in order to explore the process of reasoning about mechanisms of GSR deposition
- To explore and highlight the avenues for further research into the dynamics of GSR evidence which will further contribute to our understanding of evidence dynamics and their impact on the process of interpreting evidence
- To consider the future of research in forensic science in light of the findings of the present research project

1.4.2 Thesis outline

Chapter one

Chapter one has set out the context for undertaking the piece of research presented in this thesis. Particular attention has been afforded to elucidating the importance of research within various domains of forensic science.

Chapter two

Chapter two will introduce trace evidence theory with a focus on the process of interpreting trace evidence via the formulation and assessment of interpretative propositions. The concept of 'evidence dynamics' and its importance to interpreting forensic evidence will also be introduced. Examples of research into the science of trace evidence will be cited and concurrently, the importance of issues of secondary transfer will be emphasised.

Chapter three

Chapter three is concerned with GSR; its characteristics and formation, our understanding of its dynamics and its use in crime reconstruction. The discussion considers the significance of transfer and deposition mechanisms with respect to GSR and identifies significant knowledge gaps. As part of the review, the development and

of analytical methods for the detection and identification of GSR are be discussed. This account also serves to introduce the analytical methods that were employed in experimental phase of this thesis. This chapter concludes by elucidating the research questions which were formulated, and with which this thesis engages.

Chapter four

Chapter four details the materials and methods used in the experimental phase of this thesis, with particular attention given to the ways in which the validity of the outputs of the experimental work was assured. This account proceeds to document the procedures and processes which were involved in detecting and quantifying the presence of GSR, using SEM-EDX with automated detection software. On the one hand, this account is intended to detail the steps taken to safeguard the accuracy and reliability of the results on which the findings and conclusions are based. Meanwhile, it is also intended to serve as a guide for future analysis and research projects that employ the same (or similar) methods.

Chapter five

Chapter five reports the results of the analysis of the samples taken during the experiments. The results and observations represent a body of empirical data on various transfer and deposition mechanisms involving GSR.

Chapter six

The findings of the experimental research are discussed in chapter six with reference to their contribution to our understanding of the dynamics of GSR. Importantly, this chapter considers the implications of these findings for forensic protocol and for the various stages of an investigation. In addition to assessing the ramifications for the collection of GSR, this discussion includes an evaluation of the analytical methods used for this piece of research. It is argued that it is in the interpretation of GSR evidence that the findings of the experimental work have the greatest potential significance.

Chapter seven

This chapter introduces the application of Bayesian Networks and probabilistic reasoning in forensic science. It explores the application of a Bayesian Network approach to the interpretation of GSR evidence and to reasoning about mechanisms of GSR deposition. The capacity of a Bayesian Network approach to reason in this way is demonstrated through the incorporation of the experimental findings into graphs representing a range of casework scenarios. The discussion is set within the context of contemporary debates regarding the relationship between Bayesian reasoning and the law in light of recent judgments in legal cases in England and Wales. The commentary identifies the need for clarity and consensus regarding the status of Bayesian approaches among legal communities and emphasises the importance of research which demonstrates the utility of Bayesian Networks for reasoning about legal and forensic problems that multiple sources of uncertainty.

Chapter eight

The final chapter summarises the principal findings of the research, and considers their implications and the limitations of their applicability. The avenues for further research are charted prior to a discussion of the wider significance of the research findings.

Chapter 2 Trace evidence: Evidence dynamics, interpretation and the forensic investigation

2.1 Outline

This chapter provides an introduction to trace evidence theory, with an emphasis on the importance of evidence dynamics. Particular attention will be given to introducing secondary transfers of trace material. The interpretation of trace evidence, and the manner in which evidence dynamics are incorporated into this process, will also be introduced.

2.2 An introduction to trace evidence

The term 'trace evidence' is interchangeable with others such as 'trace material', 'trace particulate evidence', or 'trace physical evidence', the unifying feature of which is their description of 'trace', or microscopic, quantities of substances that are of probative value in a criminal investigation. The use of 'evidence' as opposed to 'material' implies that, to some extent, the probative value of the substance has been recognised in the context of a case.

The terms refer to a plethora of naturally occurring and anthropogenically generated materials such as fibres (natural and synthetic), glass fragments, paint fragments, hair and GSR (the focus of the current investigation), as well as geoforensic materials such as soils, silts, palynological material and trace minerals. This list of physical traces is not exhaustive. In theory, any particulate material could be included which occurs in trace quantities and which can be transferred between surfaces, subsequently recovered, and compared to a comparator sample. Grieve (1987) reports, for example, the importance of glitter particles, of the sort used by artists or for fancy dress, for establishing contact in the investigation of a rape case.

'Traces' need not be physical. Indeed, the growing salience of digital traces in many cyber-crimes and in the increasing number of other crimes in which a computer or other device can provide valuable evidence underlines the importance of 'computer',

'cyber' or 'digital' forensics (see, for example, Casey 2004, Vacca 2005, Hankins et al 2009, Casey 2011). Meanwhile, it may be argued that fingermarks or tool marks are 'traces', but these traditionally fall into the category of patterns, marks and impressions. Other 'traces' that are often utilised include fluids such as blood, perspiration, urine and semen, the transfer and persistence properties of which can be interpreted in a similar manner to trace physical materials (Genge 2003). Importantly, it is also possible to extract DNA from these fluids. DNA can certainly be regarded as 'trace' evidence although, as mentioned, owing to its directly individualising potential it is often considered to occupy a domain of its own (Saks and Koehler 2005, Broeders 2006). Technological advances have rendered it possible to obtain a (partial) DNA profile from ever more minute traces of material and vectors. Subsequently, the use of Low Copy Number (LCN) or 'touch' DNA in investigations has developed and concurrently, this has resulted in the emergence of a plethora of interpretation issues associated with this type of evidence (Thompson et al 2003). In this discussion of the properties of trace materials and their use in forensic investigations, trace physical materials will be most often referred to as their properties are analogous to GSR. However, where relevant, the properties of other types of evidence, especially DNA, will also be cited.

2.2.1 Trace evidence and the investigative process

Trace materials derive their forensic utility from the fact that they can be transferred from one surface to another and subsequently remain adhered. When compared to a comparator sample, these traces may represent a (spatial and temporal) record of the association between suspects, victims, crime scenes, environments, locations, objects and events. The elucidation of this logic is often attributed to Edmund Locard whose "principle of exchange" is often condensed into the axiom: "every contact leaves a trace". Accordingly, Locard observes that these 'traces' can be regarded as 'mute witnesses… of all our movements and encounters' (1930 cited in Bisbing 2001, p.87, Lee 1995, Erzinçlioglu 2006). This causal logic underpins the use of trace materials in making inferences about criminal events.

In an investigative context, the use of trace evidence can be represented as a five-stage process (Figure 2.1). Initially, material must be transferred via a contact

between surfaces and then remain *in situ* for a sufficient period of time so as to permit its collection, (from the scene of a crime or from a suspect, for instance). The material may then be analysed at the scene, but more often in the laboratory. The results derived from the analysis must, at this point, be interpreted in the context of the case. This involves the development and assessment of propositions to make inferences regarding the events that took place. Finally, the probative value of the evidence and the interpretations made must then be presented in a report or in a court of law (Morgan and Bull 2007a). Crucially, these conclusions should be supported by an empirical understanding of the issue at hand.

Figure 2.1 The 'five stage process' of a forensic enquiry involving the use of trace physical evidence. Produced by the author after Morgan and Bull (2007a)

2.2.2 The interpretation process

A series of papers, namely those by Cook et al (1998a,b), Cook et al (1999) and Evett et al (2000), explore forensic science evidence interpretation and contribute to a deeper understanding of the practicalities of the process. According to Cook et al (1998a, p.152) 'the essence of forensic science is the drawing of rational and balanced inferences from observations, test results and measurements'. This is the process of interpretation. Writing in 1998, the authors comment on the period of evolution for forensic science interpretation, brought about by work on the application of the Bayesian paradigm and associated methodologies to forensic problems and in reasoning about forensic evidence under uncertainty (see Robertson and Vignaux 1995, Aitken 1995 and, more recently, Taroni et al 2006)[4].

A central tenet of the Bayesian approach to evidence is that when considering the truth and validity of a proposition (for example, that the glass recovered from Mr X

[4] The application of Bayesian approaches to forensic interpretation will be revisited in Chapter Seven, with an emphasis on the interpretation of GSR and the incorporation of the empirical findings of this thesis

came from the broken window Y), it is necessary to consider at least one alternative proposition (for example, that the glass came from another window or glass object and not window Y). In a forensic context, this is framed by the adversarial nature of the criminal investigation; that there is a prosecution allegation and a defence allegation. The former attests that the trace incriminates the suspect in some way, while the latter will offer an alternative explanation that serves to exculpate the suspect. As a result, interpretation necessitates the formulation of a pair of propositions that represent these two allegations and under which evidence is assessed. The generation of these propositions is not a trivial process. The role of the scientist is to review the evidence in the context of the case at hand in order to develop propositions that can 'realistically' and logically be addressed (Cook et al 1998b, p.231). Accordingly, Cook et al (1998b, p.231) propose a 'hierarchy of propositions' that should be considered when attempting to frame them. This hierarchy enables the formulation of propositions that will assist the court as much as possible, while ensuring that the assessment does not digress from the limits of expertise, the conditions of the case and the probative value of the evidence and consequently, stray into the domains of jury deliberation and advocacy. There are three (overlapping) categories into which these pairs of propositions can fall:

Level I – Source level propositions

Level II – Activity level propositions

Level III – Offence level propositions

These 'levels' of proposition differ in their similarity to the ultimate issue of determining guilt or innocence that the jury must decide; the higher the level of proposition, the greater the value that is added by the forensic evidence. Importantly, the choice of propositions (and their place on the hierarchy) will depend on a number of factors including the context and circumstances of the case, the availability of research or empirical support, the observations which have been made and the expertise of the forensic scientist. As a result, Cook et al (1998b, p.232) argue, it is often necessary to 'settle' on propositions which are, to varying degrees, removed from those which the jury must ultimately address. A source level pair of propositions can be addressed via measurements, observations, analyses and through the

comparison of samples through various means. The weighing of propositions of this type enables assessment of the likelihood that a trace came from a one source as opposed to another. For example:

a) The fibre came from garment X

b) It came from some other fibre source

.....

a) The glass fragment came from car Window Y

b) It came from some other glass object

Note that these propositions do not consider how the material came to be found - the circumstances of its transfer are not considered. These propositions can be addressed through comparison, analytical examination, through the application of expertise and the consideration of background rates of different types of fibres/glass fragments. Mutually exclusive propositions such as these can be weighed against one another by calculating the likelihood ratio – a principal step in the Bayesian interpretation of evidence that will be revisited in chapter seven:

$$\frac{\textit{Probability of the evidence if the prosecution proposition is true}}{\textit{Probability of the evidence if the defence proposition is true}}$$

Addressing a pair of propositions at the activity level (level II) will enable assessment of inferences about how the trace evidence came to be in the state it was recovered. As well as using measurements and observations when addressing these propositions, considerations of transfer and persistence (and other dynamics) will necessarily be incorporated. For example, using the examples provided by Cook et al (1998b, p.234)[5]:

a) Mr A is the person who smashed window X

b) Mr A was not present when window X was smashed

Addressing these propositions will involve determining probability of finding a given quantity of glass given that Mr A smashed the window, and the probability of finding that quantity given the defence proposition that he was not present. Notably, the

[5] It is acknowledged that this illustrative example is adapted from Cook et al (1998b)

authors also point out that if evidence was not found, the propositions above could still be addressed and the probabilities that would be of interest would be those of finding no glass given that Mr A smashed the window and of finding no glass given that he was not present. Clearly, unlike 'level I' propositions, circumstantial information is crucial when addressing these 'level II' propositions. For example, in order to assess whether Mr A smashed the window or was not present, some indication of the timing of the event will be required and the persistence of the glass fragments would need to be incorporated. It would also be important to know if the suspect had engaged in activities that would mean he was exposed to glass fragments; if he was a builder, for example. Meanwhile, information regarding the *modus operandi* of the breaking of the window – whether it was smashed by throwing a brick, or whether it was kicked in, for instance, would have a bearing on the expected number and pattern of transferred fragments. Interaction, therefore, is required between the forensic scientist, the investigating team, the witnesses and the advocate to establish what Cook et al (1998b, p.234) term the 'framework of circumstances' within which propositions are generated and addressed. It will be argued in chapter seven, that Bayesian Networks are a means weighing and incorporating these multiple sources of uncertainty within a probabilistic framework.

'Level III' (or offence level propositions) relate to the commission of the offence and amount to the ultimate consideration of the jury. This often involves consideration of issues that are beyond the realm of the forensic scientist. Importantly, level III propositions are simultaneously level II propositions. Cook et al (1998b, p.232) use the following pairs as examples:

a) Mr A committed the burglary

b) Another person committed the burglary

.....

a) Mr B raped Ms Y

b) Some other man raped Ms Y

.....

a) Mr C assaulted Mr Z

b) Mr C had nothing to do with the assault of Mr Z

In reality the distinction between level II and level III propositions is often blurred, but in practice, it is more common to assess propositions about trace evidence that are 'below' the addressing of the ultimate issue of establishing the commission of a crime (ibid., Robertson and Vignaux 1995).

The representation of the investigative process in figure 2.1 is simplified and does not capture the nuance and iterative nature of interpretation. In setting out a model for case assessment, decision-making and interpretation which embodies the principles of Bayesian inference, Cook et al (1998a) stress that interpretation is not restricted to the latter stages of an investigation (a single fourth stage in figure 2.1), or to the writing of a statement. Rather, a broader view of the interpretation process is preferred whereby the interpretation of material transcends stages and begins when the scientist is first approached by law enforcement. Thus, process of interpretation beings with its collection, and prior to its analysis. The model for case assessment and interpretation which is proposed reflects this. During the first stage, where law enforcement or the investigator represents the customer, the needs of the customer must be assessed and a detailed view of the case and access to all of the relevant information should be sought. A balanced view, which includes the explanations offered by the suspect, will embody the Bayesian approach to assessing evidence. Consideration of the types of examination that may be undertaken and the results that they may generate will be made. At this point, the process of generating a pair of propositions will begin and these will be refined in the second, 'Case assessment' stage. Here, serious thought is given to the expected outcomes of an examination regarding the propositions that have been formulated in light of the circumstances of the case (ibid.). Statements such as "if this proposition were true, a small quantity of GSR particles would be expected" will be generated and considered at this stage. This will inform the decision-making later during interpretation, as will the expected weights of evidence given a range of circumstances which are (quantitatively) estimated at this stage. Here, the anticipated limitations of the interpretation should be made clear (Evett et al 2000). The last, 'service delivery', phase involves the forensic examination itself and it is here that the propositions and expectations may be adjusted as a result of the examination (Cook et al 1998a). The structure of the model means that, once the statement is written or the testimony is given, the weighing up

processes have already been followed through: expectations and propositions have been generated and assessed throughout the various phases of the interpretation and inferences, therefore, are not 'post hoc' (ibid., p.154).

The iterative nature of the process of interpretation and decision-making is underlined by Evett et al (2000) who note that it is often inevitable that propositions will have to be revised and refined in the light of results and observations in the examination and analysis stages. In addition, while the scientist formulates propositions within the 'framework of circumstances', these conditions can change if, for example, developments are presented by the suspect or defence, or elements of the framework are not admitted. In such cases, the propositions will have to be revisited in light of the alterations to the 'framework of circumstances'. Furthermore, Evett et al (2000) demonstrate how alternative explanations proffered by a suspect, witness, or victim may result in the reframing of propositions and crucially, their revision (promotion or demotion) to different levels in the hierarchy. Determining logical propositions in the first instance has been shown to be a delicate process and Evett et al (2000) suggest that between the collection of observations and the formulation of propositions there is routinely an intermediate phase whereby informal explanations are considered, which represent precursors to the final propositions. Explanations are offered which may explain the observations of the presence/absence of trace evidence, and are refined so that they form testable, opposing propositions that provide the greatest assistance to the jury; which are informative, and which are legitimately addressed within the bounds of scientific expertise and the circumstances of the case.

For Evett et al (2000) (and reflected in the remainder of the series of papers; Cook et al 1998a,b, Cook et al 1999), exploring the process of evidence interpretation reveals the difficulties and complexities, but also the fundamental importance of, the construction of informative propositions that can be meaningfully addressed within the context of a case. Doing so prompts a departure from the use of statements such as "consistent with" and "may/could have" which are uninformative; which require little rigorous interpretation, and which are simply 'statements of the obvious' (ibid. 10)[6].

[6] This will be revisited in Chapter Seven in light of recent legal rulings concerning the presentation of probabilistic conclusions in U.K. courts

This model and conception of evidence interpretation frames this thesis. By contributing to the empirical understanding of the behaviour of GSR evidence, the findings of thesis can be employed in the formulation and assessment of level II propositions during case-assessment and evaluation with regard to GSR. Meanwhile, chapter seven explores the capacity of graphical approaches underpinned by Bayesian reasoning to assist in reasoning about GSR evidence under competing propositions, particularly when faced with multiple sources of uncertainty. Bayesian Networks, it will be argued, are well placed to incorporate information about the framework of circumstances and thus among other forensic applications, can be utilised in making inferences about mechanisms of GSR transfer.

2.3 Evidence dynamics

It has been shown that when the circumstances of the case permit the forensic scientist to make inferences by addressing level II (and level III) propositions, issues of transfer and persistence must be considered. Determining the probability of observing evidence 'X' given that Mr A smashed the window, and considering, for instance "is this the kind of blood distribution on the hand of Mr B if he had punched Mr C?" inherently involves incorporation of the factors governing the deposition and longevity of evidence, which have a bearing on the state of the material when it is recovered.

When recovered from a crime-scene, victim or suspect, even if very soon after an event, trace evidence will have been subjected to multiple influences. All available material is not transferred and over time, that which is transferred will be altered. When it is recovered, trace evidence is not pristine; rather, it is partial and has been modified. Consequently, for Chisum and Turvey (2007, p.195), the assumption that material is transferred in its entirety from one surface to another and remains unaltered in its pristine state in the period between a contact and the collection of material '…has the potential to provide for misinterpretations of physical evidence'. Moreover, this assumption would result in misjudgement when determining the probability of observing a quantity of trace material 'X', given that a certain proposition was true, and would foster an incomplete answer to the question of whether this quantity is what one would expect if the suspect had engaged in a particular activity.

The mechanisms, influences and principles of interest fall under the heading 'evidence dynamics'. According to Chisum and Turvey (2000, p.2), evidence dynamics include '...any influence that changes, relocates, obscures or obliterates physical evidence' from the conditions governing the initial transfer, through the period between transfer and collection, through its processing and analysis, and ceasing with the adjudication of evidence (Chisum and Turvey 2007). It should be emphasised at this point that the influences of evidence dynamics transcend the entire forensic science process. They govern trace materials both before the forensic event, and after transfer has taken place. Variables continue to exert their influence on trace material during and after collection; as samples are packaged, stored, transported and analysed, for example. In sum, trace forensic evidence will represent a record of pre, syn and post forensic event movements, encounters and dynamics. It is during the period between the transfer and the collection of material - which can vary greatly depending on the speed of the response by law enforcement, scene of crime officers or the investigative team – that the greatest number of variables may be influential. The length of this period will determine the extent of relocation, altering or obscuring of evidence.

A catalogue of evidence dynamics will also include variables and factors that are often synonymous with 'contamination', as these too could theoretically provide explanations for the alteration of trace material from the initial state in which it was deposited. The commonly cited 'evidence dynamics' are presented in figure 2.2, which also indicates the juncture at which each factor may be influential in the sequence of a forensic investigation. It should be noted that this is a general survey and that particular trace materials will, in some cases, be subject to influences specific to the material in question[7], while the plethora of context specific influences that might be encountered mean that the catalogue in figure 2.2 is not exhaustive.

[7] Evidence dynamics will be revisited in Chapter Three with reference GSR

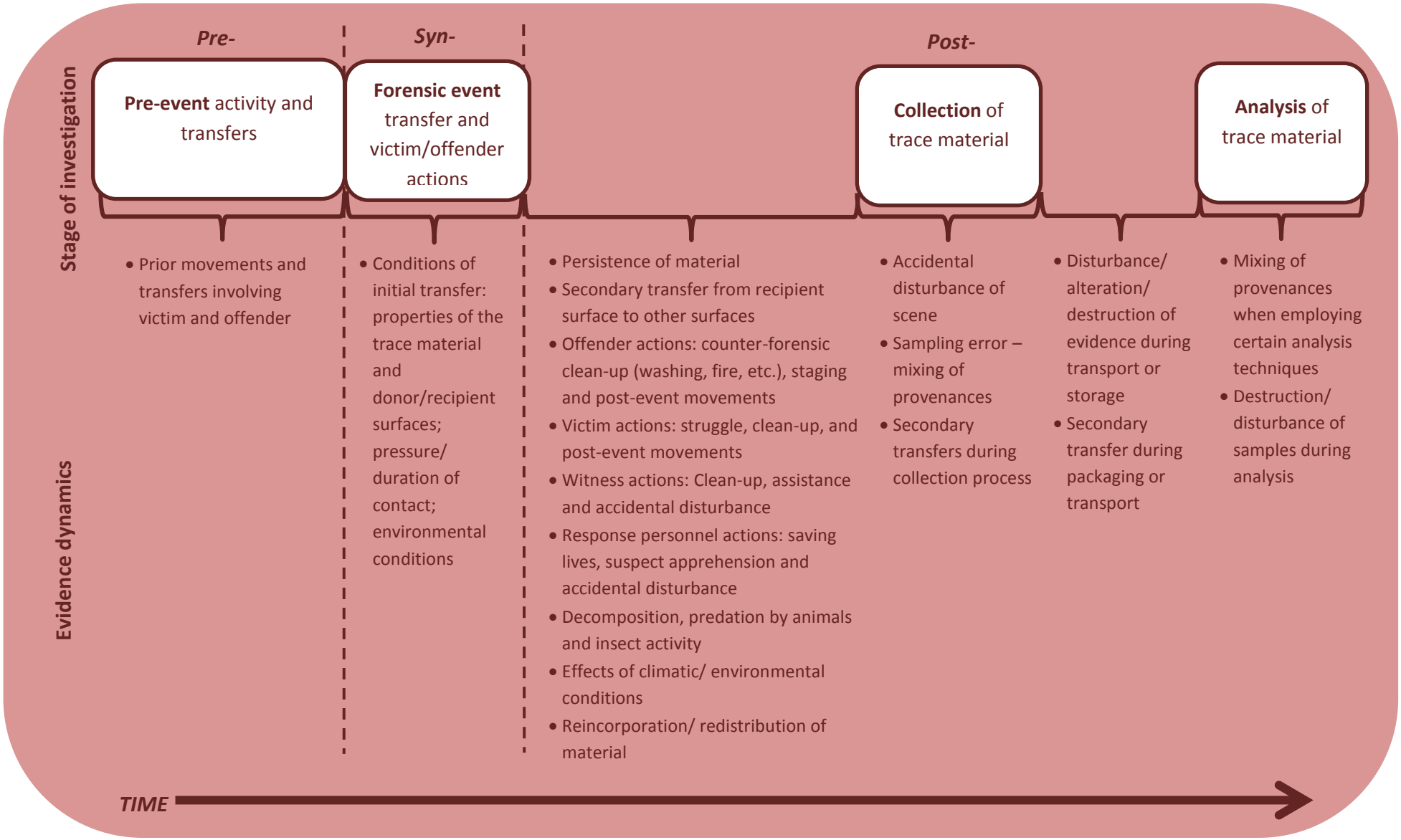


Figure 2.2 Evidence dynamics throughout the course of an investigation – *pre-, syn-* and *post-* forensic event, after various sources including Chisum and Turvey (2000, 2007)

Figure 2.2 demonstrates the array of factors which could conceivably be considered when considering how material has been transferred, altered, redistributed, obscured, added to, removed or destroyed. The interaction between these factors is also important. Material may, for example, decay from a surface naturally, only for removal to be accelerated by a change in climatic conditions. While some influences appear 'natural' (those that are a product of the physical properties of the surfaces and materials involved), there are many which are exerted by people, whether a victim, an offender, a witness, an emergency respondent or a forensic scientist/laboratory technician. In these cases, individuals wittingly (in the case of counter-forensic actions by an offender) or unwittingly (with regard to emergency personnel or forensic technicians packaging evidence) alter evidence and on occasions, compromise its probative value. Clearly, some of these variables cannot be guarded against but others can. Protocol for the retrieval, packaging and transportation of samples can be implemented with a view to maintaining the integrity of evidence and limiting the effects of contamination. A chain of custody should be enforced which tracks the integrity of the exhibit during the investigative process (Chisum and Turvey 2000, 2007). This will be revisited with regard to GSR in section 3.5.

Indubitably, unpicking the effects of evidence dynamics when determining the probability of finding a given trace given the truth of a certain proposition, can be extremely complex. However, doing so is crucial if competing propositions about how the evidence came to be are to be logically and accurately addressed. Reliable interpretation and the making of inferences which assist in the accurate reconstruction of an event will require reference to scientific research on the principles, laws and mechanisms which govern the transfer, persistence and behaviour of trace materials in a variety of contexts. The salience of experimental research to this end was introduced in chapter one will be further elucidated in chapter four with regard to this thesis. The importance of experimental work is illustrated by Bennett et al (2010) in an account of a murder case in Australia in which fibres identified as being from the suspect's car were recovered from the soles of the victim's shoes. The source was not disputed at trial, yet the length of time they had persisted was at issue and experimental work on the transfer and persistence of car carpet fibres proved crucial. Indeed, contributing to the understanding of evidence dynamics via experimental

research with respect to GSR is one of the principal objectives of this piece of research. Meanwhile, it will be demonstrated in chapter seven that Bayesian Networks can be used to incorporate this empirical knowledge and reason about the origins of trace evidence under alternative propositions.

The body of literature on the behaviour of trace evidence under different conditions can be thought of as part of the "toolkit" used by the forensic scientist to understand, account for and incorporate evidence dynamics during the iterative process of trace evidence interpretation examined by Cook et al (1998a) (set out in section 2.2.2). Through the experimental simulation of transfer and persistence in settings which mimic forensic scenarios, and through the reporting of observations encountered during casework, a body of theory and data on the effect of different variables on various types of trace evidence has been established. Development of this body of work resonates with the calls for an empirical research culture in forensic science that were discussed in chapter one. The opportunities for research continue to grow due to demands to understand the effects of particular variables in particular contexts and with technological improvements which permit detection and analysis of the previously undetectable or imperceptible. There are, however, significant gaps in our understanding of the influence of certain factors on different forms of trace material in various contexts.

The sections below deal in with concepts introduced in figure 2.1 namely, transfer, persistence and multiple transfer. In doing so, relevant experimental studies are cited which concern different forms of trace evidence. This commentary provides an overview of the principal factors that govern the (multiple) transfer and persistence of trace materials and studies which have been formulated to investigate them[22].

2.3.1 The initial transfer

While every contact leaves a trace, a number of factors determine the amount and distribution of the material that is transferred from A to B. If a direct contact between surfaces initiates a transfer of material, the nature of the donor (A) and recipient (B) surfaces are important. Surface properties will influence how readily material is shed and the extent to which trace material is able to adhere. For example, in a study of the

[22] Studies concerning GSR are reserved for consideration in Chapter Three

transfer of glass fragments, Hicks et al (1996) and Brewster et al (1985) report that the number and size of glass fragments transferred to clothing during the breaking of panes of glass is dependent on the composition and weaving of the garment. In both studies, garments with coarse woollen weaves tended to retain more and larger fragments. Fewer fragments were transferred to denim garments than woollen ones due to the existence of 'pore' spaces in woollen weaves which encouraged adhesion (ibid.804). With regard to fibres, Deedrick (2001) notes that certain fabrics do not shed (donate) fibres well, while others do not hold fibres well, and therefore, are poor recipients. In addition, Pounds and Smalldon (1975a) found that coarse garments favoured the receipt of short fibres. Following a further study, Pounds and Smalldon (1975c) concluded that fibre transfer from a garment will be encouraged when fibres are sat on the surface of a donor garment, or when fibres are loosely incorporated in its yarn. When considering garment-to-garment fibre transference, the condition, age and state of the garments involved will also be of importance. Roux et al (1999) examined the transfer of automobile carpet fibres to shoes and found that the properties of the shoes soles were influential, as well as the type of carpet involved. Interestingly, they note that increased fibre transference was encouraged when a sticky substance was on the sole of the shoe. Finally, their findings corroborated those of Scott (1985) in concluding that older carpets tended to 'donate' fewer fibres than new carpets. Logically, while the nature of the recipient surface will be influential, if a transfer is to occur the donor surface must be one that can readily donate material – if a material is a poor 'shedder', or the trace evidence is tightly enmeshed within the donor surface, a transfer will be less likely to take place.

The properties of the trace material itself will have a bearing on the propensity for transfer. The dimensions and surface textures of particles, for example, will both be of significance when it comes to the transfer of many different trace materials. Brewster et al (1985) note that the quantity of glass that is transferred will be dependent on the size of the fragments that are involved. Meanwhile, Deedrick (2001) conclude that certain fibres lend themselves to being transferred over others, depending on construction, fibre composition and fibre length (Pounds and Smalldon 1975a). In a study of animal hair transfer, D'Andrea et al (1998) found that the finest and lightest

hairs were most readily transferred. Clearly, the size of the initial source of trace material will be important in determining the extent of a transfer.

When direct contacts are made, the nature of this contact will be influential. As part of a comprehensive experimental review of fibre transference and the subsequent persistence of fibres during wear, Pounds and Smalldon (1975a) reported that considerably more fibres tended to be transferred when greater pressure was applied during the contacts. Meanwhile, fewer and fewer fibres were found to transfer when successive contacts were made with the same area of a garment. Deedrick (2001) and Roux et al (1999) report that increased duration of the contact tends to encourage higher rates of transfer. Notably, the latter study also concluded that movement of the shoe sole against a carpet creates electrostatic forces which attract extra fibres to the shoes.

Keeping with the study of the transfer of glass fragments as an illustrative example, if considering an event in which no direct contact has taken place then the distance of the recipient surface from the source of the glass fragments will be influential. It has been established that the number of fragments deposited on, and recoverable from, a surface will be fewer with increased from the source (Pounds and Smalldon 1978, Luce et al 1991, Brewster et al 1985, Allen and Scranage 1998, Brozek-Mucha 2009, Hicks et al 1996). Hicks et al (1996) also demonstrate that further striking of a glass pane when breaking it will result in greater levels of transfer.

In sum, the principal factors that have a bearing on the extent of initial transfer of trace materials in general include:

- The nature, properties and condition of the donor and recipient surfaces
- The physical and surface properties of the trace particulates being transferred
- The force, duration and conditions of contact if a direct contact is being considered
- The distance/angle in relation to the source of material if an indirect contact is being considered

The transfer and deposition of trace material is a complex process and this will be emphasised with regard to GSR in section 3.4.4a. Case-specific variables will often be influential and as such, the issues associated with applying results from experimental

studies to real cases will be addressed in section 4.2.5 and chapters six and eight with regard to this piece of research.

2.3.2 Persistence and decay

During the period between transfer and collection, trace material will be lost from the site of deposition. This loss, or decay, will reduce the size of the population of trace material which can subsequently be recovered. Incorporating the persistence of material is crucial when addressing activity level propositions and when, accordingly, timeframes and the order of events are being considered in the reconstruction of a crime. The persistence of different materials and the factors that contribute to this have, therefore, been afforded much experimental consideration. The work of Pounds and Smalldon (1975a; 1975b; 1975c) on the transfer and persistence of fibres provides a basis for understanding persistence and decay. In short, previously transferred material will usually be lost from a surface over time according to a pattern of exponential decrease; initial rapid loss of material followed by subsequent, more conservative loss (figure 2.3). As a result of this two-stage mechanism of decay, studies have demonstrated that varying percentages of the originally transferred material may remain present for many hours following an initial transfer. Comparable results have been obtained in studies of glass (Curran et al 2000, Allen and Scranage 1998, Hicks et al 1996, Brewster et al 1985), paint (Pearson et al 1971), foam fragments (Wiggins et al 2002), fibres (Akulova et al 2002 and Ashcroft et al 1988), chemical marker powder (Howarth et al 2009), scalp-hair (Dachs et al 2003) and trace DNA (Raymond et al 2009) (Bull et al 2006).

Bull et al (2006) explain, with regard to geoforensic particulates, that the two-stage pattern of decrease owes its existence the weakly-bound particulates, that are shed initially, and those which are more strongly-bound into the weave of the garment and which subsequently persist. The relative strength of these bindings and the persistence of material will also be contingent on the conditions of initial transfer (Morgan and Bull 2007a). Indeed, Robertson et al (1982) found that the persistence of fibres was strengthened with increased pressure during the initial transfer. In all of the experiments, trace particulates (all of less than 100µm diameter) were found to conform to the general shape of decay curve already mentioned, yet were also found

to exhibit a tendency to persist for long periods of time. Indeed, particulates in some instances were found to persist for several days (647 hours after the initial contact in the case of the pollen grains) (Bull et al 2006), thus extending the temporal frame of reference and the window for evidence retrieval.

Persistence and decay are the principal determinants of the changes that evidence undergo over time (Margot 2000). Studies have revealed that many more factors influence the persistence of trace material on a surface than simply the passage of time. It is these influences that serve to increase or decrease the rate of material loss. It is important to appreciate that transfer and persistence are inextricably linked; that interpreting how much material has decayed will involve estimating how much material was initially transferred. Meanwhile, a number of the factors that determine the extent of initial transfer also have a bearing on the rate of decay. These include the retentive properties of the recipient surface and the binding properties of the trace particulates themselves.

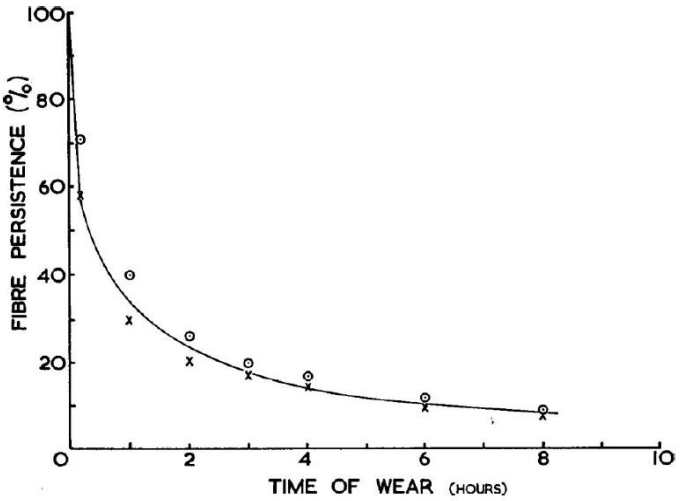


Figure 1. Persistence of wool and acrylic fibres on wool jacket r_1 plotted against time of wear. ○=Wool. X=Acrylic.

Figure 2.3 A 'classic' two-stage decay graph, taken from Pounds and Smalldon (1975b) demonstrating the persistence of fibres on a woollen jacket

Morgan and Bull (2007a) explored the impact of the characteristics of the recipient medium on persistence of trace evidence and its rate of decay. The effects of different host materials on the persistence of some geoforensic trace materials (in this case, pollen grains, fluorescent powder and lighter flint particles) were experimentally investigated. The authors reported that surface type, rather than the particulate type,

represented the controlling factor with regard to persistence. In an investigation of the persistence of fibres during wear, Pounds and Smalldon (1975b) reported no discernible difference in the rate of shedding of wool versus acrylic fibres across different garments (rendering fibre type of little significance). They concluded, however, that fibres were found to decay at a higher rate from the fine-textured sports jacket and smooth cotton laboratory coat used in the experiment. Smooth recipient surfaces, therefore, appear to encourage the rapid loss of fibres and retain them poorly. In addition, Dachs et al (2003) reported similar findings with regard to the persistence of scalp hair with rough, woollen, open-weave materials cited as being particularly conducive to retaining material for long periods and polyester surfaces prompting the most rapid shedding of hairs. The persistence of fibres on head hair, meanwhile, was shown to be greater than on clothing and was strongly influenced by hair style (Salter and Cook 1996).

In a further study of fibre persistence, Akulova et al (2002) demonstrate that recipient surface structure and texture, as well as the location of the material on the garment itself, have a greater bearing on persistence than the type of fibre that is transferred. Relief features such as studs or creases (see also Morgan et al 2010) encouraged retention, while fibres that were transferred to movable areas of the garment (i.e. sleeves) were shed more readily. The nature of post-transfer movement and activity also influence the longevity of material, particularly if skin or garments are the recipient surfaces. Sitting or immobility will encourage the retention of material, whereas walking or running accelerates the rate of decay of (Deedrick 2001, Salter and Cook 1996). Robertson et al (1982) confirmed that wearing a recipient garment will lessen the persistence of fibres (similar findings are reported by Raymond et al 2009 for DNA). Akulova et al (2002) found that transferred fibres are lost rapidly from garments when the participant uses public transport, as a result of the movements involved and the multiple opportunities for casual contacts.

Palmer and Polwarth (2011) found that fibres can persist on the skin of a deposited body for up to 12 days, with most being lost in the first two. Meanwhile, when transferred to the skin of a living, moving subject, Palmer and Burch (2009) observed a similar exponential pattern of decrease but no fibres were detectable after 24 hours. Notably, in the former study, strong winds and rain served to increase the rate of fibre

loss, thus underlining the salience of environmental influences. In a study of the persistence of *Cannabis sativa* DNA, Wilkinson and Linacre (2000) report that hand washing removed traces left after handling cannabis leaf or resin, and while rubbing hands on the trousers or placing hands in pockets encouraged dissociation, *C. sativa* DNA could still be detected. Ashcroft et al (1988) found that fibres could persist in head hair for up to six days, but that this was reduced to three days if the hair was washed. Morgan et al (2013a), meanwhile, found that large traces of pollen can be found in a room 20 days after cut flowers had been removed and that human disturbance accelerates its decay. Finally, Twibell et al (1984) considered the persistence of traces of military explosives on hands and found that while hand-washing can be expected to remove around 90% material, traces could be detected after 24 hours, but not after 48 hours and 12 hand washes. Successive hand washes were found to be progressively less efficient in the removal of the material.

In terms of the characteristics of the trace material itself, Pounds and Smalldon (1975b), Palmer and Burch (2009) and Robertson et al (1982) all note that smaller fibres (<2.5mm in the latter study) will persist for long periods of time and that concurrently, larger fibres tend to be shed first. However, during these experiments, the time elapsed since the contact was made appeared to govern the decay of fibres to a greater extent than the type and length of the fibres themselves. The persistence of glass fragments was studied by Hicks et al (1996) and it was found that while the majority of glass fragments transferred to a garment were shed in the first half an hour, some of the smallest fragments were detectable after eight hours: large fragments, however, had been lost by this time. Importantly, in some cases, a trace material of interest may be transferred as part of a conglomeration of material and in such instances its persistence will be related to that of the carrier or vector. Walsh and Horrocks (2008) provide the example of palynomorphs contained within soil, other examples include hair in body fluid, or pollen on hair/fibres.

The rate of decay of material from garments might also be complicated by reincorporation and redistribution. In the Bull et al (2006) study, it was noted that at points on the decay curve, the quantity of trace material appeared to increase. The authors propose that such anomalies may be explained by decayed material that may have become reincorporated within clothing rather than being lost. The possibility of

this phenomenon was subsequently confirmed by Morgan et al (2010), who found that trace particulates may become reincorporated at low levels of a garment, particularly in the 'lap' area and around relief or design features of a garment such as stitching. Rather than being lost to the environment, these particulates become reincorporated and, therefore, redistributed on the garments. Redistribution is also posited as an explanation for some trends in the persistence of a chemical marker powder by Howarth et al (2009). It is argued that this should be taken into account when interpreting tapings as it could be assumed that recovered particulates indicate a recent transfer, when in fact material has already decayed and has simply been redistributed. It is this kind of interpretative nuance that is revealed through experimental studies and which will be considered in the context of findings regarding the transfer of GSR in section 6.4.

The experimental work cited thus far can assist in the process of trace evidence interpretation, particularly in assessing the likelihood of observing a quantity of material given the truth of a certain activity level proposition. Additionally, understanding the persistence can also guide forensic protocol, particularly in guiding the collection of trace material. This underscores the value of experimental research for forensic practice. Kamodyová et al (2013), for example, determined that male DNA can be extracted from female saliva after enforced kissing and thus highlight the utility of sampling saliva. However, these valuable profiles could be obtained a maximum of 60 minutes after the contact, demonstrating that collection should take place as soon as possible and suggesting that the utility of sampling is likely to be limited if the incident took place several hours previously. Similarly, Matte et al (2012) report that foreign DNA can persist under fingernails but again, stress that the material does not persist for long and rapid collection is necessitated. Furthermore, male salivary DNA transferred to skin has been shown to yield a full DNA profile after 96 hours, highlighting the window for available evidence (Kenna et al 2011). The need for expeditious scene processing is also emphasised by Raymond et al (2009). Keeping with biological traces, Courts et al (2012) highlight the utility of swabbing for DNA traces on the inside of a gun barrel for biological backspatter that has persisted in the barrel following a shooting into tissue. Successful collection of material may necessitate the targeting of particular areas in sampling. Accordingly, Howarth et al

(2009), in a study of the persistence of chemical marker powder, report that what little powder remains on hands two hours after the transfer may be recovered from the webbing between fingers, the beds of the fingernails and in the creases of the hands. In some cases, the strong bindings between trace and surface that permit persistence may actually inhibit the collection of material (Pounds and Smalldon1975c). Interestingly, some studies have demonstrated the utility of searching for trace material even after the influence of extreme conditions. For example, Morgan et al (2013b) demonstrate that different forms of palynological evidence can persist and are readily identifiable after exposure to extreme heat over long periods of time. Pollen grains can also remain adhered to clothing during laundering (Bull et al 2006). The ramifications for GSR collection which are posed by experimental findings of this thesis are presented in section 6.3.1.

The property of persistence, while providing the opportunity to recover evidential material, may also be regarded as something of a problematic issue. As Bull et al (2006, see also Morgan and Bull 2007b) point out, when material persists for a long period, material recovered following a forensic event may theoretically represent a multi-provenance amalgamation of particulates comprising material that was transferred before, during, or after the event. The unpicking of this 'layering' is practically and theoretically challenging and poses a number of implications for forensic protocol (Morgan and Bull 2006). For example, techniques that require the homogenisation of layers are rendered inappropriate (ibid.). Meanwhile, visual analysis methods that discriminate between layers are recommended when examining components of soil on footwear (Morgan et al 2009a). The case of soil on footwear, therefore, effectively demonstrates the complexities of persistence and the resultant implications for forensic protocol (Morgan and Bull 2007b).

The persistence of trace materials can be a 'thorny' issue (Bull et al 2006), one that is contingent on many variables and one that can be challenging to interpret. However, an understanding of the way in which a certain material will be expected to decay from a host surface will assist in reconstructing the order of events (Margot 2000). However, the uniqueness of each case and that uniform application of experimentally derived decay curves to investigative contexts may yield errors (Dachs et al (2003). Caution is urged when making interpretations, especially as anomalies are reported

within experimental studies (Hicks et al 1996). A greater understanding of the variables that have a bearing on the persistence of different materials under different conditions will assist in informing interpretation[23].

Several factors and influences pertinent to the persistence of different materials have been identified:

- The time elapsed since the transfer took place
- The nature, properties and condition of the recipient surface
- The properties of the trace material that was transferred
- The conditions of initial transfer and resultant bindings between particulates and the recipient surface
- The nature and level of post-transfer activity and disturbance
- Environmental conditions
- The extent of reincorporation and redistribution

This list is not exhaustive and arguably, any factor which impinges on the state of the trace material (counter-forensic 'clean up' by the perpetrator, for example) is necessarily one that affects persistence and decay. Furthermore, If material persists on a recipient surface, opportunities exist for further transfers of material. These further transfers will involve the movement of particulates to a new surface and can represent a further disruption of the 'normal' pattern of decay from a recipient surface. It is to a consideration of these transfers that this review now turns.

2.3.3 Multiple transfers of trace evidence

'Multiple transfers', the subject of this thesis, are introduced in this section. The possibility exists for evidence to be transferred after it has been primarily transferred, possibly multiple times. This section defines these transfer mechanisms and surveys the (inconsiderable) body of literature devoted to their investigation.

The meaning of the term 'secondary transfer' is seldom elucidated within a forensic context. As a starting point in this discussion, the definition used by Grieve et al (1989) will be employed. Primarily concerned with fibres, but applicable to other forms of

[23] For a discussion regarding palynological evidence, see Walsh and Horrocks (2008)

trace evidence, Grieve et al (1989, p.267) label a 'secondary transfer' as the 'first indirect transfer of the donor... [trace material] after the primary transfer, taking place via an intermediary object'. Thus, in figure 2.4, a secondary transfer has taken place when surface C acquires material from surface B. The transfer of material between A and B represents the primary transfer. Crucially, the original source (A) is not directly involved in the secondary transfer:

Figure 2.4 A primary transfer (solid line) and a secondary transfer (dotted line) of trace material

Notably, however, in the aforementioned definition, the authors limit the role of the intermediary ('B' in the above diagram) to being played by an 'object'. The possibility of person-to-person-to-person transfer, whereby an individual plays the role of the intermediary, rather than an object, has been comprehensively addressed by French et al (2012), among others. Hence, the original definition may be updated by the use of 'surface' as opposed to 'object', accounting for the fact that a transfer can be facilitated by a person or an inert object (a piece of clothing, a contaminated surface such as a table, or a door handle, for instance). An arrangement of two or more surfaces in a sequence of transfers, as depicted in figure 2.4, can be referred to as a 'transfer chain'.

Grieve et al (1989, p.267) account for the possibility of subsequent transfers along a transfer chain: 'tertiary and higher transfer[s]' are 'further indirect transfers occurring from consecutive intermediary items'. Again, 'surfaces' is preferable to 'items' given the possibility of further persons playing the role of intermediaries in longer transfer chains. A multi-step transfer chain involving five surfaces and thus, primary, secondary, tertiary and quaternary transfers is depicted in figure 2.5:

Figure 2.5 A primary transfer (solid line) and secondary, tertiary and quaternary transfers (dotted lines) of trace material

In theory, 'Transfer chains' need not be linear. Rather, providing sufficient material is available for transfer at the donor surface as contacts are made, multiple surfaces may acquire material from a single intermediary. Thus, a 'transfer chain might appear as shown in figure 2.6:

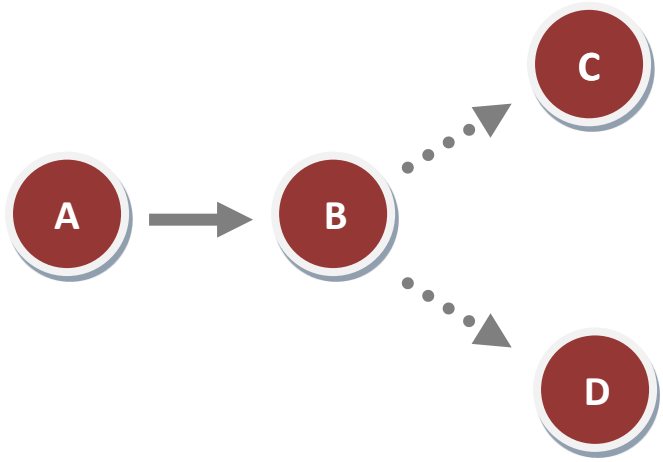


Figure 2.6 A primary transfer (solid line) and two secondary transfers (dotted lines) of trace material

Figure 2.6 illustrates two secondary transfers (to 'C' and 'D') resulting from their mutual contact with intermediary surface 'B'. Conceivably, given favourable conditions for subsequent transfer material of, a network of contacts and transfers could result. In this network, multiple surfaces could become seeded with trace material via (in)direct contacts with an initial source. Demonstrating this possibility was one of the objectives of a study by French et al (2012). The authors demonstrated that from a single introductory source, trace particulates may be transferred among surfaces (both people and inert objects) to the full extent of a contact network and that this is largely a consequence of indirect transfer mechanisms.

A 'direct' transfer is one that involves a contact between two surfaces and results in a transfer, without the presence of an intermediary. 'Indirect' transfers, on the other hand, describe a transfer between two surfaces, via an intermediary. It is important to

note that if A transfers to B and then B transfers to C, then C has acquired material from A via an indirect transfer, but the transfers between A and B, and between B and C, are direct. In addition, 'contacts' are distinct from transfers. Contacts between surfaces may or may not result in transfer, while transfer does not necessarily require physical contact (consider, for example, wind dispersed pollen). The possibility of repeat contacts and two-way transfers of material exist within transfer chains and networks. If an initial contact was made between a 'contaminated' and an 'uncontaminated' surface that rendered both surfaces 'contaminated', any repeat contact between the two surfaces would result in a two-way transfer. Rather than effecting newly 'contaminated' surfaces, this will result in the redistribution of material between surfaces.

The investigative significance of the tendency for trace evidence to be transferred in this way lies in the possibility of establishing a link between an offender and a crime event, albeit via intermediaries (French et al 2012, Lee and Ladd 2001). However, multiple transfers may also pose an array of more problematic consequences. French et al (2012, p.33) identify the following possibilities:

- Forensically relevant trace material may be indirectly transferred to unconnected individuals
- Material pertaining to an innocent individual could be deposited at the crime scene via an offender
- Material may be 'lost' from the original source as a result of further transfer
- Associative evidence could be secondarily transferred to an offender and provide an incriminating link
- Secondary transfers could compromise evidence during collection and analysis

When samples of trace evidence are interpreted, it is necessary to recognise the possibility of multiple transfer. Conceivably, investigative errors or even miscarriages of justice could result if such mechanisms are not acknowledged (ibid.). For example, consider an elementary scenario in which:

Offender 'A' acquired a quantity 'X' of material specific to the scene of a crime 'Y' which 'A' committed. Having avoided apprehension, 'A' subsequently made contact with

individual 'B' – himself unconnected to the criminal event – and transferred a quantity 'Z' of the incriminating material to 'B'. Seen by a witness to be near the crime scene at the alleged time of the offence , 'B' was later questioned and quantity 'Z' of material was recovered and used to associate 'B' with scene 'Y' at the time of the offence and became the subject of the investigation leaving 'A' at large.

Further scenarios, specific to GSR and the findings of this study will be developed for consideration in chapters six and seven. The interpretation of evidence in these contexts will be considered accordingly. Research concerned with secondary (and further) transfer is particularly timely in light of analytical advances which permit the detection of trace amounts of material, and which have elevated the possibility that secondarily transferred material may be encountered in casework. A number of notable cases have deliberated the possibility of secondary (and further) transfers of trace evidence, as well as the possibility of contamination (see, for example *R. v. Reed and Reed; R. v. Garmson* 2009, Linacre 2013).

The following sections survey the modest body of work that addresses multiple transfer mechanisms and the implications for trace evidence interpretation and forensic protocol. Most of the research cited presents experimentally derived results, and therefore, echoes the approach of this thesis which addresses GSR transfer through experimentation. The following sections discuss studies by evidence type, while a discussion of secondary transfer and contamination issues regarding GSR is reserved for section 3.5. It will be argued in chapter seven that Bayesian Networks provide a means of reasoning about alternative transfer mechanisms, with particular reference to GSR.

2.3.3a Fibres and scalp hair

Jackson and Cook (1986) conducted a study of the transfer of fibres to car seats. 'Direct' contacts (i.e. between the source of fibres and the car seat), which facilitated primary transfers tended to result in the transfer of large numbers of matching fibres. The authors cited secondary transfer mechanisms as causal mechanisms when few fibres were recovered. Grieve et al (1989) attempted to simulate the secondary transfer of fibres in the context of a homicide investigation. They report, again, that while fibres readily underwent secondary transfer, they did so in fairly small quantities.

The small quantities involved, it is argued, render these transfers difficult to interpret, especially as the quantity of material that was primarily transferred is unknown. Studies should, therefore, attempt to establish the quantities involved at different stages in a transfer chain. Factors that govern rates of primary transfer (including the nature of donor and recipient surfaces and those mentioned in 2.3.1) were found to be similarly significant in influencing the quantities of fibres that were involved in secondary transfers (ibid.). Finally, the authors found that, like any other transfer, material is not transferred in its entirety during a secondary transfer event; fibres remained adhered to the intermediate surface following the transfer.

For Lowrie and Jackson (1994), the low quantities involved in the secondary transfer of fibres mean that it is unlikely a forensic scientist will misinterpret secondarily transferred fibres as evidence of a direct contact and primary transfer. Thus, they conclude, minimal significance can be attributed to secondarily transferred quantities when interpreting fibre evidence. However, crucially, this conclusion fails to take account of the lag between deposition and collection and that a small quantity of recently secondarily transferred fibres may, in theory, resemble a primary transfer that has been subject to decay. In addition, it is assumed that samples from primary and secondary transfers will be available for comparison purposes in a casework situation, and this is not always the case. The probative value of trace samples will be context dependent and only fully realised through reference to research which informs their interpretation. Notwithstanding this, it is significant that Lowrie and Jackson (1994) observed the persistence of secondarily transferred fibres on recipient surfaces. The authors reported, however, that these fibres remained adhered for less than one hour after transfer, thus immediate collection, where practicably possible, is recommended. Meanwhile, the car seats in the study were termed ‘reservoirs’ (ibid.81) of fibres from multiple provenances, which represent a source of subsequent secondary transfer.

Palmer and Banks (2005) investigated the transfer of fibres from masks to head hair and subsequently, to pillow cases. They observed secondary transfers of fibres to pillowcases via the head of the wearer up to two weeks after the mask had been worn, with the rate of secondary transfer diminishing with increased time since wear. In accordance with previous work on fibre transfer, the amount of secondary transfer was also influenced by fibre type and hair type.

With regard to the transfer of human scalp-hair, Gaudette and Tessarolo (1987) found that in casework situations, many mechanisms and possibilities for indirect transfers exist, compared to relatively few opportunities for direct transfer. The amount and extent of secondary hair transfer were found to be extremely variable and contingent upon a number of factors including the nature of the garments worn, as well as the number of personal contacts an individual has and the number of times an individual made contact with commonly handled objects. Importantly, via these surfaces, Gaudette and Tessarolo (1987, p.1250) identified 'chains of secondary transfer' formed when material was transferred from the clothing of one individual to further individuals, via communal seating. While the authors report that it was unusual for more than one intermediary to be involved in a transfer chain, a chain consisting of five surfaces was observed in one of the experiments (figure 2.7):

Figure 2.7 The transfer of hairs along a transfer chain reported by Gaudette and Tessarolo (1987)

Simons (1986) observed secondary fibre transfer from one item of clothing to another during the laundering of items. Secondary transfers are not restricted to the period prior to evidence collection. Rather, transfers may continue to take place in the forensic laboratory. These transfers may result in the contamination of samples and the compromise of evidence. Several studies cite the potential for secondary fibre transfers to cause loss, redistribution or contamination during evidence packaging (Chewning et al 2008), during the processing of a crime scene (Deedrick 2001) and when handling samples in the laboratory (Wiggins and Houck 2001). Roux et al (2001), meanwhile, investigated the secondary transfer of fibres during an examination in a search room. Fibre populations existed in and beyond the room, with fewer fibres being transferred to areas remote from the site of the examination. The transfer mechanisms that were identified mean that search rooms are seldom 'clean' and the authors suggest precautions and protocol to control the level of contamination.

Taupin (1996) provides an account of the interpretation of secondarily transferred fibres and hair in an abduction case. Awareness of the potential for secondary transfer in this case enabled the identification of a number of complex pathways for transfer.

Secondary and tertiary transfers of material from the mother of the victim to the victim, and then to the accused, served to increase the strength of the association between suspect and victim and ultimately, when presented at trial, forced a guilty plea from the accused. For Taupin (1996), this case affirms the probative value of secondary transfer evidence and underlines the importance of understanding and being able to interpret it.

2.3.3b DNA

That DNA can potentially be used to identify an individual renders it an extremely powerful forensic tool. Coupled with advances in DNA technology, the value of DNA in a forensic investigation has increased and accordingly, so has the desire and capacity to generate a partial profile from ever decreasing quantities of biological material (Port et al 2005, Van Oorschot et al 2010). Increasing the number of polymerase chain reaction (PCR) cycles will dramatically increase the sensitivity of analysis so that a partial profile may be generated from very small amounts of material which may be easily transferred (Lee and Ladd 2001, Van Oorschot et al 2003). Gill (2002) argues that consequently, the interpretation process becomes more complex as issues such as contamination and innocent transfer have to be considered. In addition, it is often necessary to deal with samples that are mixtures of partial profiles from different sources. Clearly, the potential for misinterpretation, whereby for example, the DNA of an individual could be left at a crime scene which they had never visited, is a concerning prospect and an extreme example of the way the secondary transfer issues may manifest themselves with regard to DNA evidence. Alongside a number of criminal trials in which the interpretation and possibility of secondary transfer of DNA has been an issue (Scott and Skellern 2010, Linacre 2013, *R. v. Reed and Reed; R. v. Garmson* 2009), interest in contamination and transfer issues with regard to DNA has grown.

Studies addressing the need to comprehend the nature and extent of secondary DNA transfer are relatively numerous. Following a series of transfer experiments, Van Oorschot and Jones (1997) conclude that handled objects may yield DNA profiles from more than one user and that handshakes can result in the transfer and exchange of DNA between individuals. It was also reported that when poly-propylene tubes were

passed between individuals, it was possible to generate a profile of the initial handler from the hands of the second handler of the tube – providing evidence for the secondary transfer of DNA via an inert intermediary surface. These findings appear to counter Wickenheiser (2002) who suggested that secondary transfers are unlikely. It is not disputed, however, that when secondary transfers of DNA do occur, they tend to involve small quantities of material. Daly et al (2012), meanwhile, demonstrate that mixed profiles of touch DNA, resulting from secondary transfers, can be yielded from various surfaces.

Ladd et al (1999) concluded that DNA can be recovered from objects such as computer keyboards and telephone handsets in low quantities, yet found no evidence for the occurrence of secondary transfer and subsequently, question its interpretative impact. Lowe et al (2002), meanwhile, establish that it is possible for an individual to deposit the DNA of another individual on an inert object. This could be extremely significant if one considers that the inert object could be a firearm or knife, for instance. The propensity for transfer was shown to depend on a number of factors including the length of the period between contacts and the heterogeneity that exists between individuals in terms of their tendency to deposit, or 'shed', DNA. Similarly, Lowe et al (2003) note that longer time lags between contacts tend to reduce the likelihood that the DNA of an individual is transferred to an object via the hand of another. Importantly, the samples taken from the object in this experiment routinely yielded mixed profiles; from both the individual who handled the object and the subject who did not.

On the factors that influence the likelihood of primary and secondary DNA transfer, Phipps and Petricevic (2007) question the simple distinction between 'good' and 'bad' shedders of DNA (people who are more or less likely to deposit DNA). They report that the occurrence of transfer will be determined by the length of time that has passed since the last hand wash and the hand used to make the contact. Meanwhile, Van Oorschot et al (2003) conclude that the propensity for an individual to shed and transfer DNA will also be dependent on the number of contacts an individual has made, with a greater number of previous contacts serving to diminish the amount of transfer that will occur when a subsequent contact is made. Goray et al (2010) identify the moisture content of the biological sample and the porosity of surfaces will govern

levels of secondary transfer. A non-porous intermediary transferring a wet trace to a non-porous surface will result in the most efficient transfer and such information assists in determining the probability of a secondary transfer given certain conditions. Regarding transfer events involving saliva DNA, Warshauer et al (2012) found that increased moisture and a smooth primary contact surface will enhance the efficiency of the transfer. They also report large losses in DNA that were observed following the third step in the transfer chain and the difficulty in extracting a profile that results. Eventual samples were mixtures of multi-provenance DNA. Mixed partial DNA profiles were recovered from shoes by Hillier et al (2005) and secondary transfers were posited as an explanation for their presence.

Rutty (2002) examined the transfer of DNA during manual strangulation events. Persistence of the DNA from the victim on the offender for several days was found to be encouraged by secondary transfer mechanisms but perhaps more notably, DNA originating from a third party was transferred to the neck of the victim. Clearly, the ramifications of this could be severe. Ansell (2002), meanwhile, demonstrates the importance of secondary DNA transfer via an intermediary to the assessment of activity level propositions in a rape case. The DNA of the partner of the complainant was recovered from a penile swab taken from the suspect and assisted in establishing an association between suspect and victim. Finally, Goray et al (2012) examined multiple transfers of DNA in a mock case scenario. The results for multi-step transfers were variable and were not always well predicted by available transfer rate data. This underscores the inherent variability associated with multi-step transfer events and variations that may be attributed to the effects of surface type, the size of the transfer area and temperature/humidity. The authors identify the need for further research in this area to generate data on the factors affecting multi-step transfers which can be inform the interpretation of evidence.

Secondary transfers of biological material during the collection and examination phases can result in the contamination of samples and give rise to opportunities for misinterpretation (Goswami et al 2013). Work has been carried out to study the risks and to recommend precautions and protocol that manage and reduce them. For example, Van Oorschot et al (2005) recommend caution when powdering for fingermarks from surfaces that may bear DNA such as brushes that tend to collect,

harbour and transfer DNA. The consequences of secondary transfer in scene processing (perhaps between scenes) here are conceivably severe and steps should be taken to limit the risk of DNA contamination. Durdle et al (2009) describe how blowflies have the potential to act as secondary transfer vectors of human DNA through the consumption and subsequent excretion of human DNA from blood and semen. Sufficient DNA for typing was recovered from minute artefacts underlining on one hand, a potentially valuable source of DNA at a crime scene, but on the other, a risk of contamination. Wiegand et al (2011) conclude that there is a risk of contamination by police as they come into contact with the sort of weak blood and saliva stains that can be analysed using highly sensitive methods. Small DNA transfers were reported but their incidence was relatively low and contingent upon the surfaces involved. Poy and Van Oorschot (2006), meanwhile, report on the contamination that can result from secondary transfer and the DNA that can be recovered as a result from objects and surfaces in a laboratory. The authors identified several surfaces bearing DNA but the risk was described as relatively low due to the number of steps involved in transfer. Two 'high' risk vectors were pinpointed which yielded sufficient material for the generation of a partial profile. DNA was also shown to accumulate on laboratory gloves. Awareness of these risks is crucial for practitioners in a laboratory setting and can inform procedures for forensic examination. This process of ensuring quality control in this manner is in line with the recommendations of the 2009 NAS report and the logic of improving forensic science. Lastly, the design of experimental research projects involving trace material is also informed by such findings and this will be discussed in chapters four and six with regard to safeguarding the validity of the findings of this thesis.

2.3.3c Other trace materials

Further noteworthy studies of the secondary transfer of trace forensic evidence include an investigation into mortuary contamination by Archer and Ranson (2005). The authors identify the possibility of insects being brought into the mortuary via exhibits. These insects may establish mortuary populations and contaminate new entomology samples. This secondary transfer mechanism poses a contamination risk that, while relatively low, must be guarded against to safeguard the integrity and probative value of evidence. Montani et al (2010), meanwhile, outline a sampling kit

for ignitable liquids designed to limit the possibility of cross contamination in the processing of arson scenes. Leintz (2011) explored the risk of investigative personnel transferring blood from a floor from which blood had been cleaned. The cleaning process was found to be sufficient to prevent secondary transfer and contamination.

French et al (2012) carried out an exploratory investigation into the potential for trace particulates (mean diameter 15µm) to be transferred multiple times along transfer chains and within contact networks. Four experimental scenarios of increasing complexity were set up, involving participants and surfaces that could come into contact. The scenarios were intended to approximate a series of contacts that might occur following an initial transfer in the period prior to suspect apprehension, scene processing and evidence collection. Ultra-violet powder was employed as a proxy for trace particulate materials (after Bull et al 2006 and Morgan et al 2010), and was introduced in the experimental scenarios via the hands of a chosen individual. During the experiments, logs were kept which documented any contacts that were made and at various intervals, samples were taken from the hands of individuals and from various handled surfaces. The sample stubs were then analysed and the presence of UV powder was quantified using an image rasterisation programme that made use of photographs of the stub which were taken under a UV-lit microscope. This analysis enabled the mapping and quantification of trace material transfer, as well as an assessment of the occurrence and extent of multiple transfers. The study borrowed theories and concepts from social network theory and contact network analysis when observing and analysing the nature and extent of transfers of trace evidence.

The key findings of the French et al (2012, p.40) study are summarised as follows:

- Particulates can readily undergo secondary transfer from one individual to another, via various intermediaries
- Transfer chains involving primary, secondary, tertiary and quaternary transfers were observed. Sampling from the subjects revealed a two-stage mechanism of decrease
- Inert objects can act as ‘reservoirs’ of trace material for transfer, echoing the findings of Lowrie and Jackson (1994)

Explicit consideration of the ramifications of secondary transfer for an investigation has often been absent from studies of secondary transfer. French et al (2012), therefore, explored the possible implications of their findings, particularly for the process of evidence interpretation. The findings highlight the potential for unconnected individuals to become implicated in the investigation of a crime via trace particulate evidence which may have been inadvertently transferred to them. The importance of acknowledging this possibility is recommended when interpreting samples, particularly when dealing with small amounts of material. One of the aims of this piece of research was to demonstrate the potential for widespread transfer with a view to further, more targeted studies regarding alternative trace evidence types in a range of forensic scenarios. French et al (2012) argue that the full and accurate interpretation of transfer evidence can be aided by the use of Bayesian networks. Such an approach, it is argued, would enable the handling of multiple variables and assist in unlocking the probative potential of trace particulate evidence.

Chapter 3 Gunshot residue (GSR)

3.1 Outline

Following discussions of trace evidence interpretation, evidence dynamics and multiple transfers, this chapter introduces GSR. The chapter begins by defining GSR and outlining the process of its formation, before surveying the methods that have been developed to detect it. An account will be provided of the ways in which GSR can be used in a forensic investigation and of the types of interpretative propositions that can be addressed when it is recovered. A comprehensive review of the experimental literature concerning the dynamics of GSR behaviour will follow. A number of reviews of the GSR literature and of developments in detecting GSR particles have been carried out (see, for example, Romolo and Margot 2001, Singer et al 1996 and Dalby et al 2010), yet this chapter differs from previous work in that it is written specifically for the purposes of this thesis, with a particular emphasis on transfer issues and their interpretation. This review concludes by highlighting the potential for further research into multiple transfers and contamination issues, in light of a consideration of the investigative and interpretative implications they can potentially pose in casework scenarios involving GSR.

3.2 An introduction to gunshot residue

The term Gunshot residue (GSR) is interchangeable with the less often employed terms firearm discharge residue (FDR) and cartridge discharge residue (CDR). GSR falls into the category of 'trace physical' or 'trace particulate' forensic evidence. It is produced during the process of firearm discharge and exhibits properties of transfer and persistence similar to those described in section 2.3. GSR evidence is frequently utilised in the investigation of firearms offences, especially when a firearm has been discharged. It can provide a basis on which to assess different levels of proposition in the interpretation process and can be used to reconstruct a variety of facets of a firearms offence.

3.2.1 The formation of GSR

GSR is produced when a gun is fired and comprises solid 'partially burnt and unburnt propellant particles and combustion products from the priming compound' along with compounds from the bullet, cartridge and firearm (Heard 2008, p.241). The composition of GSR particles results from a combination of primer and bullet derived compounds that become vaporised due to the high temperature and pressure and escape the firearm as part of an expansion plume, after which the materials cool and condense to form particles (Nag and Sinha 1992). These particles are deposited on the shooter and surfaces in the vicinity of the discharge. An understanding of the formation process underpins efforts to identify and interpret GSR, and to comprehend its transfer and persistence. Figure 3.1 captures the generation of GSR via a step-by-step diagram, after various sources. It will be made evident in the subsequent discussion of GSR analysis that the capacity to detect and identify GSR particles stems from their distinctive morphology and elemental composition, which result from the formation process and the materials involved.

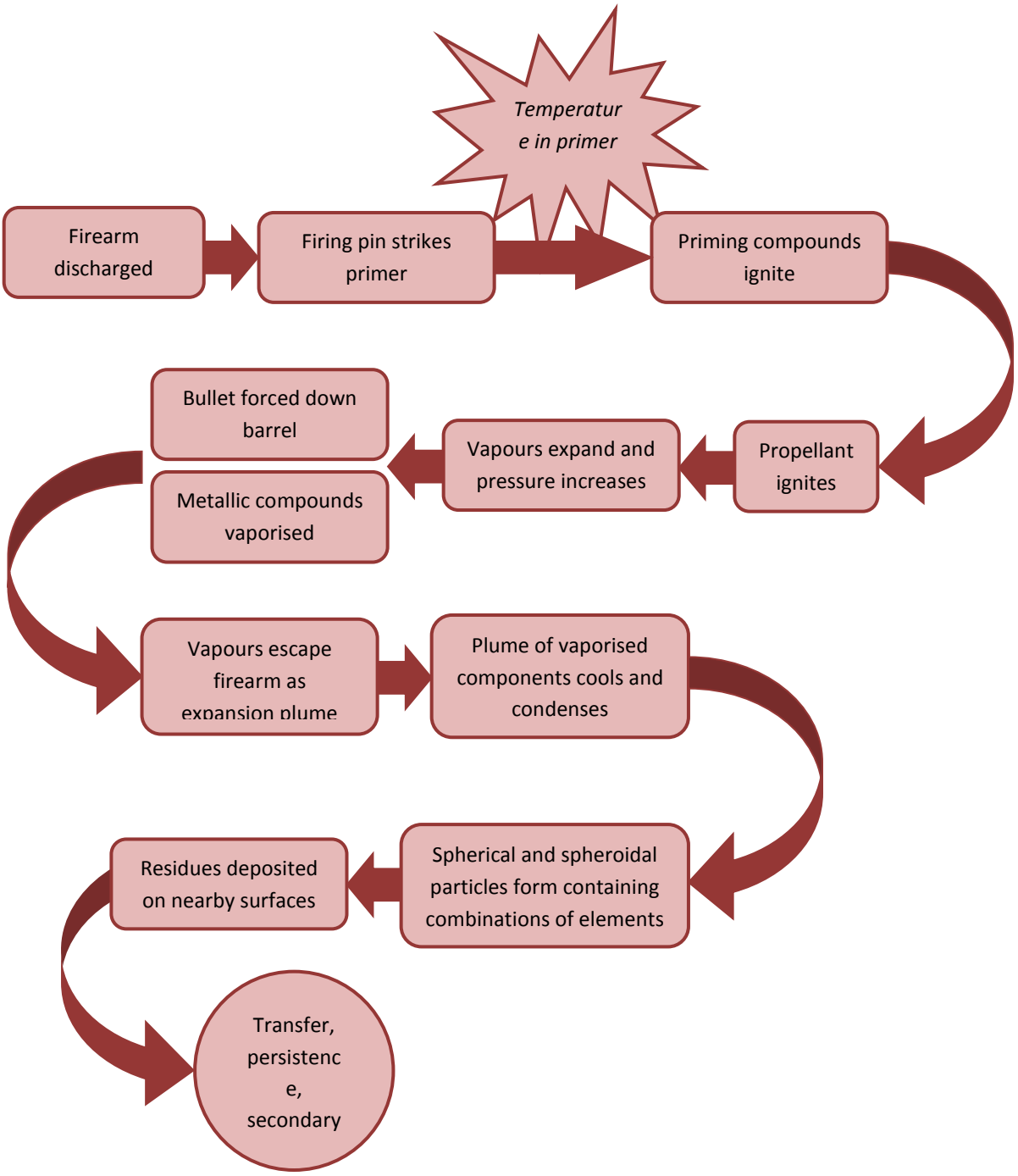


Figure 3.1 Sequence of events in the formation of GSR during firearm discharge (after Heard 2008, Rosenberg and Dockery 2008, Goode et al 2002, Molina et al 2007, Nag and Sinha 1992)

3.2.2 Morphology, shape and structure

The size, shape, morphology and texture of GSR particles owe much to the high temperature and pressure environment in which they are formed, and to the subsequent rapid cooling and condensing of the expansion plume. The elemental contents of the particles are also influential and these will be described in section

3.2.3. Various generic descriptions of the morphology of GSR particles have been offered and some variation exists. This variation is owing to the fact that, in reality, there is no "typical" GSR particle in terms of size and shape. However, there is generally a degree of agreement when attempting to provide definitions and descriptions that many GSR particles resemble metallic spheres, formed by the cooling and rapid solidifying of materials. Wright and Trimpe (2006) report that participants of the FBI Laboratory's Gunshot Residue Symposium employed terms such as "spheroid", "noncrystalline", "condensed", "rounded", "fused", "molten" and "irregular" to describe the form of GSR particles. These terms capture the variety of GSR shapes and forms, while also reflecting the fact that near-spherical, rounded particles are common. An exterior appearance consistent with cooling and solidifying from a molten state is widely reported (Brozek-Mucha 2007, 2009, Wolten and Nesbitt 1980, Basu 1982, Lindsay et al 2011a, Brozek-Mucha 2011). A summary of key findings and observations regarding the size, shape and texture of GSR particles is provided in table 3.1.

Size/Shape/Texture-appearance	Observation	Reference
Size	The majority of GSR particles measure between <1µm and 10µm	Basu 1982, Nesbitt et al 1976, Brozek-Mucha 2011, Trimpe 2011, Thornton 1994, Zeichner 2012, Zeichner 2003, Meng and Caddy 1997, Wolten et al 1977, Lindsay et al 2011a
Size	Particles measuring <1µm-1.5µm most commonly encountered	Brozek-Mucha 2009
Size	Mean particle size 2.6µm	Halim et al 2010
Size	Particles measuring >30µm are sometimes encountered	Andrasko and Maehly 1977
Size	Particles measuring >50µm are formed by the joining of smaller particles	Basu 1982
Shape	Spheroid particles prevalent	Basu 1982, Nesbitt et al 1976, Brozek-Mucha 2011, Trimpe 2011, Thornton 1994, Zeichner 2012, Zeichner 2003, Meng and Caddy 1997, Wolten et al 1977, Lindsay et al 2011a
Shape	Categories of shape proposed: regular spheroids, nodular spheroids, irregular spheroids	Basu 1982
Shape	Airborne GSR found to consist of regular/irregular spheres and assemblages of spheres. Plate and branched structures among cartridge GSR	Brozek-Mucha 2007

Shape	Shape can modify on impact with target	Burnett 1989
Shape	Shape and morphological features vary according to ammunition type	Meng and Caddy 1997, Brozek-Mucha 2007, Collins et al 2003
Shape	Large, fragmented particles that appear as fragments of a bigger object recovered from shooter	Brozek-Mucha 2011
Texture-appearance	Holes, cavities, hollows and peeled textures	Basu 1982
Texture-appearance	Appearance consistent with cooling from a molten states	Wright and Trimpe 2006, Brozek-Mucha 2007, 2009, Wolten and Nesbitt 1980, Basu 1982, Lindsay et al 2011a, Brozek-Mucha 2011
Texture-appearance	Smooth surfaces, as well as scaly exteriors	Wolten et al 1979a, Basu 1982

Table 3.1 Summary of findings and observations regarding the size, shape and texture-appearance of GSR particles

The texture of particles is readily observable using the Backscattered electron function on the SEM. Wolten et al (1979a), for example, describe smooth surfaced particles, those with scaly, fuzzy exteriors, and particles that are covered in small spheres. External layering and cracking are also often observed, while it is common for GSR particles to be adhered to, or have associated with them, other materials from the firearm discharge. In terms of their size, particles may be very small and measure less than one micrometre (µm) and can also be relatively large, measuring 20µm, 30 µm, or possibly in excess of 100µm. Frequently, the majority of particles in a population of GSR will exhibit a spheroid appearance and measure in the order of a few micrometres: between <1µm and 10µm, for example (Basu 1982, Nesbitt et al 1976, Brozek-Mucha 2011, Trimpe 2011, Thornton 1994, Zeichner 2012, Zeichner 2003, Meng and Caddy 1997, Wolten et al 1977, Lindsay et al 2011a). Andrasko and Maehly (1977) report that most particles encountered in their examination measured between one and five micrometres and were chiefly near-spherical, with a few large particles (>30µm) amongst the population. Brozek-Mucha (2009) report that, following test firings, particles measuring between <1µm and 1.5µm were most common. Finally, Halim et al (2010) examined the GSR produced by the firing of 9mm ammunition from a semi-automatic pistol and report a mean particle size of 2.6µm, with the majority of particles of this size exhibiting a spherical shape.

Classification of GSR particles, particularly via shape and morphology is challenging as their heterogeneity serves to resist rigid categorisation. Notwithstanding this,

attempts at classification have been made. For example, in an examination of GSR from different sources, Basu (1982, p.77) acknowledged the prevalence of spheroids but also accounted for the variance in particle morphologies. As such, three categories of particle morphology were proposed: regular spheroids with surfaces ranging from 'smooth' to 'knobbly', nodular spheroids formed by the fusion of large and small spheres, and irregular spheroids with 'large knobs and spikes' on their surface. Basu (1982) links these morphologies to the formation process, explaining that irregularities can be caused by extreme thermal exposure. Basu (1982) also identified the possibility of the coalescence of spheres, which resulted in the formation of large particles measuring >50µm. The large particles observed by Basu (1982, p.72) measured up to 55µm and had the appearance of 'peeled oranges'. Small holes, cavities and large hollows were also observed and are routinely reported in GSR analysis (see also Brozek-Mucha 2011). Brozek-Mucha (2011, p.977) recovered particles formed by the collision of smaller pieces of material, as well as 'fragmented solid particles' that consisted of several segments of a larger, 'broken' piece of material.

Brozek-Mucha (2007) sought to compare the size and shape of GSR that is airborne and deposited in the vicinity of the firearm discharge, to that which can be recovered from the spent cartridge. This is salient as often in casework, deposited GSR is compared to a reference sample from a spent cartridge. Airborne GSR was found to predominantly consist of regular and distorted spheres with sizes ranging from sub-micrometre to several micrometres, with many measuring around 20µm. Occasionally, assemblages of spheres and 'sponge-like' or 'shell-like' fragments were encountered, while irregular particles not conforming to these descriptors were also identified (ibid., p.400). On the other hand, GSR within the cartridge exhibited features that were also suggestive of rapid cooling from a molten state, yet divergences existed in terms of shapes and sizes. For example, spherical particles tended to be larger and the majority of GSR particles were best described as solid or porous 'plates' or structures resembling branched webs of material (ibid., p.400). Akin to Basu (1982), morphological variations are attributed to the formation process. It is argued that, while airborne, GSR cools in the air resulting in the formation of spheroid particles. Conversely, GSR recovered from a spent cartridge is formed as material collides with the inner surface of the cartridge and cools.

Ueyama et al (1980) hypothesise that irregularities in GSR particle morphologies can be linked to firing distance. Burnett (1989), meanwhile, reports that the shape of GSR particles can be modified on impact with a target. This is explained by the fact GSR is molten when it collides with the target and as a result, spherical forms are flattened and modified on impact. The type of ammunition used will also have an impact on the morphological form of GSR particles (Meng and Caddy 1997). Indeed, Brozek-Mucha (2007, p.401) observe that some ammunition types result in GSR structures which appear 'splashed', rather like viscous liquid on a hard surface. Furthermore, Brozek-Mucha (2007, p.400) notes that 'elongated' particles or those resembling 'sponge-like' structures are produced by ammunition that contains powdered glass in its primer. Collins et al (2003) document glass-containing GSR particles produced by rimfire ammunition that were found to measure up to 25µm and exhibit a range of morphological features. While spheres were observed, surface fracturing was also noted and this was hypothesised to have been caused either during the formation process or during sampling. Many of these particles were formed around a glass core.

While the morphology of GSR particles can be distinct and can be used to distinguish them from other similar particles with environmental and occupational sources (Garofano et al 1999), morphological features do not always provide a sufficient basis on which to make a distinction. Wolten et al (1979b), for instance identified spheroid, metallic particles that emanated from environmental sources. Meanwhile, it has been shown (see, for example, Brozek-Mucha 2007) that GSR particles can take many shapes and consequently, to depict GSR as consisting exclusively of spherical particles is potentially misleading. The elemental composition of particles must also be considered.

3.2.3 Composition and classification

Ammunition comprises a projectile, a cartridge case, a propellant and a primer. GSR emanating from a firearm discharge will correspond, elementally, to the composition of the primer. This can be illustrated by observing the presence of lead styphnate, barium nitrate and antimony sulphide in many ammunition primers (Molina et al 2007). These compounds are responsible for the 'classic' composition of GSR - lead, antimony and barium in combination (Pb–Sb-Ba). It is the pursuit of particles with this

combination that represents the most diagnostic detection of GSR. These primer contents are however, not exhaustive. Residues resulting from different primers, such as those containing mercury (Hg) will yield elemental combinations such as mercury and antimony (Hg-Sb). Meanwhile, in a recent review, Brozek-Mucha (2011) refers to relatively common primers that contain mercury fulminate, potassium chlorate and antimony sulphide (after Bydal 1990 and Brozek-Mucha 2009) and which produce corresponding GSR deposits. Comprehensive reviews of the residues emanating from the use of different primers are available (see Wallace 2008 for a suitable example). Such reviews highlight the evolution of alternative lead-free, non-toxic and heavy metal-free primers which have subsequently been accommodated into GSR classification systems (see also Martiny et al 2008).

It is acceptable, particularly within the context of this thesis (given the ammunition that was used for the experimental phase and which is introduced in chapter four), to consider the detection of a Pb-Sb-Ba ("three-component") GSR particle as the typical benchmark for a positive GSR detection. Indeed, this combination is the most commonly cited combination in the literature, and has been the focus of several decades of development with regard to its detection. In surveys of ammunition, GSR particles with this elemental composition are widely reported due to the prevalence of certain primers (see, for example, Gökdemir et al 1999). The specificity of this composition to GSR particles has been demonstrated. Accordingly, in the latest ASTM Standard Guide for Gunshot Residue Analysis by Scanning Electron Microscopy/Energy Dispersive X-Ray Spectrometry, E1588–10e1, this particle composition is alone in being considered to be 'characteristic' of GSR. 'Characteristic' compositions are those which are most likely to have emanated from a firearm discharge, as opposed to some other source:

- Lead, antimony, barium[24] [see footnote]

[24] The standard accounts for the fact that traces of further elements may be associated with these tri-component particles. These include, but are not limited to, one or more of the following: aluminium, silicon, phosphorus, sulphur (trace), chlorine, potassium, calcium, iron (trace), nickel, copper, zinc, zirconium, and tin (ASTM E1588-10e1)

'Characteristic' particles are rarely recovered in great quantities without the presence of GSR particles with other compositions. These particles may contain one or two of the elements, lead, antimony and barium, as well as many other elements besides. Therefore, a host of other particle compositions are deemed consistent with GSR. Particles with these elemental compositions may originate from firearm discharge but could also be traced to other, unrelated sources. 'Consistent' compositions include:

- Barium, calcium, silicon (with or without a trace of sulphur)
- Antimony, barium (with or without a trace of iron or sulphur)
- Lead, antimony
- Barium, aluminium (with or without a trace of sulphur)
- Lead, barium
- Lead (only in the presence of particles with compositions mentioned thus far)
- Antimony (only in the presence of particles with compositions mentioned thus far)
- Barium (with or without a trace of sulphur)[25] [see footnote]

Evidently, this category of compositions is somewhat broad and clearly a firearm discharge will not represent the only source of particles with some of the compositions listed. Hence, careful interpretation is required, along with contextual information when propositions about the source of particles are being addressed. Particles cannot be considered in isolation and the presence of different compositions in the sample will also determine the evidential weight of a particular particle. Studies that have attempted to identify and catalogue environmental and occupational sources of similar particles are reviewed in section 3.2.4.

The above classifications are those most generally referred to in the literature. However, these only account for GSR generated from primers which contain compounds of lead, antimony and barium. The standard also lists elemental compositions of GSR that have been found to originate from the use of ammunition

[25] Once again, it is acknowledged that particles exhibiting the compositions above may also incorporate one or more of the following: aluminium, silicon, phosphorus, sulphur (trace), chlorine, potassium, calcium, iron (trace), nickel, copper, zinc, zirconium, and tin (ASTM E1588-10e1)

which has a lead-free or non-toxic primer. Particles with compositions that are characteristic of such GSR can contain the following:

- Gadolinium, titanium, zinc
- Gallium, copper, tin

Other compositions are consistent with GSR originating from lead-free or non-toxic primers:

- Titanium, zinc[26] [see footnote]
- Strontium

These compositions and classifications are not exhaustive and a particular primer may generate particles that may require additional classification. Such classifications may be generated via case-specific test firings or experimental research, but should be effective in distinguishing the GSR from environmentally or occupationally generated material of similar composition.

The elemental composition of particles within a population of GSR formed as a result of firing a particular type of ammunition will not be homogeneous. Rather, a population will include a mixture of characteristic, consistent and environmental particles. Additionally, analysis of individual particles has shown that the elemental composition can vary across different regions of the same particle (Andrasko and Maehly 1977). Matricardi and Kilty (1977) observed particles with a lead exterior which encased a bulk of barium, calcium and antimony. In an examination of GSR from 0.22 calibre ammunition, Coumbaros et al (2001) linked the distribution of lead and barium within particles to the formation process and found that many particles exhibited a barium core that was covered by lead.

[26] Elements such as aluminium, silicon, calcium, copper, or tin from the jacketing of the ammunition may be found in place of zinc

Certain exotic materials have also been found to occur within GSR and these compositional features can represent an additional discriminatory tool with which to make source level inferences. For example, Collins et al (2003) observed a previously undocumented GSR particle type consisting of glass fused with the primer components. These particles were produced by firing 0.22 calibre rimfire ammunition in which the primer is sensitised with glass. The observed particles tended to be large and exhibited a core of glass, with a surface coating of lead and barium. Alternatively, spheres of Pb-Ba were fused to the glass. Rimfire ammunition generally produces GSR consisting of lead only or lead and barium which, as described above, can be identified as GSR with less certainty. The authors argue that owing to the environmental rarity of these glass-containing particles, the presence of glass in the manner described renders these particles highly characteristic of GSR and indeed, of the use of certain types of 0.22 calibre ammunition. Meanwhile, chemical taggants, such as lanthanide ions (Lucena et al 2013) which are added to some ammunition, can be identified in resultant GSR. These can assist in the determination of GSR presence and in distinguishing ammunition types, particularly with regard to identifying GSR from law-enforcement ammunition (Wright and Trimpe 2006, Niewoehner et al 2005, Zeichner 2012). Owing to these compositional nuances, Dalby et al (2010) advocate a case-by-case approach to identifying GSR.

3.2.4 GSR-like particles from environmental and occupational sources

Elements routinely encountered in the analysis of GSR can also be traced to many other environmental and occupational sources (see, for instance, Havekost et al 1990). For example, lead is used in glazing and plumbing, and is recoverable from battery terminals and leaded fuels. Lead compounds, meanwhile, are commonplace in ceramics. Barium compounds are responsible for the green colouring of some fireworks, are present in paper, and are used in welding and in the production of face make-up powders (Wolten et al 1979b, Thornton 1994). Finally, antimony is present in many alloys and is used to coat fibres, while its compounds are used in the heads of safety matches (Heard 2008).

As articulated in 2.2.2, the formulation and addressing of source (Level I), as well as activity and offence (Level II and III) level propositions involves accounting for the background rates of the material being interpreted. When interpreting the presence of Pb-Ba or Sb particles, for example, the scientist will be required to consider alternative sources of particles with this composition and the activities and environments that could result in the presence of such particles. Consider the following:

a) The particles were produced by a firearm discharge

b) The particles were produced by some other source of elementally similar particles

The assessment of the above pair of propositions requires knowledge of particles that may have similar elemental or morphological properties to GSR. Some estimation of the background rate of such materials is required.

Consider the following:

a) Mr A fired the gun

b) Some other person found the gun

When addressing the pair of propositions above, some information regarding activities engaged in by Mr A, which may leave him predisposed to having GSR on his person will be required. Moreover, activities that he has engaged in which may have resulted in the presence of particles that have similar properties to GSR and that could result in a false positive GSR identification will also need to be considered.

Thus, interpreting the source of GSR-like particles requires an appreciation of sources of similar particles. The environmental occurrence of compositions detected in GSR determines whether they can be classified as 'characteristic', 'consistent' or 'environmental'. Studies addressing this important issue are numerous. A summary of the findings of a number of relevant studies is presented in table 3.2.

Study	Environmental/occupational source	Observation
Garofano et al 1999	Various occupational sources including plumbing, welding, automobile work and fireworks handling	Generally low false-positive risk. Ba-Sb, Pb-Ba and Pb-Sb particles from vehicle sources
Wolten et al 1979b	Plumbers, machinists and technicians	Some spheroidal lead particles detected. Pb-Sb and Pb-Ba particles from lead-acid battery plants and leas smelting operations
Garofano et al 1999	Cartridge-operated industrial tools	Ba, Pb, Sb particles detected measuring 5-55µm
Gerard et al 2011a	Cartridge-operated/powder-actuated tools	Pb-Ba, Pb and Ba particles deposited
Wolten et al 1979b	Cartridge-operated tools	Particle elementally consistent with GSR in some cases
Wolten et al 1979b	Cap guns and blank cartridges	No GSR-like particles observed
Garofano et al 1999	Fireworks	Irregular Sb, Ba, Pb-Ba, Pb-Sb particles measuring 10-20µm detected
Grima et al 2012	Fireworks	Small proportion of Pb, Sb, Ba, Sr, Sb-Ba, Ba-Al particles detected
Mosher et al 1998	Fireworks	Pb, Sb, Ba particles
Torre et al 2002	Brake linings	Pb-Sb-Ba and Pb, Sb, Ba containing particles detected. Many contained elements incongruous with GSR
Giacalone 2000 and Martiny et al 2005	Brake pads	GSR-like particles detected. Many found to have irregular morphologies and elements incongruous with GSR

Table 3.2 Summary of findings and observations regarding environmental and occupational sources of GSR-like particles

Garofano et al (1999) surveyed the hands of various individuals engaged in a range of occupations (plumbing, electrical-work, printing, welding and painting, etc.), as well as participants who had handled various parts of automobiles and others who had used industrial tools or who had handled fireworks. The authors found that, generally, occupational sources did not present a risk of false-positive GSR detection and accordingly, samples tested negative for the presence of GSR-like particles using SEM-EDX, despite the nature of the materials involved. This finding echoes those of Wolten et al (1979b) who, in a similar survey of plumbers, machinists and technicians found little in the way of GSR-like particles other than some lead and spheroidal particles that could be discriminated by various means. However, Garofano et al (1999) found that mechanics, vehicle electricians and tyre-fitters were exposed to Ba-Sb, Pb-Ba and Pb-Sb particles, which proved difficult to distinguish from GSR. The authors comment on the irregular morphologies of these particles that with careful evaluation, in most

cases, should enable discrimination from GSR. However, Ba-Sb particles in the presence of other elements were recovered that were extremely hard to distinguish from GSR particles with more irregular morphologies. Brake hubs and batteries yielded Pb-Sb and Pb-Ba particles, while the presence of particles compatible with GSR in vehicle interiors was found to be negligible. Wolten et al (1979b) detected spheroidal Pb-Sb and Pb-Ba particles with diameters of 2µm, 3µm and some >5µm from individuals in lead-acid battery plants and it was only the presence of other particles that enabled discrimination from GSR. Wolten et al (1979b) took samples from employees at a lead smelting operation. Pb and Pb-Sb particles were subsequently detected, although the authors noted the high proportion of particles with irregular morphologies or divergent compositions that were observed on the samples. It is noted that in cases in which only a few particles exist on a sample, the potential to use the particle population in this discriminative fashion will be more limited and interpretation problems will be exacerbated.

Garofano et al (1999) determined that cartridge-operated industrial tools (nail staplers) can generate particles that can conceivably be mistaken for GSR. The authors explain this with reference to the antimony and lead present in the primers used in these cartridges. These particles measure between 5µm and 55µm, can be irregularly or spherically shaped, and can exhibit 'cratered or nodular' appearances (ibid.11). These results regarding industrial tool residues followed those previously presented by Wallace and McQuillan (1984). In the study, residues from cartridge-operated tools used in building and construction were compared to those from firearms. The paucity of Pb-only particles from cartridge tools was highlighted as a distinguishing feature and this underscores the importance of examining the entire particle population. Crucially, interpretative issues may be exacerbated when only a few particles are recovered. The authors also point to the importance of what Cook, Evett and others (see section 2.2.2) term the 'framework of circumstances' in the interpretation process. For example, knowledge about the occupation of a suspect could be valuable; if it may involve exposure to cartridge tools, then an indication of the time since handling the tool would inform the assessment of the likely provenance of the material. Finally, the authors highlight the importance of particle analysis methods in distinguishing the elemental contributions of relevant particles. These are discussed in 3.3.2.

Gerard et al (2011a) examined residues from cartridge-operated/powder-actuated tools and their relative similarities to GSR. The use of such tools by subjects resulted in the deposition of Pb-Ba, Pb and Ba particles, yet no Pb-Ba-Sb particles. However, rimfire cartridges which were fired from a firearm and which were used for comparison also did not yield and Pb-Ba-Sb particles. Thus, because the residues from this ammunition and from the tools were not characteristic of GSR, a basis for discriminating between the two types of residues could not be identified. Wolten et al (1979b) submitted samples taken from users of cartridge-operated tools for blind-testing by GSR examiners. While some particles were identified that were consistent with GSR when examined in isolation, the wider context of particles rendered the sample inconsistent with GSR. In other cases, exotic elements not found in GSR were identified and this, or an absence of spherical particles, was used to distinguish the material on the sample from GSR. While inconsistent particles can be used to discriminate a sample, the authors note that if a sample contained both types of residue, a false-negative could result from taking this approach. Wolten et al (1979b) also examined residue from children's cap guns and from blank cartridges, with neither producing any particles approximating GSR.

Garofano et al (1999) sampled subjects who had handled and set off fireworks. These samples yielded Sb, Ba, Pb-Ba and Pb-Sb particles that were irregularly shaped and measured between 10µm and 20µm. When these particles occur in composite configurations, their appearance renders them readily distinguishable from GSR. Grima et al (2012) carried out an investigation into the propensity of fireworks to produce GSR-like particles that are subsequently deposited at a display site and on spectators. Taking the entire firework particle population into account, discrimination of particles from GSR was possible but some particles were recovered that, if taken in isolation, could give rise to a false-positive GSR detection. A relatively small proportion of the particles recovered contained Pb, Sb, Ba or Sr, the latter consistent with GSR from lead-free ammunition. The presence of magnesium and sodium in some of these restricted the possibility of a false-positive. Around 0.5% of recovered particles were termed 'GSR-similar' (ibid.51) on the basis of their elemental composition, amounting to nine Sb-Ba and three Ba-Al features among well over 2,000 particles. Some of these were recovered from spectators who had no direct contact with the fireworks

themselves. A situation in which one or two of these particles were deposited in isolation or in a case in which it was not possible to compare the sample to a reference population from a firearm discharge, these particles could represent a source of error. These particles were also found to persist for several hours, akin to GSR. Mosher et al (1998) also recovered particles containing lead, antimony and barium from fireworks, thus underlining them as a potential source of GSR-like particles.

Torre et al (2002) surveyed brake linings and their products for the presence of GSR-like particles. The elemental constituents of brake linings and the high temperatures they are exposed to means that residues are produced in conditions which are analogous to those observed during the formation of GSR. Elemental profiles echoing those obtained from GSR were generated when the samples were analysed using SEM-EDX. Particles containing Sb, Ba and Pb in combination were found, as well as many containing Pb, Sb and Ba in various combinations and forms. However, high iron content and the presence of exotic elements (such as Mg) were sufficient to discriminate most of these particles. The authors suggest that when composition and particle size are compatible with GSR, the shape of the particle can be used to discriminate. GSR, it is argued, consists of spherical, smooth, globular, nodular or cratered particles which are not 'rough or dusty' (ibid.504). However, as shown in section 3.2.2, GSR particles can often have shapes which are irregular and which prove resistant to classification. In samples taken from brake mechanics, Wolten et al (1979b) found two particles (one spheroidal and one irregular) that were elementally consistent with GSR but elements other than lead and barium which accompanied them, such as iron and sulphur, were present unusually high quantities. Giacalone (2000) and Martiny et al (2005) found GSR-like particles associated with brake pads, yet incongruous elements and inconsistent morphologies were again sufficient to permit discrimination from GSR.

In summary, environmental and occupational sources of GSR-like particles pose a potential source of error in the detection of GSR. Careful examination is required, as well as the consideration of morphology and the context of the remainder of the particle population. Meanwhile, the importance of contextual information regarding the exposure of a suspect to sources of GSR-like materials is evident and this is in accordance with the account of interpretation provided by Cook et al (1998b)

(Garofano et al 1999). Cursory examinations that ignore the wider particle context and the morphology of particles, particularly if interpreted without information regarding possible exposure of environmental and occupational sources, will leave room for error (ibid.). While the experience of a GSR examiner is cited as aiding his/her ability to discriminate sources (Wolten et al 1979b), the development of automated particle analysis methods coupled with complementary manual morphological examination and verification can assist in making such discriminations. The latest standard for GSR examination (ASTM E1588-10e1) refers to particles which are 'characteristic and 'consistent' with rather than "unique" or "indicative", as used in the old nomenclature. This change is significant and reflects the findings of studies like that of Torre et al (2002) in light of which it is not prudent or accurate to describe the presence of some GSR compositions as an unequivocal indicator of GSR. Moreover, as described in chapter one, the principle of 'uniqueness' has been questioned amid recent debates in forensic science and consequently, this change of classification also reflects an adaptation of forensic discourse more generally.

3.3 The detection and analysis of GSR

The use of GSR evidence in formulating and addressing different levels of proposition relating to a firearms offence relies on the analytical detection (and often quantification) of its presence. Samples may have been taken from the hands, clothing or face of a suspect, from a wound, or from surfaces at the crime scene, and these must be analysed in the laboratory. Various methods have been developed and subsequently employed in this process, each with their own strengths and drawbacks. The unifying feature of each of these approaches is that they seek to exploit the aforementioned characteristics of GSR which result from the formation process and the materials involved. The development of these detection methods is presented in section 3.3.1 before an account of contemporary techniques using scanning electron microscopy and those that are to be utilised in the present investigation.

3.3.1 The development of analytical detection methods

The various GSR detection methods reported in the literature rely on the detection of certain elements, often lead, barium and antimony in some combination. Wet chemical tests (Harrison and Gilroy 1959) provided confirmation regarding the presence of lead, barium and antimony, while earlier tests confirmed the presence of their nitrates (Romolo and Margot 2001). These tests along with paraffin cast examinations, while rapid, easily executed and inexpensively conducted, were found lacking in their sensitivity and in their GSR specificity. Positive results could be yielded by materials other than GSR that contained the elements of interest (ibid.). Further techniques that have been widely employed in the detection of GSR and that have undergone significant development and refinement include instrumental methods such as neutron activation analysis (NAA) (Ruch et al 1964, Rudzitis et al 1973, Krishnan 1974, Saferstein 1982) and atomic absorption spectroscopy (AAS) (Krishnan 1971, Koons et al 1987). A method involving photoluminescence has also been explored (Jones and Nesbitt 1975, Nesbitt et al 1977).

Further methods that have been trialled, developed and utilised for the detection of the inorganic fraction of GSR include X-ray microfluorescence (Brazeau and Wong 1997, Flynn et al 1998), inductively coupled plasma mass spectrometry/atomic emission spectroscopy (ICP-MS/AES) (Koons 1998, Koons et al 1988), as well as anodic stripping voltammetry (ASV) (Liu et al 1980) (Romolo and Margot 2001). All of the methods described exhibit a number of drawbacks. For example, some are able to identify certain elements but do not have the capacity to detect all those which might comprise a characteristic GSR particle. Most problematic of all is that bulk quantitative elemental analysis methods provide a measurement of the total elemental presence from the entire sampled area. While confirming the presence of certain primer-derived elements of interest, such methods lack GSR specificity as the total elemental content is considered and quantified. Unavoidably, this can result in a false-positive identification of GSR when the elemental contribution has in fact been made by one or more of the environmental and occupational sources described in section 3.2.4. These methods, therefore, are unable to rule out the possibility that the presence of individual elements is attributable (at least in part) to a source other than a firearm discharge (Bird et al 2007). Moreover, they are not sufficiently sensitive to permit the

identification and quantification of the elemental contribution of individual (GSR) particles (Tillman 1987).

3.3.2 Detection and particle analysis using SEM-EDX

In response to the shortfalls and difficulties associated with many methods, the evolution of scanning electron microscopy with energy-dispersive X-ray spectrometry (SEM-EDX/EDS) as a means of identifying GSR particles has followed the early work of Boehm (1971). Detection using SEM-EDX has the advantage of being a non-destructive technique, meaning that samples may be re-analysed, and results verified, at a later date. Furthermore, very little sample preparation is required. SEM-EDX is considered a superior method as it permits the analysis of individual particles and enables the analyst to specify them as GSR both morphologically and elementally (Tillman 1987). It is this capacity which has for some time rendered SEM-EDX as the preferred analytical method for GSR detection (Brozek-Mucha and Jankowicz 2001), and concurrently as that which will be used in the experimental phase of this thesis (see chapter four). SEM-EDX represents a two-pronged approach to detecting the presence of GSR in a sample; at once, high quality, magnified images of individual particles can be examined to distinguish particle shapes, size and features, while it is possible to identify X-rays pertaining to the atomic structure of a particular element and thus, to determine the elemental composition at a point on an object. This dual approach reduces the possibility for error as elemental profiles can be obtained for individual particles, which themselves can be morphologically examined with a view to satisfying the conditions for a positive GSR identification. It also means that there is greater scope to distinguish GSR from environmental and occupational sources of GSR-like materials.

There are two approaches to searching for and detecting GSR particles using SEM-EDX. Until quite recently, manual, operator-based search approach to detection using SEM-EDX was the only option. Prior to discussing automated search and detection facilities and the benefits they provide in detecting and analysing GSR, it is useful to provide an account of the manual process and its limitations. The work of Matricardi and Kilty (1977), which describes the manual approach to search and detection with SEM-EDX, represented an important early contribution to the exploration of GSR detection and analysis using this method. Generally, the preferred method of sampling involves the

use of aluminium SEM stubs with a self-adhesive tab (see section 4.2.3). The surface of these stubs should be carbon coated prior to analysis to avoid the charging of background material. Under the SEM, the first stage is to conduct a visual examination of the samples expected to contain GSR. A particle of interest, that is, one which seems to be of suitable size, brightness and shape/sphericity, prompts the increase of magnification until the full beam is centred upon it. Note that this examination should take place using backscattered electron (BSE) imaging rather than secondary electron imaging, as inorganic particles will be better distinguished from background material. The object is then scrutinised using EDX, which provides an indication of its elemental composition. However, the authors note that many of these apparently "promising" particles are subsequently found not to contain the elements of interest and instead may contain large amounts of silicon, calcium or iron. Problematically, trace amounts of an element (Sb, for example) can often be masked by the greater presence of another (Ca, for example). It is noted that particles are often hard to see and locating them is dependent on achieving a clear screen resolution and carrying out a careful, thorough and methodical examination. Clearly a learning process, as well as a development of expertise, is involved in successfully "spotting" GSR particles. While a GSR particle may be located very quickly if there are many present in the sample, full and reliable analysis of the entire sample is curtailed by the time taken for the manual search and the potential for error inherent in this process.

Despite the drawbacks described, Wolten et al (1979c, p.868) proclaimed analysis by SEM-EDX the most 'definitive' method in GSR detection. Citing its use in securing a number of convictions, the authors assert that detection by SEM-EDX is more effective than previous methods in discriminating between elemental contributions by GSR and environmental/occupational sources. Moreover, unlike bulk analysis methods, SEM-EDX can potentially be used to identify tiny traces of GSR. These would have previously gone undetected as they would not have satisfied the elemental threshold of many techniques. Thus, successful GSR detection several hours after a shooting was rendered possible by the advent of SEM-EDX. However, problems still existed. The slow, laborious task of manual particle analysis had somewhat prevented the potential of SEM-EDX being fully realised (Wallace 2008). Matricardi and Kilty (1977) recognised that manual analysis was an extremely time-consuming process, requiring great

operator experience and patience (notwithstanding the cost of the manpower involved). Matricardi and Kilty (1977) understandably considered the excessive operator time required to be the major shortcoming of the method, and also highlighted the potential for false-negatives. The process involves a trained eye searching the visualisation of the sample area for objects which look morphologically similar to GSR. These can be missed if, for example, the operator loses concentration and/or the particles are too small to see at a certain magnification, or are obscured by extraneous material (ibid., Tillman 1987). The quantity of GSR is likely to be underestimated and if the entire particle population is not scanned, incongruent particles which might indicate that particles came from an environmental source may be missed. Issues are further amplified when investigating multi-suspect cases and other incidents that may necessitate the analysis of several samples (Wallace 2008). The confirmation of GSR presence (yes/no) via this approach is achievable, although this may be more difficult if only one or two small particles exist in the entire sample. Achieving accurate particles counts, however, will prove elusive when manually searching for particles.

Romolo and Margot (2001) explain how efforts were subsequently made to increase the efficiency of sampling, to clean up and concentrate samples (Wallace and Keeley 1979), and to decrease area being sampled. Reducing background contamination by using a sampling surface that contains no elements that generate 'bright' noise under BSE imaging was advised (DeGaetano et al 1992). Despite these efforts, problems associated with the time taken to manually search a (noisy) sample area continued to represent an impasse. Statistical methods have been proposed that can be used to reduce the area which needs to be searched when analysing a sample. However, Owens (1990, p.699) warned that efforts to determine the 'necessary' search area in an attempt to overcome the 'prohibitive' timeframes required for manual analysis should be treated with caution. Owens (1990) explained that, particularly if only a very small number of GSR particles exist on a sample, the possibility of 'missing' particles, and therefore, of a false negative result, is very real when statistical methods are used to justify a reduced search area. In short, the question of when to "call off" a search for GSR is an inherently risky one.

In recognition of the problems associated with manual searching, Tillman (1987) as well as Matricardi and Kilty (1977), responded by calling for the development of automated search techniques that would reduce operator time and simultaneously, limit the potential for error:

> *'In our opinion, automation of the search process is one of the essential developments needed before this technique can be routinely used'*
> *(Matricardi and Kilty 1977, p.738)*

Efforts towards automation have thus followed and much progress has been made (Kee and Beck 1987, Germani 1991, White and Owens 1987). Tillman (1987) employed an automated particle search and characterisation program that enabled an unattached search for GSR particles. The investigation served as a feasibility study for the use of similar programs in GSR analysis. Tillman (1987) explains how 'X' and 'Y' locations are generated for each GSR particle by the program, and reports that measures of the diameter and chemical typing of each particle are recorded. To evaluate the reliability of the technique, manual analysis was used to verify the automated detection. No false-positives were highlighted as a result of this verification process, although it should be noted that this does not confirm that no particles were missed entirely by both the automated and manual search processes (false-negatives). Tillman (1987) concluded that the system could provide reliable data and accurate detection via chemical typing and was effective in the characterisation of particle shape and morphology, while dramatically reducing the time taken to examine a sample.

The use of SEM-EDX with automated particle search and recognition has since become more ubiquitous and has undergone significant development. As technology and processor capacities have evolved, rapid and reliable automated search and detection packages have been created. These are commercially available and are used in many forensic laboratories that carry out GSR particle analysis. Modern systems automate the SEM and detector, and combine processing techniques and rule-based classification of particles of interest (Krüsemann 2000). Many of the problems associated with scanning a large, highly populated sample area have thus been eased. Krüsemann (2000) observes that these packages enable reliable, fast, unattended analysis which can even take place overnight. The software also enables the analysis

of non-GSR particles to provide information regarding the wider particle context and further salient evidence regarding the commission of the crime and the activities of the suspect. According to Garcia and Martinez (2000), the advent of automated systems has enhanced the ability of the forensic scientist to search for and detect GSR. As a result of its less labour-intensive nature, automated analysis opens up the possibility to analyse multiple samples and samples taken from surfaces other than the hands, such as clothing and other surfaces at the crime scene (ibid.). Thus, the evidential utility of GSR is potentially increased and new interpretative possibilities are opened up. An automated analytical system of the type described is employed in the analysis of samples from the experimental phase of this thesis and its use will be described in chapter four[27].

When surveying automated methods a number of caveats must be stressed. For example, the assertion that analysis may take place unattended perhaps oversimplifies the intricate set-up and calibration processes involved. It also overlooks the in-run monitoring, manual post-sample processing and filtering that form part of the process. In short, the expertise and experience required to carry out an automated analysis is not insignificant and the potential for overlooking particles of interest still exists if there are errors in the set-up (see section 4.3 and the discussion in section 6.3.2). Furthermore, depending on the sample area and the size of the population of material on the sample, analysis can still take very long time. However, the level of accuracy and repeatability in determining particle counts is demonstrably increased. Automatic identification programs have been employed in many studies of GSR including, for example, those by Brozek-Mucha and Jankowicz (2001) in differentiating ammunition via the analysis of GSR and Brozek-Mucha (2007) in a comparison of airborne and spent-cartridge GSR.

Nakai et al (2009) explored the utility of a SEM-EDX system coupled with a transition edge sensor (TES) for the forensic analysis of paint and GSR. The high spatial resolution of the elemental mapping offered by this system renders it a powerful analytic tool for GSR analysis. Further contemporary applications of alternative methods for the detection and analysis of GSR have included the use of time-resolved

[27] A detailed account of the setting up, running and processing of an automated detection programme, INCAGSR, is provided in 4.3 with reference to the analysis process that was followed in the experimental phase of this thesis

fluorescence microscopy (TRFM), which is routinely implemented in monitoring the dynamics of intricate biological systems, by Bird et al (2007). The authors concluded that TRFM represents a non-destructive imaging method for individual GSR particles and one capable of identifying their origin in terms of the likely firearm/ammunition combination. However, as a result of the complexity of the particles and their formation conditions, an unequivocal determination of the source of fluorescence is problematic. Meanwhile, Schumacher et al (2010) recognise the problems associated with visualising the distribution of lead, copper or nitrocellulose in shooting range estimation when lead-free primers are involved. Milli-X-ray-fluorescence (m-XRF) was found to be useful in visualising GSR distributions and in the identification of bullet holes.

Bailey and Jeynes (2009) demonstrated the use of ion beam analysis (IBA) for the identification of trace elements within GSR. Meanwhile, Romolo et al (2013) assessed the use of IBA in the characterisation of GSR particles. The increased sensitivity of this method for detecting trace element contributions is cited as possessing great discriminative power in the characterisation of GSR from different sources. Finally, Christopher et al (2013) employed a scanning proton microbeam and particle induced X-ray emission (μ-PIXE) coupled with Elastic Backscattering Spectrometry (EBS) in the elemental analysis of individual GSR particles. This rapid, non-destructive method was used to group particles from different ammunition sources.

3.4 GSR: Evidential value, evidence dynamics, reconstruction and interpretation

The value of GSR evidence in reconstructing different aspects of firearms offences is outlined in the sections below. When GSR evidence is interpreted in casework, it may inform conclusions about one or more of a number of issues. Accordingly, a number of facets of GSR evidence may be drawn on in the formulation and assessment of different levels of interpretative proposition.

3.4.1 Identification of the shooter of a firearm

Of paramount importance in the context of this thesis is the possibility of using GSR recovered from a suspect to make an inference about their involvement in discharging a firearm. As will be described in 3.4.4a and 3.5, GSR is deposited in the vicinity of the shooter and along the projectile path when a firearm is discharged (Perdekamp et al 2010). This results in deposition not only on the shooter, but also on bystanders and surfaces that may later be handled by persons unconnected with the shooting. Airborne GSR may even be acquired simply by entering a room in which a gun was recently fired. These issues will be fully considered in discussions of transfer, deposition, secondary transfer and contamination but at this juncture it is important to emphasise that, owing to multiple methods of its transfer and deposition, the presence of GSR does not necessarily indicate that an individual fired a gun, or even handled one (see, for example, Matricardi and Kilty 1977 and Lindsay et al 2011a).

Notwithstanding this, the presence of GSR has been used successfully in many instances to make inferences regarding the identity of the shooter. Achieving this involves addressing activity level propositions and will necessitate the incorporation of information about environmental sources of GSR-like particles and a consideration of evidence dynamics, particularly the transfer and persistence properties of GSR. These will be discussed in section 3.4.4. The potential to discriminate between individuals who have acquired GSR via different mechanisms through the interpretation of GSR counts and other pieces of evidence will be discussed in section 6.4 and chapter seven.

The reconstructive value of GSR in identifying the shooter is also demonstrated by cases in which GSR evidence has been used to designate a fatal shooting as a suicide or homicide/suspicious death (Reed et al 1990). The processes of examination and interpretation in such cases involve comparing the presence/absence and distribution of GSR particles from the victim to expected quantities given that, on the one hand, they discharged the firearm themselves and on the other, that some other person fired it. Nelson et al (2000) document a case in which the absence of GSR on the hands of the victim was deemed inconsistent with suicide.

3.4.2 Identification of the ammunition and firearm combination

An important element of the reconstruction process is the potential to infer characteristics about the ammunition used from GSR evidence (Lebiedzik 2000, Schütz et al 2001, Murdock 1984, Brozek-Mucha and Zadora 2001, Yanez et al 2012). Methods and techniques that permit the discrimination of sources of GSR can be of great value in a forensic investigation (Bailey and Treverrow 2010). Brozek-Mucha and Zadora (2003) examined the chemical classes of GSR produced by four ammunition types and cluster analysis revealed that some ammunition types could be readily distinguished from one another based on the composition of the GSR produced, while others resisted discrimination. Brozek-Mucha and Jankowicz (2001), meanwhile, reported success in statistically differentiating GSR from six ammunition types with reference to the percentages of particles in different chemical classes. In addition, Rijnders et al (2010) were able to identify different compositional profiles and to make positive and negative associations regarding GSR from different ammunition types. Halim et al (2010) observed different sizes and shapes of GSR produced by the firing of different ammunition types. Furthermore, Brozek-Mucha et al (2003) explored the possibility of distinguishing the inorganic GSR produced by firing 9mm Luger ammunition produced by different manufacturers. Although some compositional differences were noted, most populations were found to be similar to one another, despite variations in their origins.

Christopher et al (2013) characterised populations of GSR particles using μ-PIXE and multivariate analysis. This dual method was deemed to be successful in grouping populations of particles according to ammunition type. Others, such as Heard (2008), have provided comprehensive reviews of the composition of GSR derived from primers and propellants with different geographical and manufacturing origins for reference purposes. DiMaio (1985) reports that GSR patterns in and around wounds can be expected to vary as a function of the composition of the ammunition propellant, thus making inferences about ammunition type possible.

Identification of the source of GSR in casework routinely involves the comparison of GSR recovered from, for instance, a suspect to GSR from a spent cartridge that may have been recovered from a scene. However, Brozek-Mucha (2007) reports that airborne GSR and that which can be recovered from a spent cartridge can differ elementally and morphologically. Rijnders et al (2010), meanwhile, warn that the

chemical compositions of GSR deposited around the firearm can differ from that which is recovered from the barrel. Thus, caution and also consistency in sampling is advised when attempting to infer information about the source of GSR. Andrasko and Maehly (1977) note that it can be very difficult to determine the type of ammunition due to the fact that the amounts of lead, barium and antimony can differ between particles from the same source. It is also true that different regions of the same particle may have differing elemental compositions (see section 3.2.3). However, as detailed in section 3.2.3, other compositional features such as taggants can assist in the identification of ammunition type, while GSR from lead-free ammunition can be readily identified. It is also important to note that when considering the source of the recovered evidence, it is necessary to consider the possibility that environmentally and occupationally produced GSR-like particles may represent the true source. A consideration of these sources was the focus of section 3.2.4.

Inferences about the firearm that was used may be made from the pattern and quantity of GSR deposition. Large differences have been noted between the GSR depositions resulting from firing handguns and long-arms (see for example, Ditrich (2012) and section 3.4.4a for a full exploration of this issue).

3.4.3 Estimation of shooting distance and direction

Much of the research that has been undertaken on the reconstruction of shooting incidents has centred on the use of GSR for providing an estimation of shooting distance and direction. In the literature, it is not unreasonable to suggest that there is something of a preoccupation with these estimations and that this arguably clouds the potential utility of GSR in other areas of firearm incident reconstruction. Shooting distance/range estimation rests on the ability of the forensic scientist to examine and interpret patterns and distributions of GSR on targets (Schumacher et al 2010). Brozek-Mucha (2002), for example, provides an account of the reconstruction of a shooting incident involving a policeman in which testimonies relating to the positions of the actors in relation to one another differed considerably. Through consideration of the distribution of GSR particles on the victim, along with other lines of evidence, this issue was resolved. Meanwhile, Brozek-Mucha and Jarosz (2001) report a similar case in which the testimony of a suspect was rendered invalid by analysis of a GSR

distribution and the resulting reconstruction of the relative positions of the parties involved.

The issue of firing distance (the distance from muzzle to target) is often of a critical issue in the reconstruction of shooting incidents. It can be estimated through interpretation of the distribution and quantity of deposited particles around the bullet impact site (De Forest et al 2008). Cecchetto et al (2011), in an experimental study involving the firing of guns at sections of human skin, found that as shooting distance increased, the quantity of GSR deposited on the surface of the target was reduced. Furthermore, the distribution of these particulates can be expected to change. At close range (under 23cm), GSR was found to be deposited on the dermis and epidermis around the entry wound as well as within the cavity itself, while at greater distances (above 23cm), GSR was recovered from the surface of the skin only. Nag and Sinha (1992) similarly report that at close range, GSR exhibits a radial distribution a few centimetres around the bullet hole with some particulates being transported, along with the bullet, into the wound. The ratio of GSR which has been delivered via these two transfer mechanisms is posed as a means of distinguishing between long and close range firings. However, Haag (2005) notes that care must be taken because quantity of GSR transferred to the target surface and its distribution at a shooting distance, 'X', will vary as a function of the particular propellant used. Plattner et al (2003) experimentally investigated the shape and pattern of GSR deposits from near-contact and contact shots at different angles and distances to explore the potential of using them as a means to infer shooting distance and direction. Brozek-Mucha (2009) also identified trends in GSR composition and particle size when shots were fired at targets over increasing distances. The relationships were, however, complex and difficult to interpret.

3.4.4 Evidence dynamics

Section 2.3 introduced the concept of evidence dynamics and the way that such dynamics are incorporated into the assessment of propositions about trace evidence. The section dealt with findings from a range of experimental studies concerned with a variety of different trace materials. This section revisits evidence dynamics, with regard to GSR.

3.4.4a GSR transfer and deposition

When considering the transfer of GSR it should be noted that, unlike many other trace evidence transfers, direct contact is not always involved. Rather, GSR emanating from the discharging weapon becomes airborne and is deposited rather than transferred. Hence it is appropriate to refer to the transfer and deposition of GSR. During a firearm discharge, GSR is deposited on the shooter (on the face, hands, clothing and hair) and also in the vicinity which may include objects, bystanders, the firearm itself, and the target. Consequently, it is agreed that GSR presence can result from a number of mechanisms including deposition on the shooter from a discharge, deposition on surfaces or subjects in the vicinity, or handling of a surface "contaminated" with GSR such as a firearm or spent cartridge (Singer et al 1996, Lindsay et al 2011a, Zeichner 2012, Andrasko and Maehly 1977, Romolo and Margot 2001, Wolten et al 1979c). For Lindsay et al (2011a), multiple mechanisms of transfer and deposition serve to complicate the interpretation of GSR presence. Factors affecting rates of deposition and transfer are discussed below, while secondary transfer issues are addressed in section 3.5.

The amount of GSR which is produced and deposited during the firing of a gun has been shown to be poorly reproduced from firing to firing, even when using the same firearm and ammunition, and under the same conditions (Matricardi and Kilty 1977, Jalanti et al 1999, Schütz et al 2001, Lindsay et al 2011a, Brozek-Mucha 2011). This is attributable to the dynamic and complex process of GSR formation (Brozek-Mucha 2011). Predicting expected quantities of GSR can, therefore, be challenging when attempting to assess activity level propositions concerning GSR presence. While the results of Lindsay et al (2011a) were insufficient to assess whether the ammunition type, calibre, or features of the firearm were responsible for some of the variation in the GSR produced, other studies have offered some indication of the effects of some of these variables. Rates and patterns of GSR deposition will vary according to the firearm used (Murdock 1984). For instance Krishnan (1982) compared short-barrelled handguns to long arms and concluded that when the former are fired, the hands of the shooter are closer to the muzzle and therefore, are closer to the cloud of GSR that emanates from the muzzle blast. The result is an increased contribution of muzzle-blast GSR to the population of particles on the hands of the shooter when handguns

are discharged. Ditrich (2012) employed high-speed video to examine the GSR plumes produced by different firearms. A high degree of variance between weapons was reported, with revolvers depositing much material near the shooter in contrast to relatively sealed shotguns. Basu et al (1997) found that firing a cleaned shotgun will result in little GSR deposition on the hands of the shooter. While concurring with the conclusion that long and short arms will generate different patterns and levels of GSR, Basu et al (1997) also noted that the nature of the breeches can also be influential. Revolvers, for example, with open breeches and multiple avenues for escape will encourage deposition of GSR on the shooter.

Wolten et al (1977) argued that the GSR deposited on hands will chiefly emanate from the breeches, but a contribution will be made from the muzzle-blast. Basu et al (1997, p.580) also highlighted these two mechanisms of deposition and argue that GSR from the breeches undergoes a 'backward thrust' and is directly deposited on the hands (including the support hand) and other surfaces, including the firearm itself. The Basu et al (1997) study provides a detailed survey of the mechanisms of GSR deposition. In the study, the authors also attest that the rate of deposition is not influenced by the substrate onto which GSR is deposited and that the population of GSR recoverable from the back of the firing hand will be fairly constant if the gun is cleaned between test firings. The latter view has not generally been expressed elsewhere. Brozek-Mucha (2011) argues that the adhesive properties of the hands of different shooters will influence the effectiveness of sampling and that this contributes to the variation between the particle counts which are recovered following different firings. Meanwhile, Brozek-Mucha (2011) attributes some of the between-firing variation to the deposition of certain types of particles. Large, fragmented structures and clusters of smaller particles, when deposited, serve to inflate the particle count.

While GSR is deposited on the shooter, some may become airborne and be deposited on bystanders, or may even remain suspended in air, for later deposition. Renfro and Jester (1973) employed neutron activation analysis (NAA) to analyse GSR remaining in the air following the firing of a single shot. Remarkably, airborne GSR was detected over 72 hours after the discharge. The amount of GSR remaining suspended in air was found to be a function of time and to be of potential utility in estimating the time of firing, although variation from shot to shot is likely to render accurate temporal

reconstruction difficult. Levels of GSR in the air were found to decrease rapidly in the first 48 hours, after which the rate of loss was found to slow (akin to the two-stage mechanism of decay discussed in 2.3.2). The authors explain that sub-micron particles remained suspended for the longest periods of time. Matricardi and Kilty (1977) recovered many spherical GSR particles by suspending tape in the air one minute after a gun had been fired in a clean room. Fojtášek and Kmječ (2005) reported that while determining a time curve for GSR sedimentation from the air following a shooting is difficult, it can be demonstrated that GSR remain in the air and are subsequently deposited for several minutes after discharge. The time periods for deposition were shown to vary according to the firearm used, with the firing of a pistol resulting in fallout for eight minutes, while GSR continued to be deposited for ten minutes when a revolver was fired. This effect, the authors argue, will not only contribute to the GSR which is recoverable from the shooter if he/she remains present after the shooting, but can also pose a risk of contamination to other individuals who enter the environment. These issues will be fully addressed in section 3.5.

The distribution of GSR around the site of discharge is potentially useful for reconstruction purposes and has been studied experimentally. Fojtášek et al (2003) experimentally investigated the distribution of GSR at a number of points around the firing of a 9mm pistol. The highest concentrations of GSR particles were not found directly in front of the firearm, but instead were recovered between two and four metres to the front-right of the discharge. The authors also recovered GSR ten metres from the firearm and argue that climatic variances in external environments will influence the distribution of GSR deposited around the shooter. Brozek-Mucha (2009) examined the distribution of GSR emanating from the firing of a 9mm Luger pistol. The spatial scope of this investigation was smaller than that of the Fojtášek et al study and a single shot was fired at targets 10cm, 20cm, 30cm, 70cm and 100cm from the muzzle. In each repeat, the greater the distance from muzzle to target, the fewer GSR particles were deposited on the target. In separate experiments, samples were taken from the right and left hands of the shooter as well as from their sleeves, the front and back of their upper garments, and the target. In each experiment, most GSR was recovered from the target, followed by the hands. The sleeves, front of the upper garment and back of the upper garment (30cm, 70cm and 90 cm from the discharge

respectively) yielded smaller quantities of GSR. Generally, the trend that was observed was one of decreased deposition with distance from the discharge, save for the target. In addition to influencing the quantities of deposited GSR, the distance from the shooting and the direction of a surface in relation to it tended to affect the chemical classes and sizes of recovered particles. This is attributable to the processes of formation and dispersion. The relationship between the distance from the shooting and the sizes of recovered particles was shown to be a complex one. While the average size of particle recovered from the hands was 1.80µm, multiple mechanisms of deposition were identified. Large GSR particles (akin to those recoverable from a spent cartridge) are formed in the rear of the gun and these were shown to have been emitted from the ejection ports at the back of the gun and to have settled on the shooter.

Gerard et al (2011b), meanwhile, examined the distance that GSR can travel horizontally during discharge and the distance over which it is deposited along the firing range. The largest deposition was recovered 13.5 metres along the bullet path and some particles were found 18 metres down-range of the discharge. GSR particles are associated with the bullet and with the broader cloud of gases. Owing to the multiple means of deposition, the authors conclude that it may be difficult to distinguish a shooter from someone along the projectile path using GSR counts alone. It is important to note when interpreting the results of this study that it was carried out in a room with no ventilation, meaning that the dispersion of GSR will have been limited compared to an outdoor setting.

Given that GSR remains airborne after discharge, that it is deposited around the scene of discharge, and is deposited along the bullet path, it follows that there exists a possibility that a bystander in the vicinity of a discharge may acquire GSR by passive exposure. Accordingly, this has been studied experimentally. Lindsay et al (2011a) report that in 17 of 30 test firings, at least one GSR particle was recovered from a bystander in close proximity to the firing. Between zero and 27 GSR particles were recovered from these bystanders and the quantity was found to be independent of whether the subject was standing to the left, right or rear of the shooter. In some cases, the authors recovered similar quantities from shooters and bystanders,

rendering these mechanisms of deposition indistinguishable on the basis of GSR counts alone.

Rather than being ejected via the muzzle or breeches, Rijnders et al (2010) note that some GSR is deposited on the inside of the firearm during discharge. These deposits may be loosened during subsequent firings and ejected amongst the GSR pertaining to the second firing. This two-stage mechanism of deposition describes the "memory effect" (detailed in section 3.4.4b), which is outlined by Basu et al (1997) who observed the deposition of old residues from the breeches of a gun when it was not cleaned between firings.

3.4.4b GSR persistence

As with other forms of trace evidence, the accurate interpretation of GSR will necessitate an understanding of its persistence under different circumstances. Issues of persistence and decay are especially salient in instances where a suspect has not been apprehended immediately after the incident took place (Jalanti et al 1999, Krishnan 1977, Meng and Caddy 1997). Jalanti et al (1999) consider the literature on the persistence of GSR on the hands of a shooter and observe that, owing to different experimental conditions, previous studies vary in terms of the timeframes of GSR longevity. The authors summarise that GSR has been detected one (Nesbitt et al 1977), two (Kilty 1975), three (Andrasko and Maehly 1977), four (Heard 2008), five (Knechtle and Gallusser 1996), 12 (DiMaio 1985, Murdock 1984, Wolten et al 1979a), 13 (Wolten et al 1979c), 17 (Krishnan 1974), 24 (Krishnan 1977, Zeichner and Levin 1993) and 48 hours (Harrison and Gilroy 1959) after deposition, with long timeframes being reported in casework (ibid., Zeichner and Levin 1995). Furthermore, Rosenberg and Dockery (2008), attempt to establish a timeframe for forensically relevant sampling following six shots from a revolver. Using laser-induced breakdown spectroscopy (LIBS), the authors observed positive test results for GSR on hands some 126 hours (5.25 days) after shooting. Meanwhile, Lindsay et al (2011b) recovered 121 particles from a firearms technician who had discharged a gun the previous day. In the persistence experiments carried out by Jalanti et al (1999), a large decrease was reported in the number of recovered GSR particles from the hands of a shooter as a function of time following a firearm discharge. The authors report that much of this

particulate loss occurred in the first two to four hours after discharge and that importantly, the chemical composition of the particles did not affect their persistence.

When examining the factors influencing the persistence of GSR on hands, Schütz et al (2001) observed a two-stage mechanism of decay with the greatest losses occurring the first two hours after discharge (see also Murdock 1984 and Nesbitt et al 1977). Interestingly, particles were not retained preferentially according to factors such as size, shape, or chemical composition. Andrasko and Maehly (1977) detected GSR on the hands of a shooter after three hours of normal activity following a firearm discharge, but none was detected after five hours. Crucially, the authors report that larger GSR particles (>10µm) were absent after the first hour and that the recoverable GSR after two hours consisted of small particles (<3µm). Lindsay et al (2011a) examined the persistence of GSR on bystanders. Referring to the decay of GSR from a shooter's hands, the authors report a comparable pattern of loss for those who have experienced passive exposure to GSR, with most bystanders testing negative for GSR presence after two hours. The bystanders to whom GSR had persisted after this period had no more than four particles on their hands. Thus, the trend of initial rapid loss was replicated.

The decay of GSR from a surface has been shown to be extremely variable. Indeed, even when experimental conditions are not altered, the rate of loss has exhibited irreproducibility from firing to firing (Jalanti et al 1999, Rosenberg and Dockery 2008). This is owing to the high degree of variability and dynamism in the processes of GSR formation and deposition which has been outlined previously. Meanwhile, divergences between the results of different studies can be attributed to variations in experimental design, the firearm/ammunition used, the number of shots fired, and the sampling method employed. Furthermore, different studies have employed various detection and analysis methods that exhibit varying degrees of sensitivity and diverging capacities to detect precise quantities of particles (ibid.). That studies have taken place at various points across several decades as analytical techniques were being developed, has only served to exacerbate the differences between firings. Notwithstanding this, a number of factors have been demonstrated to govern the persistence and decay of GSR.

Brozek-Mucha (2011) undertook a comprehensive study of GSR persistence on the shooter, using SEM-EDX and an automated search system in a very similar manner to that which will be described in the context of this thesis. Samples were collected at intervals from the face, hands and clothing of the shooter and as expected, rapid initial loss was reported. The half-lives of particle numbers varied according to sample site, with half of the deposited particles decaying in less than one hour from the hands, in over one hour for clothing, while half-lives of between two and three hours were observed for the face. Particles persisting for four hours tended to be small and have irregular shapes. In these cases, particles measuring <1µm were found to prevail and any remaining large (10-20µm) particles exhibited irregular and complex shapes, in contrast to those which were prevalent after the shooting. Smooth round particles which were larger than one micrometre decayed rapidly, compared to those with a complex shape, while smooth, sub-micrometre particles exhibited greater persistence within hair, fibres and skin folds. The chemical content of particles was found to have no bearing on their longevity. It was concluded that sampling from the face and clothing of a shooter can be productive in yielding GSR in situations when a suspect is apprehended several hours after a shooting. Rates of particle loss were apparently influenced by the nature of the surface, with contrasts noted between smooth skin on the hands, hair-covered skin (on the face or head) and fibrous clothing. Zeichner and Levin (1993) also observed GSR longevity in hair, with particles being successfully recovered from unwashed hair 24 hours after deposition. Meanwhile, Schwartz and Zona (1995) found that GSR can persist in the nasal mucus of a shooter. Finally, Charles et al (2013) found that the fabric type affects the collection efficiency of GSR, owing to the propensity of various materials to shed GSR and to 'clog' the sample stub with fibres. In the study, leather was found to donate significantly more GSR during sampling than the surface that was made of wool.

As for other types of trace material, the persistence of GSR is affected by the nature and extent of post-transfer activity and movement. Wolten et al (1979c) reported that in cases in which the presence of GSR has been used in the verification of a verdict of death by suicide, large quantities of GSR are often recoverable from a body that has lain undisturbed. In one case, sampling yielded GSR 120 hours after deposition. The authors concluded that handling, or transport, of the body will encourage the decay of

GSR, while for live subjects, wiping and moving the hands may have a similar effect. Furthermore, the distribution of GSR that has been transferred to hands may be altered over time, owing to reincorporation during the decay of material, and owing to transfer mechanisms that are initiated as parts of the hand come into contact with one another (Heard 2008). Andrasko and Maehly (1977) found that rinsing and wiping the hands after firearm discharge did not result in the removal of all GSR, although the amount of recoverable material was found to be much smaller and no particles larger than 3µm persisted during the washing process. Thorough hand washing was much more effective in the removal of GSR (see also Nesbitt et al 1976) yet, two particles measuring 1-2µm were recovered from the hands after they were washed. In one case, Andrasko and Maehly (1977) report that two hand washes were not sufficient to effect the removal of at least one extremely persistent GSR particle. Finally, Wolten and Nesbitt (1980) point out that thorough cleaning of a firearm, using brushes and solvents, is not always successful in removing all GSR.

Vinokurov et al (2001) examined the effects of both machine washing and target brushing on the amount of residue that can be recovered from the surrounds of a bullet entrance hole and thus, on the potential to successfully estimate shooting distance. The authors establish experimentally that machine washing at 40°C considerably reduces the quantity of GSR around a bullet entrance hole, although sufficient amounts remain to permit range estimation when the shooting distance is very small. Brushing tended to have the same effect, but was found to be less efficient in the removal of GSR. These mechanical interventions more effectively removed GSR when the shooting distance was greater. The authors attribute this observation to the strength of the bonds between the particles and the target which will be strongest when the shooting distance is smaller and the deposits possess greater kinetic energy as they interact with the target.

The so called “memory effect”, that is effected by the persistence of GSR within the firearm itself, has also been experimentally studied (López-López 2013). Charles et al (2011) explain that the “memory effect” can be observed when GSR is deposited that is elementally incongruent with the primer that was fired. Instead, these residues are in part contributed to by primers that have previously been associated with that firearm. Zeichner et al (1991), Harris (1995) and Lebiedzik and Johnson (2002) have

also observed this phenomenon. Charles et al (2011) experimentally explored the "memory effect" and were able to demonstrate how, in an extreme case, 44% of recovered particles could be attributed to it. They add, however, that it is often hard to attribute particles to this effect as many heavy metallic elements do occur in trace quantities within different primers, thus masking the effect. It is assumed that the type of weapon fired will, in part, govern the strength of the "memory effect", with barrel length and gaps between cylinder and barrel cited as being influential. In the experiments that were carried out by Charles et al (2011), relatively low contributions by the "memory effect" are reported for .38 calibre ammunition, while a strong effect was observed when .22 calibre ammunition was fired. The authors concluded that the combination of weapon and ammunition is likely to be influential and stressed the importance of acknowledging the influence of the "memory effect" during analysis and interpretation. That cleaning a firearm does not always remove all GSR will exacerbate this issue in the interpretation of casework samples and in the design of research experiments. Theoretically, the "memory effect" could represent an important investigative and reconstructive tool.

While not of direct relevance in the context of the current investigation into the inorganic fractions of GSR, but nevertheless important for a comprehensive understating, the persistence of the organic components of GSR (OGSR) has been studied. Arndt et al (2012) target diphenylamine (DPA) using ion mobility spectrometry (IMS) to establish the longevity of this component of OGSR following a shooting. The timeframe for persistence was determined to be four hours but a half-life estimate was not possible due to the variability between tests. Notably, hand washing with soap and water was effective in removing the targeted organic components.

3.5 GSR multiple transfer and contamination

A number of studies have focused on multiple transfer and contamination issues with respect to GSR. This body of work is valuable in the formulation and assessment of propositions during the interpretation process, and ultimately, in the reconstruction of firearms incidents. Meanwhile, as well as having interpretative value, this work also guides and informs forensic protocol, particularly concerning the handling, collection

and processing of samples. It has been shown that the capacity exists to successfully recover and detect, for example, a single sub-micrometre GSR particle that has persisted for several hours. However, as the timeframe in which GSR can be recovered has extended, so too has the possibility that we might detect GSR from a previous firearm discharge or from another source, or transfer mechanism. This is one of the quandaries posed by persistence and by the improved capacity for analysis and detection.

Lindsay et al (2011b) sampled members of staff at firearms factories who did not fire guns themselves. The sample taken from a shipper charged with handling recently test-fired firearms yielded 424 GSR particles, while nine particles were recovered from a tour guide who had handled two firearms several hours previously. Meanwhile, a receptionist, an accountant and an engineer (none of whom handled firearms or their components) yielded between zero and two GSR particles. Large secondary transfers can result when discharged firearms are handled, yet high levels of GSR are not necessarily acquired by being in a GSR-rich environment – small traces are more likely to be transferred, and subsequently recovered. Mann and Espinoza (1993), meanwhile, investigated the incidence of GSR on recreational hunters in Oregon and Washington. A total of 30 hunters were sampled, of which half regularly fired guns and of whom 80% were wearing the same clothing or were sat in the vehicle that they were when they last handled a gun. The environmental incidence resulting from the persistence of GSR from a legitimate source was found to be low - only one Pb-Sb-Ba particle was recovered across all samples. It is noted that because long arm weapons were being considered in this study, initial populations of unique GSR particles deposited on surfaces would have been relatively low. So, while activities and behaviour can increase the risk of innocent GSR presence, the incidence of particles in this case was found to be limited. Mann and Espinoza (1993) concluded that the risk of secondary GSR transfer that results from the handling of cleaned long-arms is also low.

The issue of contamination was discussed at the FBI Laboratory Gunshot Residue Symposium (Wright and Trimpe 2006). A background survey of 102 people with different occupations yielded only a single GSR particle and this was recovered from an individual who had cleaned a hunting rifle 12 hours prior to being sampled (Martinez

cited in Wright and Trimpe 2006). Garcia, cited in Wright and Trimpe (2006), found that groups including military personnel will be exposed to greater levels of GSR as a result of background contamination. Acknowledging the previous activity and occupation of an individual is, therefore, important when assessing the likelihood of contamination. The creation of a threshold of GSR particles (for example, two or three particles) for a positive GSR identification is one method of overcoming the risk of contamination in interpretation, but in certain contexts these particles may have probative value and should not be overlooked. Kotrly and Turková (2010) monitored potential sources of environmental GSR contamination in the city of Prague. No GSR particles were found on samples taken from public transport systems, civilian vehicles and public areas such as supermarkets and banks. However, some particles were found at the city Institute of Criminalistics, while the number of particles recovered from police vehicles and in some cases, from policemen (depending on their position), was high. It has also been experimentally demonstrated that merely entering a room in which a gun has been fired (within a certain timeframe) may pose a high risk of contamination from airborne GSR (Matricardi and Kilty 1977 and Fojtášek and Kmječ 2005). Gerard et al (2012) surveyed police officers; their equipment; their vehicles, and police workers and as a result, found several potential sources of secondary transfer and contamination. One or more GSR particles were yielded from 60% of officers sampled and from 24% of police equipment tested. Two of the 18 police vehicles that were sampled yielded a single GSR particle, while 25% of the forensic identification officers had at least a single GSR particle recoverable from their person. All civilians who worked in the police environment tested negative for GSR presence.

Berk et al (2007) note that following a firearm discharge, a plethora of opportunities exist for contamination as a result of secondary transfer mechanisms. Suspect detention facilities and the vehicles used to transport suspects were tested for GSR, to determine the extent to which these surfaces could represent sources of secondary GSR transfer. When particles were recovered, they were detected in relatively small numbers – the highest being the seven particles yielded from an interview room restraining bar and from an office table surface. The incidence of GSR particles was low with respect to police vehicles. The authors argue that while the possibility of a secondary transfer exists, the probability of such transfers occurring in casework

scenarios is relatively low. Wright and Trimpe (2006) cite a number of similar surveys including one in which at least one Pb-Sb-Ba particle was detected in samples taken from 14 of 26 police vehicles. A further study is cited in which 45 of 50 samples taken from the creases in police vehicle seats yielded two-element GSR particles, while Pb-Sb-Ba particles were detected in four cases. In a final study, samples were taken from the backseats of 20 police vehicles and while none revealed any Pb-Sb-Ba particles, two yielded a single Pb-Sb particle. When reviewing studies concerned with background contamination or contamination by law enforcement, it is important to appreciate the nature of the experimental setting. For example, the background rates of GSR particles in police facilities in general are likely to be higher in the U.S. compared to the U.K., where the risk of exposure to GSR might be assumed to be limited to Tactical Firearms Units and their officers, as opposed to affecting police facilities more generally.

Charles and Geusens (2012) acknowledge that the risk of contamination via secondary transfer of GSR to suspects is potentially serious, given that the probative value of a few particles can often be high. However, it was also pointed out that previous studies have indicated that the extent of such risks is negligible. The authors simulated arrest scenarios involving suspects and police special force units who are routinely exposed to high levels of GSR. It is reported that levels of observed secondary transfer were non-negligible in both low and high contamination scenarios. Contaminated vests, and particularly gloves, were found to effect high rates of transfer. Measures are recommended that are aimed at identifying and minimising opportunities for contamination. Wright and Trimpe (2006) describe a study in which an individual, known to have GSR on their hands, was handcuffed and placed in a vehicle. Ten minutes later, a GSR-free individual sat in the seat and subsequently, it was found that 22 GSR particles had been transferred to the second individual via the seat. In another simulation, GSR-free individuals were handcuffed by officers and placed in a patrol car; 24 of 41 of these previously ‘clean’ subjects subsequently tested positive for GSR presence after the experiment. While contamination and secondary transfer from law enforcement environments are possible, insufficient data exist to predict exact rates of expected transfer (ibid).

Cetó et al (2012) indicate that GSR can be acquired by handling a firearm and that the quantities transferred in this way can be analytically distinguished from those deposited during shooting. Basu et al (1997) concur and demonstrate experimentally that contact between a non-firing hand and the cylinder, trigger, rear and barrel of a fired revolver can initiate a secondary transfer. They report secondary transfers of 36, 40 and 42 particles when the revolver was held and contact was made with the trigger. More than 500 particles were secondarily transferred to the palm of the subject when the barrel and cylinder were grasped tightly and 268 were transferred when the cylinder and barrel were brushed. Notably, these latter transfers resulted in greater numbers of GSR particles on the handler than on the shooter who discharged the firearm. Nelson et al (2000) hypothesise that the distribution of GSR encountered during a particular forensic reconstruction may have been the result of GSR secondary transfer via a pillow, although this was not experimentally established.

Gialamas et al (1995) explored the possibility of GSR transfer from officers to suspects. Considering the fact that a firearm was carried by all officers who were tested, the incidence of GSR particles was markedly low. 18 of 43 officers yielded at least one unique GSR particle, while no GSR particles were recovered from the 25 remaining subjects. Again, while existent, the risk of contamination and the potential for secondary transfers from officers to suspects was concluded to be low. It is important to note, however, that this study is concerned with contamination via secondary transfer during arrest or suspect processing, rather than attending to the secondary transfers that could conceivably occur in the period between the firearm discharge and suspect apprehension. It is during this period that contacts may be made between a shooter and another individual, or between a non-shooter and a recently discharged firearm. At present, there is a need for detailed and extensive consideration of the transfer mechanisms that may alter the distribution of GSR following an initial transfer. Moreover, the ramifications of these secondary transfer mechanisms for the collection, analysis, interpretation and presentation of GSR evidence remain largely under-researched. How the forensic scientist might go about interpreting such samples and determining their probative value, therefore, remains an avenue for exploration.

The risk of secondarily transferring GSR during arrest and suspect processing should be minimised in order to safeguard against the contamination of the hands of a suspect. Wright and Trimpe (2006) cite several discussions and studies on this subject which featured at the FBI Laboratory Gunshot Residue Symposium. It was agreed that preferably, sampling should take place prior to bagging the hands of a suspect, as the bagging process can initiate a secondary transfer from hand to bag and result in a loss of GSR (Wolten 1979c). If sampling cannot be carried out at the scene, bagging is advised before transporting the suspect in a vehicle. Moreover, firearms equipment and exhibits should always be kept remote from sampling kits and sampling areas (Wright and Trimpe 2006). The incorporation of detectable chemical taggants into ammunition which is used by law enforcement is recommended so that GSR originating from contamination mechanisms can be readily identified (ibid., Niewoehner et al 2005, Zeichner 2012).

An awareness of the possibility of contamination and secondary transfer mechanisms should inform practices in the GSR analysis workplace and influence protocol in the laboratory. This matter is also explored by Wright and Trimpe (2006) who cite the need to monitor the laboratory working environment for GSR presence. Martinez (cited in Wright and Trimpe 2006) identified the need to establish zones in the laboratory which are likely to represent sources of contamination and accordingly, outlined a policy whereby no examiner who had entered a firearm zone on a given day could enter the GSR instrument space. Similar measures will also need to be replicated in experimental research if reliable, valid results are to be generated (see chapter four).

Previous reviews of the secondary (and further) transfer of trace physical material (French et al 2012, for example) have demonstrated that the extent of multiple transfer mechanisms and their potential investigative implications are not inconsiderable (see also section 2.3.3). Indeed, the aforementioned study posits that findings related to the transfer of trace particulate materials may be applicable to further forms of trace material, including GSR. The studies of GSR contamination and transfer outlined in this section clearly demonstrate the potential salience of secondary transfer in the formulation and assessment of interpretative propositions regarding the transfer of GSR. Thus, these issues warrant in-depth study. In a piece

that outlines some of the concerns associated with forming conclusions based on trace samples of GSR, Mejia (2005) suggests that transfer mechanisms cast doubt on the reliability of GSR evidence generally. Mejia (2005) suggests that because an individual who had never fired a gun could acquire GSR through contamination, and that other environmental particles exist which can be mistaken for GSR, doubt can be cast on the reliability of reconstructions based on GSR. While perhaps an extreme outlook, it is certainly the case that further research into the extent and rates of these transfer mechanisms is necessary. The possible implications of these mechanisms for the process of interpreting GSR evidence are relatively uncharted and this is concerning given some of the interpretative issues that could conceivably be posed by the multiple transfer of GSR:

- GSR could, in theory, be transferred from a shooter/firearm, thus incriminating an unconnected individual, potentially leading to a wrongful conviction or an offender remaining at large
- GSR could be 'lost' from the original site of deposition

Clearly, the consequences of a failure to acknowledge the effects of multiple transfer could lead to misinterpretation and have severe ramifications in the pursuit of safe justice. Very little attention has been afforded to understanding the nature and extent of these transfers and even less consideration has been given to assessing the probative value transferred GSR evidence. Moreover, developing an empirical basis to inform the interpretation of such evidence, and exploring the way this may be used to distinguish between mechanisms of transfer, represent avenues for further research. Goray et al (2010) concur with this call for further investigation. The authors highlight a lack of work that identifies the plausible modes or scenarios in which secondary transfers may occur, concluding that further research will enhance our ability to assess the likelihood that secondary transfers have taken place and to make inferences about the nature of the activity that resulted in the deposition of GSR.

3.6 Summary

This review has demonstrated the evidential value of GSR to the reconstruction of firearms-related offences. The morphological and compositional features of GSR

particles have been described, along with an account of the formation process to which these features are attributable. The development of analytical methods for the detection of GSR has been surveyed, with a particular focus on the evolution of detection using SEM-EDX assisted by an automated search capability.

Significant bodies of research exist in the field of GSR with regard to analysis and detection techniques, the environmental and occupational sources of GSR-like particles, and the reconstruction of shooting angles and distances. It has been demonstrated that formulating and addressing interpretative propositions (according to the process set out in section 2.2.2) may necessarily involve considerations of alternative sources of GSR-like particles and an acknowledgement of the dynamics of GSR, as well as the various possible mechanisms of GSR transfer and deposition. While issues of contamination, particularly those which involve law enforcement, have been well studied, significantly less attention has been afforded to the formal assessment of secondary (and further) transfer mechanisms involving GSR and the interpretation of GSR presence resulting from different transfer and deposition mechanisms. In general, evidence dynamics and their impact on the interpretation of GSR evidence remain avenues for further research.

For Lindsay et al (2011a, p.90) '…the interpretation of the presence of GSR particles is complicated by the fact that there are several possible mechanisms of deposition.' These include deposition on the hands of the shooter during discharge, deposition on a bystander during or after discharge, and secondary transfer via contact with a surface contaminated with GSR. Further experimental work aimed at understanding these mechanisms is required if these possibilities are to be effectively incorporated into the formulation and addressing of interpretative propositions regarding the mechanism of GSR deposition in casework.

In their review of the identification of GSR, Romolo and Margot (2001) also acknowledge these multiple means of deposition and argue that calculation of the likelihood ratio of GSR evidence under competing hypotheses can assist in making inferences regarding suspect activity. For this to be possible, activity and offence level (level II and III) propositions regarding the origin of GSR must be formulated and addressed. Assessing the weight of GSR evidence under prosecution and defence propositions at this level will consider the probability of evidence transfer and

persistence, and the likelihood of GSR presence or absence under these conditions. The incorporation data from experimental work that examines these mechanisms will be crucial. For Romolo and Margot (2001), a Bayesian approach for dealing with transfer evidence under competing hypotheses should represent the basis for interpretation. They conclude by recommending research into models and data, akin to those which have been explored for other types of trace evidence, to develop a Bayesian approach to interpreting GSR.

In order to address these issues, an experimental investigation into mechanisms of GSR deposition was carried out. Subsequently, two phases of discussion and interpretation are embarked upon, the first of which will consider the implications of the experimental findings for our understanding of GSR dynamics and the ramifications for a forensic investigation, particularly when interpreting GSR evidence. Secondly, these findings are employed in exploring and developing an approach to the interpretation of GSR transfers using Bayesian Networks. In experimentally addressing GSR transfer and considering the process of making inferences under competing hypotheses, this piece of research aims to contribute to our understanding GSR deposition mechanisms by producing repeatable experimental data. It also seeks to explore a model of interpretation and reasoning that is rooted in a Bayesian approach and that is applicable to casework scenarios that involve GSR.

3.7 Research questions

In light of the preceding review and summary, a set of research questions and have been generated. It is these which the experimental and interpretative phases of this thesis will seek to address, explore and resolve. Each major research question comprises a number of subsidiary and associated research questions.

RESEARCH QUESTION ONE: Can GSR particles undergo secondary transfer from the hands of a shooter to those of an individual who was not present at the scene of a firearm discharge?

While much attention has been afforded to the use of GSR in shooting angle/distance estimation, firearm/bullet identification and in the reconstruction of bullet entry/exit, the investigation of GSR transfer has been limited to a small number of studies. These

studies have been primarily focused on transfer to hands during shooting, or have attended to issues of contamination. Secondary transfer has been given very little explicit consideration. The hands of subjects were targeted in order to explore the potential for secondary transfer. This decision was made as it has been demonstrated that greater quantities of GSR are deposited on the hands of the shooter compared to other sampling sites (Brozek-Mucha 2009). Meanwhile, samples are most frequently taken from the hands during the sampling of suspects in casework scenarios.

This question will be answered experimentally through the replication of a real-world scenario involving a participant firing a live firearm and engaging in subsequent contact with an individual[28]. Samples taken from the hands of individuals will then be analysed for the presence of GSR.

Several related subsidiary research questions will be addressed when exploring Research question one, which include:

- If secondary transfer does occur, what quantities of particles involved?
- If secondary transfer does occur, what sizes of particle are involved?
- What are the implications of any findings for the collection, analysis, interpretation and presentation of GSR in an investigative context?

Particle size has been selected as the variable of interest as opposed to the elemental content of particles, owing to the findings of previous experimental work which were presented in section 3.4.4. For example, Brozek-Mucha (2011) and Jalanti et al (1999) have found that the persistence of GSR particles is not affected by their chemical content. By contrast, the deposition, transfer and persistence of particles has been found to be affected by their size (see, for example, Andrasko and Maehly 1977).

RESEARCH QUESTION TWO: Can particles of GSR undergo multiple transfers (i.e. tertiary) from the hands of a shooter to another surface and then be transferred to subsequent surfaces which were not present at the scene of a firearm discharge?

Gaudette and Tessarolo (1987) and French et al (2012) demonstrate the possibility of multiple transfers which may result in the formation of transfer chains and networks. The latter study considers the implications of such mechanisms for real-world forensic

[28] Section 4.1 provides a detailed account of the reasons for employing an experimental approach

investigations and given the findings, recommends further in-depth study of multiple transfers with regard to different types of trace evidence. Very little work on this subject has been undertaken with respect to GSR and this represents a further gap in understanding that this study aims to resolve.

Again, this research question will be explored via the analysis of results derived from transfer experiments simulating scenarios involving successive contacts between surfaces. The subsidiary research questions that will be addressed here include:

- If multiple transfers do occur, what are the quantities of material involved?
- If multiple transfers do occur, what sizes of GSR particle are involved?
- Are any discernible trends or patterns identifiable in any transfer chains that are formed?
- What are the implications of any findings for the collection, analysis, interpretation and presentation of GSR in an investigative context?

RESEARCH QUESTIONS THREE AND FOUR: Can GSR particles undergo secondary transfer from a discharged firearm to the hands of an individual who was not present at the scene of a firearm discharge but who handled the firearm afterwards?

Can GSR particles be deposited on a bystander who was in the vicinity of a firearm discharge?

In both cases the following questions will also be addressed:

- What quantities of particles involved?
- What sizes of particle are involved?
- What are the implications of any findings for the collection, analysis, interpretation and presentation of GSR in an investigative context?

Again, these research questions will be answered through experimentation and the interpretation of results from sample analysis.

To some extent, previous empirical studies have provided a positive answer to both research questions two and three. However, these questions have not been addressed using the same experimental conditions, methods and procedures as those employed

when answering research question one. Moreover, these previous contributions are not sufficient to address the answer to the following research question:

RESEARCH QUESTION FIVE: On the basis of samples of GSR taken from individuals, can shooters, secondary transfer recipients and bystanders be distinguished?

And accordingly:

- Are GSR counts of interpretative value in this process?
- Are the sizes of recovered GSR particle of interpretative value in this process?
- Does the possibility of misinterpretation exist?

In accordance with recent work in forensic science, the utility of Bayesian Networks as an interpretative tool will be explored and demonstrated when answering this question. The use of GSR evidence to make inferences about the likely mechanism of GSR acquisition by an individual will be explored using a Bayesian Network approach, assisted by the use of a Bayesian decision support tool, AgenaRisk. Thus:

RESEARCH QUESTION SIX: Can Bayesian Networks be used to provide a framework to make inferences about the mechanism of GSR deposition from GSR evidence?

Furthermore:

- Can they assist in inference-making in casework scenarios?
- How might other items of evidence be incorporated?
- Are there any practical or computational issues associated with this approach?
- What are the issues associated with presenting evidence in this way?

Alongside the research questions, two further areas have been identified that will be afforded explicit consideration during and after the experimental phase of the thesis:

1. An assessment of the use of SEM-EDX with an automated search and detection method for the analysis of (multiple) GSR samples

2. An assessment of both the methods used, and the implications of findings for, future experimental research projects concerning GSR

The experimental and interpretative phases of this thesis will be undertaken with a view to identifying key issues and concepts within the field of GSR and trace evidence more generally, and pursuing issues that maybe unforeseen at this stage. A

commitment to demonstrating the practical utility and applicability of the research findings will be demonstrated throughout, while attention will be given to identifying and highlighting avenues for further, complementary research. These convictions resonate strongly with the ideals of a research culture in the forensic sciences that were surveyed in chapter one.

Chapter 4 The experiments: Materials, methods and procedures

4.1 Introduction: an experimental approach

It is necessary to elucidate the reasons behind the decision to adopt an experimental approach to addressing the research questions outlined in section 3.7. Theoretically, one alternative means of exploring GSR deposition and transfer could involve gathering data from various published experimental and case-related work. However, this would not be feasible as different studies will have employed different firearms; they will vary in terms of the number of shots fired, the method of sampling and the method, sensitivity and accuracy of analysis. To develop a body of coherent, comparable and accurate data on the occurrence, rate and patterns of GSR multiple transfer, it was concluded that data would best be generated experimentally (see, for example the experimental work of Pounds and Smalldon 1975a, 1975b, 1975c, Bull et al 2006 and van Oorschot and Jones 1997 for work relating to different types of trace evidence). The experiments were designed so that the quantity of transferred GSR under different scenarios and conditions could be compared. The experimental design process was guided and informed by the methods, findings and recommendations of previous studies on trace evidence such as those described in sections 2.3, 3.4.4 and 3.5. The objective of the experimental phase was to develop a body of repeatable data on GSR transfer and deposition that contributes to the body of literature on GSR dynamics. This same body of data will be used to highlight implications for forensic protocol and to explore of the use of a Bayesian Network approach to assessing GSR evidence. This approach represents the novelty of the present study. First, it is a practical determination of the science, nature and extent of GSR transfer and its implications, and secondly, it represents a commitment to exploring a model for reasoning about GSR evidence using Bayesian Networks in light of the experimental findings.

On the role of experimental studies in forensic science research, Morgan et al (2009b) argue that experimentation which mimics the forensic reality is vital if the behaviour of trace materials is to be understood and then successfully interpreted within an

investigative context. Such experimentation may be undertaken to resolve a specific case-related issue or, alternatively, informed by knowledge of the sorts of scenarios encountered in an investigative context. The results can be used to support inferences during the process of interpretation set out in section 2.2.2 (Linacre 2013). While the present study echoes the commitment of other experimental work to understanding the behaviour of forensic evidence in different scenarios, it also considers its probabilistic interpretation in chapter seven.

4.1.1 A progressive experimental design

In a similar manner to a number of previous forensic transfer studies (see French et al 2012 and Lowe et al 2002, for example), a "progressive" approach to experimentation was chosen, whereby transfer scenarios - each building on the findings of the former - represent portions of the forensic reality which is being mimicked. This allows a number of possible forensic scenarios to be investigated and for data to be derived for each scenario in turn. For example, after establishing the quantity of GSR transferred to the hands of a shooter, a further experiment assessed the quantity of material that is transferred when a shooter makes contact with an individual not present at the scene of the shooting. Each scenario or experiment contributes in part to the overall approximation of a set of simulated transfers and depositions involving GSR. Details of the specifics of each scenario will be provided in this chapter as well as an account of the relevant materials, methods and procedures that were standardised throughout the experimental work.

4.2 Materials and methods

This section outlines the methods and materials which were standardised across the experimental transfer scenarios. The individual experimental scenarios are described alongside an account of the procedures and control measures that were implemented during the experimental phase of the research

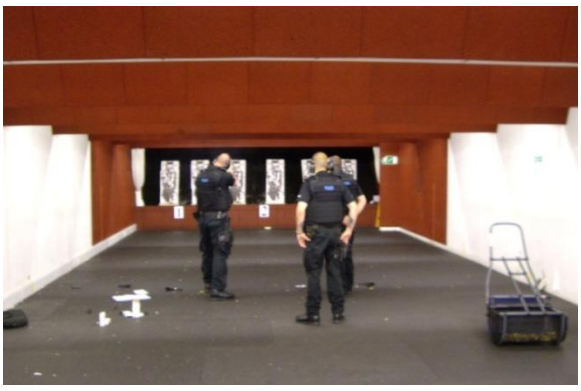
4.2.1 The test firings

Firing of the weapons was carried out by firearms officers from the Tactical Firearms Unit of Surrey Police at their firing range in Guildford, U.K. One officer fired at a time,

overseen by the Chief Firearms Instructor. Sampling was undertaken by the author. A SIG Sauer P226 9mm self-loading pistol was used for the firings and the firearm was loaded with 9mm Luger 95 grain jacketed soft point 9P1 ammunition (manufactured by FEDERAL Ammunition). This ammunition was chosen as a result of preliminary testing of residues recovered from the inside of spent cartridges. Testing revealed that GSR produced by this ammunition contains lead, antimony and barium in combination, in accordance with the most commonly encountered ammunition types (see section 3.2.3). The use of this ammunition for the present study, therefore, serves to ensure that results and findings are applicable to a wide range of ammunition types (akin to Brozek-Mucha 2011). A 'firing' comprised five rounds of ammunition. Five rounds were fired in order to generate a population of GSR that was considerable enough to properly assess the potential for secondary transfer, given the variations that were expected in the amount of deposited GSR between firings (see section 3.4.4a). The firearm was not cleaned between experiments, as it was decided that a 'dirty' firearm would best serve the approximation of forensic reality. The use of an indoor firing range limited the effects of GSR dispersion by climatic conditions (Fojtášek et al 2003).

Above: **Figure 4.1** The SIG Sauer P226 self-loading pistol

Top Right: **Figure 4.2** The ammunition used for the test firings



Bottom Right: **Figure 4.3** The test firings in progress

4.2.2 The experimental scenarios

The experimental phase of this thesis comprised five experimental scenarios. The methods, materials and sampling procedures documented in this chapter were employed uniformly across all of the experiments which were carried out. The decision was taken to simulate contacts and transfers immediately after the firearm discharges had taken place. In the absence of comprehensive studies on the extent and rates of GSR transfer, it was deemed important to ensure that the maximum quantity of GSR available for transfer was present at the time of contact. Thus, without a noteworthy window for GSR decay, the full extent of possible transfer could be captured. The interpretative implications of this will be discussed in chapter six.

4.2.2a Scenario one

Firearm → Shooter

In the initial and most straightforward experiment, samples were taken which enabled the measurement of the number of GSR particles deposited on the hands of the shooter during the firing of the pistol. The hands of the shooter were thoroughly cleaned and control samples were taken prior to the commencement of any shooting with a view to ensuring no GSR was present on the subjects prior to the experiment (described in detail in section 4.2.4a). The SIG Sauer P226 9mm self-loading pistol was loaded with 9mm Luger 95 grain jacketed soft point 9P1 ammunition (manufactured by FEDERAL Ammunition) and was fired five times. Following the shots, the firearm was laid down, and no contacts were made with any other surface (including garments). These measures limited the loss of GSR or acquisition of further particles by contamination mechanisms. The shooter then made his way to the designated sampling location that was set up 15 metres from the shooting location to ensure the safety of the sampler, while also restricting the possibility of contamination. The hands of the shooter were then sampled according to the established sampling procedure using ½ inch SEM stubs (described in section 4.2.3). Three runs of this experiment were carried out so that the repeatability of results could be tested and demonstrated.

4.2.2b Scenario two

Firearm → Handler

Experimental scenario two involved a second individual who, following the discharging of the handgun by the shooter held the gun for five seconds. This experiment simulated, for example, a scenario in which an accomplice handled a firearm following a discharge. Both the shooter and handler washed their hands as a precaution against contamination from GSR already present on the hands. Prior to the experiment, control samples were taken from the subjects. In the same manner as scenario one, five rounds were discharged by a shooter although, when the firing was complete, the shooter made his way over to the handler who took the gun and held it by the handle as if about to fire it, for five seconds, before placing it on the ground. The handler then made his way to the sampling area and hands were sampled according to the standard procedure. Again, three runs of the experiment took place.

4.2.2c Scenario three

Firearm → Shooter → Subject

Scenario three was set up in order to establish whether GSR which is deposited on the hands of the shooter during a discharge can subsequently be transferred to the hand of a second individual who was not present at the scene of the shooting, via a direct (hand-to-hand) contact. Both the shooter and subject washed their hands and were control sampled before the firing was carried out. When the shooter had completed the five rounds and left the firing location, he was instructed to shake hands with the subject who was not present at the shooting. The shooter used his firing hand (the right hand in all cases) and shook hands with the second individual. Following the handshake, both the shooter and subject were sampled so that the quantity of GSR remaining at the shooter could be measured, in addition to that which was transferred. Three runs of the experiment were carried out.

4.2.2d Scenario four

Firearm → Shooter → Subject → Subject

In this experiment, the shooter made hand-to-hand contact with a subject who then made hand-to-hand contact with a second subject. The shooter and two subjects had control samples taken from them following hand-washing, before the firing then took place. After the five rounds had been discharged, the shooter made his way over to the two subjects who had not been present at the firing. He shook hands (right-to-right) with the first subject, who then shook hands with the second subject in the same manner, thus completing a chain of three individuals. Following the handshakes, all three participants had their hands sampled for the presence of GSR. In this way, the GSR which remained at the donor surfaces (and thus, did not undergo transfer) during the two contacts could be quantified, as well as the GSR that was transferred to the third individual in the chain. Three runs of the experiment took place.

4.2.2e Scenario five

Firearm → Subject in proximity to firing

In this experimental scenario, the quantity of GSR deposited on the hands of an individual in the proximity of a firearm discharge was the subject of interest. The shooter and bystander washed their hands and had control samples taken from them. When firing took place, the subject stood one metre behind the shooter. When firing had ceased, both individuals made their way to the sampling area and were sampled. Three runs of the experiment took place.

4.2.2f Summary

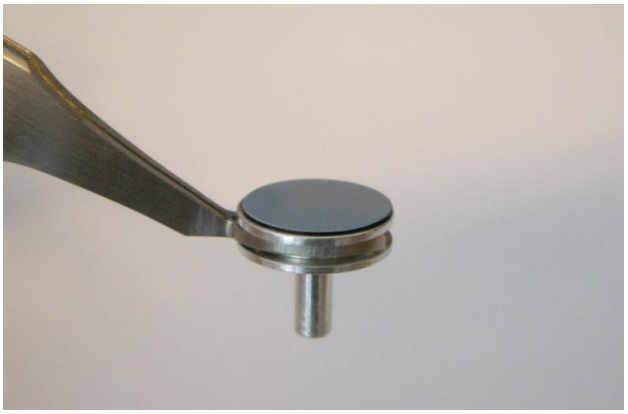
Across the five experimental scenarios, five different mechanisms of GSR deposition and transfer were simulated:

1) Shooter: via airborne GSR from a firearm discharge
2) Subject handling: via handling of a recently discharged firearm
3) Subject via handshake: with a shooter
4) Subject via handshake (2): via direct contact with a subject who has had direct contact with a shooter
5) Bystander: via airborne GSR from a firearm discharge

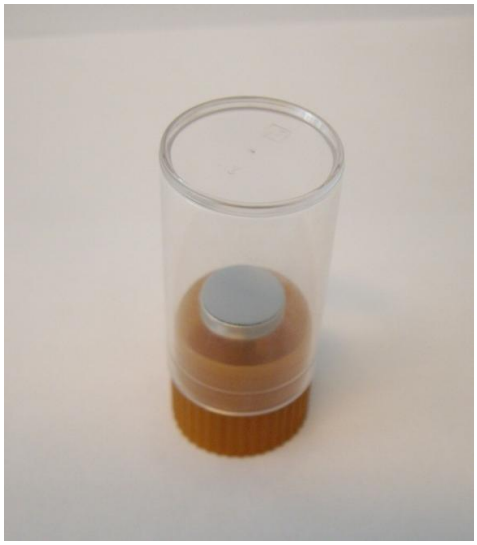
4.2.3 Sampling strategy and procedures

Sampling from the hands of subjects was standardised across all experimental scenarios. In an investigation into 'stub' and 'swab' methods of GSR collection, Reid et al (2010) conclude that the use of stubs is superior in terms of collection efficiency. The use of stubs is also preferable in terms of speed and simplicity, and also involves little preparation prior to analysis, thus minimising the potential for particle loss and contamination. The use of stubs is commonplace in research studies involving GSR (Brozek-Mucha 2007, 2009, 2011) and in real-world forensic settings (Wright and Trimpe 2006). Accordingly, the stub sampling method was chosen for this piece of experimental work.

½ inch diameter pin-type aluminium SEM stubs (supplied by TAAB Laboratories, U.K.), coated with 12mm diameter self-adhesive carbon discs (supplied by TAAB laboratories, U.K.), were used to collect material from hands (figure 4.4). Following the recommendations of Heard (2008), each stub was stored in its own sealed SEM tube (supplied by TAAB laboratories, U.K.), the lid of which was removed for sampling and then returned and sealed prior to analysis (figure 4.5). This procedure prevented the cross-contamination of stubs which could arise when six stubs are stored and transported together. Meanwhile, given the sealed nature of the tubes, unnecessary exposure to the potentially GSR-contaminated surroundings was limited[29].



Above: **Figure 4.4** Aluminium stub in stub gripper



Right: **Figure 4.5** Aluminium stub in sealed stub container

[29] An inventory of the materials used, including catalogue numbers, is included in Appendix I

When sampling from hands, Heard (2008) recommends that the sampled area is covered at least three times, in order to ensure that any particles embedded in minute skin creases are collected. Reid et al (2010) indicate that stubs should be 'dabbed' over the area of interest until the tackiness of the adhesive has been lost in order to capture as much GSR as possible. Further dabbing beyond this stage could result in the loss of sampled material from the stub. According to the results of unpublished trial experiments carried out by the author (see table 4.1), this loss of tackiness occurs after circa 20-30 dabs, or up to circa 50 dabs, depending on the surface being sampled (in keeping with the findings of Charles et al 2013). For the purposes of the present experiments, stubs were 'dabbed' fleetingly with light but not insignificant pressure onto the area of interest (i.e. the hands) 50 times, or as many as required to cover the area three times; whichever was fewest.

Test	Sample surface	Dabs before tackiness lost
1	Palm of hand	55
2	Palm of hand	61
3	Palm of hand	52
4	Cotton t-shirt	22
5	Arm of male - hair	28

Table 4.1 Results of preliminary testing of the tackiness of self-adhesive tabs on different surfaces

When sampling from the hands of participants, a standard procedure was followed. In all experiments, the entire hand surface (i.e. front and back of the left and right hands) was sampled using one stub so that one sample was taken from each individual (figure 4.6). Both hands were included in the sampling following the recommendations of Heard (2008) and Molina et al (2007) who note that GSR is deposited on the stabilising hand of the shooter, as well as the hand in contact with the handle and trigger. The same strategy was applied to sampling the handshake recipients, even though only one hand would have made contact with the shooter. In a real-world forensic scenario, sampling from a group of suspects would be carried out without prior knowledge of the identity of the shooter and a uniform sampling strategy would be applied to each suspect. Sampling from all participants in a standard manner safeguarded the GSR counts from sampling bias and would enable between-run and between-scenario comparisons. It was not considered fruitful to sample from the left

and right hands separately, or to make a distinction between the front and back of hands. This was because, in a real-world scenario, GSR may be redistributed between left and right hands and between the front and back, during the period between deposition and collection (Heard 2008). One sample per subject was deemed an appropriate sampling technique for this study and one that would enable the comparison of various mechanisms GSR deposition.

A variety of sampling strategies have been employed in the literature in an attempt to maximise the yield of GSR that can be collected. Rosenberg and Dockery (2008), among others, refer to sampling the 'knuckle' of the trigger finger, the 'knuckle' of the thumb and the 'webbing' in-between. These regions can be expected to be particularly 'GSR-rich' following a firearm discharge. Consequently, when sampling during the present set of experiments, particular attention was paid to sampling from this area so that the full extent of GSR deposition could be captured. The sampling regions proposed by Heard (2008) were effectively extended for this study to represent a more comprehensive sample of the hand as opposed to just the palm by incorporating the fingers, thumbs and webbing in-between when sampling from each subject (figure 4.6).

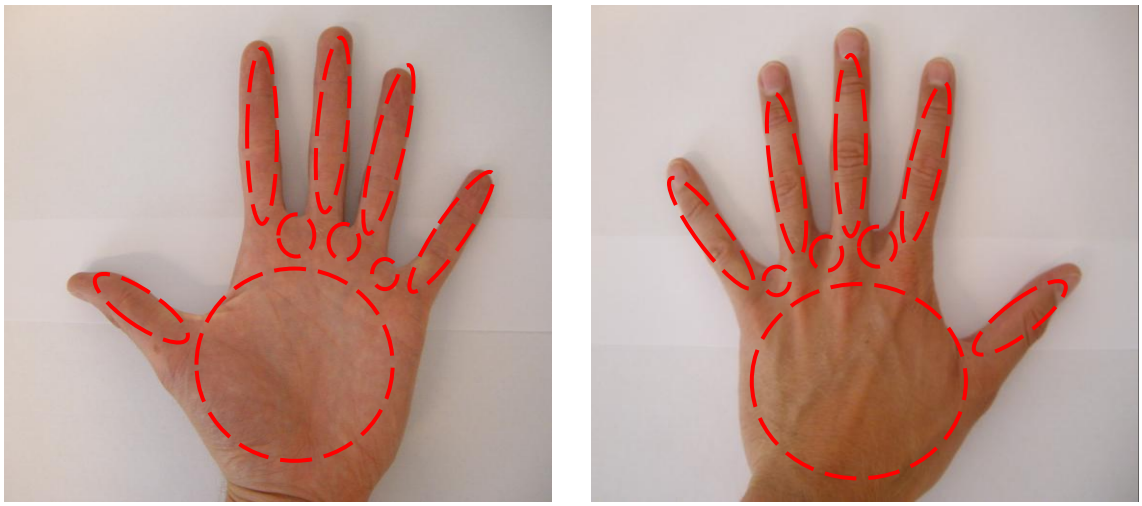


Figure 4.6 Palm (front) and back of left hand showing areas that were sampled

The decision was taken to sample subjects immediately after the firearm had been discharged, or after contacts had taken place. The opportunity for the decay of GSR between deposition and sampling was, therefore, limited and ensured that the full extent of any deposition or transfer was captured in order to inform our understanding

of GSR evidence dynamics. The implications of this decision for the applicability of findings will be discussed in chapter six.

(Clockwise from top-left): **Figure 4.7** Sample stubs in labelled sample tubes, pre-sampling

Figure 4.8 Sampling the subject post-firing

Figure 4.9 Sample in sealed tube, secured in two re-sealable bags and labelled

Figure 4.10 Removing the adhesive film from the SEM sample stub

4.2.4 Avoiding errors and stub contamination

The propensity of GSR to be transferred from one surface to another, even when direct contact between surfaces does not take place, posed the problem of unwanted transfer during the experiments. Meanwhile, the persistence of GSR – its propensity to remain adhered to a surface (as discussed in section 3.4.4b) – gave rise to the possibility of material from a previous experimental run being retained on surfaces involved in a subsequent experiment. Moreover, the range was a 'GSR-rich' environment and the potential for acquisition of GSR from various surfaces was high. The transmission of GSR had to be limited to that which was intentionally being

simulated by the experiments. Ultimately, if not controlled, unwanted transfers could have resulted in erroneous results. These errors would either have been false-positive GSR presence whereby GSR was detected which had been deposited by a mechanism other than that which was being tested, or false-negative GSR presence, whereby GSR was unintentionally transferred away from a surface of interest. In this way, the very 'evidence dynamics' being investigated would have been the source of contamination and error, and posed a threat to the accuracy and reliability of results.

Control measures were implemented which were intended to reduce the risks of contamination. This was particularly crucial given that small numbers of particles were expected in many of the experimental transfer scenarios. The development of appropriate measures and procedures was assisted by creating a step-by-step "script" of each experimental scenario. These were examined to locate the junctures at which contamination or unwanted transfer might occur. This process necessitated an appreciation of the 'evidence dynamics' associated with GSR (outlined in section 3.4.4). A section of one such script is provided in figure 4.11. In this simple case, a shooter discharges the firearm and makes contact with a second subject, before both individuals are sampled. The script demonstrates that a plethora of opportunities for contamination and unwanted transfer existed when carrying out the experimental work. Not represented in this script are the risks that were present during the analytical phase and during processing in the laboratory, these are discussed in section 4.2.4c.

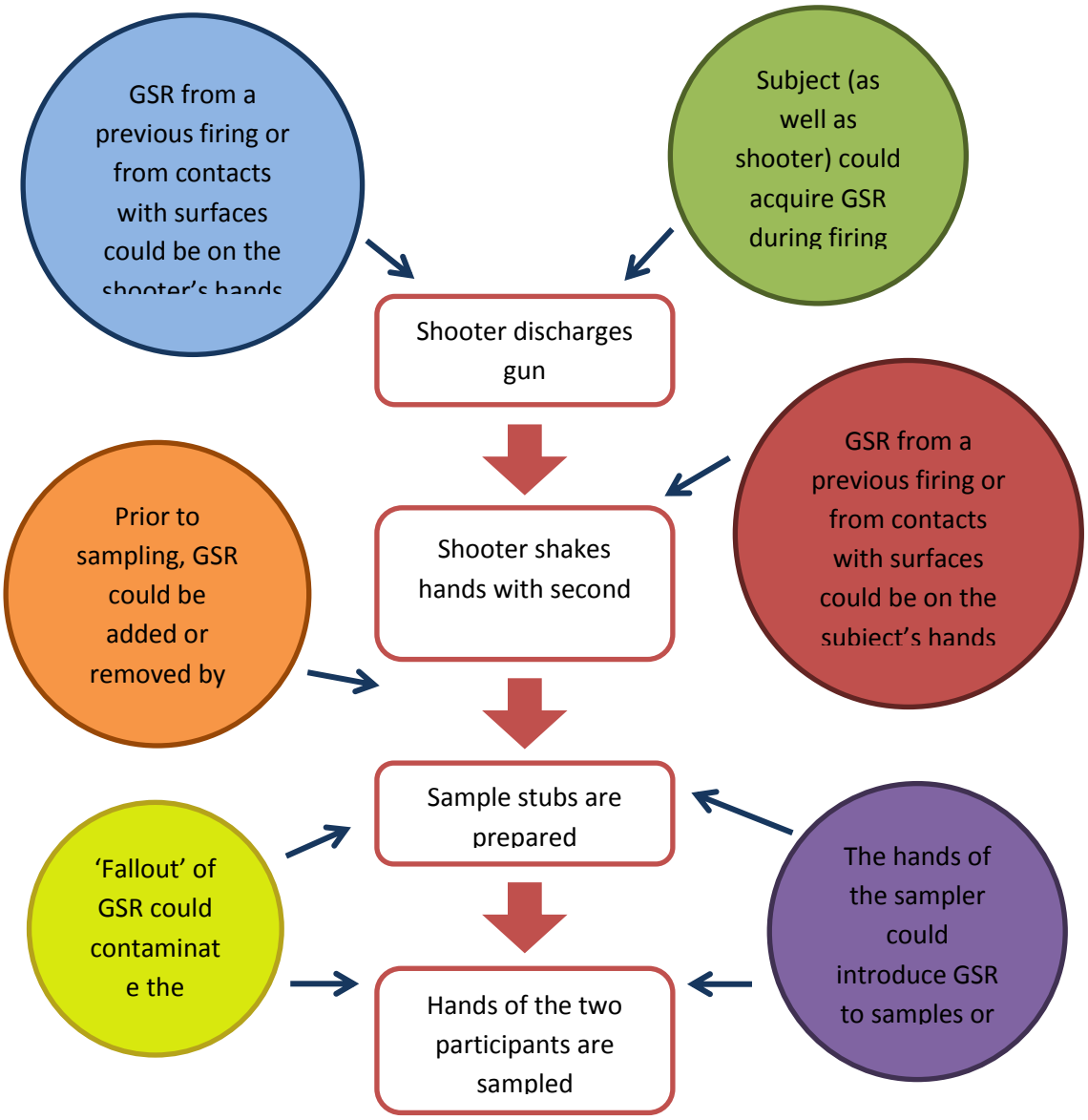


Figure 4.11 'Script' of events and potential contamination risks highlighted which correspond to different points in the script

4.2.4a Controlling GSR contamination on hands

It was vital to ensure that any GSR recovered from the hands was a result of the transfer mechanism being simulated. In the absence of any countermeasures, participants (shooters or transfer recipients) could have taken part in an experiment already contaminated with GSR from a previous experiment, or from contact with a surface at the range. Therefore, all participants were instructed to wash their hands

thoroughly using soap (from a dispenser) and water. This was deemed adequate for the removal of GSR (Andrasko and Maehly 1977, Nesbitt et al 1976). Control samples taken from participants following hand-washing during the pilot experiments had corroborated this. Hands were then dried with disposable kitchen towel, avoiding the contamination that may have resulted from the use of a communal hand towel. This washing took place in an adjacent room following each experimental run in preparation for the next. Participants were instructed not to make contact with other surfaces such as doors or their own garments, from which GSR could conceivably have been acquired, or to which material have could been transferred. Following hand-washing and prior to the commencement of each experimental run, participants were control sampled. The experiments and movements of participants were scheduled in such a way that there was very little delay between hand-washing and control sampling and between control sampling and participation in the experiment.

4.2.4b Controlling contamination during the sampling process

The sampling process involved a number of risks of contamination. As a result, a systematic sampling protocol aimed at minimising the potential for stub contamination was developed. All sampling was carried out 15-20 metres from the scene of the firing to restrict the possibility of contamination from the 'fall-out' of GSR (Fojtasek and Kmjec 2005, see section 3.4.4a). Meanwhile, the sampler did not enter the shooting area, nor did any individual who was not involved in the experiment. After Heard (2008), each stub was stored in its own, sealed stub container (manufactured by TAAB laboratories U.K.). This would ensure that the stub was not exposed to the environment following sampling at the range and in the lead up to analysis in the laboratory. This method of storage was chosen over storage boxes which can hold six stubs because of the risk of cross-contamination that might be associated with storing sample stubs next to one another. These boxes were also deemed to be less effective in keeping stubs securely in position.

The lid of the stub storage tube and the adhesive film covering the stub were not removed until the stub was about to be used. Once the sample had been taken the stub was sealed in its labelled storage tube which, in turn, was placed within two re-sealable plastic bags (supplied by TAAB Laboratories, U.K.), according to the procedure

set out by Heard (2008) (figure 4.9). During sampling, powder-free vinyl gloves were worn and disposed of between samples in order to minimise the risk of contamination (figure 4.8). Tweezers were used to remove the adhesive film from the stub (figure 4.10). While sampling, care was taken to prevent any contact between the sampler and the hand being sampled.

4.2.4c Contamination risks during the laboratory analysis

Opportunities for contamination also existed in the laboratory. Measures that can assist in preventing contamination in this setting were surveyed in section 3.5 (see also Wright and Trimpe 2006). Equivalent procedures were implemented during the analysis phase of this research project. For example, samples were stored separately and not exposed to the surrounding environment, while carbon coating of the samples did not take place in the same room as the microscope equipment and stub grippers were thoroughly washed after each use. The carbon coater was cleaned between sessions and new rods were used for each coating. Analysis of the control samples confirmed that no contamination resulted from the coating procedure. Importantly, the laboratory in question had never previously been used for GSR analysis and was, therefore, a 'GSR-clean' laboratory.

Pilot experiments

Pilot experiments were carried out prior to the experimental work. As well as familiarising the author with the facilities, this set of experiments enabled the testing, piloting and rehearsal of the experimental procedures and scenarios which would be run. The pilot experiments also served as training for the subjects.

Issues were identified during the piloting and adjustments were made to ensure the smooth running of the live experiments. Most of these issues concerned the choreography of experiments and sampling.

The samples from the pilot experiments represented an initial guide to the level of GSR that might be expected in each scenario. However, most significantly, these samples were used in the pilot analysis phase in the optimisation of the operating conditions and settings for the analytical equipment and software. This process is described in detail later in the chapter (see section 4.3).

4.2.5 Validity

When designing the experimental phase of the research, particular attention was paid to ensuring that any findings that were generated would be applicable to real-world forensic contexts. In addition, the conditions of the experiments and the procedures of sample collection were intended to approximate the occurrence of, and response to, a firearms incident. Formulating experiments that satisfy these requirements involves consideration of their 'external' and 'ecological' validity.

In research design terminology, the 'external' validity of a study refers to the extent to which the results of a study may be generalised, or applied, to situations outside the laboratory. Particularly in the context of laboratory-based (in this case, firing-range) experiments in forensic science, approximating the forensic reality and ensuring what is termed 'ecological' validity – as suggested by Morgan et al (2009b) – will ensure that the findings can be employed to assist interpretation within a real-world forensic investigative context.

In conducting the experimental phase of the investigation, there were a number of unavoidable limitations that affected the ecological validity. Chiefly, there is the very fact that the experiments were simulations themselves and not real-world firearm incidents. To control and gather the necessary data from criminal activity would be unethical, unsafe and impractical. Experimentation at a police firing range was deemed the most suitable alternative. Despite this, various steps were taken to ensure that the experimental scenarios that were developed were carried out in a way which mimicked real world scenarios. These steps, including the decision not to clean the gun between test firings, are documented in the account of methods and procedures included in this chapter. In addition, procedures for sampling (including sample preparation and the act of sampling), packaging, storage and subsequent analysis were intended to reflect the response to a firearms offence.

The very aim of the experiments – to understand the transfer of GSR when contacts are made following the discharge of a firearm – is inherently linked to approximating the sorts of scenarios that may be played out following a firearm discharge. In considering that a shooter may transfer GSR to another individual or that GSR may be deposited on a bystander, this investigation is concerned with what might actually be

occurring following forensic events, but which may be overlooked if it is believed that GSR is only deposited on the hands of the shooter. Clearly, it was necessary to control a number of variables during the experiments. Controls (such as hand-washing) were vital to safeguarding from threats to internal validity, but were perhaps not wholly "realistic" in the sense that such controls would not be in place in the real world. The conflict between providing ecological and external validity and ensuring that the GSR transfers were a result of the mechanisms being investigated necessitated a number of methodological decisions and compromises. However, controls and measures implemented during collection, storage and analysis, while countering threats to internal validity, also ensured external and ecological validity as these measures approximated those implemented in the real world to safeguard against contamination and to maximise the evidential value of the material which is collected.

The applicability of the findings to forensic contexts will be discussed in greater detail in chapter six, while the limitations of extrapolating from the present study, and from experimental studies in general, will be discussed in section 8.2.4. Consideration will be afforded to the application of experimental findings to the interpretation of GSR evidence in real world forensic contexts, taking into account multiple sources of uncertainty. It will be suggested that a Bayesian Network approach can facilitate this.

4.3 Sample analysis

All samples stubs taken during the experiments were analysed in order to quantify the presence of GSR. Detection and analysis methods were extensively reviewed in section 3.3. Particle analysis using SEM-EDX with automated detection and analysis software (INCAGSR, Oxford Instruments, U.K.) was employed in the analysis phase of the experimental work. The principles of imaging and detection using SEM-EDX are surveyed before details are provided of the specific procedures involved in the use of the automated SEM-EDX system for this piece of research.

4.3.1 Imaging and detection using SEM-EDX

Imaging and detection using SEM-EDX relies on the interaction of the specimen with an electron beam. The application of thermal energy to the tungsten filament results in the generation of an electron beam by thermionic emission. Within a vacuum, that

prevents oxidisation of the filament and interference with the electron beam, the beam is focused, moved and angled using electromagnetic coils. The development of field emission guns provides an alternative means of producing an electron beam and enables enhanced current density, enhanced spatial resolution of imaging and increased emitter longevity.

The electron beam interacts with the sample in a number of ways:

1. Secondary electrons are emitted when the electron beam results in the ionisation of atoms in the specimen. These secondary electrons are used by a secondary electron detector to form an image. Bright areas correspond to regions and features that are responsible for the emission of large quantities of these electrons
2. Backscattered electrons are those which are detected following the interaction of the beam and specimen. Electrons are reflected by elastic scattering. The number of these backscattered electrons, and therefore, the strength of the signal are dependent on the atomic number of the constituent element; with elements of higher atomic number appearing brighter on an image owing to the production of greater number of electrons (this is central to the detection of features of interest using INCAGSR).
3. X-rays are emitted by atoms and correspond to the change in energy associated with the dislocation of an electron from an inner shell, owing to excitation caused by the electron beam. This vacancy is filled by an electron from an outer shell and it is the difference in the energy associated with these shells that is emitted in the form of X-rays.

X-rays are measured using an energy-dispersive spectrometer. The energy and signature of the emitted X-rays correspond to the energy differences between shells and their energy is characteristic of the atomic number of the specimen. It is this principle that enables the identification of specific elemental contributions from the sample.

While each element has a family of characteristic X-rays associated with it, several issues can arise when interpreting spectra. These stem from spectral artefacts and the limited resolution capacity for certain pairs of elements. 'Escape peaks' arise as a

result of X-rays that are generated by the detector crystal. In some cases, X-rays that are processed almost simultaneously are not distinguished. Rather, the energies are summed and the signals are 'piled-up' on the spectrum plot. The software package (INCAGSR) that was employed during the analysis of GSR samples in the research project was able to deal with these issues. The 'pulse pile-up' inspector resolved instances across the energy range that would otherwise have caused 'sum peaks'. The input rate set during the analysis was such that any sum peaks that remained would have been equivalent to a negligible concentration. The INCA AutoID algorithm used by the system to analyse the contents of the spectrum peaks ensured that the elemental contributions to peaks were correctly identified, even in cases when peaks overlapped. The classification scheme used INCAGSR is compliant with the ASTM standard (documented in section 3.2.3) and upon interpretation of the spectra, the system assigned features to 'GSR' or 'Environmental' categories. INCAGSR also allows the operator to reacquire spectra for individual features to verify their composition, while it is also possible to reclassify features according to their elemental composition (this will be revisited in section 4.3.5).

The peaks that were of particular interest when detecting the GSR produced by the ammunition used in the experiments were:

- Lead (Pb) Lα 10.5517 and Mα 2.3426
- Barium (Ba) Lα 4.663
- Antimony (Sb) Kα 26.3595 and Lα 3.4440

The peak positions corresponding to a 'Characteristic' GSR particle that was detected during the analysis are shown on the spectrum in figure 4.12.

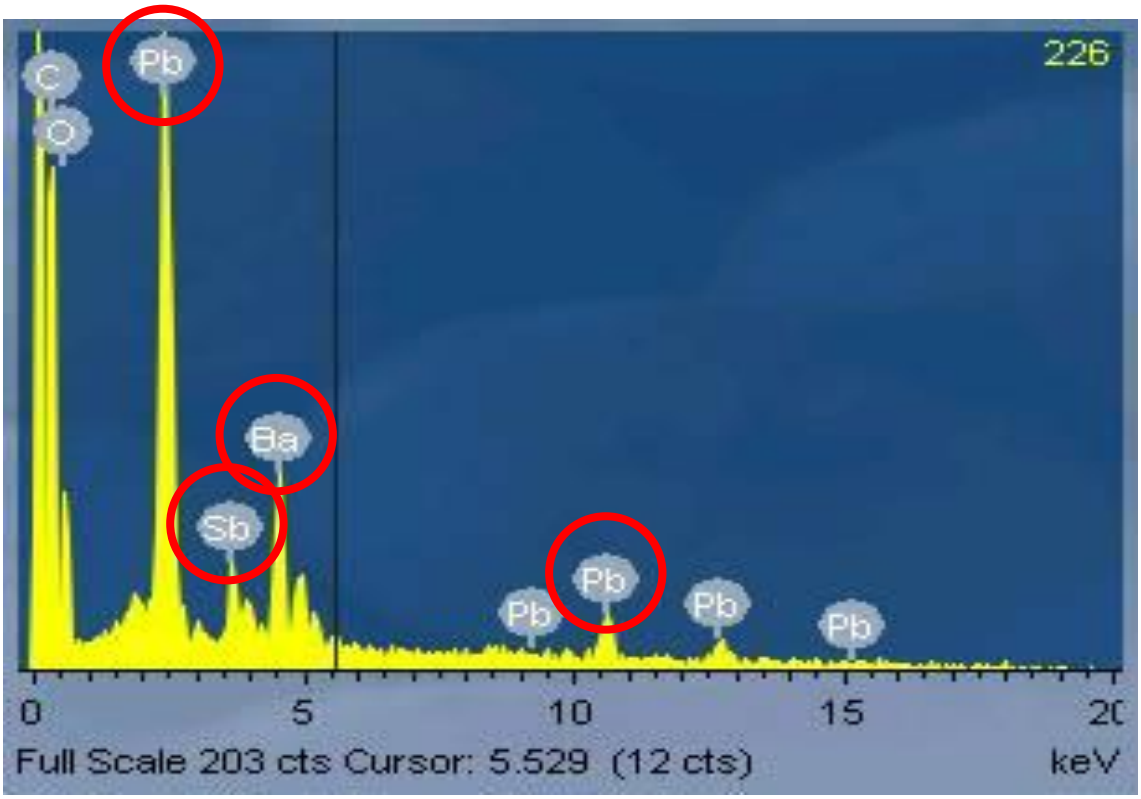


Figure 4.12 EDX Spectrum of a 'Characteristic' GSR particle with peaks of interest marked

4.3.2 The equipment

4.3.2a The microscope and detector

The SEM used for the analysis was a JEOL JSM-6480LV SEM which was fitted with an Oxford INCA X-sight Energy Dispersive Spectrometer[30] (figure 4.14).

4.3.2b The analysis software

INCAGSR (Oxford Instruments, U.K.) was the analysis platform used for the detection and analysis of GSR on the samples[31]. This is one of a suite of add-ons which are available to supplement the basic INCA suite used to run the SEM-EDX for analytical work. Realising the analytical potential of INCAGSR required extensive training and refinement of the set-up process, effective sample preparation and careful setting-up and calibration of the SEM and software. A detailed account of these procedures is presented in the following sections, beginning with the preparation of samples and culminating with the filtering and extraction of relevant data. This represents on the

[30] Located in the Department of Earth Sciences, University College London (UCL)
[31] The software was provided as part of a collaboration with the manufacturers, Oxford Instruments Ltd

one hand, an explanation of the measures taken to ensure the accuracy, reliability and consistency of results, as well as representing a guide for future research or work which employs a similar approach to sample analysis.

4.3.3 The procedure

4.3.3a Sample preparation

One at a time, stubs were removed from their individual stub containers and carbon coated to prevent charging, using an Emitech K950 coater. Samples were then returned to their individually labelled container. This was the full extent of the sample preparation required before the SEM-EDX analysis and meant that samples were only briefly exposed to the environment.

4.3.3b Loading the samples and setting up the SEM

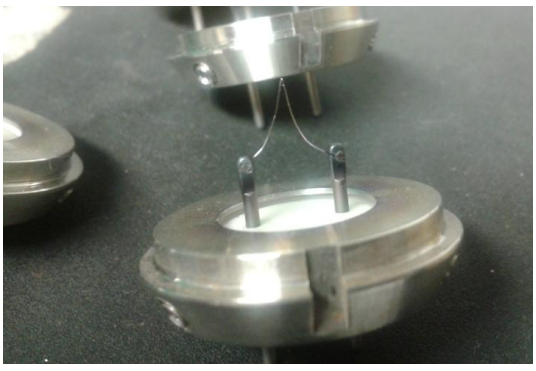
In each session of sample analysis (from henceforth, an analysis 'run'), one, two, three, four, or more carbon-coated stubs were removed from their containers using stub-grip tweezers and placed on the SEM plate, the centre of which was always occupied by the calibration stub (see section 4.3.4f). Care was taken to record the positions of the individual stubs on the plate. The plate was placed carefully in the vented chamber of the SEM whilst wearing vinyl gloves to prevent the introduction of any debris. A vacuum was then created and the stage driven so that the 'x' and 'y' positions meant that the beam was centred on the cobalt (Co) on the calibration stub. The working distance was set to 10mm (a requirement for INCAGSR), the accelerating voltage was set to 20kV and the backscattered electron mode was activated on the SEM control screen. At this point, the 'z' (height) was adjusted (without altering the working distance) so that the cobalt appeared more or less in focus, while the gun was aligned and the aperture adjusted so that there was a clear image with no disturbance at the perimeter.

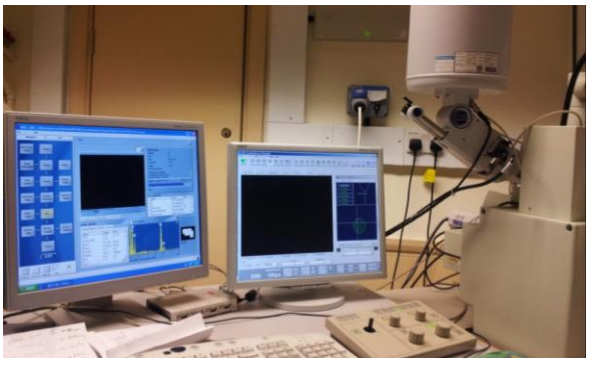
Next, the stage was driven so that the beam was centred on the sample which was to be analysed. Secondary electron mode was enabled and the beam was finely focused on the sample. This involved coarse focusing, correction of 'X' and 'Y' stigmatisms and fine focusing on a feature that was relatively flat at between 5,000 and 10,000 times magnification. It was vital that the stage remained at this final 'z' position for the run.

Owing to the minute difference in height of the GSR sample and the calibration sample, if the 'z' was changed so that the calibration sample was in perfect focus, the target sample would not have been in focus and small features would have been missed (for settings and operating conditions see table 4.2).

SEM filaments

Periodically, SEM filaments will burn out and will need to be replaced. The longevity of the filament depends on a number of factors. Turning the beam on and off and running at a high kV will reduce the lifetime of a filament, while a defective batch or debris on the filament will limit its life or cause its output to fluctuate. SEM filaments (JEOL K-type filaments) represented the major consumable during the analysis process (figure 4.13). Measures were taken which prolonged the existence of a filament such as thorough cleaning of the Wehnelt cap, gradually increasing the kV and minimising the turning on/off of the beam. Nevertheless, the nature of the analysis meant that the filament was active for long periods; fluctuations in filament performance and intermittent filament 'burn outs' were inevitable. Supplies of new filaments and clean Wehnelt caps were kept on hand so that when problems did occur, interruptions to analysis runs were minimised.





Left: **Figure 4.13** The JEOL K-type filaments used in the SEM during the sample

Right: **Figure 4.14** The SEM and two control screens. INCAGSR control screen (left) and microscope control (right)

Conditions for automatic search using INCAGSR, Oxford Instruments, U.K.	Setting
Magnification	200 X
Accelerating voltage	20 kV
Working distance	10 mm
Field width[32]	626.8 µm
Detector	Backscattered electron

Table 4.2 Operating conditions for SEM and INCAGSR

4.3.4 INCAGSR and calibration of the SEM: setting up and running the automated search and analysis

Setting up the GSR detection software and calibrating the SEM prior to an analysis run comprised several stages. At least one hour was needed to set up the system, although the process was sometimes longer due to variation in the performance of the SEM. Careful preparation and calibration ensured the generation of accurate, reliable and repeatable results.

4.3.4a File management

The GSR navigator was opened in INCA and at the beginning of each session. The system prompted the naming of the project, say 'Run 1', for example and then the naming of the sample(s) to be analysed (figure 4.15). Rather than using a complex code (Scenario 3: Run 1: Shooter Control, for instance), samples had previously been labelled 1, 2, 3... etc. and the more complex reference assigned on a master sheet. This helped to ensure that results were assigned to the corresponding sample. All samples on the current SEM plate were entered and saved as part of the project before moving to the next step.

[32] 'Field' is the term used in INCAGSR to describe the units into which an analysis area is divided. INCA generates a backscattered image of each field and highlights features within this field which are to be analysed. The number of fields will vary as a function of the size of the area being analysed and as a function of the magnification.

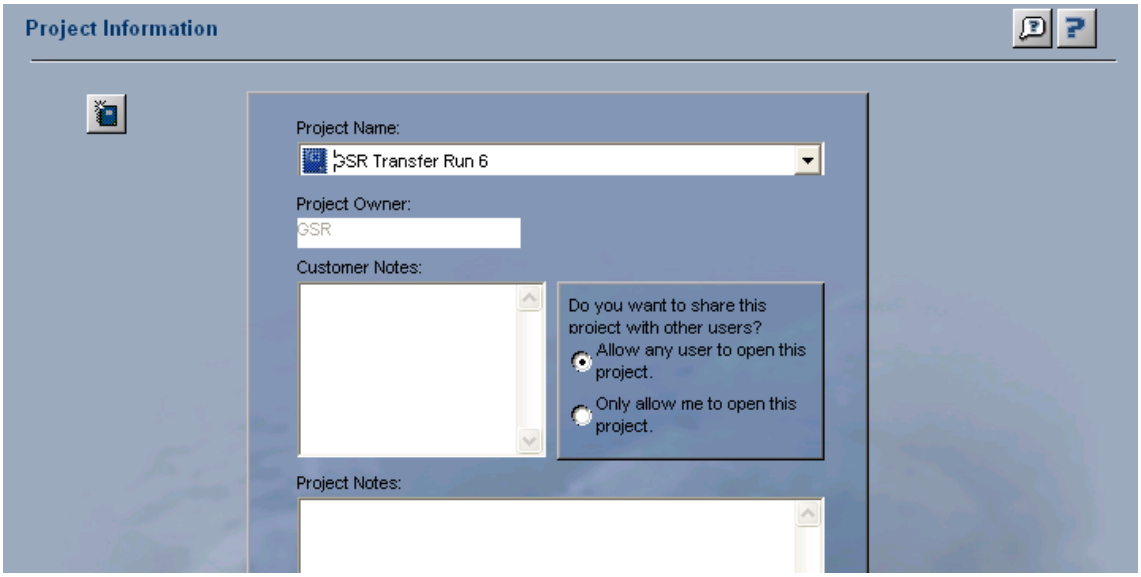


Figure 4.15 INCAGSR screenshot – project naming and file management under the 'Project' tab

Random access memory (RAM)

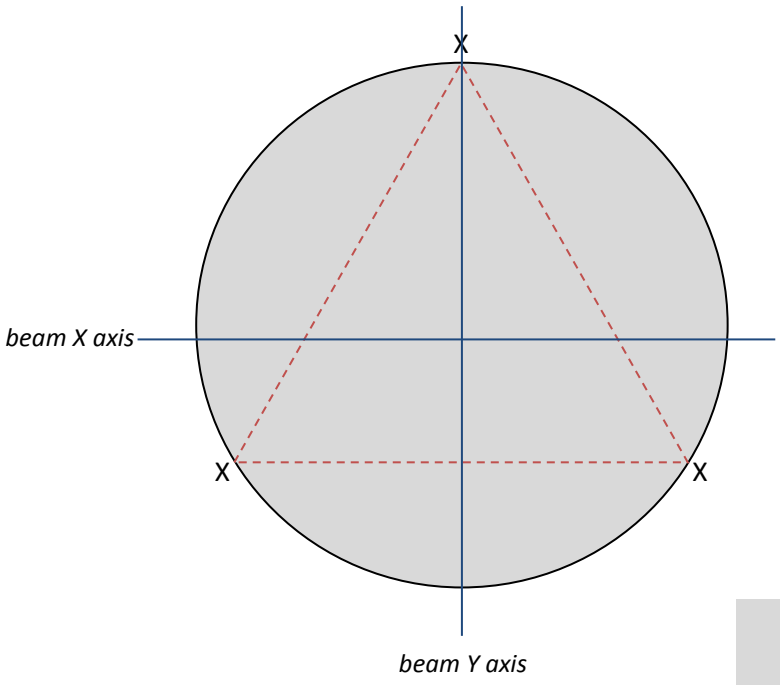
INCAGSR is a complex program which involves many processes running simultaneously. Technicians from Oxford Instruments, U.K., recommended that extra RAM was installed to prevent INCAGSR becoming restrictively slow or crashing during set-up and analysis.

4.3.4b Area layouts

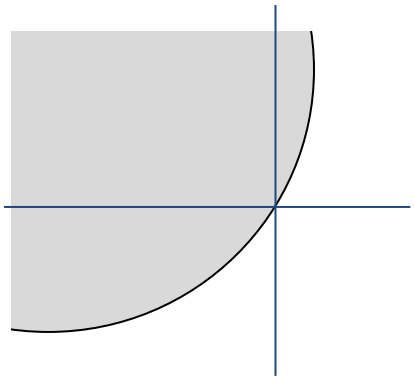
Defining areas at the 'Area Layout' stage has already been mentioned with regard to instructing the system as to the location of the 'Cobalt reference position'. During this stage, areas that were to be part of the analysis were defined; this involved marking where they were located on the stage. In INCAGSR, areas can take the form of a point, a circle, a rectangle, a line, or a reference position (for quant optimisation/beam compensation). The layouts created for this project consisted of reference positions and circles – the samples were taken using circular SEM stubs and the whole of the stub was of interest. 'New area layout' was selected and the layout was named and saved. 'Add' was selected under the 'Area Layout' tab and 'Reference' was selected from the dropdown menu. The stage was driven so that Cobalt filled the field of view, then 'Next' was clicked so that the centre of the field was saved as the reference

position. Once named 'Cobalt reference' this position appeared as a very small circle at the centre of the stage mimic.

In order to define the samples as areas, 'Add' was clicked and this time, 'circle' was selected. INCA then prompted the operator to drive the stage 'to the first reference position' and subsequently, to the second and third. These reference positions corresponded to three points on the circle from which INCA could 'draw' a circular area. In Secondary electron mode (to render the edge of the stub visible) the stage was driven so that the centre of the beam corresponded to 12 o'clock, then 4 o'clock, and finally, 8 o'clock, clicking 'next' between stage movements before clicking 'finish' at the end (figures 4.16 and 4.17). The area was named according to the sample being analysed ('sample 1', 'sample 2', etc.).

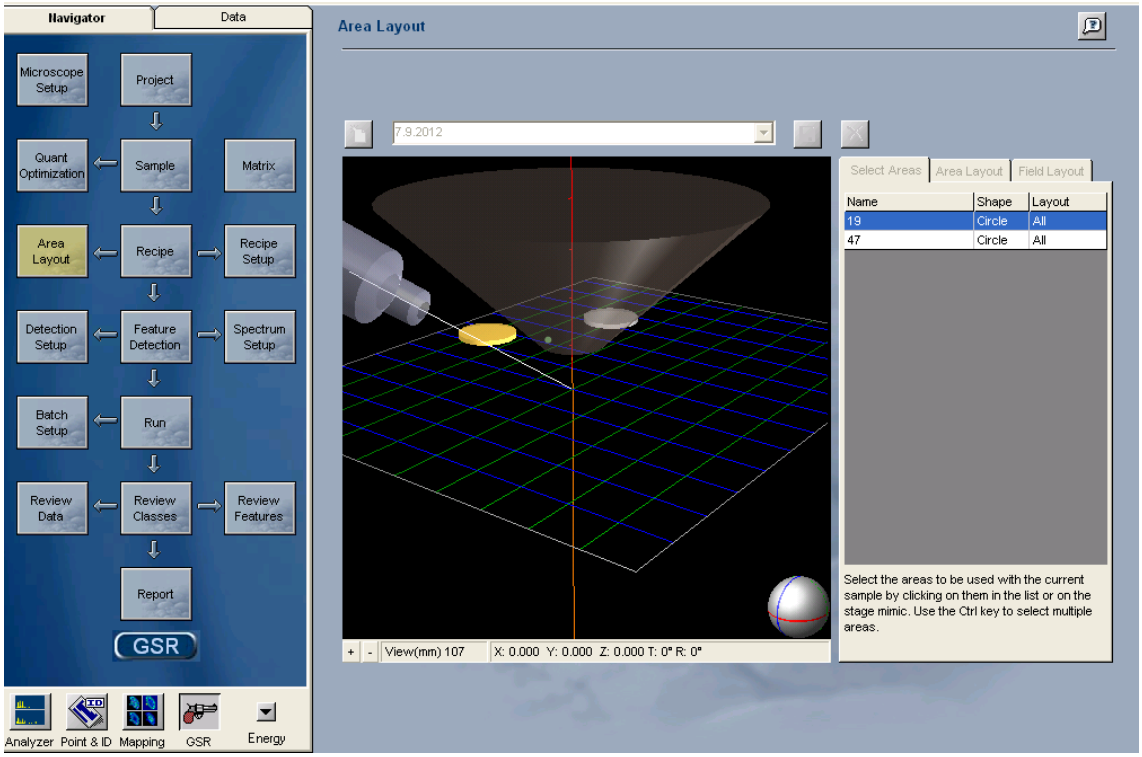


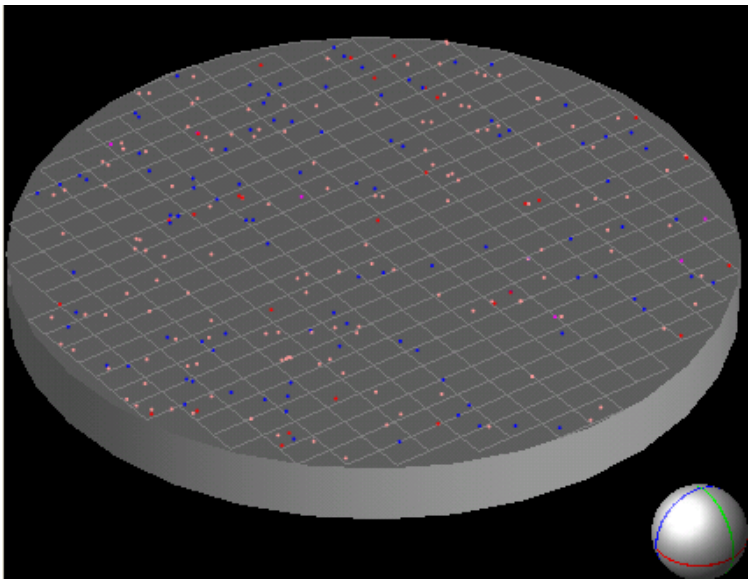
Above: **Figure 4.16** Diagram showing three marked points on sample stub (X) from which INCAGSR was able to draw the area layout. Centre of stub shown in line with beam position



Right: **Figure 4.17** Cutaway of bottom-right of stub showing beam position being aligned to edge of stub at 4 o'clock

Each area layout contained a reference (Cobalt) position and one or more sample areas, depending on the number of samples to be analysed. Each sample area was split into regular fields by INCAGSR. The number of fields into which an area is divided varies as a function of the level of magnification. For 200 times magnification, the stub was divided into around 336 fields. When scanning and analysing the contents of these fields, the beam ran from one field to the next from right to left. At the end a row, the stage would move so that the beam began the next row on the right hand side and again, ran from right to left (figures 4.18 and 4.19).





Above: **Figure 4.18** INCAGSR screenshot – two stub areas (one highlighted) and a Co reference position shown on an area layout relative to the stage and beam under the 'Area Layout' tab

Left: **Figure 4.19** INCAGSR screenshot – stage mimic showing sample stub area divided into 335 regular fields. Detected features are shown

The facility existed to select a number or percentage of fields to be analysed. Moreover, this sample could be a regular line or segment (for example, the first 50 fields) or a random selection of fields. During this study the entirety of each sample was analysed, meaning that this facility was not used for the analysis phase. However, field selection was employed during the pilot analysis for the optimisation of settings. The potential for the use of this feature for routine analysis will be assessed in section 6.3.2.

4.3.4c The recipe set-up

Parameters which define the detection, acquisition, measurement and classification of features during a run comprise a 'recipe' in INCAGSR. These recipes may be modified, refined, or deleted and are saved as '.rdb' files for use with different samples at different times and can be associated with multiple projects. The default recipe 'GSR' was selected was chosen and the project saved so that the recipe was embedded as part of the project (figure 4.20). The same recipe was used for all runs; all samples were thus analysed under the same settings and parameters. The default recipe was modified slightly for this study. High magnification will enable the detection of the smallest particles but will significantly increase the time taken to analyse a sample. During 'pilot' analysis and testing, it was determined that sub-micron particles could be detected at 200 times magnification

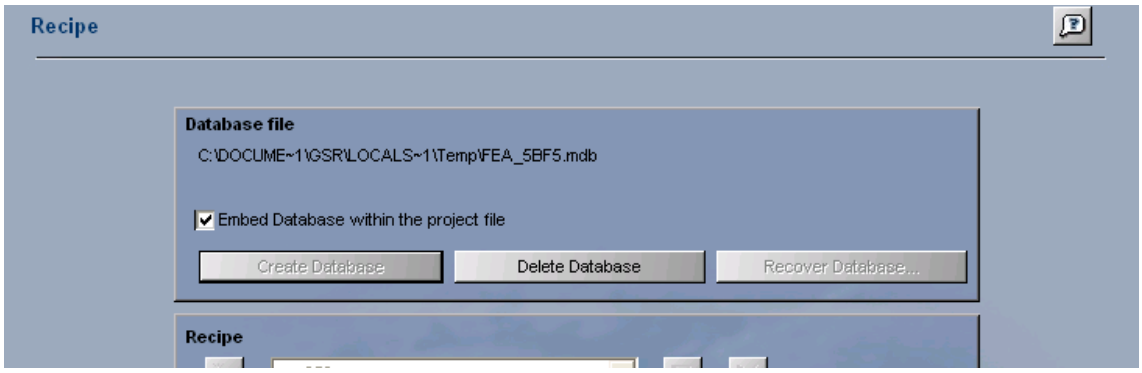


Figure 4.20 INCAGSR screenshot – Selecting the recipe and creating and embedding the database under the 'Recipe' tab

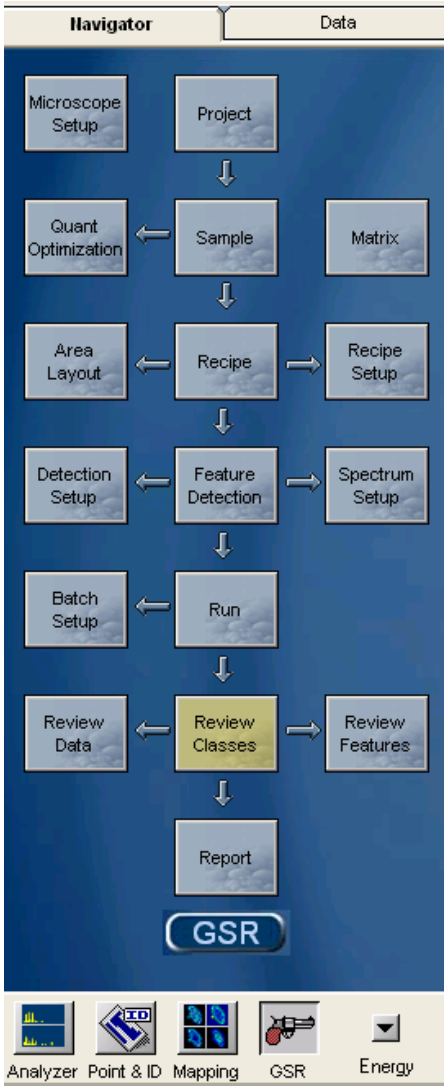


Figure 4.21 INCAGSR screenshot – INCAGSR tab navigator

Training and pilot analysis

The author was provided with an introduction and practical tutorial in using INCAGSR by an applications specialist from Oxford Instruments Ltd and also had access to the INCA feature Instruction Manual for GSR (Oxford Instruments, U.K.). A period of 'pilot' analysis followed the training. Using samples taken from the pilot test firings, an appropriate recipe was developed and time was spent optimising conditions. Particular time was taken to determine appropriate threshold levels, a suitable magnification and to perfect the brightness and contrast levels as well as the microscope settings required to optimise the X-ray count rate.

4.3.4d Microscope set-up

The first step in this stage of the process was to optimise the X-ray count rate. The stage was driven to the cobalt section of the calibration stub and a spectrum was acquired. Around 3,000 counts are required for analysis using INCAGSR and the spot size was tweaked to achieve this. Depending on the status of the filament, a spot-size of 48-53 was needed to optimise the count rate.

4.3.4e Quant optimisation

This important stage served to measure peak positions and the resolution of the detection system with relation to the reference sample. Completion of this process permitted the identification of elemental contributors to the peaks produced by EDX. The microscope stage was manually driven so that the beam was centred on the Cobalt section of the calibration stub (see section 4.3.4f) and 'Cobalt (Co)' was chosen as the optimisation element from the dropdown list. Co, along with Si, Ti, V, Cr, Mn, Fe, Ni and Cu are cited as elements with which accurate calibration is possible. Cobalt was selected as Oxford Instruments recommend it as an optimisation element when using an accelerating voltage of 20kV. A livetime of 50.00 seconds was chosen, in accordance with the guidelines provided in the feature manual, thus ensuring that the spectrum generated was of sufficient quality to provide an accurate reading of the peak positions. Acquisition then began and on completion, 'measure' was pressed and INCAGSR compared the counts in the peak to any previous acquisition; if this was the first 'quant opt' of the run, 'Measurement OK' would appear (figure 4.22).

During the Quant Optimisation stage, it was possible to set up periodic 'quant opt' measurements during an analysis run which serve as a measure of the stability of the beam current. By intermittently performing a 'quant opt' from a standard reference (in this case the cobalt), INCAGSR was able to compare the counts in the elemental peak that was acquired to the previous value, thus monitoring any variation in the beam current over time. While small variations (often due to temperature) do not affect the quantitative results, larger shifts are undesirable. The run was set up so that these quant optimisations were performed every 120 minutes. The manufacturers recommend performing at least one quant optimisation per analysis run and that repeats during long runs are advisable. However, the system is designed to maintain

stability given variations in temperature and most routine analysis can be carried out uninterrupted. During the pilot analysis, quant optimisations were performed at 30 minute intervals, although the variability that was observed was very minimal. Such a small delay was, therefore, deemed unnecessary and quant optimisations were scheduled to take place every two hours. The result of this set up meant that, at the commencement of the run, and every two hours thereafter:

1) Analysis of the current field would pause
2) The stage would drive so that the beam was centred on the 'Co reference' position
3) A Quant optimisation would be performed and a spectrum would be generated over a 50.00 second period
4) The measurement would be compared to the previous value and: a) the conditions would be satisfied and the stage would drive back to the field being analysed prior to the quant optimisation and resume, or: b) the quant optimisation would be deemed to have failed, analysis would be halted and an error message would be displayed

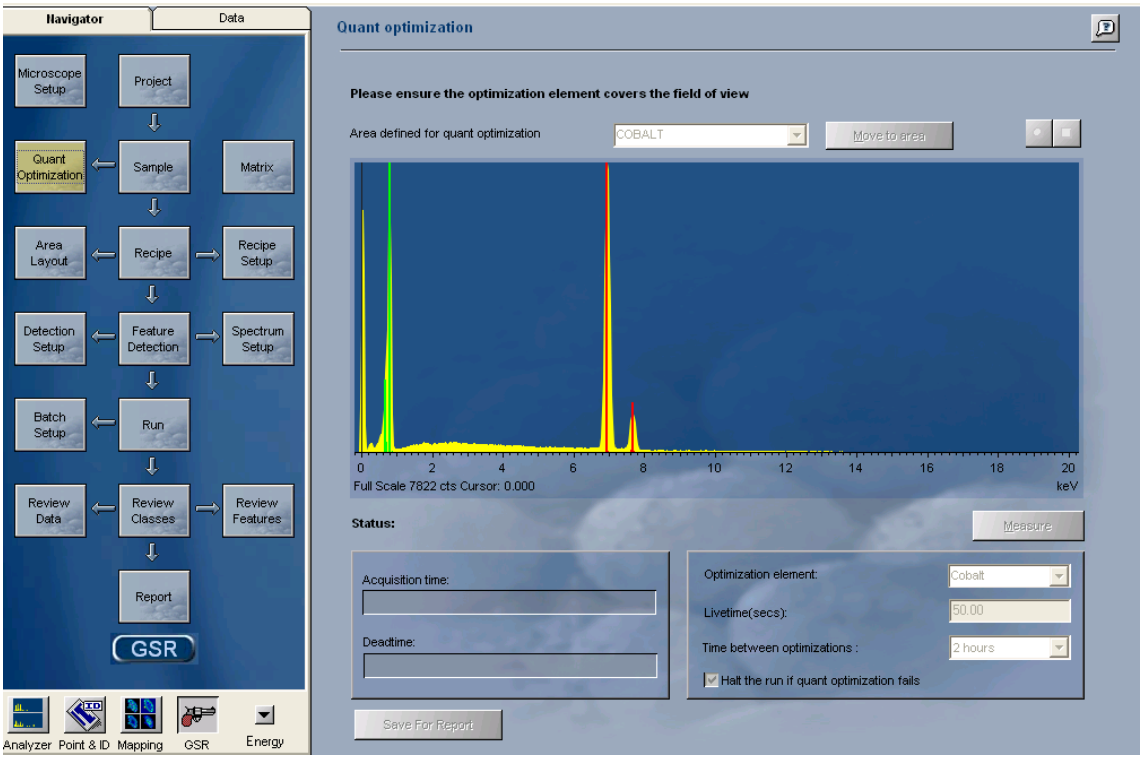


Figure 4.22 INCAGSR screenshot – performing a quant optimisation using the cobalt reference under the 'Quant Optimization' tab

4.3.4f Feature detection

During this part of the set-up, the detection of features by the system was optimised. Again, due to varying conditions and the orientation of the samples, this stage had to be completed at the beginning of each run. The feature detection screen has two tabs: 'Calibration' and 'Thresholds'.

A) Calibration

This tab was addressed first and involved setting up the backscatter detector. Essentially, the object here was to calibrate the 'eye' of the system so that black (background) areas were ignored and bright features were detected and subjected to analysis. Upper and lower level grey thresholds were set so that any feature that fell within this range was detected. Effective settings here ensured that unnecessary time was not spent detecting and acquiring spectra for unwanted features (lower than optimum thresholds), thus increasing the time per field and ensured that features of interest were not overlooked (higher than optimum thresholds).

A calibration stub was needed for this stage of the process. According to the INCA feature manual, the reference sample employed should display a range of black/grey/white under the SEM. During the aforementioned introductory tutorial demonstration, a stub on which pieces of cobalt, gold and rhodium were aligned was used. Details of the preparation of a replica backscattered electron calibration stub are provided below:

1) A ½ inch aluminium SEM stub was taken and the top 5mm was 'machined' off and smoothed
2) A self-adhesive carbon disc was affixed to the surface
3) Pure cobalt (Co) and rhodium (Rh) samples set in silver and brass mounts, as well a strip of pure gold (Au) film were cleaned with methanol and placed in an ultrasound cleaner to remove any impurities or debris
4) Under a light microscope and using a pair of cleaned tweezers, the Co and Rh were set side-by-side with a small gap between them

5) The Au was set in silver cement between the Co and Rh and manipulated until all three elements were aligned on a horizontal plane that was also level with the top of a regular aluminium stub coated with a carbon disc

N.B gold leaf was used initially but it proved to be too thin and fragile to be securely mounted. A strip of thicker gold film was sourced instead and was mounted on its thin edge on silver cement so that it aligned on a horizontal plane with the cobalt and rhodium.

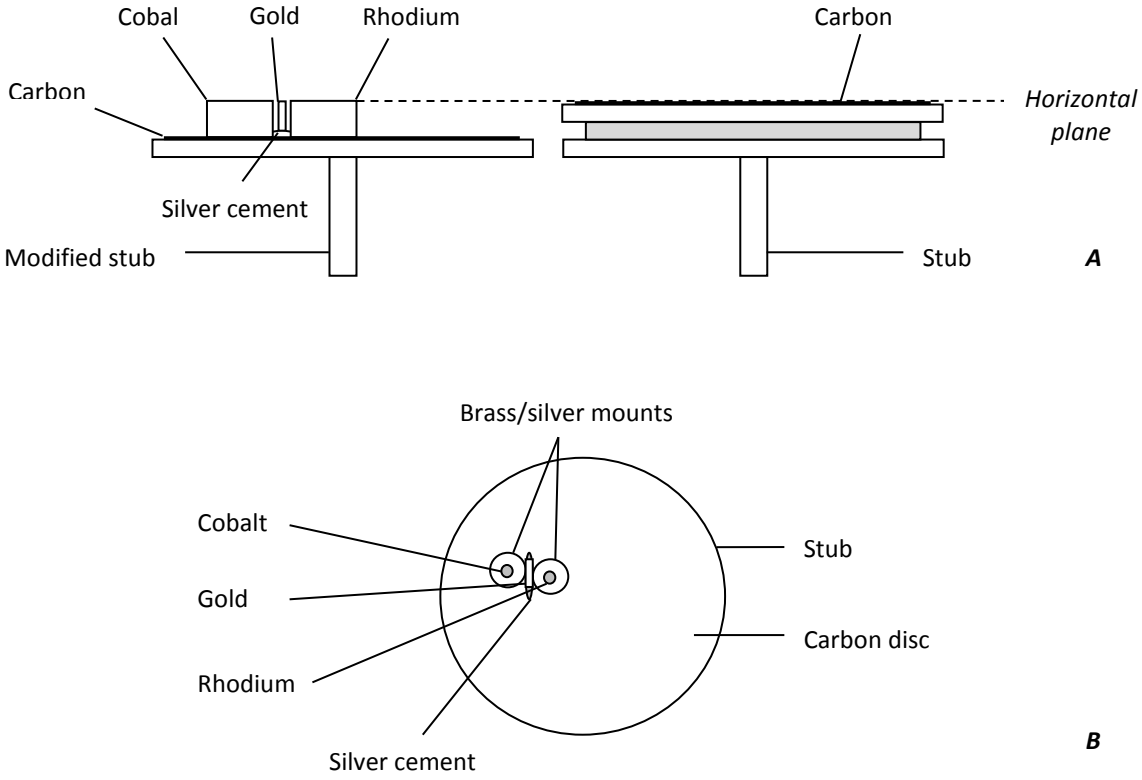


Figure 4.23 (*A)* Side view of backscattered electron calibration stub showing the three reference materials on a horizontal plane relative to an unaltered sample stub

(B) Plan view of backscattered electron calibration stub

The three materials were placed as close as possible to ensure that all three could be included in the same field of view at 30 times magnification. It was also important to make sure that the three materials were aligned along a horizontal plane and moreover, to ensure that this plane was also on a level with the tops of the target sample stubs in the mount. Failure to achieve this would have meant that the system was calibrated to detect features at distances that were inconsistent with the samples

being analysed, thus potentially giving rise to errors. The beam was always focused on the sample rather than the calibration stub to account for any minor discrepancy in distance from the beam.

With the reference sample in place, the field of view was driven over the reference stub so that all three elements were viewed on the same screen. Making sure that the sample was being viewed using BSE imaging, the auto contrast and brightness (ACB) was turned off and the start button was clicked in order for the system to generate a continuous live image. The yellow line that appeared was dragged so that the two ends of the line were over the Co and the Rh, passing over the Au. A graph simultaneously appeared with peaks corresponding to the distribution of signal intensity along the area that the line covered. In this case, eight peaks appeared – each of which pertained to a different material along the line, in order from left to right. Peaks appeared for the different materials (chiefly brass) in which the Co and the Rh were mounted and for the background carbon. These irrelevant peaks had to be highlighted and ignored and only the Co, Au and Rh peaks were considered. The Co appeared grey on screen with Au and Rh bright white, while the background carbon was black. The brightness and contrast were manually adjusted so that the three peaks of interest on the graph settled and appeared as follows: Co was mid grey, roughly half of the height of the histogram, peaking at about 128 on the scale; Au reached the top of the histogram and was saturated as much as possible; Rh also reached the top of the histogram and was slightly less saturated (more 'spiky' than the Au peak). Optimising the signal level to this pattern was achieved by toggling the gain (contrast) which altered the separation of the plateaux of the waveform and adjusting the offset (brightness) which moved the waveform up and down. The required levels of contrast and brightness varied slightly as a function of SEM and filament performance from day to day.

B) Thresholds

Under this tab, the same calibration stub was used to set thresholds on the image. In essence, if the features (i.e. the Co, Au and Rh) could be seen on the threshold image, features of interest on the samples being analysed would not be missed. The reference sample was used here rather than a stub containing GSR particles because it would have proved difficult to locate and verify the small and rare features. The

‘cobalt’ reference was selected in the dropdown menu before ‘Move to Reference’ was clicked; clicking ‘Start’ generated an electron image. The grey level (representing signal intensity) was displayed on a graph, along with lower and upper thresholds. These thresholds were adjusted by dragging them along the peak so that the Co was just detected (i.e. it was set at the point where Co was displayed red and the background black). Routinely, this corresponded to a peak on the graph with a threshold at 128 and 155. Also at this stage of the process, it was possible to schedule beam compensation checks during the analysis run. Drift of the beam current affects the image thresholds and INCAGSR allows for the automatic compensation of this drift during the run. Rather like the quant optimisation scheduling, the system periodically returned to a reference and adjusted the thresholds to ensure the consistent detection of features. ‘Cobalt reference’ defined as the area to be used for the beam compensation check. The checks were set to take place every 30 minutes (this was deemed appropriate for a run time of several hours) and ‘save for report’ was checked which meant that a graph of the alterations in beam current would be plotted in the report (figure 4.24). At this point, it was also possible to instruct the system as to the acceptable levels of fluctuation in beam current. Following the advice of technicians from Oxford Instruments, the system was set to halt the run if the Cobalt peak position changed by +/- 20 from its original peak position (usually 128).

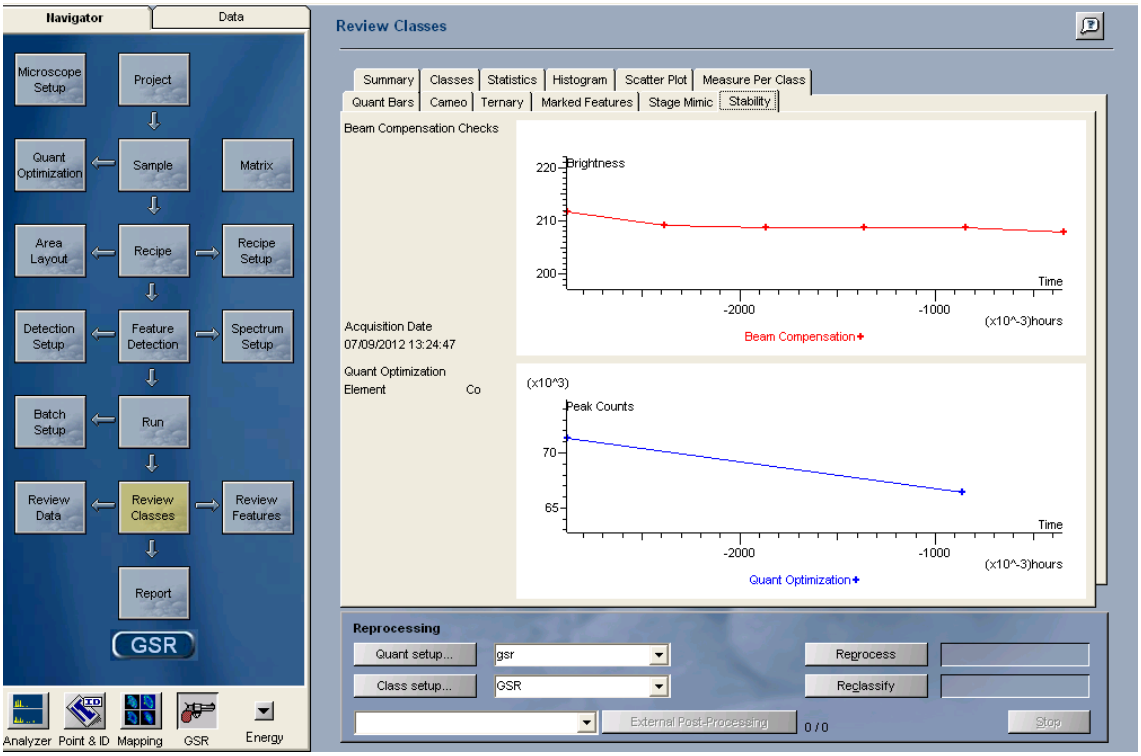


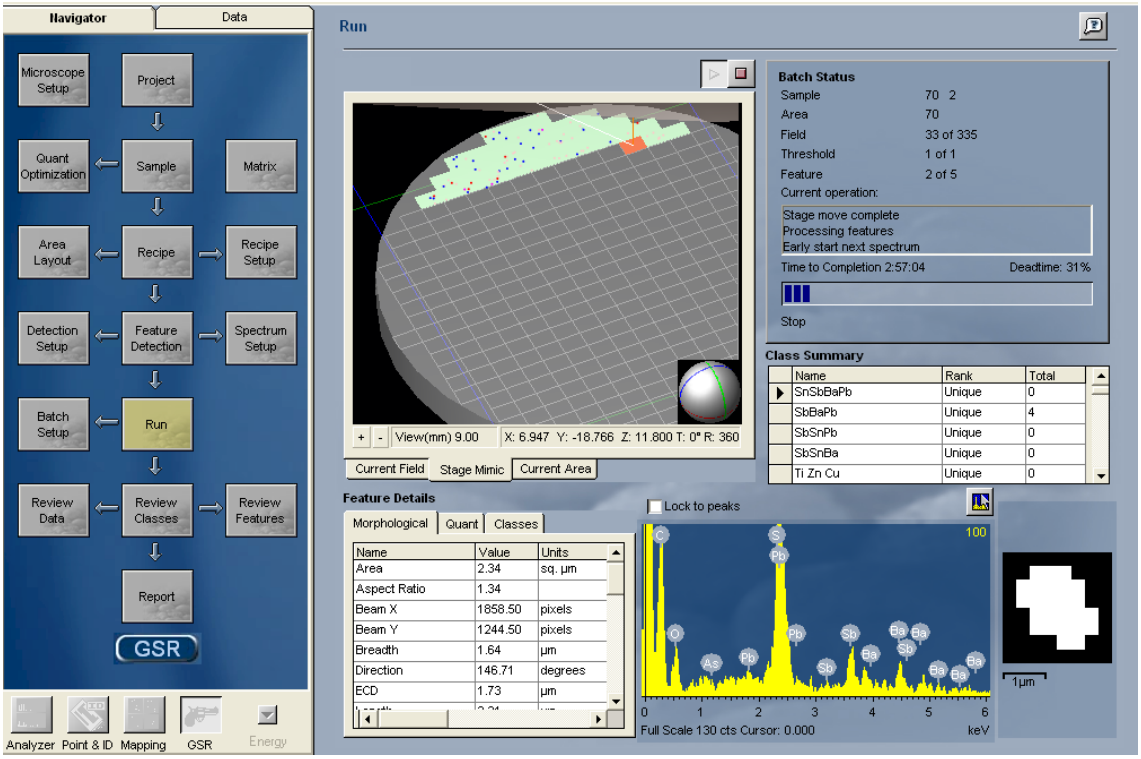
Figure 4.24 INCAGSR screenshot – beam compensation and quant optimisation graphs relating to the analysis of a sample stub. 'Stability' tab under 'Review Classes' tab

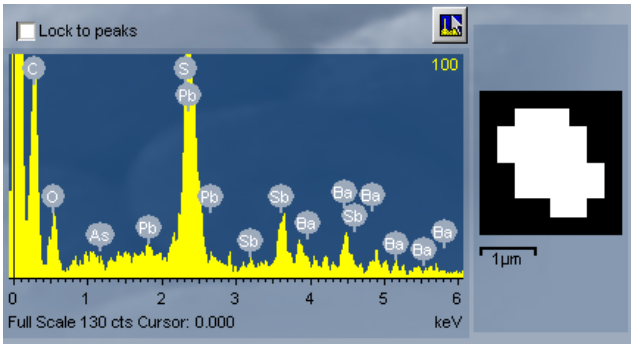
4.3.4g Commencing and running the analysis

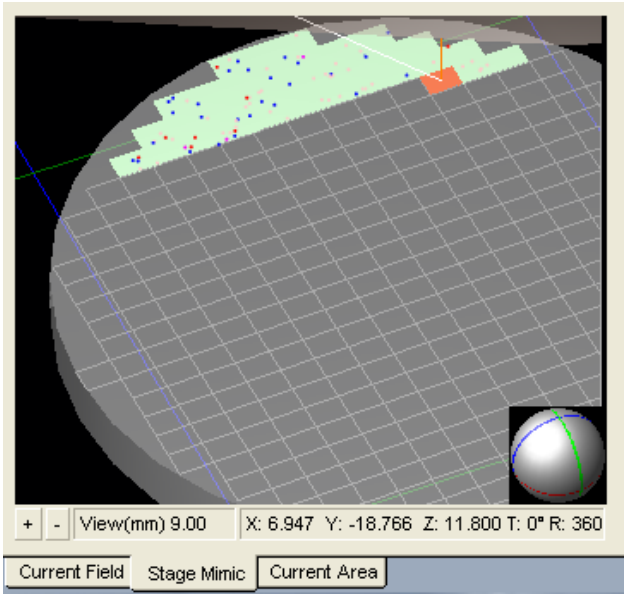
Once the set-up was complete, the 'batch set-up' (or analysis schedule) was examined to verify that all stages of the set-up had been completed and that the samples were assigned to the corresponding areas for analysis.

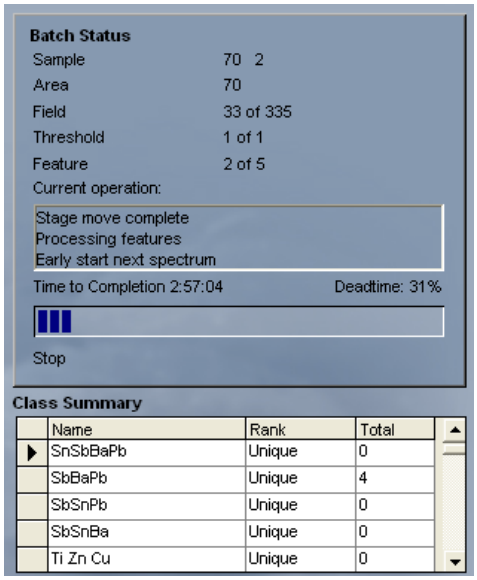
'Play' was clicked to start the run. During the run, a stage mimic was displayed on which the progress in analysing the sample could be charted and on which the locations of detected features were displayed. On another tab, a live backscattered electron image of the current field could be viewed on which the GSR particles were shown. A third tab displayed a list of the detected and analysed features, while a spectrum derived from the feature which was most recently analysed appeared on the central screen along with a backscattered image of the particle. Finally, a progress bar displaying an estimate of the 'remaining analysis time' appeared alongside a count of the number of completed fields (figures 4.25, 4.26, 4.27, 4.28).

It was possible to leave INCAGSR unattended. At the end of the run, the system had been programmed to automatically turn off the beam and filament and to save the results to disk. However, occasionally, owing chiefly to the burning out of the filament, analysis was halted. In order to be able to rectify any interruptions as they emerged, it was elected that the analysis should be attended as far as was possible.









Top: **Figure 4.25** INCAGSR screenshot – run screen showing live analysis of a sample under the 'Run' tab

Middle-left: **Figure 4.26** Spectrum and image of the latest feature in the analysis

Middle-right: **Figure 4.27** Status of analysis run showing field progress, time to completion and a running total of detected features by category

Above: **Figure 4.28** Live stage mimic showing analysis progress. Features are displayed on completed (light green) fields; current field of analysis (orange) is shown, and the remaining fields are shown (grey)

4.3.5 Post-run sample processing

On the completion of a run, it was possible to explore the saved data, backscattered images and spectra for all features (figures 4.29, 4.30. 4.31, 4.32, 4.33). However, the outputs were not, at this stage, suitable for extracting GSR counts. Rather, a number of processes were carried out before the data could be exported into a software package for analysis. The 'Review Features' stage on the INCA flowchart revealed all of the features that were detected and for which spectra were obtained in every field From the drop down menu, only 'Characteristic' and 'Consistent'[33] features were checked so that the feature list was now a list of GSR particles only; environmental and unclassified particles were ignored for the time being. For each sample, the stage was driven to a number of features and fields for verification via the 'relocate' field/feature button which drove the stage back to a particular field/feature from the list. It was then possible to 'reacquire' an image of the fields and to reacquire a spectrum for an individual feature. This process served as a manual verification of a random sample of the detected features. In no cases during the investigation was a conflicting spectrum obtained on a second pass.

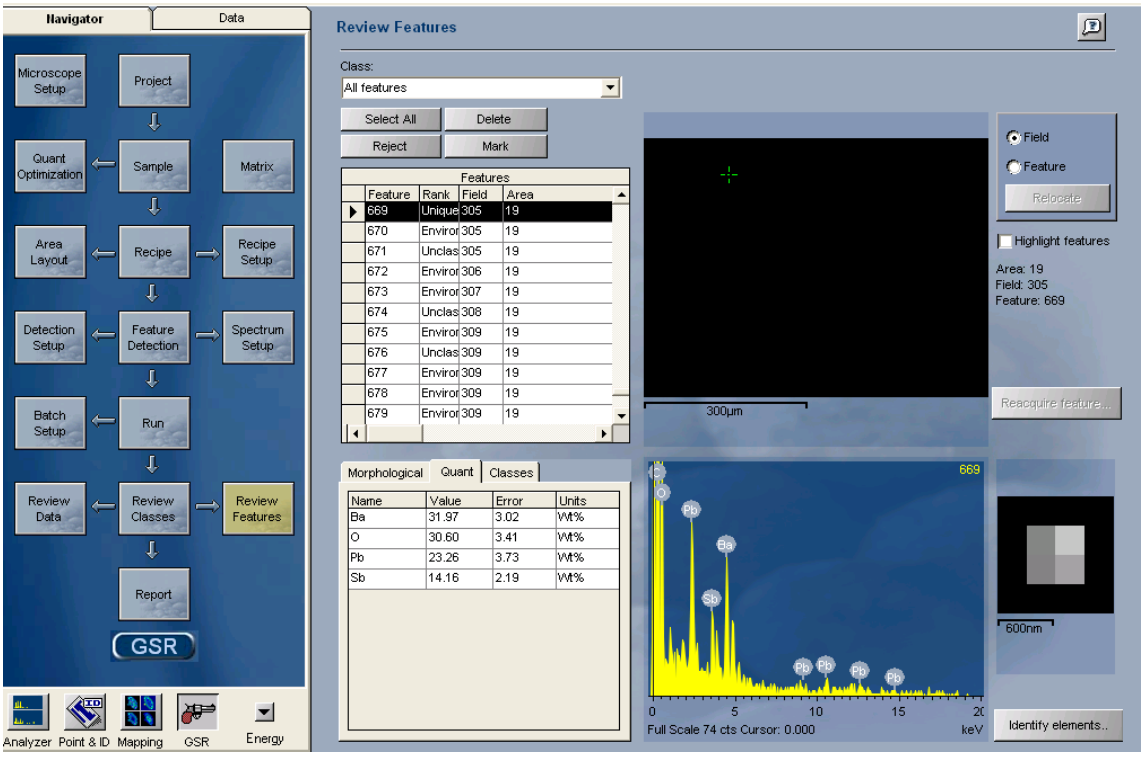
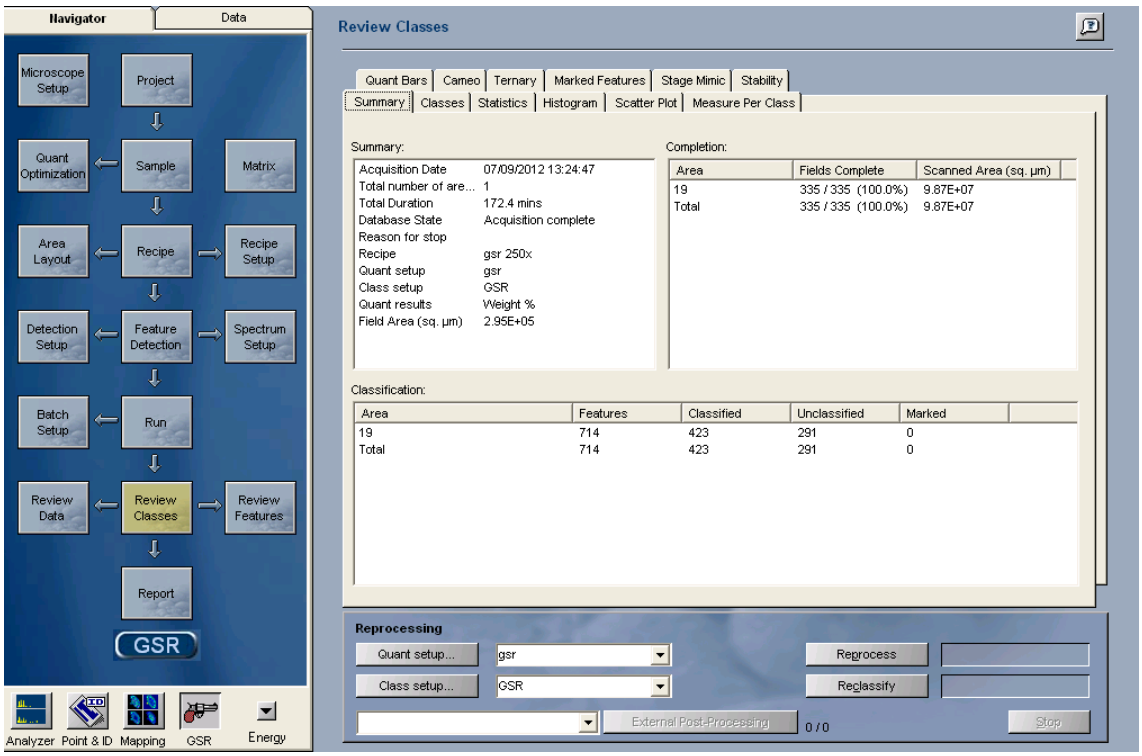
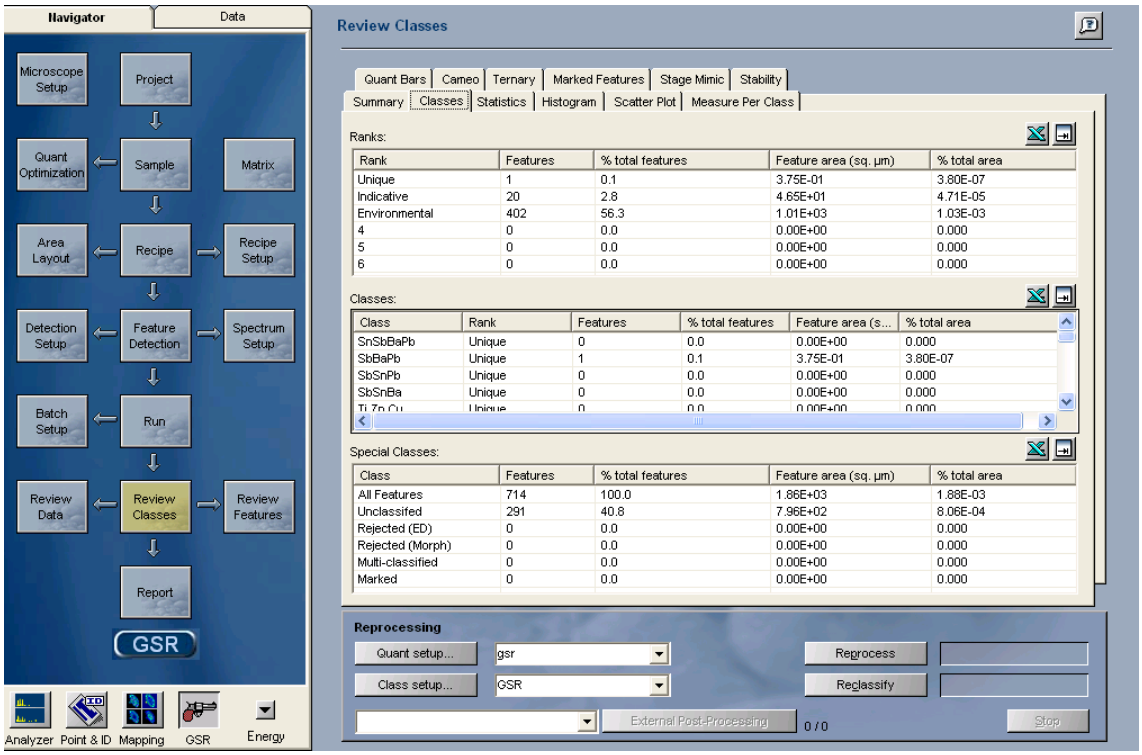


Figure 4.29 INCAGSR screenshot – List of detected features and associated data, image and spectrum for the selected feature. Backscattered image of the selected field is also shown under the 'Review Features' tab

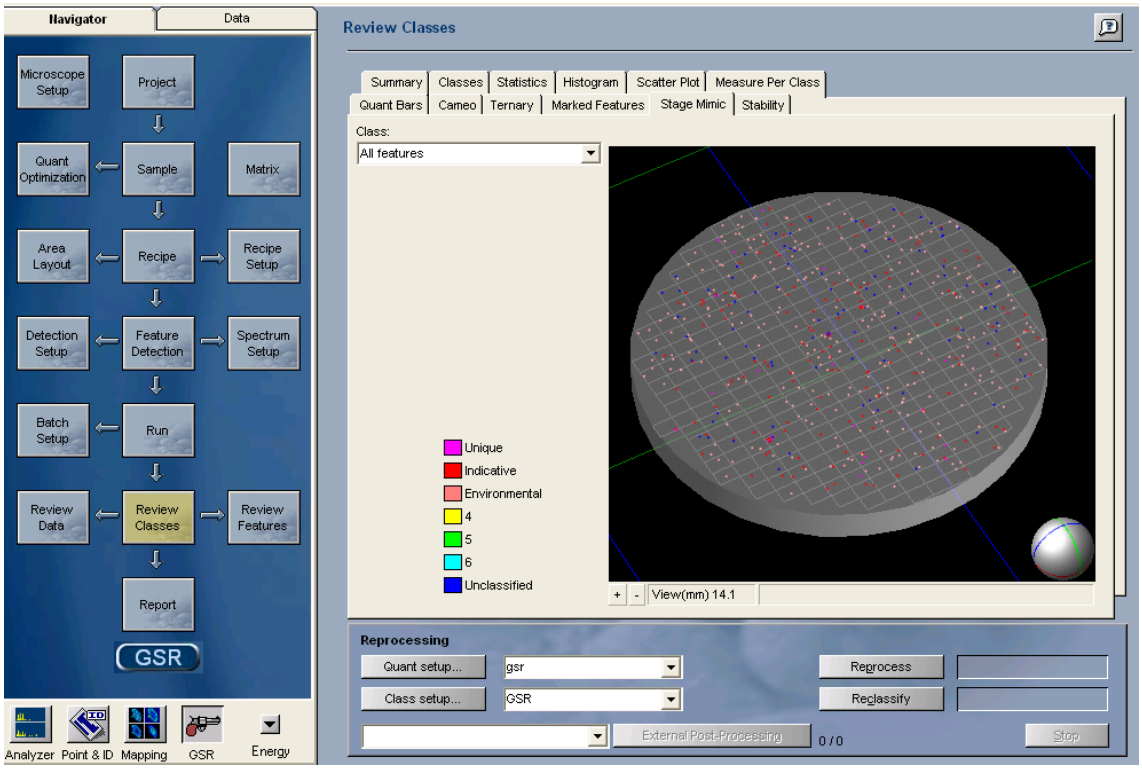
[33] N.b. INCAGSR employs the terms 'Unique' and 'Indicative'. The use of 'Characteristic' and 'Consistent' is now preferred, according to the latest ASTM standard (ASTM E1588-10e1) (see section 3.2.3)

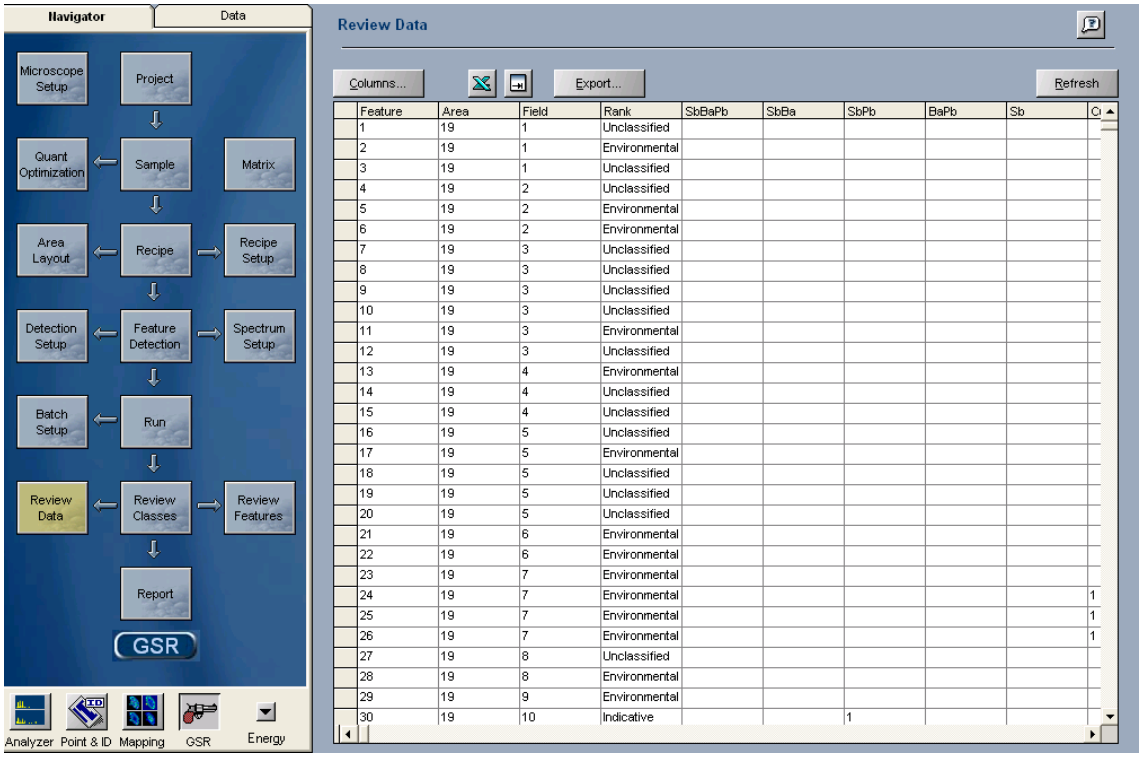




Top: **Figure 4.30** INCAGSR screenshot – summary of completed analysis of a sample stub. 'Summary' tab under the 'Review Classes' tab

Bottom: **Figure 4.31** INCAGSR screenshot – summary of detected features for a sample stub by feature classes. 'Classes' tab under the 'Review Classes' tab





Feature	Area	Field	Rank	SbBaPb	SbBa	SbPb	BaPb	Sb
1	19	1	Unclassified					
2	19	1	Environmental					
3	19	1	Unclassified					
4	19	2	Unclassified					
5	19	2	Environmental					
6	19	2	Environmental					
7	19	3	Unclassified					
8	19	3	Unclassified					
9	19	3	Unclassified					
10	19	3	Unclassified					
11	19	3	Environmental					
12	19	3	Unclassified					
13	19	4	Environmental					
14	19	4	Unclassified					
15	19	4	Unclassified					
16	19	5	Unclassified					
17	19	5	Environmental					
18	19	5	Unclassified					
19	19	5	Unclassified					
20	19	5	Unclassified					
21	19	6	Environmental					
22	19	6	Environmental					
23	19	7	Environmental					
24	19	7	Environmental					1
25	19	7	Environmental					1
26	19	7	Environmental					1
27	19	8	Unclassified					
28	19	8	Environmental					
29	19	9	Environmental					
30	19	10	Indicative			1		

Top: **Figure 4.32** INCAGSR screenshot – stage mimic showing all detected features on a sample by class. 'Stage mimic' tab under the 'Project' tab

Bottom: **Figure 4.33** INCAGSR screenshot – list of all detected features and corresponding data which was exported to Excel under the 'Review Data' tab

Routinely, the list of features did contain a number of other errors which had to be manually processed. These included double counting of GSR particles at boundaries and instances where INCAGSR had split one particle into several smaller particles.

Without processing, these anomalies would have introduced error into the GSR count data. Identifying, processing and rectifying these results (particularly in a highly populated sample) took extreme care. A set of procedures and rules for completing the task was developed.

4.3.5a Double-counting at boundaries

In a limited number of instances, GSR particles (especially large ones) came into contact with the left-hand edge or bottom edge[40] of a field and consequently, spanned two fields. In some cases, when this overlap was large enough, the same feature would be counted more than once. Clearly, this was undesirable as the GSR count would be overestimated. The following process was carried out

1. Scrolling down the list of GSR particles, features that touched, or that were markedly near, the left-hand or bottom edge of the saved image of the field were noted
2. The adjacent field was located by a) selecting the next numerical field if concerned with a particle which touched the left-hand edge b) locating the field directly below using the stage mimic
3. If a feature was found at the corresponding edge it was necessary to determine if it was the same feature. A checklist was used here:

    - *Is the feature located at a point along the edge which corresponds to the original feature?*
    - *Is the shape of the feature broadly the same (allowing for a degree of cut off)?*
    - *Do the spectra and element quantification correspond?*

If the answers to the questions above were 'yes', the feature had been double counted. If features needed to be merged, the largest feature would be taken and its size amended in Excel. The length of the feature was combined with the length of the

[40] INCAGSR covered fields from right to left in rows. At the end of a row, the stage would drive to the next row down and cover fields from right to left again. Fields were never covered from left to right. Hence, if a feature was to span two fields it would touch the left-hand/bottom edge of the first field it spanned and would be seen at the right-hand or top edge of the adjacent field

feature to be joined with it if the two features were adjacent. Failing this, the callipers on INCAGSR were used to provide a measurement of the feature across the two fields. The original spectra was retained and merges were marked in the Excel spreadsheet by use of a '/' between the feature numbers. For example, if features 203, 204 and 205 had to be merged together, the new feature would appear as 203/204/205 with a length measurement combining all three features. Finally, the feature(s) which became part of another feature were deleted from the list (and saved for reference on another sheet) so that they were no longer counted as separate particles.

4.3.5b Feature fragmentation

The problem of 'feature fragmentation' was more commonly encountered. In certain instances a single feature was designated as several separate features by INCAGSR. This splitting of the feature into a number of separate particles was encountered when the brightness varied over the particle according to its surface texture rather than due to variations in the elemental composition across the particle. Instances of this were easily identified according to the following process:

1. Scrolling down the list of GSR particles, features which were located which were located in the same field
2. On examination of these features, if they were clearly separate particles no change was made, yet if they appeared to be part of a single feature, a checklist was used:

- *After zooming in on the highlighted features, are the features clearly joined with no blank (black) space between?*
- *Do the suspected joined features share corresponding elemental spectra?*

If the answers to the questions above were 'yes', the features were considered to be part of the same particle and were merged. In such cases, the same merging process outlined for double-counting was carried out. There were a few occasions when this process was made more complicated. For example, separate GSR particles frequently occurred in close proximity or were joined via another piece of debris. These particles had markedly different elemental spectra and could thus be identified as being separate. Sometimes, existing within the same cluster, were particles that had been correctly treated separately as well as those which had erroneously divided. In such

cases it was necessary to merge some particles and maintain some separate features. Determining which features to merge and which to retain was more complex here but followed the same procedure as above.

There were a few particles which, when divided into constituent parts, exhibited slightly different spectra across the surface of the feature. Particularly in the case of (large) spherical particles it was not uncommon for a single particle to be divided into many separate features as a result of these variations (and also due to a very uneven surface texture). When some of these features, which clearly formed part of the same particle were, for example, PbSb and others were PbSbBa, the merged feature would be assigned the PbSbBa spectra. Finally, it is worth noting that a handful of particles were both 'double counted' at field boundaries and erroneously 'fragmented' by INCAGSR. In these situations, both filtering and merging processes were followed.

4.3.5c Concentrations of particles

There were a number of instances in which a conglomerate of large particles was detected on a sample. These conglomerates contributed significantly to the particle count for the sample in question. Such concentrations of particles could be identified by scrolling down the list of particles to find fields which contained a very high number of GSR particles, or, alternatively, these instances could be identified by viewing the BSE image for each field. It was necessary to determine whether these concentrations represented clusters of many individual particles, or whether these has been anomalously separated by INCAGSR and were in fact best treated as a single particle and 'merged' in the manner described above.

Clusters or conglomerates were relatively rare. Some of those which were identified consisted of angular fragments which appeared to 'fit' together, suggesting that they originated as a single piece of material. The concentrations of material included many smaller, satellite and fragmented particles that were associated with the larger particles. During the post-run sample processing, the 'fragmented' particles were assessed and it was decided that where there was clear separation between the fragments, the particles would be treated as separate entities. These 'fragmented' particles and clusters will be revisited in sections 5.5.2 and 6.2.1.

4.3.5d Summary

The need for post-run feature filtering and processing underlines the dangers associated with merely 'reading off' the GSR count produced by INCAGSR. Failure to address the inconsistencies or errors in feature counting by the system could, in theory, result in an inaccurate final GSR count. In the case of some of the samples analysed as part of this project, significant false positives could have resulted without manual verification. In one instance, for example, before processing a sample registered 549 GSR particles only for that number to be reduced to 443 following examination and filtering of the feature list during the post-run sample data processing stage. Clearly, such a shift in the GSR count underscores the importance of checking the outputs of the system, particularly when determining the quantity of GSR is crucial (as in this study). Conceivably, over-estimation of the GSR count could have serious ramifications in a real-world forensic investigation and this will be addressed in section 6.3.2.

Chapter 5 The experiments: Results, analysis and observations

5.1 Outline

This chapter presents the results of the SEM-EDX analysis of the samples taken during the experimental work[41]. The results that are presented were generated during analysis using INCAGSR and have been processed according to the procedures outlined in section 4.3.5. The particle counts for the runs of each scenario are presented and then the data on the sizes of the particles involved in the different simulated mechanisms of transfer and deposition are considered. An analysis of the efficiency and dynamics of the transfers in scenarios three and four is provided, while additional observations that were made during the sample analysis phase are documented.

5.2 GSR particle counts

This section deals with the GSR particle counts that were generated during the SEM-EDX analysis of the samples. It is important to note that the particle counts documented below only include those particles that were 'characteristic' or 'consistent' with the presence of GSR, according to the latest ASTM standard (see section 3.2.3). Thus, only GSR particles were counted; environmental and unclassified features had been filtered out. These sections deal with the results of each scenario in turn.

A note on control samples

As outlined in chapter four, a control sample was taken from each participant prior to each experiment in order to identify any contamination that had not been removed by hand-washing. As anticipated, the majority of control samples that were subsequently analysed yielded no GSR particles. However, in two cases, a small number of GSR particles were detected on the control sample. The samples in question were taken from the individual who would receive the handshake in

[41] A selection of the results in this chapter are presented in French et al (2013), see Appendix II

the third run of scenario three, and from the shooter before the gun was fired in the third run of scenario four. One and five GSR particles were recovered respectively (table 5.1).

Control sample	Number of GSR particles
Scenario three, run 3, transfer subject	1
Scenario four, run 3, shooter	5

Table 5.1 GSR particle counts for control samples which tested positive for GSR

In the following sections, acknowledgement is made of cases in which the results from the two control samples meant that there was the possibility of a small error in the results for that sample/run. The possible implications of these errors are considered. When no such acknowledgement is made, it should be assumed that the relevant control sample was negative[42]. No further action was taken and the particle counts and particle size analysis were not adjusted as it could not be determined which, if any, particles were not present as a result of the firearm discharge. Explicitly stating the presence of low levels of contamination rather than attempting to adjust the particle counts was also the approach adopted by Lindsay et al (2011a). The level of contamination in both cases is likely to have been very low, as indicated by the control sample. Moreover, although control sampling is unlikely to have removed all material from the subject's hands, it will have assisted in the removal of at least some of the few persistent GSR particles. As a result, the influence of contamination on the results would have been even smaller.

That in a very limited number of cases, some GSR either persisted thorough hand-washing is a noteworthy finding in itself. The possible impact on the conclusions which can be drawn from this data will be discussed in chapter six. Meanwhile, the potential implications for forensic protocol, for interpreting small numbers of GSR particles in casework, and for undertaking further experimental research will also be discussed in sections 6.3 and 6.4.

[42] Indeed, only control samples which tested positive for the presence of GSR are included in table 5.1

5.2.1 Scenario one

The GSR counts from samples taken from the hands of the shooter immediately after discharging the firearm are provided in table 5.2. As expected, large numbers of GSR particles were recovered from the hands of the shooter following the discharge in each of the three experimental runs. 206, 335 and 443 particles were recovered in run one, two and three, respectively. A degree of variability exists in the GSR counts across the three runs, yet such variation in the amount of GSR produced between firings is not unprecedented in the literature and was to be expected (see, for example, Matricardi and Kilty 1977, Jalanti et al 1999). A proportion of the variation in this case may be attributable to the "memory effect" caused by firing a 'dirty' firearm in runs two and three (this was an experimental design decision that was made to ensure ecological validity, see section 4.2.1). The results suggest that a few hundred particles can be expected if the hands of the shooter are sampled following the firing of five rounds under the conditions set out in scenario one.

Run	Particles recovered from shooter
1	206
2	335
3	443

Table 5.2 Particles recovered from the shooter in runs one, two and three of scenario one

Further approximations of the quantity of GSR recovered from the shooter were made using the data from scenarios three and four. In both of these scenarios, the shooter was sampled after shaking hands with another individual (after some of the material deposited during discharge had been transferred to the handshake recipient). Combining this particle count with that which was derived from the subsequent individual(s) provided an approximation of the initial particle count at the shooter. Assigning these transferred particles to the shooter is logical given that any transferred GSR originated at the shooter. As particles were recovered once the handshakes(s) had taken place there was no possibility that:

1) Particles could have been double counted

2) Particles could have been removed from the 'system' through sampling before transfer, which would have meant that less material was available for transfer

Combined particle counts were calculated as follows[43]:

For run one of scenario three (figure 5.1):

- 746 GSR particles were recovered from the shooter after a handshake and 88 GSR particles were recovered from the individual
- 746 + 88 = 834 GSR particles originally at the shooter

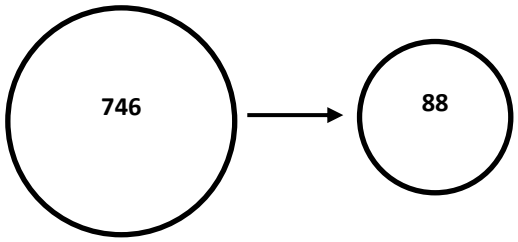


Figure 5.1 Particles recovered from the shooter in runs one, two and three of scenario one

For run one of scenario four (figure 5.2):

- 647 GSR particles were recovered from the shooter after the handshakes, 26 GSR particles were recovered from the first individual (who shook hands with the shooter and then the second individual) and 18 GSR particles were recovered from the final individual in the chain
- 647 + 26 +18 = 691 GSR particles originally at the shooter

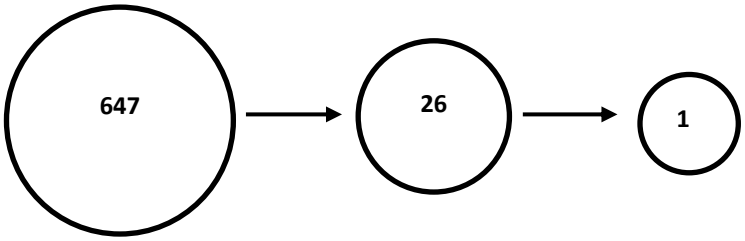


Figure 5.2 Particles recovered from the shooter in runs one, two and three of scenario one

It must be stressed that combining counts in this way involves the assumption that all of the material which transferred to the recipient was collected. It is assumed that the sample

[43] Particle count data for scenarios three and four, including corresponding samples are presented in section 5.4

represents all of the material that would have been available for collection from the shooter if no transfer had taken place. Clearly, to assume the total veracity of the sampling technique in this way is problematic, but because the sampling strategy was maintained across all runs, any potential for error was consistent. Approximations of the shooter GSR count, which have been generated by combining samples, are likely to consistently underestimate the true figure, albeit slightly. This caveat is explicitly stated here and will be acknowledged where appropriate. By combining counts in the manner described, six 'new' runs[44] of scenario one were created. It is noted that the count for the handshake recipient used to form the result for 'run' six (431) may have introduced a very slight error as one particle was detected on the relevant control sample (see table 5.1). It is suggested that the influence of any error is negligible among several hundred particles. Similarly, in 'run' nine, five particles were detected on the shooter prior to firing. Once again, the possibility exists that a small error is associated with this result but given between-run variability and the number of particles involved, this is unlikely to significantly impact the conclusions that may be drawn from this result. Table 5.3 includes these supplementary 'runs', totals for runs six and nine are marked '†' to denote GSR presence on a control sample. Control samples in all other runs were negative.

Run	Particles recovered from shooter
1	206
2	335
3	443
4*	834
5*	238
6*	431†
7*	691
8*	462
9*	221†
Mean	429
Range	628
Standard deviation	215.72

Table 5.3 Particles recovered from the shooter in all runs (including supplementary) of scenario one, with descriptive statistics

Taking all observations into consideration, including the combined runs, the conclusion that in the order of several hundred particles can be expected to be recovered from

[44] Combined 'runs' are marked by '*' in the following tables

the hands of the shooter in conditions analogous to these test firings is confirmed. The results serve to re-emphasise the observation that the particle counts varied between runs; counts ranged from 206 to 834 (standard deviation 215.72). The mean particle count recovered from the shooter was 429.

5.2.2 Scenario two

The particle counts for experimental scenario two are presented in table 5.4.

Run	Particles recovered from firearm handler
1	86
2	18
3	14

Table 5.4 Particles recovered from the firearm handler in runs one, two and three of scenario two

In all three runs of scenario two, a secondary transfer of GSR particles took place from the discharged firearm to the second handler. In other words, GSR that was deposited on the firearm during discharge was subsequently transferred to a handler upon contact. Samples from the hands of the second firearm handler yielded much lower numbers of GSR particles than the hands of the shooter, although as many as 86 GSR particles (run one) were transferred. Results were again variable; while 86 particles were detected in run one, this was markedly higher than the counts of 18 and 14 yielded from runs two and three, respectively. Notwithstanding this variation, potentially significant numbers of GSR particles were transferred in each case.

5.2.3 Scenario three

The particle counts for experimental scenario three are presented in table 5.5.

Run	Particles recovered from handshake individual
1	88
2	30
3	129

Table 5.5 Particles recovered from the handshake recipient in runs one, two and three of scenario three

A hand fer of GSR particles to the hands of the second subject in all three runs of scenario three. This represented a secondary transfer from the shooter, who had previously acquired material via a primary deposition from the firearm discharge, to a second individual who was not present at the firing. The transfer of as many as 129 particles (run three) was observed. As was the case with the counts in scenario one, the amount of GSR detected on the samples taken during the experiments varied across the three runs (88, 30 and 129). Akin to scenario two, samples that were recovered from the secondary transfer subjects yielded fewer particles than the samples taken from the shooters in scenario one (88, 30 and 129 compared to 206, 335 and 443 in the first three runs of scenario one). However, these samples (particularly in runs one and three) did yield relatively large numbers of particles (129, for example) that contrast the very low, perhaps negligible, levels of secondary contamination that have been reported in the literature and this will be discussed in section 6.2.2. It is acknowledged that in run three the possibility of a small error exists due to one GSR particle that was detected on the control sample taken from this individual (see table 5.1). However, given that only one particle was detected, it is likely that any influence of contamination would have been minimal and very unlikely to have contributed to the high particle count in run three.

In a similar manner to scenario one (section 5.2.1), further results for scenario three were generated, this time by combining counts from scenario four. The number of particles recovered from the second handshake individual was combined with the particle counts that remained at the first handshake individual in the three runs of scenario four. In this manner, three further measures of the secondary transfer in scenario three were approximated. Estimating counts in this way, as discussed in 5.2.1, does involve certain assumptions, yet it is reasonable to include these results in table 5.6 with the caveats that have previously been elucidated. The result for run six was yielded from the experimental run in which five GSR particles were recovered from the control sample taken from shooter prior to firing. However, as discussed, the contribution of any contamination to the high number of particles recovered from the

shooter is likely to have been small and therefore, the possibility that it then contributed to the number of particles transferred to the handshake recipient is slim.

Run	Particles recovered from handshake individual
1	88
2	30
3	129
4*	44
5*	51
6*	21
Mean	60.50
Range	108
Standard deviation	40.75

Table 5.6 Particles recovered from the handshake recipient in all runs (including supplementary) of scenario three, with descriptive statistics

With the inclusion of these supplementary results, the variability between runs continues to be observable; with results ranging from 21 particles to 129. An average of 60.5 particles was secondarily transferred from shooter to the recipient individual via a handshake. All six counts for this scenario were lower than the lowest particle count yielded form a shooter in scenario one (206 particles). However, in the case of runs one and three the difference between the secondary transfer particle counts and this lowest quantity recovered from the shooter was less pronounced.

5.2.4 Scenario four

When a third individual shook hands with a subject who had shaken hands with a shooter in scenario four, GSR was transferred in each of the three runs (table 5.7).

Run	Particles recovered from second handshake individual
1	18
2	22
3	12

Table 5.7 Particles recovered from the second handshake recipient in runs one, two and three of scenario four

These particles, collected from the third subject, had undergone tertiary transfer. In other words, these particles had been transferred to the shooter during firearm discharge before being secondarily transferred via a handshake, and subsequently underwent a tertiary transfer from the second to the third subject. Some variation between runs is evident (22 particles in run two and 12 particles in run three, for example), but this was not unexpected given the further variables that were introduced by initiating successive transfers. Fewer GSR particles were recovered following the tertiary transfers than were deposited during most of the secondary transfers in run three. The quantities that were recovered (18. 22 and 12) are similar to the number of particles observed in runs two and three of scenario two (18 and 14) when the 'dirty' firearm was handled by the subjects. The result for run three (12 particles) was yielded from the experimental run in which five GSR particles were recovered from the control sample taken from the shooter prior to firing. However, as discussed the contribution of any contamination to the high number of particles present on the shooter was likely to have been small. Therefore, the possibility that it would then have contributed to the number of particles transferred to the handshake recipient and from there, to the second handshake recipient, is very slim.

5.2.5 Scenario five

In all three experiments in which an individual was standing one metre behind the shooter, GSR was recovered from the hands of that individual, due to GSR that was deposited in the vicinity of the discharges. Moreover, the results in table 5.8 demonstrate that the quantity of GSR recovered from the hands of the bystanders was fairly similar across the three runs (21, 36 and 28 particles). The particle counts resulting from this deposition mechanism were similar to some of the counts encountered in scenarios two (18 particles in run two), three (30 particles in run two) and four (22 particles in run two), in which secondary and tertiary transfers took place.

Run	Particles recovered from individual in proximity
1	21
2	36
3	28

Table 5.8 Particles recovered from the bystander in runs one, two and three of scenario five

5.2.6 Summary

The particle counts for the individual experimental runs, including the supplementary runs generated by combining particle counts, for each scenario are provided for comparison purposes in figure 5.3.

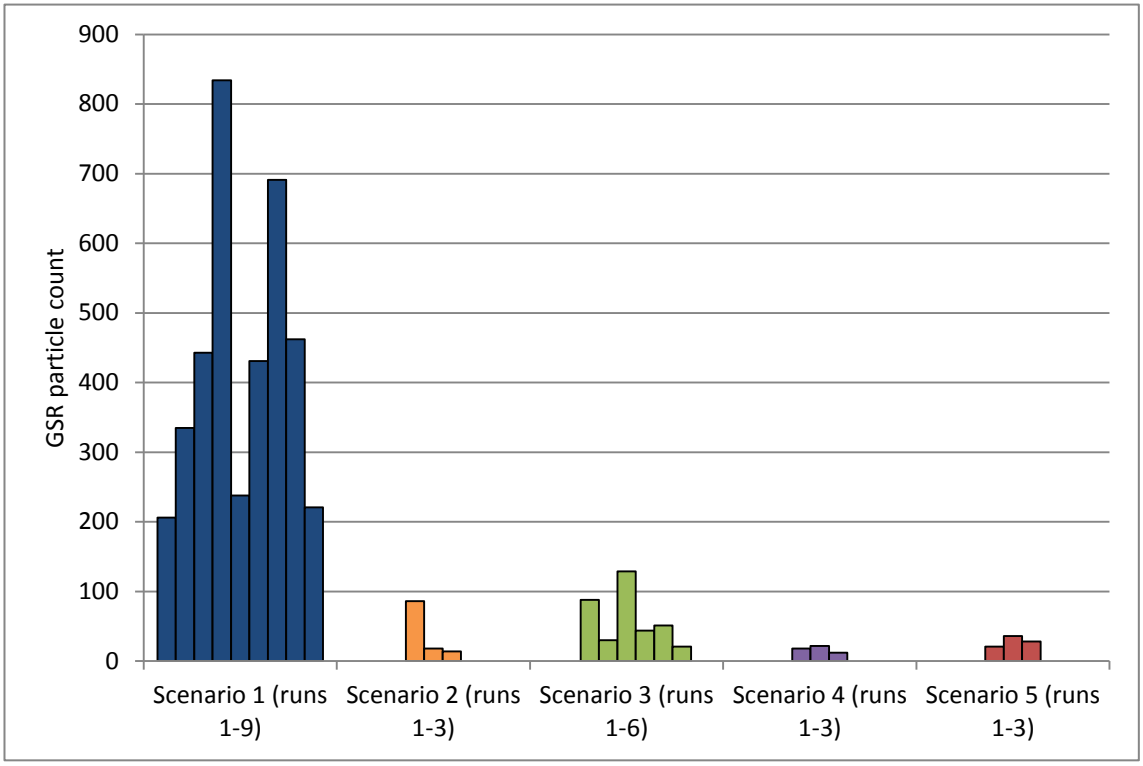


Figure 5.3 Particle counts recovered from subjects in all runs (including supplementary) of scenarios one, two, three, four and five (each bar represents the count for a single run)

Unsurprisingly, the GSR counts yielded from the shooters in the runs of scenario run stand out as being markedly higher than the counts recovered from subjects in the remaining four scenarios. Experimental scenario one aside, run one of scenario two (86 particles) and runs one and three of scenario three (88 and 129 particles) yielded the highest counts in the remaining experiments. It should be emphasised that in none of the simulated transfer or deposition scenarios did the analysis fail to detect GSR presence: all transfers and depositions were effective in resulting in the acquisition of GSR by the recipient subject.

5.3 GSR particle sizes

INCAGSR provides data relating to each detected particle according to a number of categories including 'X' and 'Y' position, brightness and size. Measurements of particle 'length' were generated and filtered to identify cases requiring manual verification and correction according to the procedures set out in section 4.3.5. Analysis of the particle size data was carried out in order to explore a number of the Research Questions (see section 3.7). The particle size data and subsequent analysis are presented in sections 5.3.1-5.3.5. For the purposes of this analysis and in a manner akin to Basu et al (1997), size classes were created into which the GSR particles were sorted. Seven classes of particle sizes were created (0-0.99µm; 1-2.99µm; 3-4.99µm; 5-9.99µm; 10-29.99µm; 30-99.99µm, and 100+µm). Particle size data for each scenario are dealt with in turn. The particles that make up the counts presented in section 5.2 have been categorised according to their size and the average and maximum particle sizes for each run included. In addition, the number of GSR particles in each size class is displayed as a percentage of the total particle count for that sample. The use of these proportional distributions renders it possible to make between-run and between-scenario comparisons of the particle size data despite the high levels of variation in particle counts both between and within the experimental scenarios.

The experimental runs that may have been influenced by a small degree of contamination owing to the results of the control samples were acknowledged in section 5.2 during the presentation of the particle counts. The same acknowledgements apply to the particle size analysis for the runs in question although, as argued previously, any influence of contamination on the results is likely to be negligible. For this reason, and owing to the impossibility of identifying which individual particles, if any, may have derived from contamination, particle size data are presented without modification.

4070 particles were detected and analysed across all sample stubs. These particles were sorted into classes according to their size and are presented in table 5.9 and proportionally, in table 5.10 and figure 5.4.

	Particles
0-0.99µm	620
1-2.99µm	1980
3-4.99µm	655
5-9.99µm	442
10-29.99µm	263
30-99.99µm	100
100+µm	10
Total Number of Particles	4070
Average Particle Size (µm)	4.90
Largest Particle (µm)	214.29
Range	213.86
Standard deviation	10.26
Percentile 50% (median)	4.16
Percentile 95%	18.67

Left: **Table 5.9** Particles per size category and descriptive statistics for overall particle population

	Particles
0-0.99µm	15.23%
1-2.99µm	48.65%
3-4.99µm	16.09%
5-9.99µm	10.86%
10-29.99µm	6.46%
30-99.99µm	2.46%
100+µm	0.25%

Right: **Table 5.10** Percentage of particles per size category for overall particle population

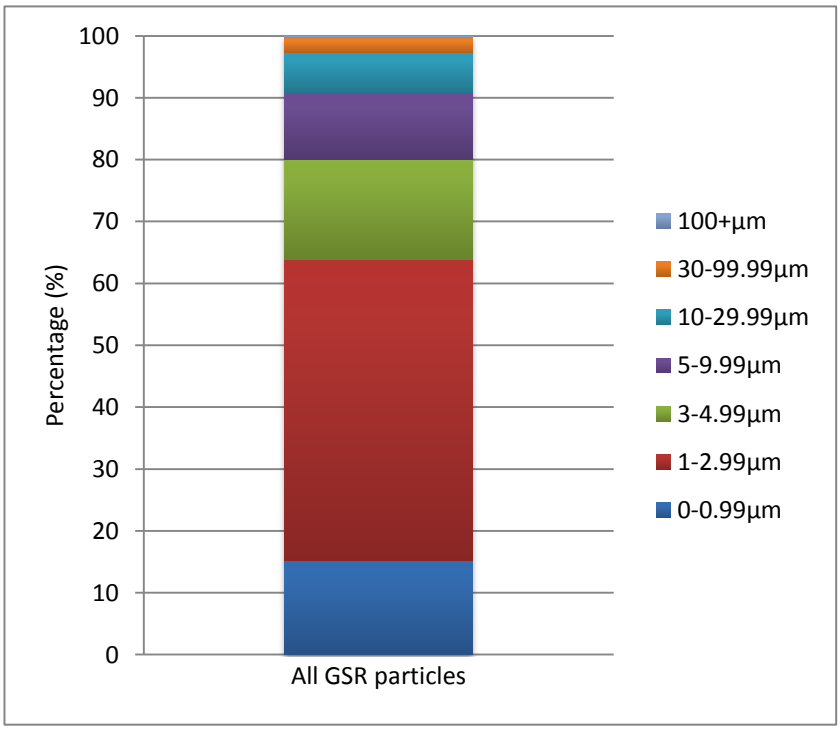


Figure 5.4 Percentage of particles per size category for overall particle population

The particle size data for the overall GSR particle population will be compared to the data for different samples throughout the following sections. The modal class of particle was 1-2.99µm and the mean particle size was 4.9µm, while proportionally, few particles were recovered that measured >10µm and very few were >100µm. It is clear that sizes of particles are heavily skewed towards the smaller particle sizes (under 10µm).

5.3.1 Scenario one

In each of the three runs of scenario one, the modal class of GSR particles was 1-2.99µm (table 5.11).

	Run 1	**Run 2**	**Run 3**
	GSRs on shooter	GSRs on shooter	GSRs on shooter
0-0.99µm	20	51	56
1-2.99µm	112	163	225
3-4.99µm	39	58	82
5-9.99µm	23	39	52
10-29.99µm	7	18	21
30-99.99µm	5	6	7
100+µm	0	0	0
Total Number of Particles	206	335	443
Average Particle Size (µm)	4.09	4.13	4.11
Largest Particle (µm)	66.05	81.4	83.55

Table 5.11 Particles per size category for runs one, two and three of scenario one

The proportional distribution of particles among the size categories in each of the three runs was remarkably similar with around 50% of the GSR particle count in each run falling within the 1-2.99µm size category (table 5.12).

	Run 1	Run 2	Run 3
	GSRs on shooter	GSRs on shooter	GSRs on shooter
0-0.99µm	9.71%	15.22%	12.64%
1-2.99µm	54.37%	48.66%	50.79%
3-4.99µm	18.93%	17.31%	18.51%
5-9.99µm	11.17%	11.64%	11.74%
10-29.99µm	3.40%	5.37%	4.74%
30-99.99µm	2.43%	1.79%	1.58%
100+µm	0.00%	0.00%	0.00%

Table 5.12 Percentage of particles per size category for runs one, two and three of scenario one

Figure 5.5 demonstrates that the distribution of particles among the size classes was very closely replicated in each of the three experimental runs. The distribution of particles apparent in this experiment suggests that an increase in the number of particles generated did not prompt a departure from the distribution. In other words, 'extra' particles were not, for example, exclusively small. It is notable that the average particle sizes for the three runs (4.09µm, 4.11µm and 4.13µm) are almost identical. In addition, the largest particles that were encountered in each of the three runs were broadly similar (66.05µm, 81.40µm and 83.55µm).

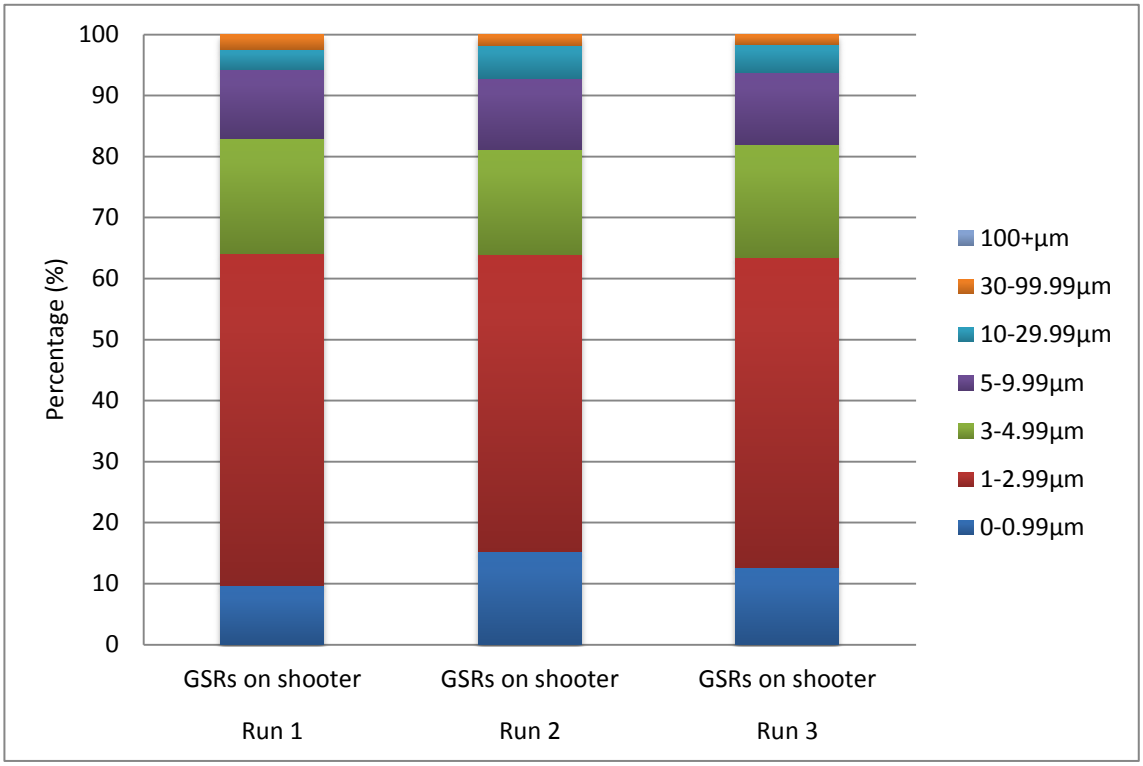


Figure 5.5 Percentage of particles per size category for runs one, two and three of scenario one

As discussed with regard to the analysis of the particle counts, further results for the GSR deposited on the shooter during firearm discharge were generated via the combination of reciprocal GSR counts from scenarios three and four. When combining the counts (in the manner described in section 5.2.1), the particle counts were also combined so that, for example, if 20 GSR particles that were 3-4.99µm in size were recovered from the transfer recipient and 15 remained at the donor surface, then it was estimated that 35 (20+15) particles measuring 3-4.99µm were initially deposited on the hands of the shooter. As with the particle counts that were generated in this manner, the particle size results produced by combining samples need to be treated with a degree of caution. The same assumptions outlined in section 5.2.1 are made and in addition, it is assumed that sampling did not favour the recovery of a certain size of particle (very large particles, for instance) over another. However, the sampling strategy was maintained in all experimental runs meaning that any slight error will have been consistent. The potential for some error in these combined results was acknowledged during the analysis and when comparing particle size data with those of the first three runs. Accordingly, results for 'runs' four to nine are marked: '*'. Table 5.11 has been extended in table 5.13 to include 'runs' four to nine that have been generated by combining data for reciprocal samples. The particle size data have been converted to percentages in table 5.14 to permit analysis of the distribution of particles within the size categories. The proportional data are displayed graphically in figure 5.6.

	Run 1	Run 2	Run 3	Run 4*	Run 5*	Run 6*	Run 7*	Run 8*	Run 9*
	GSRs on shooter	GSRs on shooter	GSRs on shooter	GSRs on shooter	GSRs on shooter	GSRs on shooter	GSRs on shooter	GSRs on shooter	GSRs on shooter
0-0.99µm	20	51	56	109	37	61	129	92	35
1-2.99µm	112	163	225	427	104	234	264	233	115
3-4.99µm	39	58	82	154	40	70	93	59	30
5-9.99µm	23	39	52	80	40	40	68	55	20
10-29.99µm	7	18	21	45	10	21	86	20	16
30-99.99µm	5	6	7	17	6	4	46	3	4
100+µm	0	0	0	2	1	1	5	0	1
Total Number of Particles	206	335	443	834	238	431	691	462	221
Average Particle Size (µm)	4.09	4.13	4.11	4.50	5.88	4.02	8.07	3.37	4.69
Largest Particle (µm)	66.05	81.4	83.55	110.55	214.29	102.46	113.27	54.64	118.62

	Run 1	Run 2	Run 3	Run 4*	Run 5*	Run 6*	Run 7*	Run 8*	Run 9*
	GSRs on shooter	GSRs on shooter	GSRs on shooter	GSRs on shooter	GSRs on shooter	GSRs on shooter	GSRs on shooter	GSRs on shooter	GSRs on shooter
0-0.99µm	9.71%	15.22%	12.64%	13.07%	15.55%	14.15%	18.67%	19.91%	15.84%
1-2.99µm	54.37%	48.66%	50.79%	51.20%	43.70%	54.29%	38.21%	50.43%	52.04%
3-4.99µm	18.93%	17.31%	18.51%	18.47%	16.81%	16.24%	13.46%	12.77%	13.57%
5-9.99µm	11.17%	11.64%	11.74%	9.59%	16.81%	9.28%	9.84%	11.90%	9.05%
10-29.99µm	3.40%	5.37%	4.74%	5.40%	4.20%	4.87%	12.45%	4.33%	7.24%
30-99.99µm	2.43%	1.79%	1.58%	2.04%	2.52%	0.93%	6.66%	0.65%	1.81%
100+µm	0.00%	0.00%	0.00%	0.24%	0.42%	0.23%	0.72%	0.00%	0.45%

Top: **Table 5.13** Particles per size category for all runs (including supplementary) of scenario one

Bottom: **Table 5.14** Percentage of particles per size category for all runs (including supplementary) of scenario one

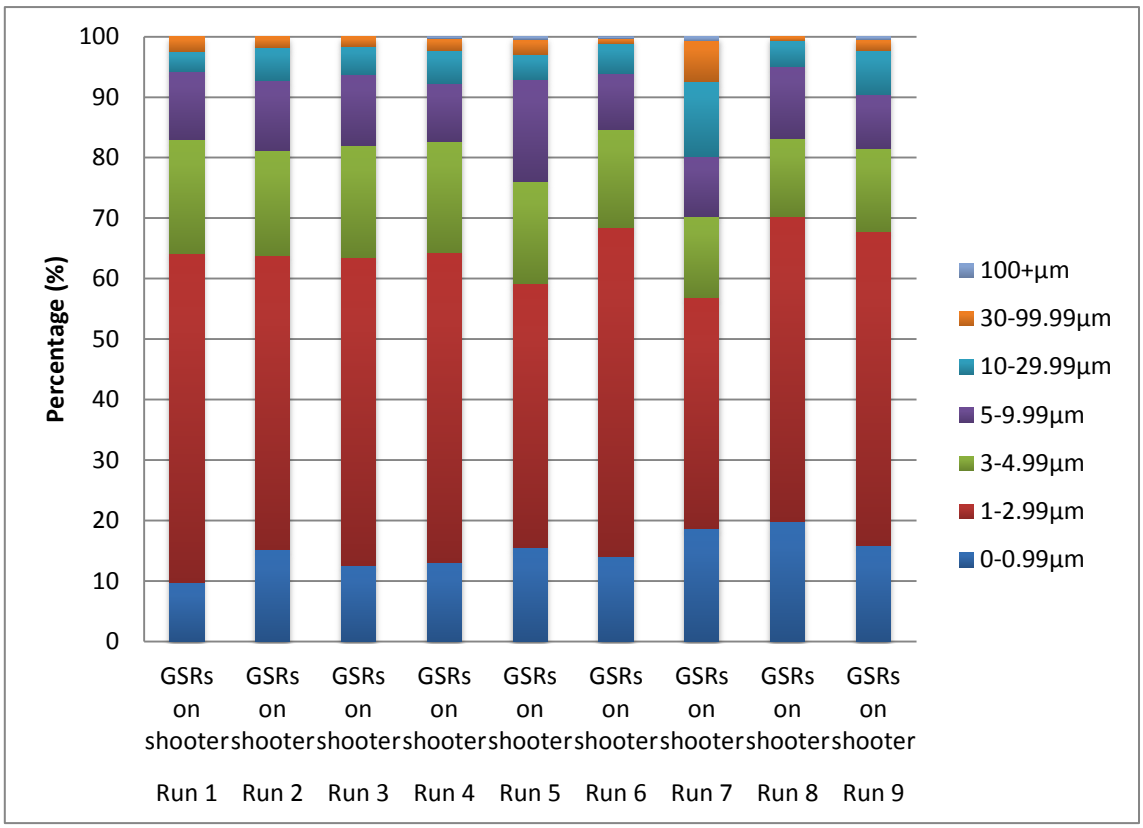


Figure 5.6 Particles per size category for all runs (including supplementary) of scenario one

Taking all nine runs into consideration, the modal class of particle in all runs was 1-2.99µm. In six of the nine runs, the average particle size of the GSR particles which were deposited on the shooter was between four and five micrometres. This figure was slightly higher in run five and slightly lower in run eight, although given the variability in the number of particles that were deposited during the discharge event (the range was 628), these figures are all remarkably similar. Run seven does stand out as having a larger average size of particle (8.07µm) and this is owing to the relatively high numbers of particles in the 10-29.99µm and 30-99.99µm categories, as well as the proportionally lower numbers of particles in the 1-2.99µm category compared to the other runs. All runs yielded large particles in the 30-99.99µm category, while five firings also resulted in the deposition of particles of over 100µm. The largest particle encountered in each run varied from 54.64µm in run eight to the extremely large particle measuring 214.29µm in run five.

From the proportional size data displayed in table 5.14 and figure 5.6, it is evident that the distribution of particles among the size categories is replicated closely, with relatively few notable

departures, across all nine runs. For example, circa 50% of recovered particles measured between 1-2.99µm in most runs, the slight exceptions being runs five and seven. Regardless of the numbers of particles that were deposited during each firearm discharge, it appears that the proportional distribution of these particles among the size categories was much less variable, this is also despite any error that may have been introduced in calculating results for runs four to nine. Run seven, as mentioned previously, perhaps represents a departure from the other results owing to a greater proportion of larger particles. In this run, 19.83% of recovered particles measured in excess of 10µm, compared to 5.83% for run one, yet this does not detract significantly from the relative uniformity of the distributions of each run of the test firing that deposited such variable quantities of GSR.

5.3.2 Scenario two

Compared to the data for scenario one, the particle size results from the three runs of scenario are somewhat more variable. Unlike scenario one, the distribution of particles among the size categories varied across the three runs (tables 5.15 and 5.16, figure 5.7) despite. It is re-emphasised that the gun was held in the same manner in each run.

	Run 1	**Run 2**	**Run 3**
	GSRs on firearm handler	GSRs on firearm handler	GSRs on firearm handler
0-0.99µm	18	4	0
1-2.99µm	50	6	1
3-4.99µm	12	3	5
5-9.99µm	2	1	6
10-29.99µm	4	3	2
30-99.99µm	0	1	0
100+µm	0	0	0
Total Number of Particles	86	18	14
Average Particle Size (µm)	2.61	6.96	6.17
Largest Particle (µm)	20.35	41.44	18.03

	Run 1	**Run 2**	**Run 3**
	GSRs on firearm handler	GSRs on firearm handler	GSRs on firearm handler
0-0.99µm	20.93%	22.22%	0.00%
1-2.99µm	58.14%	33.33%	7.14%
3-4.99µm	13.95%	16.67%	35.71%
5-9.99µm	2.33%	5.56%	42.86%
10-29.99µm	4.65%	16.67%	14.29%
30-99.99µm	0.00%	5.56%	0.00%
100+µm	0.00%	0.00%	0.00%

Top: **Table 5.15** Particles per size category for runs one, two and three of scenario two

Bottom: **Table 5.16** Percentage of particles per size category for runs one, two and three of scenario two

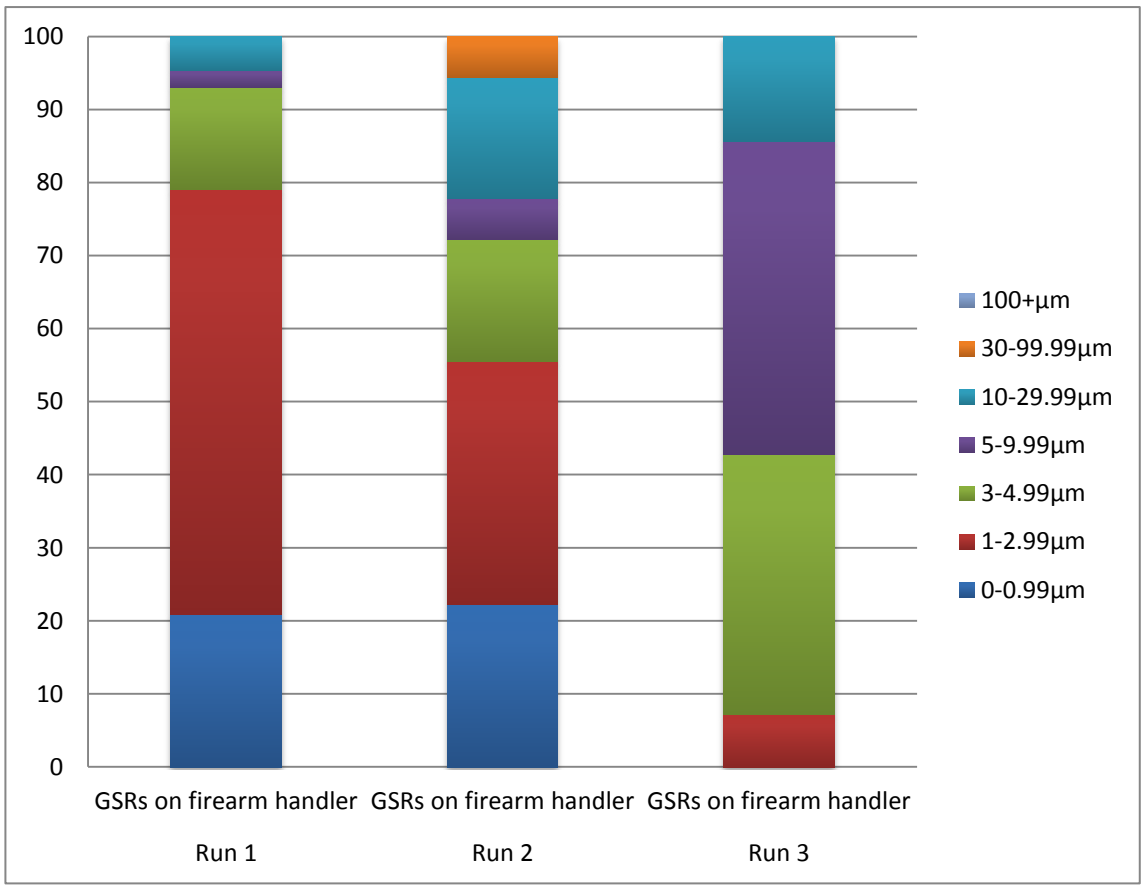


Figure 5.7 Percentage of particles per size category runs one, two and three of scenario two

Akin to the experiments in scenario one, 1-2.99µm was the modal class of particles in the first and second runs of scenario two, while in run three the modal category was 5-9.99µm. In terms of the distribution of particles among size categories, run one exhibited a somewhat similar distribution to that observed in most runs of scenario one, save for an absence of particles in the larger particle classes and a greater proportion of particles under 3µm. The size distribution of the 18 particles in run two also replicated the distributions encountered in scenario one to some degree. The particles in run three, however, represented a departure from this distribution owing to an absence of sub-micrometre particles and the fact that the bulk of the 14 particles were concentrated in the mid-range to large particle size categories.

In this scenario, the largest particles encountered tended to be smaller than those detected in the previous scenario; particles measuring 20.35µm, 41.44µm and 18.03µm were recovered in runs one, two and three, respectively. The largest

particles deposited during the firearm discharge, it seems, tended to be deposited on hands rather than on the firearm and later transferred to a firearm handler. The average particle size varied across the three runs. The average particle in run one measured 2.61µm and this was markedly smaller than the mean particle sizes encountered in scenario one, which were generally circa 4µm (ranging from 3.37µm to 8.07µm). However, the average particle size was higher in runs two and three (6.96µm and 6.17µm), owing to a relative absence of smaller particles. It appears that as well as generating variable particle counts, handling the discharged firearms resulted in the transfer of sets of particles that were variably distributed among the size categories.

5.3.3 Scenario three

The modal class of particle in each of the three runs of scenario three was 1-2.99µm, as was the case for all runs of scenario one (table 5.17, table 5.18 and figure 5.8).

	Run 1	**Run 2**	**Run 3**
	GSRs on handshake individual	GSRs on handshake individual	GSRs on handshake individual
0-0.99µm	8	6	20
1-2.99µm	40	12	73
3-4.99µm	19	7	17
5-9.99µm	15	4	11
10-29.99µm	4	0	6
30-99.99µm	2	1	1
100+µm	0	0	1
Total Number of Particles	88	30	129
Average Particle Size (µm)	4.71	4.62	4.21
Largest Particle (µm)	64.39	57.22	102.46

	Run 1	**Run 2**	**Run 3**
	GSRs on handshake individual	GSRs on handshake individual	GSRs on handshake individual
0-0.99µm	9.09%	20.00%	15.50%
1-2.99µm	45.45%	40.00%	56.59%
3-4.99µm	21.59%	23.33%	13.18%
5-9.99µm	17.05%	13.33%	8.53%
10-29.99µm	4.55%	0.00%	4.65%
30-99.99µm	2.27%	3.33%	0.78%
100+µm	0.00%	0.00%	0.78%

Top: **Table 5.17** Particles per size category for runs one, two and three of scenario three

Bottom: **Table 5.18** Percentage of particles per size category for runs one, two and three of scenario three

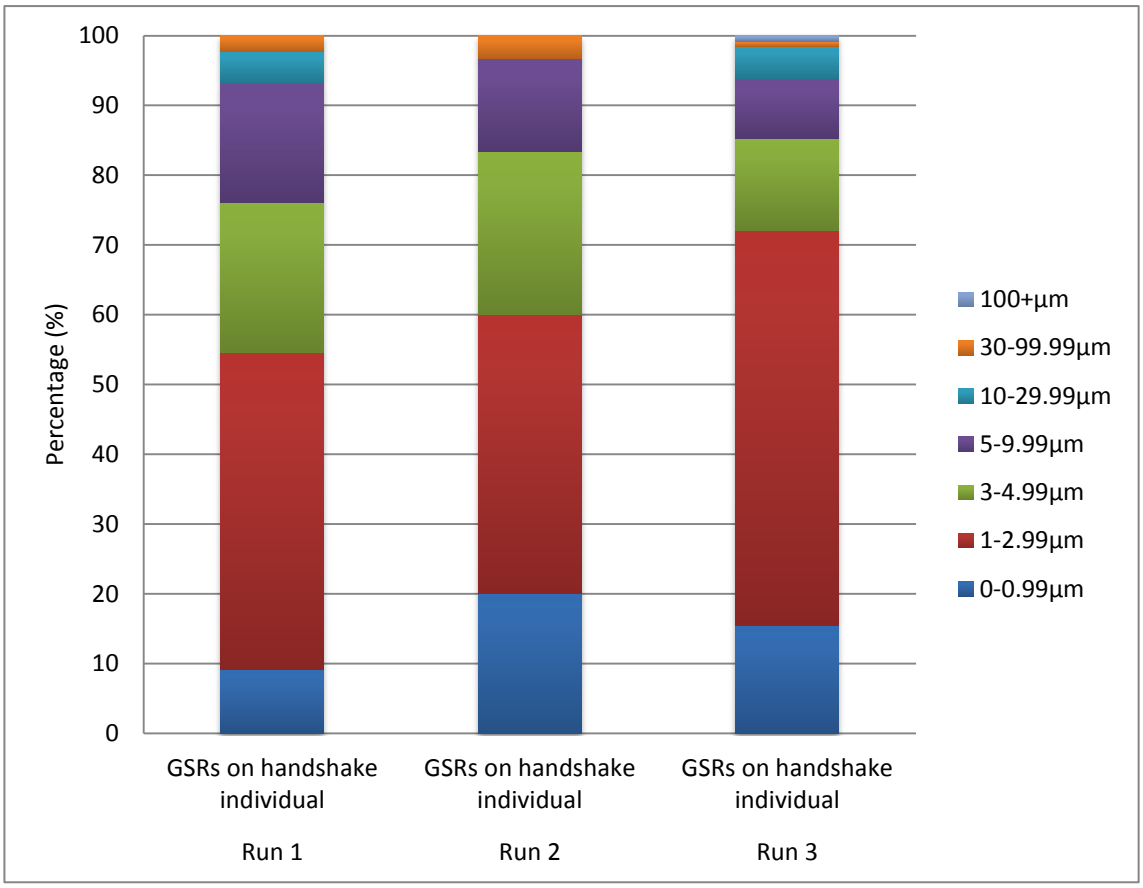


Figure 5.8 Percentage of particles per size category runs one, two and three of scenario three

The average particle sizes for the three runs of scenario three are strikingly similar (4.71µm, 4.62µm and 4.21µm), and are also very similar to the majority of the mean particle sizes of the samples taken from the shooters in run one. In each run there was at least one particle in the 30-99.99µm category, while in run three a particle measuring 102.46µm was detected. The largest particle sizes encountered in each run are similar to the largest that were recovered from the shooter in run one, suggesting that the full extent of particles (from the very smallest to the very largest) were transferred from the shooters to the individuals via handshakes, with no size of particle seemingly less likely to have undergone transfer.

With reference to the proportional data, it is clear that the particle distribution is replicated closely across the three runs. Moreover, these distributions (when compared to those in section 5.3.1) bear a close resemblance to those exhibited by the GSR particles transferred to the shooters in scenario one. The particles detected on samples in this scenario clearly represent the population of particles transferred to the

shooter initially. That is, their 'source', namely the population of particles deposited on the shooter, can be identified with reference to the particle size profile. The proportional data also show that the full extent of particles, in more or less representative proportions, seemed to be transferred from shooter to subject via the handshakes.

Supplementary results for scenario three were generated by combining counts from scenario four in the manner described in section 5.2.1. The particle size data for these extra 'runs' are provided alongside the first three runs in table 5.19. Proportional size data are calculated in table 5.20 and displayed in figure 5.9. The caveats and assumptions associated with combining results in this way have been described previously.

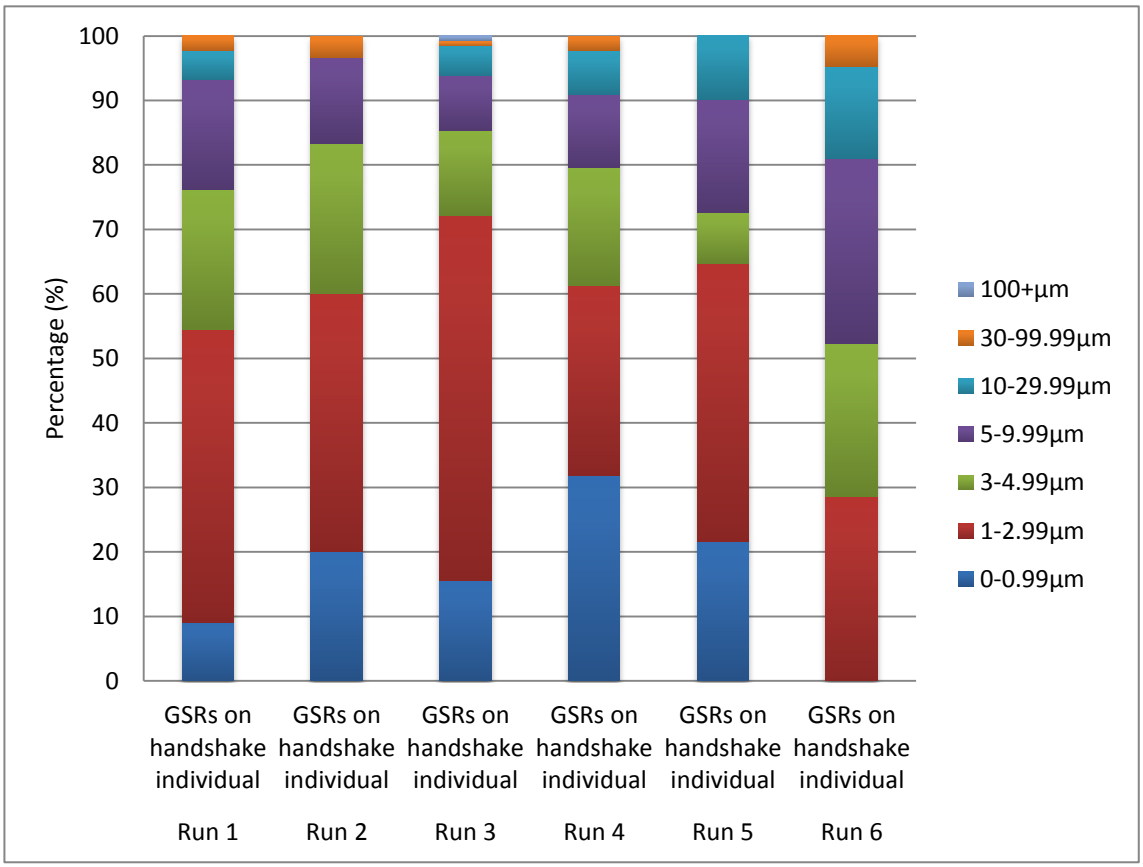


Figure 5.9 Percentage of particles per size category for all runs (including supplementary) of scenario three

	Run 1	Run 2	Run 3	Run 4*	Run 5*	Run 6*
	GSRs on handshake individual	GSRs on handshake individual	GSRs on handshake individual	GSRs on handshake individual	GSRs on handshake individual	GSRs on handshake individual
0-0.99µm	8	6	20	14	11	0
1-2.99µm	40	12	73	13	22	6
3-4.99µm	19	7	17	8	4	5
5-9.99µm	15	4	11	5	9	6
10-29.99µm	4	0	6	3	5	3
30-99.99µm	2	1	1	1	0	1
100+µm	0	0	1	0	0	0
Total Number of Particles	88	30	129	44	51	21
Average Particle Size (µm)	4.71	4.62	4.21	5.45	4.50	7.85
Largest Particle (µm)	64.39	57.22	102.46	35.47	29.39	49.19

	Run 1	Run 2	Run 3	Run 4*	Run 5*	Run 6*
	GSRs on handshake individual	GSRs on handshake individual	GSRs on handshake individual	GSRs on handshake individual	GSRs on handshake individual	GSRs on handshake individual
0-0.99µm	9.09%	20.00%	15.50%	31.81%	21.57%	0.00%
1-2.99µm	45.45%	40.00%	56.59%	29.55%	43.14%	28.57%
3-4.99µm	21.59%	23.33%	13.18%	18.18%	7.84%	23.81%
5-9.99µm	17.05%	13.33%	8.53%	11.36%	17.65%	28.57%
10-29.99µm	4.55%	0.00%	4.65%	6.82%	9.80%	14.29%
30-99.99µm	2.27%	3.33%	0.78%	2.27%	0.00%	4.76%
100+µm	0.00%	0.00%	0.78%	0.00%	0.00%	0.00%

Top: **Table 5.19** Particles per size category for all runs (including supplementary) of scenario three

Bottom: **Table 5.20** Percentage of particles per size category for all runs (including supplementary) of scenario three

Examination of the extended dataset shows that 1-2.99µm was the modal category of particle in five of the six runs (in run six, it was the joint modal class along with 5-9.99µm) and contained one particle less than the model class (0-0.99µm) in run four. The average particle sizes for the first five runs were all very similar; between 4.21µm and 5.45µm. These average particle sizes also resemble closely those that were calculated for the majority of runs in scenario one when shooters were sampled. Runs four, five and six yielded maximum particle sizes that were slightly smaller than those encountered in the first three runs, yet these may still be considered large GSR particles. Taking the 'extra' runs into account, it is evident that the transfers in these experiments involved the full range of particles, including the largest[45]. Notably, run six yielded no particles in the 0-0.99µm category and represented a departure from the other five runs in which a full range of particles was transferred. The relative absence of smaller particles in this run is responsible for the higher average particle size of 7.85µm.

The proportional data demonstrate that, despite some variation, the distribution among the size categories was fairly closely replicated by each set of particles that underwent transfer. Moreover, these distributions closely resemble those produced by the data for particles recovered from the shooter in scenario one. The only anomaly in this sense is represented by run six. The GSR particles that were transferred during this run included no particles measuring 0-0.99µm and proportionally, more particles measuring between 3µm and 9.99µm. Generally, the distributions of particle sizes between runs in scenario three were slightly more variable when compared to the well replicated distributions in scenario one. However, this is perhaps to be expected given that smaller numbers of particles were detected in scenario three, meaning that a small number of particles of a similar size will significantly inflate the relevant size category. In addition, scenario three is concerned with particles that were deposited onto hands from a firearm discharge before being transferred to a second hand by direct contact. Therefore, it is reasonable to assume that during the contact, variables such as the location of particles on the donor hand and the strength of their adherence on the hand may be

[45] Incidentally, the particle measuring 49.19µm in run six in fact underwent two transfers, as will be described in 5.3.4

responsible for the slight divergences in particle size distributions in some runs. Given this consideration, the close resemblance between the proportional distributions for runs one to five of scenario three and the distributions in runs one to nine of scenario one, is all the more notable. Evidently, the particles that were transferred via the handshakes were representative of those generated and deposited on the shooter in the first instance by the firearm discharge. Thus, the particles deposited on the shooter and the particles transferred to the subject via the handshakes are representative of similar initial populations of particles that were generated during the test firings.

5.3.4 Scenario four

Echoing the majority of experimental results so far, 1-2.99µm was the modal category of GSR particle size in runs one and two of scenario four, yet this was not the case in run three (table 5.21).

	Run 1	**Run 2**	**Run 3**
	GSRs on second handshake individual	GSRs on second handshake individual	GSRs on second handshake individual
0-0.99µm	4	5	0
1-2.99µm	7	10	2
3-4.99µm	2	2	4
5-9.99µm	3	4	5
10-29.99µm	2	1	0
30-99.99µm	0	0	1
100+µm	0	0	0
Total Number of Particles	18	22	12
Average Particle Size (µm)	3.92	3.25	8.82
Largest Particle (µm)	15.69	13.25	49.19

Table 5.21 Particles per size category for runs one, two and three of scenario four

The average particle size for runs one and two were similar (3.92µm and 3.25µm, respectively) to one another and were similar, if a little lower, to the average figures for the majority cases in scenarios one and three. The slightly lower average particle size in these runs can be attributed to the relative absence of larger particles. This observation is supported by referring to the size of the largest particle for these two

runs; 15.69µm and 13.25µm, respectively. These particles are significantly smaller than the largest particles encountered in scenarios one and three. In run three, the observations reported for runs one and two were not replicated. The absence of very small particles in this tertiary transfer resulted in the average particle size on the recipient being significantly higher (8.88µm) than that observed in the previous two runs. Meanwhile, a particle measuring 49.19µm in length was transferred from the shooter to the subject and then to the second subject in this run. It is worth making explicit that this large particle underwent a tertiary transfer. Furthermore, the presence of this particle meant that the largest particle encountered in this run echoed more closely the larger particles that featured in scenarios one and three.

Proportional size data for scenario four are provided in table 5.22 and figure 5.10.

	Run 1	**Run 2**	**Run 3**
	GSRs on second handshake individual	GSRs on second handshake individual	GSRs on second handshake individual
0-0.99µm	22.22%	22.73%	0.00%
1-2.99µm	38.89%	45.45%	16.67%
3-4.99µm	11.11%	9.09%	33.33%
5-9.99µm	16.67%	18.18%	41.67%
10-29.99µm	11.11%	4.55%	0.00%
30-99.99µm	0.00%	0.00%	8.33%
100+µm	0.00%	0.00%	0.00%

Table 5.22 Percentage of particles per size category for runs one, two and three of scenario four

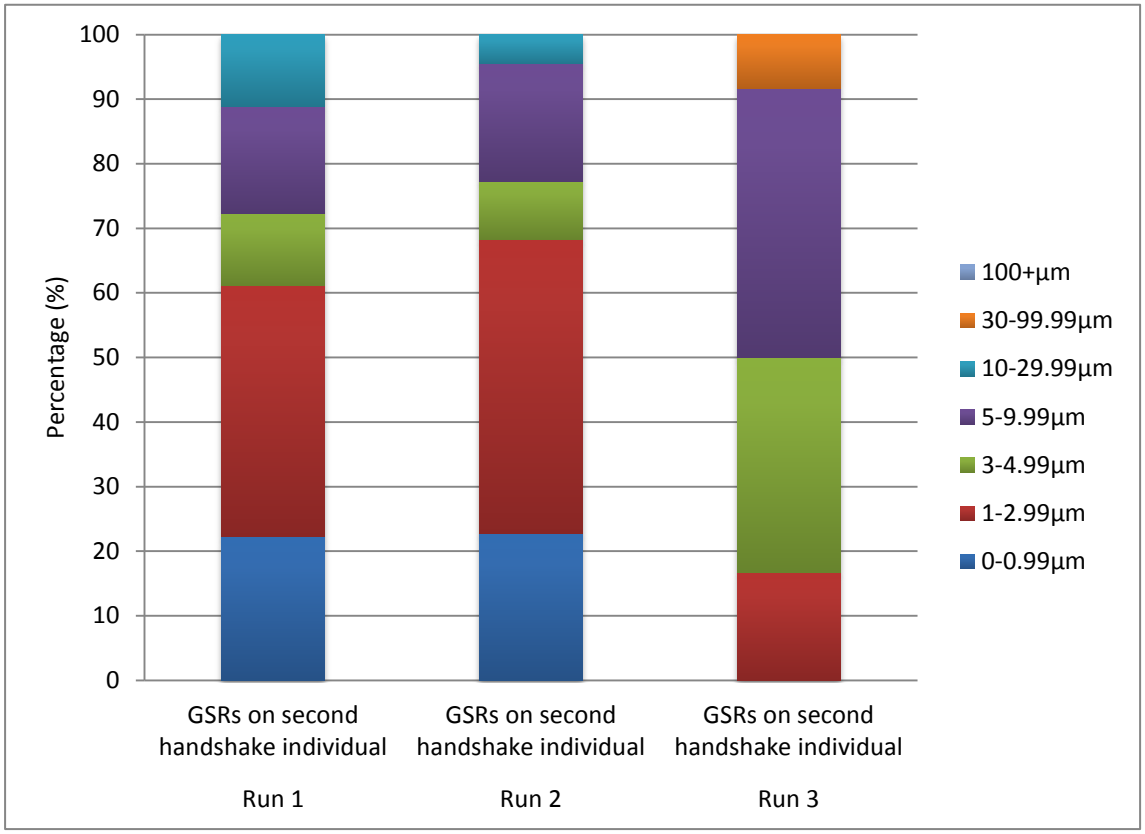


Figure 5.10 Percentage of particles per size category for runs one, two and three of scenario four

There is a clear disjunction between the particle size distributions of runs one and two the distribution for run three. Taking only the first two runs into account, the distribution of particles among the size categories, save for an absence of the particles in the largest size classes, resemble the majority of the distributions for scenarios one and three. It is clear that in these two runs, the largest particles aside, a representative range of particles was transferred from A to B and then to C – the particles received by the recipient of the tertiary transfer were similarly distributed among the size classes when compared to the population of particles deposited on the shooter in the first instance. The largest particles, it might be deduced, did not undergo tertiary transfer and either remained at the shooter (not initially transferred), or were transferred (secondarily) to the first handshake recipient and not to the third, thus they would have remained at the first handshake individual. This hypothesis will be examined in greater detail in section 5.4.2.

As mentioned, the distribution of particles in run three diverges from these trends. An absence of the smallest particles is the most notable departure, with the majority of particles measuring between 3µm and 9.99µm in length. In run three, the particles that were transferred to the third individual in the chain were not fully representative of those transferred to the shooter in terms of their distribution among the size classes: a full range of particles was not recovered. Only 12 particles were recovered from this subject and consequently an absence of particles in some categories, particularly after two transfers, is to be expected. However, in runs one and two, it was the larger particles that failed to undergo transfer to the second handshake subject meaning that in run three, the absence of the smallest particles is conspicuous. Whether this was due to a small initial population of small particles deposited on the shooter at the outset of this run, or whether they simply did not undergo transfer and remained at the shooter or first handshake individual will be examined in section 5.4.2.

5.3.5 Scenario five

In all three runs of scenario five, where particles were deposited on an individual who was standing in the proximity of the discharging gun, the modal class of recovered particles was 1-2.99µm (table 5.23).

	Run 1	**Run 2**	**Run 3**
	GSRs on proximity individual	GSRs on proximity individual	GSRs on proximity individual
0-0.99µm	7	4	2
1-2.99µm	12	18	9
3-4.99µm	1	6	4
5-9.99µm	1	4	7
10-29.99µm	0	4	5
30-99.99µm	0	0	1
100+µm	0	0	0
Total Number of Particles	21	36	28
Average Particle Size (µm)	1.88	3.67	7.27
Largest Particle (µm)	7.47	12.90	32.35

Table 5.23 Particles per size category for runs one, two and three of scenario five

The average particle sizes, however, varied greatly across the three runs. The mean was only 1.88µm in run one, suggesting that deposition from airborne GSR in this run involved the smallest particles. Indeed, over 90% of particles in this run fell into the 0-0.99µm and 1-2.99µm categories. Meanwhile, the average of 3.67µm in run two was more akin to the average particle sizes that were generally encountered in scenarios one, three and four, albeit slightly lower as a result of the relative paucity of larger particles among those deposited on the individual standing in the proximity of the firearm discharge. By contrast, the average particle size was much greater in run three (7.27µm).

	Run 1	**Run 2**	**Run 3**
	GSRs on proximity individual	GSRs on proximity individual	GSRs on proximity individual
0-0.99µm	33.33%	11.11%	7.14%
1-2.99µm	57.14%	50.00%	32.14%
3-4.99µm	4.76%	16.67%	14.29%
5-9.99µm	4.76%	11.11%	25.00%
10-29.99µm	0.00%	11.11%	17.86%
30-99.99µm	0.00%	0.00%	3.57%
100+µm	0.00%	0.00%	0.00%

Table 5.24 Percentage of particles per size category for runs one, two and three of scenario five

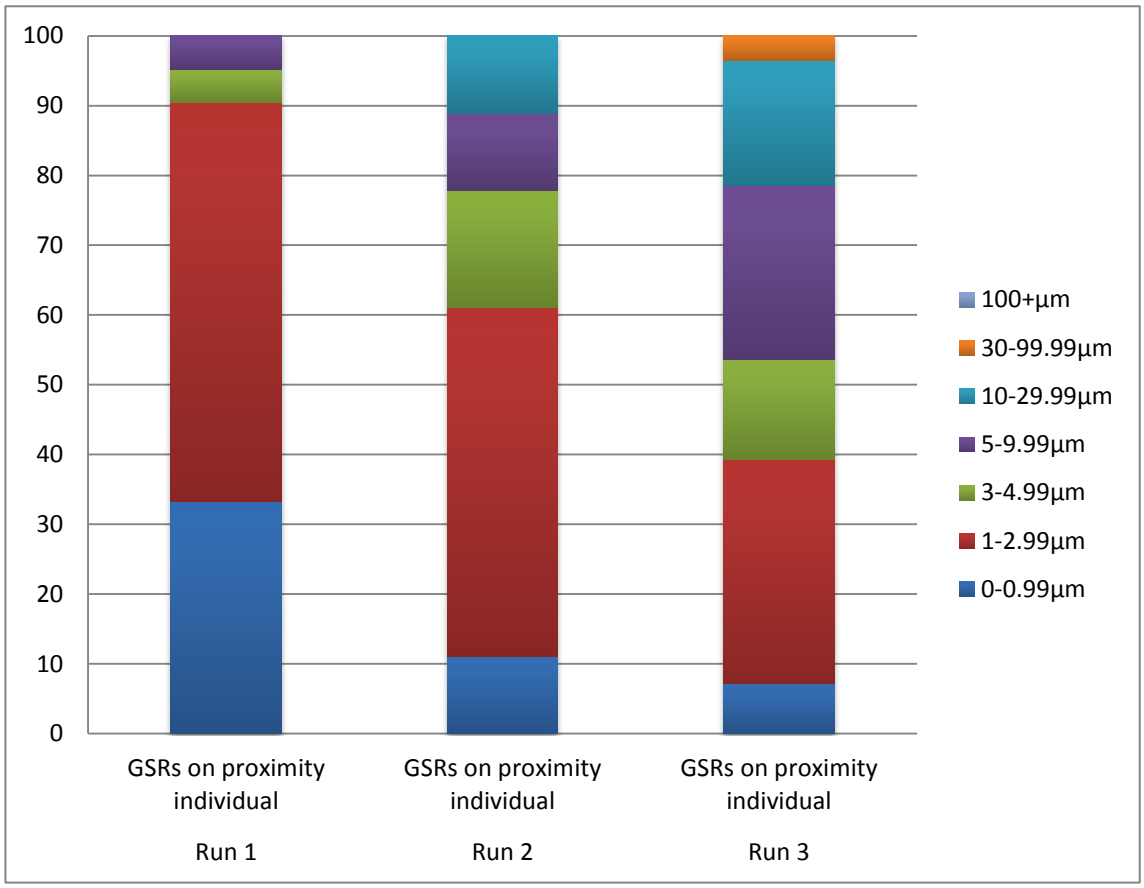


Figure 5.11 Percentage of particles per size category for runs one, two and three of scenario five

Compared to runs one and two, greater proportions of particles fell into the 5-9.99µm, 10-29.99µm and 30-99.99µm categories in run three, while only around 39% of particles fell into the 0-0.99µm and 1-2.99µm categories. The largest particles deposited on the individual in runs one and two (7.47µm and 12.90µm, respectively) are fairly small when compared to many of the largest particles encountered in the previous experimental scenarios, suggesting that larger particles may have been less likely to become airborne and be deposited on the hands of an individual a short distance from the shooter, than to have been deposited on the hands of the shooter himself. However, in run three, a particle measuring 32.35µm was recovered from the hands of the subject in proximity. 32.35µm is a lower maximum particle size than those encountered in run one but similar to the maximum particle sizes recovered in the runs of scenario two and most of the runs in scenario three. This result indicated that the deposition of larger (>30µm) particles onto an individual in the proximity of a firearm can take place. In summary, while fairly similar numbers of particles were

deposited on the nearby subjects in the three runs, the size profiles of the deposited particle populations deposited varied between the three runs.

The proportional size data provided in table 5.24 and figure 5.11, demonstrate that the distribution of particles among size class varied over the three runs. The particle size distribution in run one was heavily weighted towards the smaller particles, and therefore, differed from the particle distributions encountered in the precious scenarios. The data for run two, however, generated a particle size distribution that was not dissimilar to those encountered for some runs of scenarios one and three. However, the absence of large particles rendered this distribution more akin to runs one and two of scenario four. That most categories are represented by the particles recovered in run three means that the distribution for this run is somewhat similar to the distributions of most runs in scenarios one, although by contrast, proportionally, the smallest categories (0-0.99µm and 1-2.99µm) are underrepresented.

5.4 Transfer mechanisms and efficiency

In experimental scenarios three and four, person-to-person contacts took place between shooters and handshake recipients and between primary handshake recipients and secondary handshake recipients. These contacts initiated the secondary and tertiary transfers of GSR that have been described and analysed in this chapter so far. The following section deals with these transfers in more detail by considering the reciprocal samples that were taken during these experiments[46]. The reciprocal samples are those that were taken from donor surfaces after transfers had taken place. Equipped with these results, it was possible to calculate the efficiency of each transfer and to carry out further analysis in order to understand the dynamics and mechanisms of each simulated transfer in greater detail.

[46] N.B. These 'reciprocal' samples were used to generate the supplementary runs of scenarios one and three as described earlier in this chapter

5.4.1 Scenario three

5.4.1a Particle counts and transfer efficiency

During the runs of experimental scenario three, samples were taken from the hands of the recipient (handshake individual) and the donor (shooter) following the handshake. Using these samples, it was possible to calculate the efficiency of the transfers, to demonstrate how much GSR was transferred and what proportion, if any, remained at the donor surface. The corresponding particle counts for each run of scenario three are provided below in table 5.25.

Run	Particles recovered from shooter after handshake	Particles recovered from handshake recipient
1	746	88
2	208	30
3	302	129

Table 5.25 Post-transfer donor and recipient particle counts for runs one, two and three of scenario three

In each of the three runs, following the handshake, more particles were recovered from the shooter than from the recipient of the handshake. The highest number of particles transferred during a handshake was 129. However, the particle count yielded from the shooter in this run was not the highest, thus the large quantity of transferred particles was not the result of an unusually large quantity of initially deposited particles. It seems that this transfer may have been a particularly efficient one. To calculate the percentage of GSR particles that were transferred a measure of the particles that were initially deposited on the shooter, prior to transfer, was needed. Combining the counts recovered from the shooter and the second subject following the handshake, as described in section 5.2.1, can be used to approximate this initial population. The caveats that must be acknowledged when taking this approach are described in section 5.2.1. Using these figures, it was possible to calculate the efficiency of the transfers (table 5.26).

Run	Original particles on shooter*	Particles recovered from handshake recipient	Transfer efficiency
1	834	88	10.55%
2	238	30	12.61%
3	431	129	29.93%

Table 5.26 Transfer efficiency of runs one, two and three of scenario three

The percentage of GSR particles that were transferred from the shooter to the subject via a handshake varied across the three runs. Runs one and two were similar (10.55% and 12.61 % of particles undergoing transfer, respectively), despite the very different initial GSR counts (834 and 238). Thus, these two transfers were very similar in terms of efficiency regardless of the difference between starting GSR populations on the shooter. In run three, by contrast, a particularly efficient transfer took place in which 29.93% of GSR particles were donated from shooter to the subject via the handshake. In this run, the GSR count on the sample recovered from the handshake recipient was the highest of all three runs, yet the initial population was not the highest. It is possible to conclude that the efficiency of transfers of GSR which are initiated by hand-to-hand contacts can vary, in the same way that the amount of GSR initially deposited on a shooter can vary from firing to firing.

Supplementary results for scenario three were generated in section 5.2.3 by combining particle counts from scenario four. In table 5.27, particle counts for the six 'runs' of scenario three are provided. The use of counts for 'particles recovered from shooter after handshake' in 'runs' four, five and six is unproblematic as these were derived from samples from the shooter after one handshake. However, the same assumptions and caveats that have been described previously apply to the combined counts for 'particles recovered from handshake recipient' in 'runs' four, five and six. Again, while assumptions may be involved in combining counts in this fashion, the consistency in sampling should render any underestimation of the 'true' count as consistent as well as slight.

Run	Particles recovered from shooter after handshake	Particles recovered from handshake recipient
1	746	88
2	208	30
3	302	129
4*	647	44
5*	411	51
6*	200	21

Table 5.27 Post-transfer donor and recipient particle counts for all runs (including supplementary) of scenario three

Echoing the particle counts for the first three runs, far fewer particles were recovered from the handshake recipient than remained at the shooter, following the handshakes in 'runs' four, five and six. Taking all six runs into consideration, there was considerable variation between the numbers of particles that were transferred (standard deviation: 40.75, range: 108). However, this variation did not necessarily correlate with the numbers of particles that were recovered from the shooters, or indeed with the numbers of particles that were initially available for transfer. The efficiency of the transfers in the supplementary 'runs' of scenario three is calculated in the table below (table 5.28).

Run	Original particles on shooter*	Particles recovered from handshake recipient	Secondary transfer efficiency
1	834	88	10.55%
2	238	30	12.61%
3	431	129	29.93%
4*	691	44	6.37%
5*	462	51	11.04%
6*	221	21	9.50%

Table 5.28 Transfer efficiency of all runs (including supplementary) one, two and three of scenario three

It should be noted that the efficiency of the transfers in runs four, five and six is likely to be slightly underestimated. Notwithstanding this caveat, run three still stands out as a remarkably efficient transfer in which 29.93% of particles were transferred (compared to run five in which 11.04% of a similar initial quantity of particles underwent transfer). During the runs with the smallest initial populations of GSR, runs two and six (238 and 221 particles), 12.61% and 9.50% of particles were transferred. These were neither the most or least efficient transfers. In runs one, two, five, six and

to an extent, run four, the efficiency of the transfers was fairly similar despite variations in the initial populations of GSR (10.55%, 12.61%, 11.04%, 9.50% and 6.37%). The efficiency of the transfer in run three represents a departure from the other results. This could have been the result of random variation, or attributable to a stronger physical contact. In sum, while the efficiency of transfers was shown to vary (from 6.37% to 29.93%), the variation was not solely governed by the initial quantity of available particles.

Control samples indicated that the results for runs three and six may contain a very small error owing to the presence of a very small number of GSR particles that were present on subjects before the firing. However, as described earlier in this chapter, any contamination, if indeed it was influential, is likely to have been very limited given the large numbers of particles involved and the multiple transfer steps. Thus, its effect on results and on the accuracy of the conclusions is minimal.

5.4.1b GSR particle sizes

Examination of the particle size data was carried out in order to provide a more detailed analysis of the dynamics of the secondary transfers that took place. In this way, it could be assessed, for example, if some particles were generally more prone to transfer while others tended to remain at the donor surface. The particles detected on each sample (shooter and subject post-handshake) in each run (including supplementary runs) were categorised according to their size. Thus, it was possible to compare the sizes of particles that underwent transfer to the sizes of those that did not and which, consequently, remained at the donor surface. While to some extent, observations have already been made regarding the sizes of particles which were deposited on shooters or which were secondarily transferred, this section deals with corresponding samples from the same experimental run and test firing. Particle counts per size category for each of the six runs (including the supplementary runs) are provided in table 5.29, along with mean and maximum GSR particle sizes.

	Run 1		Run 2		Run 3	
	GSRs remaining on shooter	GSRs on individual	GSRs remaining on shooter	GSRs on individual	GSRs remaining on shooter	GSRs on individual
0-0.99µm	101	8	31	6	41	20
1-2.99µm	387	40	92	12	161	73
3-4.99µm	135	19	33	7	53	17
5-9.99µm	65	15	36	4	29	11
10-29.99µm	41	4	10	0	15	6
30-99.99µm	15	2	5	1	3	1
100+µm	2	0	1	0	0	1
Total Number of Particles	746	88	208	30	302	129
Average Particle Size (µm)	4.48	4.71	6.07	4.62	3.93	4.21
Largest Particle (µm)	110.55	64.39	214.29	57.22	81.55	102.46

	Run 4*		Run 5*		Run 6*	
	GSRs remaining on shooter	GSRs on individual	GSRs remaining on shooter	GSRs on individual	GSRs remaining on shooter	GSRs on individual
0-0.99µm	115	14	81	11	35	0
1-2.99µm	251	13	211	22	109	6
3-4.99µm	85	8	55	4	25	5
5-9.99µm	63	5	46	9	14	6
10-29.99µm	83	3	15	5	13	3
30-99.99µm	45	1	3	0	3	1
100+µm	5	0	0	0	1	0
Total Number of Particles	647	44	411	51	200	21
Average Particle Size (µm)	8.24	5.45	3.23	4.5	4.36	7.85
Largest Particle (µm)	113.27	35.47	54.64	29.39	118.62	49.19

Table 5.29 Post-transfer particles per size category remaining on the shooter and recovered from the individual for all runs (including supplementary) of scenario three

Upon an examination of the data, it is evident from the six runs that the transfers involved GSR particles representing the full range of particle sizes. Across the runs, the very smallest (sub-micrometre), to the very largest (30-100+µm) particles were transferred. Meanwhile, there was not a size of particle which appeared not to undergo transfer or one which was extremely prone to transfer. For all samples (both

donor and recipient) in the first three runs, the modal category of particles was 1-2.99µm. In runs four, five and six 1-2.99µm was the modal class of the particles remaining on the shooter. It was also the modal category of particles that were recovered from the recipient of the handshake in runs five and six (in the case of the latter, it was the joint modal category) and was one particle short of being so in run four. This aligns with the vast majority of samples comprising this investigation and indeed, with the overall particle size distribution when all particles encountered in this experimental investigation are considered (section 5.3).

Across the three runs, generally, if particles of a particular size class were found to have remained on the shooter, particles of that size range were also present on the handshake recipient. There were, however, some exceptions. In runs one and two particles measuring >100µm were not present on the handshake recipient samples but such particles were recovered from the donors, albeit only two particles and a single particle in the respective runs. Neither the 100+µm particle in run four nor the 100+µm particle in run six were transferred. Meanwhile, in run two, 10 particles measuring between 10 and 29.99µm were detected on the donor sample following transfer, yet particles of this size were absent on the recipient sample. Run six represented an anomaly in that no sub-micrometre particles were transferred, yet particles in all other size categories were present on the sample taken from the handshake recipient. These anomalies do not appear to significantly depart from the trend of a full range of different sized particles being secondarily transferred. Indeed, the absence of transfer in these categories is not surprising given the small numbers of particles of this size that existed initially.

In run three, the transfer of particles across the entire size range was observed. In this instance, however, no particles in the 100+µm category were recovered from the donor surface but a particle measuring 102.46µm was recovered from the recipient. Run three was an exception in this sense. This demonstrates that very large GSR particles can undergo secondary transfer. Examination of the maximum particle sizes for each pair of samples reveals that large GSR particles were deposited on the shooter initially. Only in the third run was the largest particle transferred and subsequently recovered from the handshake recipient. Across all runs, the very largest particles were less prone to transfer, although this may be due to the fact that, with the

exception of run three, a maximum of 12.61% of particles were generally transferred, rather than because of a physical mechanism that inhibited the transfer of these largest particles. It was previously noted that the transfer in run three was more efficient than those which took place in the remaining five runs. Being similar in terms of efficiency to runs one and two, the transfers in runs four five and six did not involve the largest particle in the population, which instead remained on the shooter.

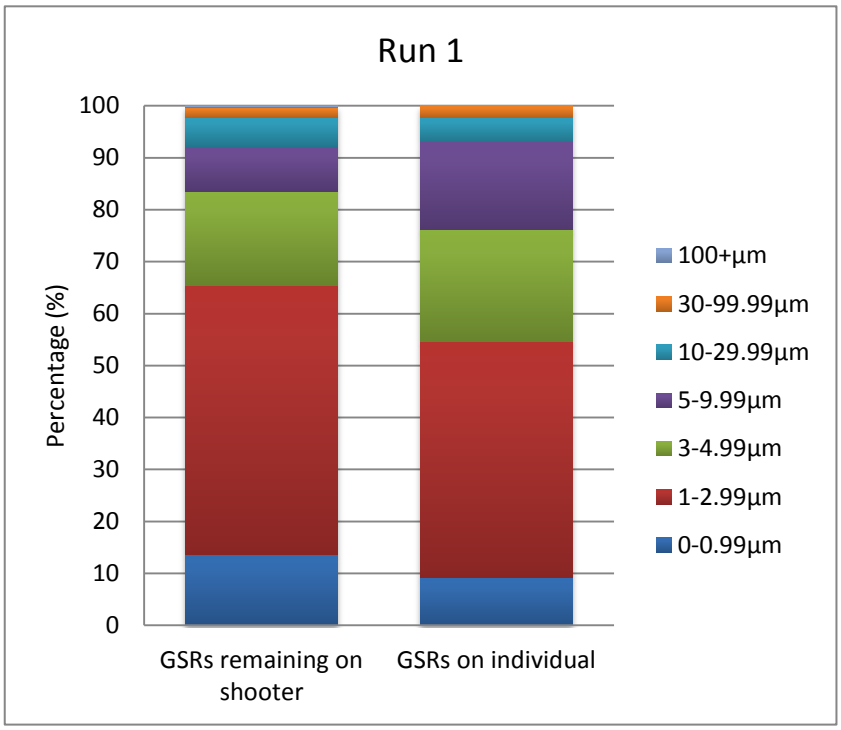
Examination of the mean particle sizes for the sample pairs in the six runs reveals that in some cases values were similar for shooter and handshake recipient (runs one and three, for example), while in some cases they were less so. For instance, in run two, the mean size of particle remaining at the shooter was 6.07µm which was somewhat larger than the mean particle recovered from the handshake recipient (4.62µm). The difference between these means can be explained by the limited transfer of the largest particles in the second run and the consequent remainder of the largest particles (including one extremely large particle measuring 214.29µm) at the donor surface. In run four the mean size of particle remaining at the shooter was higher owing to the particularly efficient transfer of the smallest (sub-micrometre) particles. In run six the mean particle size for the sample taken from handshake recipient average was much higher than that for the donor sample due to the lack of movement of sub-micrometre particles.

Further comparison of the particle size distributions of the donor and recipient samples following the handshakes can be made by examining the proportion of particles in each size category. The percentages of GSR particles in each category for each of the six sample pairs are displayed in table 5.30 and are plotted graphically for each run in figures 5.12-5.17.

	Run 1	**Run 2**	**Run 3**

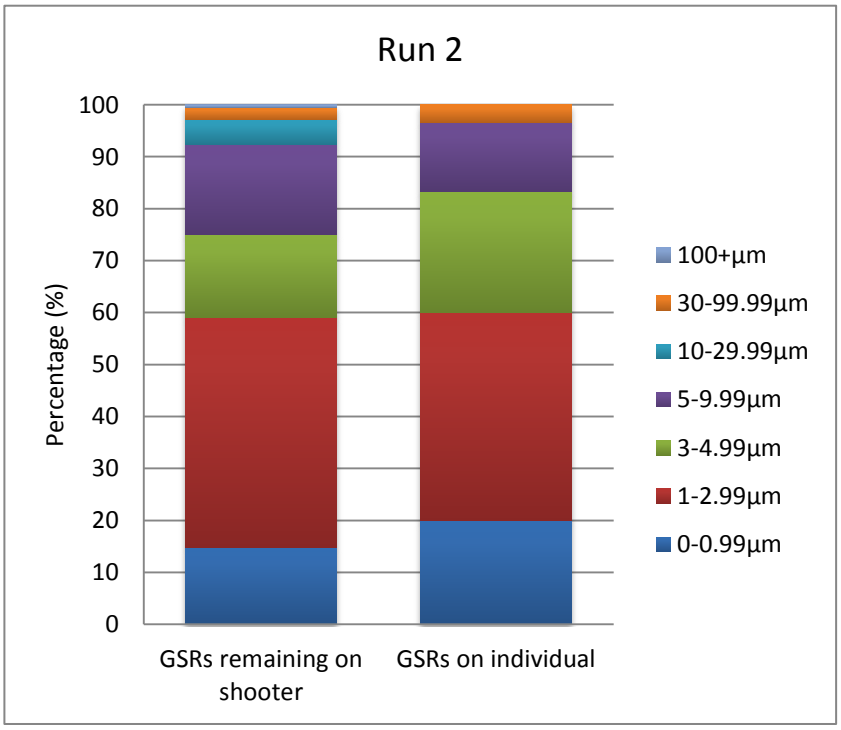
	GSRs remaining on shooter	GSRs on individual	GSRs remaining on shooter	GSRs on individual	GSRs remaining on shooter	GSRs on individual
0-0.99µm	13.54%	9.09%	14.90%	20.00%	13.58%	15.50%
1-2.99µm	51.88%	45.45%	44.23%	40.00%	53.31%	56.59%
3-4.99µm	18.10%	21.59%	15.87%	23.33%	17.55%	13.18%
5-9.99µm	8.71%	17.05%	17.31%	13.33%	9.60%	8.53%
10-29.99µm	5.50%	4.55%	4.81%	0.00%	4.97%	4.65%
30-99.99µm	2.01%	2.27%	2.40%	3.33%	0.99%	0.78%
100+µm	0.27%	0.00%	0.48%	0.00%	0.00%	0.78%

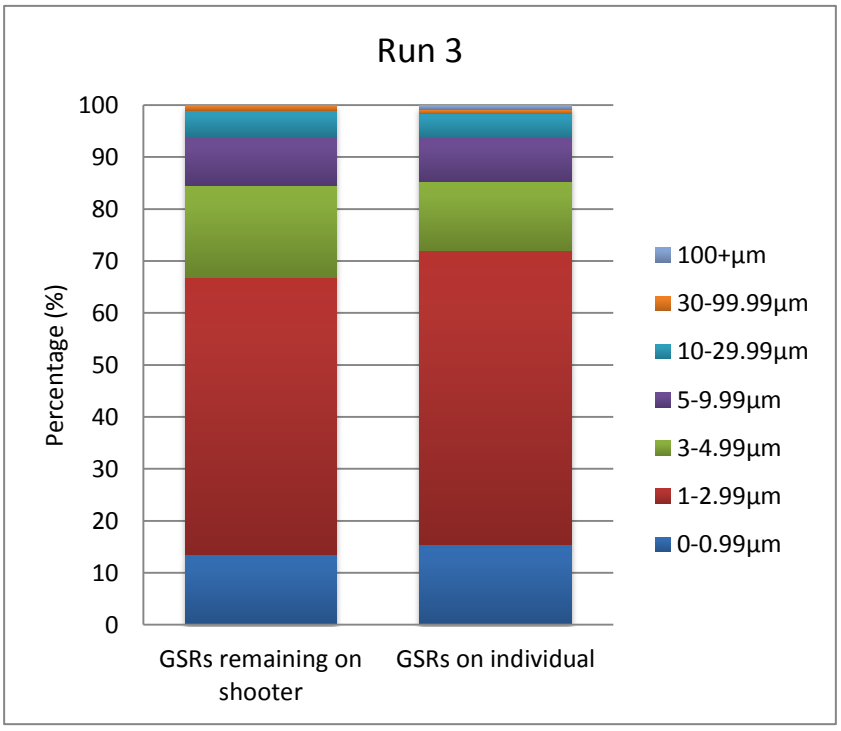
	Run 4*		**Run 5***		**Run 6***	
	GSRs remaining on shooter	GSRs on individual	GSRs remaining on shooter	GSRs on individual	GSRs remaining on shooter	GSRs on individual
0-0.99µm	17.77%	31.81%	19.71%	21.57%	17.50%	0.00%
1-2.99µm	38.79%	29.55%	51.34%	43.14%	54.50%	28.57%
3-4.99µm	13.14%	18.18%	13.38%	7.84%	12.50%	23.81%
5-9.99µm	9.74%	11.36%	11.19%	17.65%	7.00%	28.57%
10-29.99µm	12.83%	6.82%	3.65%	9.80%	6.50%	14.29%
30-99.99µm	6.96%	2.27%	0.73%	0.00%	1.50%	4.76%
100+µm	0.77%	0.00%	0.00%	0.00%	0.50%	0.00%



Top: **Table 5.30** Post-transfer percentage of particles per size category for all runs (including supplementary) of scenario three

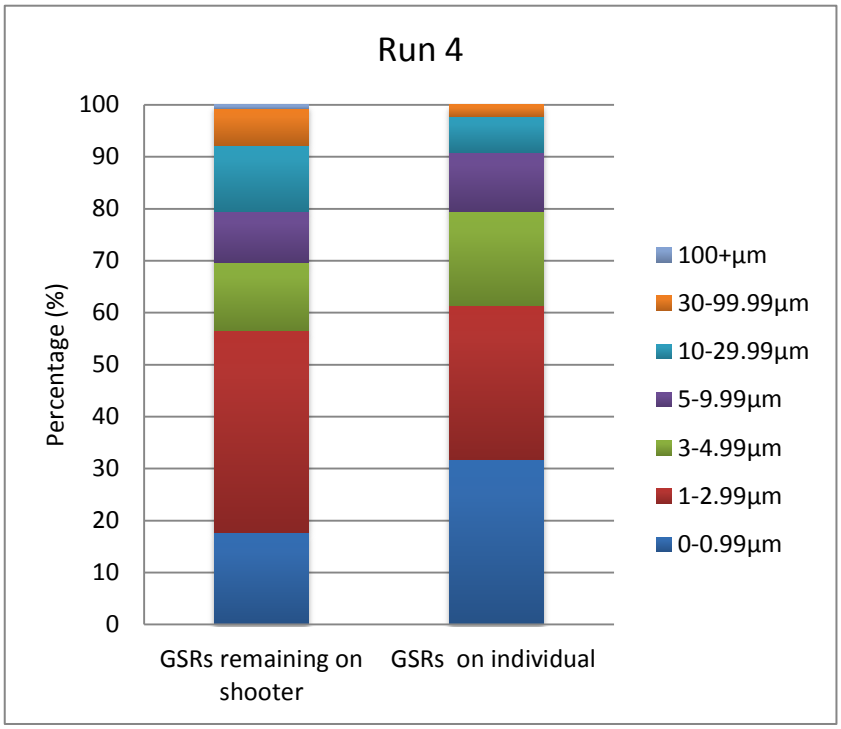
Bottom: **Figure 5.12** Post-transfer percentage of particles per size category for run one of scenario three

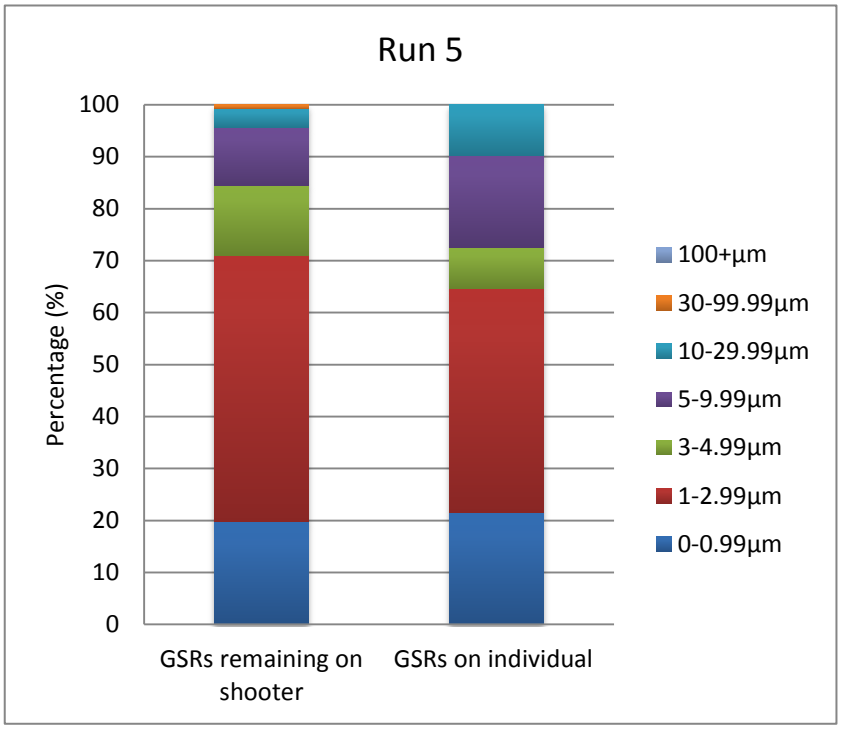




Top: **Figure5.13** Post-transfer percentage of particles per size category for run two of scenario three

Bottom: **Figure 5.14** Post-transfer percentage of particles per size category for run three of scenario three





Top: **Figure5.15** Post-transfer percentage of particles per size category for run four of scenario three

Bottom: **Figure 5.16** Post-transfer percentage of particles per size category for run five of scenario three

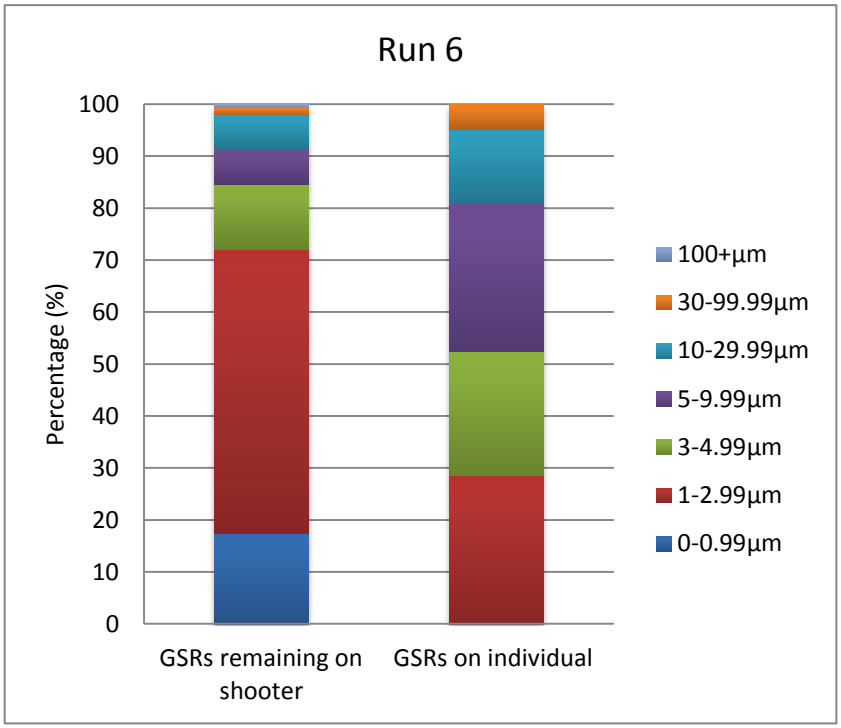


Figure5.17 Post-transfer percentage of particles per size category for run six of scenario three

The data in table 5.30 and figures 5.12-5.17 effectively demonstrate the similarity of the proportional distribution of particles among size categories between the pairs of donor and recipient samples in the first five runs. In most cases, the percentages of particles in each size class for the handshake recipients are very similar to the percentages for the corresponding donor sample (for example, 51.88% and 45.45% of particles measured 1-2.99µm on the corresponding samples in run one). When paired graphically, it is evident that the donor and recipient samples for each run correspond with one another and both appear representative of the same initial starting population of GSR particles for that particular run. Furthermore, it is apparent from the graphs that 11 of the 12 samples are fairly similar in terms of the proportional distribution of particles among the size categories, the exception being the sample taken from the handshake recipient in run six. These eleven samples appear representative of similar populations of GSR particles that were deposited during the firearm discharges. However, it should be noted that there was a relative absence of larger particles in run five. This is exemplified by the fact that, for example, in each sample, the proportion of particles measuring <3µm ranged between 54.54% and 72%.

Run six departed from the trends that have been observed. The absence of sub-micrometre particles on the recipient meant that the pair of samples differed in terms of their particle size distributions. The distribution of particles remaining on the shooter in run six did, however, resemble the distribution exhibited by the other samples in the scenario. This suggests that that a similar initial population of particles was deposited during firearm discharge in run six, yet due to the lack of sub-micrometre particle transfer, this would not be obvious from the recipient sample alone.

5.4.1c Particle sizes before and after transfer

It was possible to assess the change in the particle size distribution of the particle GSR population that was recoverable from the shooter following a transfer event. By combining particle size data in the manner outlined previously in section 5.4.1b, the population of particles that was initially present on the shooter following firearm discharge could be approximated. The data could then be compared to the corresponding data from the sample taken from the shooter following the handshake, during which some particles had been lost. The first three 'runs' in table 5.31 are derived from scenario three, while 'runs' four, five and six are a result of combining data from scenario four.

	Run 1		**Run 2**		**Run 3**	
	GSRs initially on shooter	GSRs remaining on shooter	GSRs initially on shooter	GSRs remaining on shooter	GSRs initially on shooter	GSRs remaining on shooter
0-0.99µm	109	101	37	31	61	41
1-2.99µm	427	387	104	92	234	161
3-4.99µm	154	135	40	33	70	53
5-9.99µm	80	65	40	36	40	29
10-29.99µm	45	41	10	10	21	15
30-99.99µm	17	15	6	5	4	3
100+µm	2	2	1	1	1	0
Total Number of Particles	834	746	238	208	431	302
Average Particle Size (µm)	4.50	4.48	5.88	6.07	4.02	3.93
Largest Particle (µm)	110.55	110.55	214.29	214.29	102.46	81.55

	Run 4*		Run 5*		Run 6*	
	GSRs initially on shooter	GSRs remaining on shooter	GSRs initially on shooter	GSRs remaining on shooter	GSRs initially on shooter	GSRs remaining on shooter
0-0.99µm	129	115	92	81	35	35
1-2.99µm	264	251	233	211	115	109
3-4.99µm	93	85	59	55	30	25
5-9.99µm	68	63	55	46	20	14
10-29.99µm	86	83	20	15	16	13
30-99.99µm	46	45	3	3	4	3
100+µm	5	5	0	0	1	1
Total Number of Particles	691	647	462	411	221	200
Average Particle Size (µm)	8.07	8.24	3.37	3.23	4.69	4.36
Largest Particle (µm)	113.27	113.27	54.64	54.64	118.62	118.62

Table 5.31 Pre and post transfer particles per size category on the shooter for all runs (including supplementary) of scenario three

Despite between-run variation in the number of particles that were 'lost' from the shooter during the transfer (see table 5.28), and despite the variation in the initial average particle sizes in the six runs (between 3.37µm and 8.07µm), the change in average particle size following a transfer is negligible. For example, in run one the average particle size was initially 4.50µm and was 4.48µm once the transfer had taken place. Similarly, in run four, the pre-transfer average particle size was 8.07µm and following the transfer, the average size of the recovered particles was 8.24µm. This confirms that the groups of GSR particles that underwent transfer from shooters to subjects via the handshakes were representative of those deposited on the shooter initially and that transfer was not limited to either small or large particles. In sum, a full range of particles were transferred, leaving a similar average particle size at the donor surface to that which existed prior to the transfer.

Taking only the largest particles into consideration, the only in run in which the largest particle present at the outset was subsequently transferred was run three (a particle measuring 102.46µm underwent a secondary transfer). When there was no movement of particles of a particular size, as in the case of particles measuring 30-99.99µm category in run five, this may not be suggestive of a tendency for these

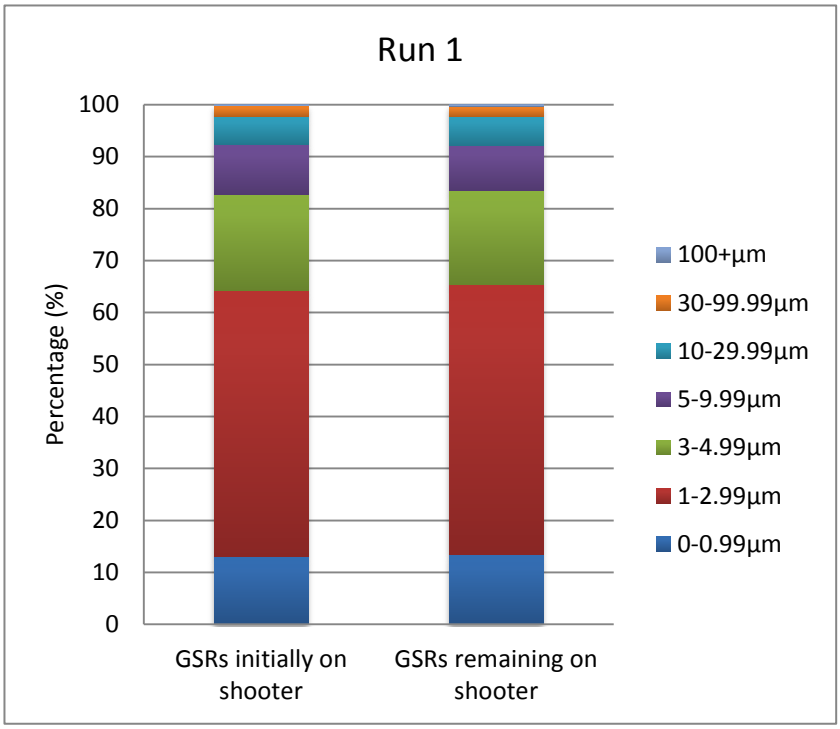
particles to remain at the donor surface. Instead, it might be reasonable to assume that they were not among the transferred proportions of particles as a result of random selection.

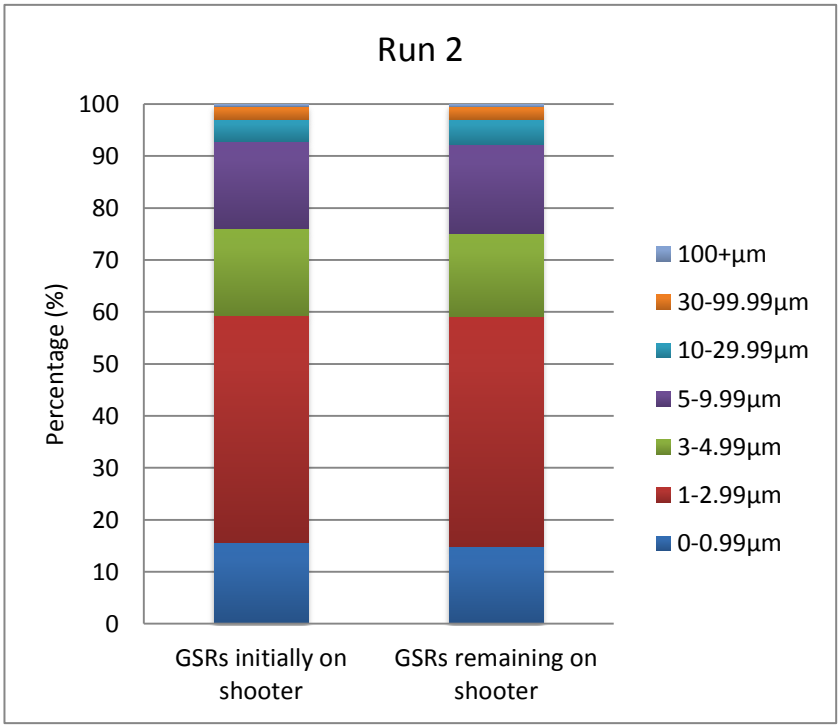
Pre- and post-transfer proportional particle size distribution data are provided in table 5.32 and are displayed graphically in figures 5.18-5.23 for each run in turn. Given what has been revealed through examination of the data in table 5.31, it is unsurprising that the distribution of particles among the size categories on the shooter was almost identical before and after the transfer in each of the six runs. A 'loss', or donation, of particles resulting from a handshake did not significantly alter the proportional distribution of particles among the size classes.

	Run 1		**Run 2**		**Run 3**	
	GSRs initially on shooter	GSRs remaining on shooter	GSRs initially on shooter	GSRs remaining on shooter	GSRs initially on shooter	GSRs remaining on shooter
0-0.99µm	13.07%	13.54%	15.55%	14.90%	14.15%	13.58%
1-2.99µm	51.20%	51.88%	43.70%	44.23%	54.29%	53.31%
3-4.99µm	18.47%	18.10%	16.81%	15.87%	16.24%	17.55%
5-9.99µm	9.59%	8.71%	16.81%	17.31%	9.28%	9.60%
10-29.99µm	5.40%	5.50%	4.20%	4.81%	4.87%	4.97%
30-99.99µm	2.04%	2.01%	2.52%	2.40%	0.93%	0.99%
100+µm	0.24%	0.27%	0.42%	0.48%	0.23%	0.00%

	Run 4*		**Run 5***		**Run 6***	
	GSRs initially on shooter	GSRs remaining on shooter	GSRs initially on shooter	GSRs remaining on shooter	GSRs initially on shooter	GSRs remaining on shooter
0-0.99µm	18.67%	17.77%	19.91%	19.71%	15.84%	17.50%
1-2.99µm	38.21%	38.79%	50.43%	51.34%	52.04%	54.50%
3-4.99µm	13.46%	13.14%	12.77%	13.38%	13.57%	12.50%
5-9.99µm	9.84%	9.74%	11.90%	11.19%	9.05%	7.00%
10-29.99µm	12.45%	12.83%	4.33%	3.65%	7.24%	6.50%
30-99.99µm	6.66%	6.96%	0.65%	0.73%	1.81%	1.50%
100+µm	0.72%	0.77%	0.00%	0.00%	0.45%	0.50%

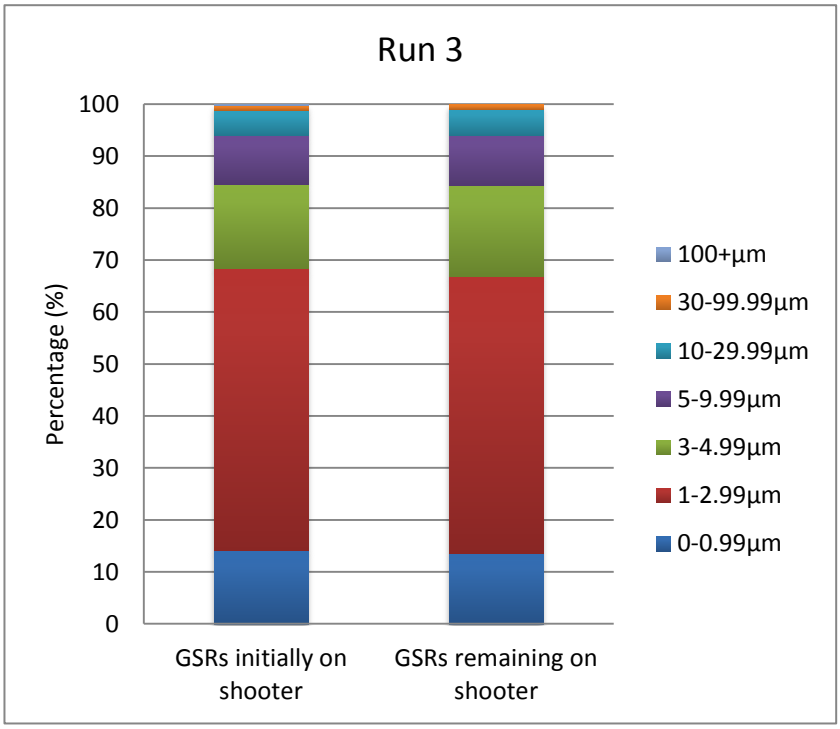
Table 5.32 Pre and post transfer particles per size category on the shooter for all runs (including supplementary) of scenario three

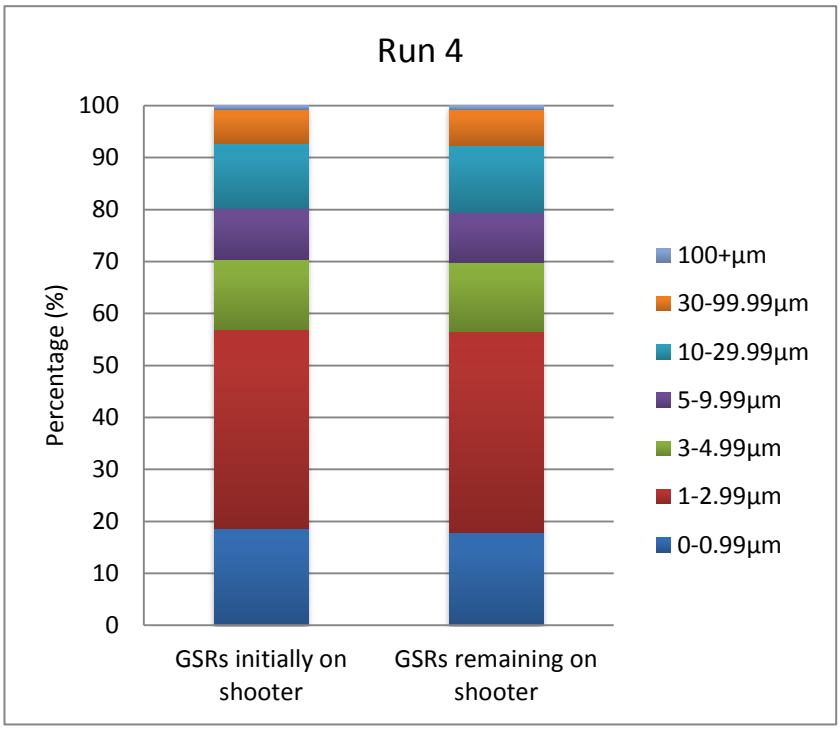




Top: **Figure 5.18** Pre and post transfer particles per size category on the shooter for run one of scenario three

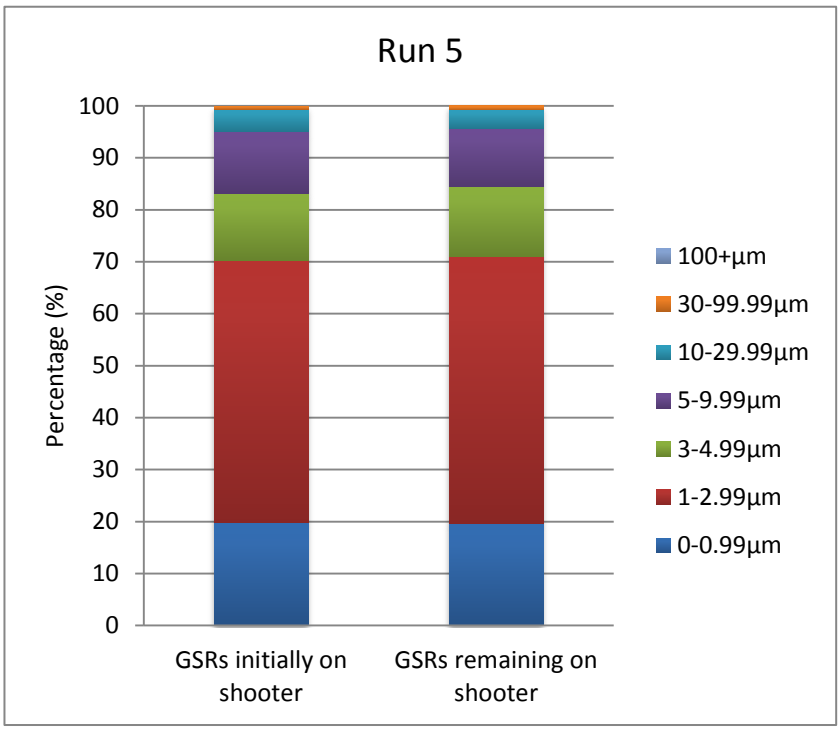
Bottom: **Figure 5.19** Pre and post transfer particles per size category on the shooter for run two of scenario three

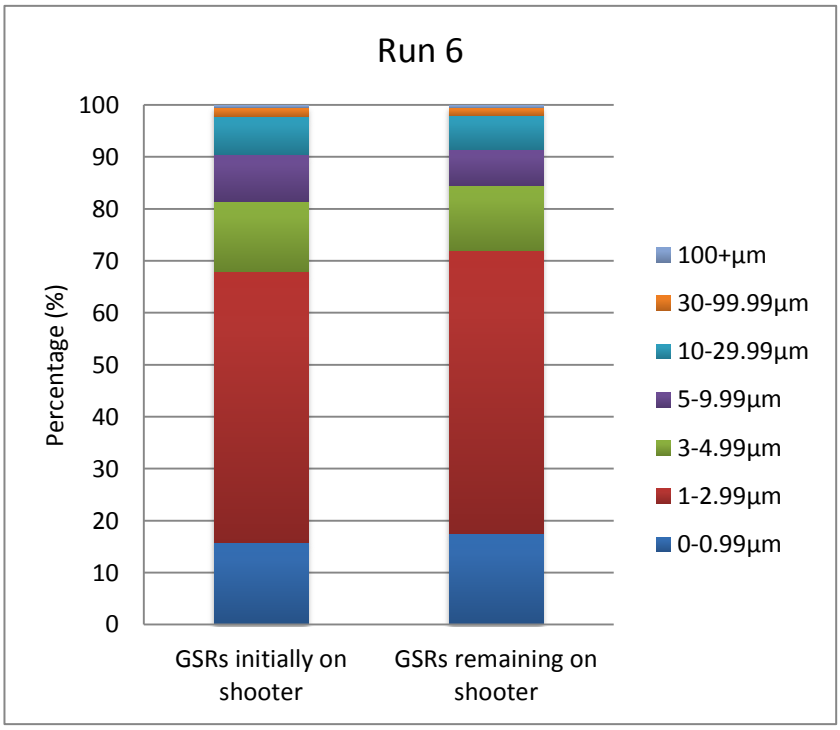




Top: **Figure 5.20** Pre and post transfer particles per size category on the shooter for run three of scenario three

Bottom: **Figure 5.21** Pre and post transfer particles per size category on the shooter for run four of scenario three





Top: **Figure 5.22** Pre and post transfer particles per size category on the shooter for run five of scenario three

Bottom: **Figure 5.23** Pre and post transfer particles per size category on the shooter for run six of scenario three

5.4.2 Scenario four

5.4.2a Particle counts and transfer efficiency

During experimental scenario four, samples were taken from the hands of the shooters, the first handshake recipients and the second handshake recipients following the transfers. As in section 5.4.1 with regard to scenario three, the efficiency and dynamics of the transfers could be examined. The corresponding particle counts for each run of scenario four are provided below in table 5.33.

Run	Particles recovered from shooter after handshake	Particles recovered from first handshake recipient after handshakes	Particles recovered from second handshake recipient
1	647	26	18
2	411	29	22
3	200	9	12

Table 5.33 Particles recovered from the participants following the transfers in scenario four

In each of the three runs, on completion of the handshakes (from shooter to first individual and from first individual to second individual), the quantity of GSR remaining on the hands of the shooter was far greater than that which was recovered from both the individual who shook hands with the shooter and the third individual in the chain (for example, 647 particles were recovered from the shooter in run one, while 26 and 18 particles were recovered from the remaining two subjects). In all three runs, the particle count at the second handshake recipient was comparable to the corresponding particle count remaining at the first handshake recipient. In runs one and two, slightly more particles remained on the first handshake recipient than were recovered from the second recipient (26 compared with 18, and 29 compared with 22), yet in the third run, the reverse was true as slightly fewer particles remained at the first handshake recipient than were recovered from the second recipient (9 compared with 12).

In a similar manner to that outlined in the analysis of scenario three, the efficiency of the transfers from A to B and from B to C could be calculated. An approximation of the initial quantity of GSR on the hands of the shooter was needed and was calculated by combining the particles remaining at the shooter (A), the particles remaining at the

first handshake recipient (B) and those recovered from the second handshake individual (C). So, for run one:

- Original particles on shooter = 647 + 26 + 18 = 691

In addition, an approximation of the particle count at the first individual following the first transfer, and prior to the second handshake, was required (this was also necessary for calculating the efficiency of the transfer from B to C). This figure was calculated by combining the particles remaining at the first handshake individual (B) with those recovered from the second handshake individual (C). So, for run one:

- Original particles on first handshake recipient (after first handshake and before second handshake) = 26 + 18 = 44

As discussed previously, combining the particle counts to generate pre-transfer approximations involves certain assumptions about the veracity of sampling, yet because the sampling strategy was uniform across all samples any slight underestimation of counts will be relatively consistent.

Run	Original particles on shooter*	Original particles on first handshake recipient*	Secondary transfer efficiency	Original particles on first handshake recipient*	Particles recovered from second handshake recipient	Tertiary transfer efficiency
1	691	44	6.37%	44	18	40.91%
2	462	51	11.04%	51	22	43.14%
3	221	21	9.50%	21	12	57.14%

Table 5.34 Transfer efficiency of the transfers in runs one, two and three of scenario four

Despite the variation in the number of particles on the shooter prior to any transfers (as expected given the variation observed between runs in scenario one), the efficiency of secondary transfers from the shooter to the first handshake recipient were similar across the three runs (6.37%, 11.04% and 9.50%; results which were calculated and presented in 5.4.1a). By comparison, the tertiary transfers between the first and second handshake individuals were much more efficient (40.91%, 43.14% and 57.14%) and resulted in similar quantities of GSR being recovered from the first and second handshake individuals at the culmination of the experiment (table 5.34). The efficiency

was similar across all three runs, but the tertiary transfer in run three was markedly efficient.

In run three, five GSR particles were recovered from the control sample taken from shooter prior to firing. However, as discussed in section 5.2.4 the contribution of any contamination to the high number of particles that were recovered from the shooter was likely to have been small. Furthermore, the possibility that those particles could have then contributed to the number of particles transferred to the handshake recipient and from there, to the second handshake recipient is minimal. Any influence of contamination is likely to have been very limited and its impact on results and on the accuracy of the conclusions that will be drawn from them is relatively minor. The implications of this contamination for interpreting the data and indeed, for experimental and forensic protocol, will be fully addressed in chapter six.

5.4.2b GSR particle sizes

Examination of particle size data was carried out in order to provide a more detailed analysis of the dynamics of the transfers which took place in scenario four. The particles detected on each sample in each run were categorised by their size and are presented in table 5.35. These permit the comparison of the sizes of particles that underwent transfer to those which remained at the donor surfaces.

	Run 1			Run 2			Run 3		
	GSRs remaining on shooter	GSRs remaining on individual 1	GSRs on individual 2	GSRs remaining on shooter	GSRs remaining on individual 1	GSRs on individual 2	GSRs remaining on shooter	GSRs remaining on individual 1	GSRs on individual 2
0-0.99µm	115	10	4	81	6	5	35	0	0
1-2.99µm	251	6	7	211	12	10	109	4	2
3-4.99µm	85	6	2	55	2	2	25	1	4
5-9.99µm	63	2	3	46	5	4	14	1	5
10-29.99µm	83	1	2	15	4	1	13	3	0
30-99.99µm	45	1	0	3	0	0	3	0	1
100+µm	5	0	0	0	0	0	1	0	0
Total Number of Particles	647	26	18	411	29	22	200	9	12
Average Particle Size (µm)	8.24	3.90	3.92	3.23	5.45	3.25	4.36	6.56	8.82
Largest Particle (µm)	113.27	35.47	15.69	54.64	29.39	13.25	118.62	16.11	49.19

Table 5.35 Post-transfer particles per size category following the transfers in runs one, two and three of scenario four

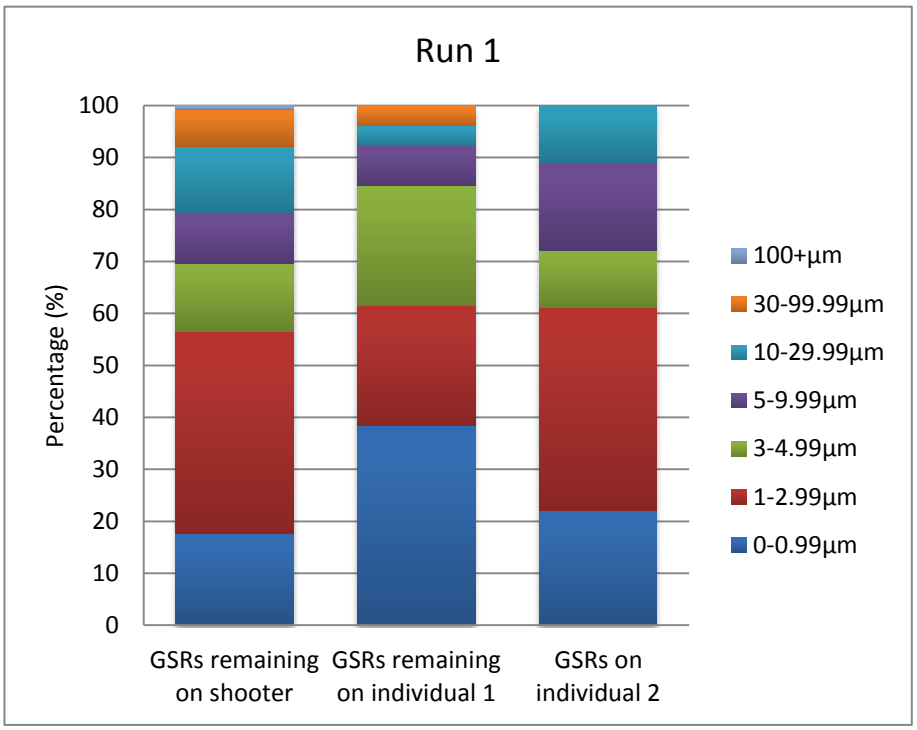
The modal class of particle for most samples (echoing the many runs of other scenarios and the overall investigation) was 1-2.99µm. This was the case for all three of the shooter samples, for two of the three first handshake recipient samples, and for two of the three second handshake recipient samples. In runs one and two, particles from almost the full range of size categories were involved in the transfers from shooter to individual one, and subsequently, from individual one to individual two. The transfer of a range of particle sizes during tertiary transfer has not been documented in the published literature on GSR dynamics. Some very small and some of the larger (but not the largest) particles underwent transfer to the third individual in the chain in runs one and two. The distribution of transferred particles among the size categories in run three was irregular. For example, no sub-micrometre particles were transferred from A to B and nor from B to C. The largest particle size data reveals that the largest particle encountered in each run was detected on the sample taken from the shooter. In other words, in each run, the largest particle was not secondarily transferred and remained at its site of deposition. In runs one and two, the largest particle recovered from the first handshake individual was larger than that detected on the second individual. However, in run three the largest particle recovered from the third individual (49.19µm) in the chain was larger than that recovered from the previous individual in the chain (16.11µm). The particle measuring 49.19µm underwent a tertiary transfer.

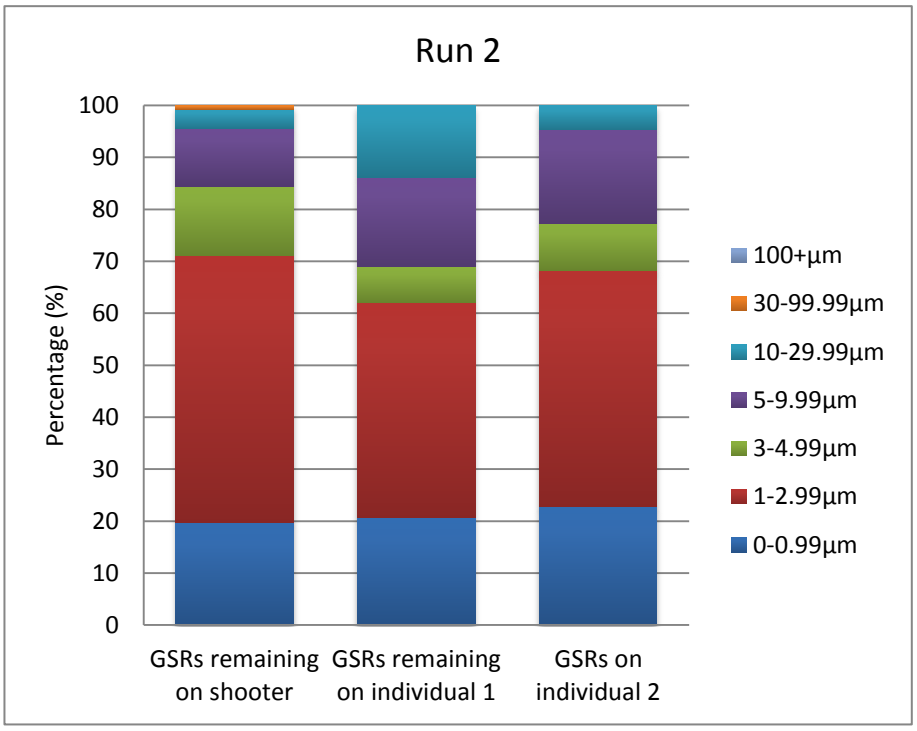
Comparison of the mean particle sizes for each sample yields few observable trends. In run one, the mean particle sizes on B and C were much lower than on the shooter, owing to the relative lack of transfer of large GSR particles that instead remained at the shooter. Average particle sizes at B and C were very similar (3.90µm and 3.92µm). In run two, at the culmination of the handshakes, the mean sized particle remaining on the shooter and the mean sized particle eventually transferred to the second handshake recipient were, again, very similar (3.23µm and 3.25µm), while the figure for the first handshake recipient was slightly higher (5.45µm). In run three, the mean particle size recovered from the individuals increased along the chain of three (4.36µm, 6.56µm, 8.82µm). This was owing to the relative lack of movement of small particles from the shooter during the first transfer. Further comparison of the similarities and differences between the particle size distributions relating to the three

samples in each run can be made by examining the proportion of particles in each size category. The percentage of GSR particles in each category for each sample is displayed in table 5.36 and figures 5.24-5.26.

	Run 1			Run 2			Run 3		
	GSRs remaining on shooter	GSRs remaining on individual 1	GSRs on individual 2	GSRs remaining on shooter	GSRs remaining on individual 1	GSRs on individual 2	GSRs remaining on shooter	GSRs remaining on individual 1	GSRs on individual 2
0-0.99µm	17.77%	38.46%	22.22%	19.71%	20.69%	22.73%	17.50%	0.00%	0.00%
1-2.99µm	38.79%	23.08%	38.89%	51.34%	41.38%	45.45%	54.50%	44.44%	16.67%
3-4.99µm	13.14%	23.08%	11.11%	13.38%	6.90%	9.09%	12.50%	11.11%	33.33%
5-9.99µm	9.74%	7.69%	16.67%	11.19%	17.24%	18.18%	7.00%	11.11%	41.67%
10-29.99µm	12.83%	3.85%	11.11%	3.65%	13.79%	4.55%	6.50%	33.33%	0.00%
30-99.99µm	6.96%	3.85%	0.00%	0.73%	0.00%	0.00%	1.50%	0.00%	8.33%
100+µm	0.77%	0.00%	0.00%	0.00%	0.00%	0.00%	0.50%	0.00%	0.00%

Table 5.36 Particles per size category following the transfers in runs one, two and three of scenario four





Top: **Figure 5.24** Particles per size category following the transfers in run one of scenario four

Bottom: **Figure 5.25** Particles per size category following the transfers in run two of scenario four

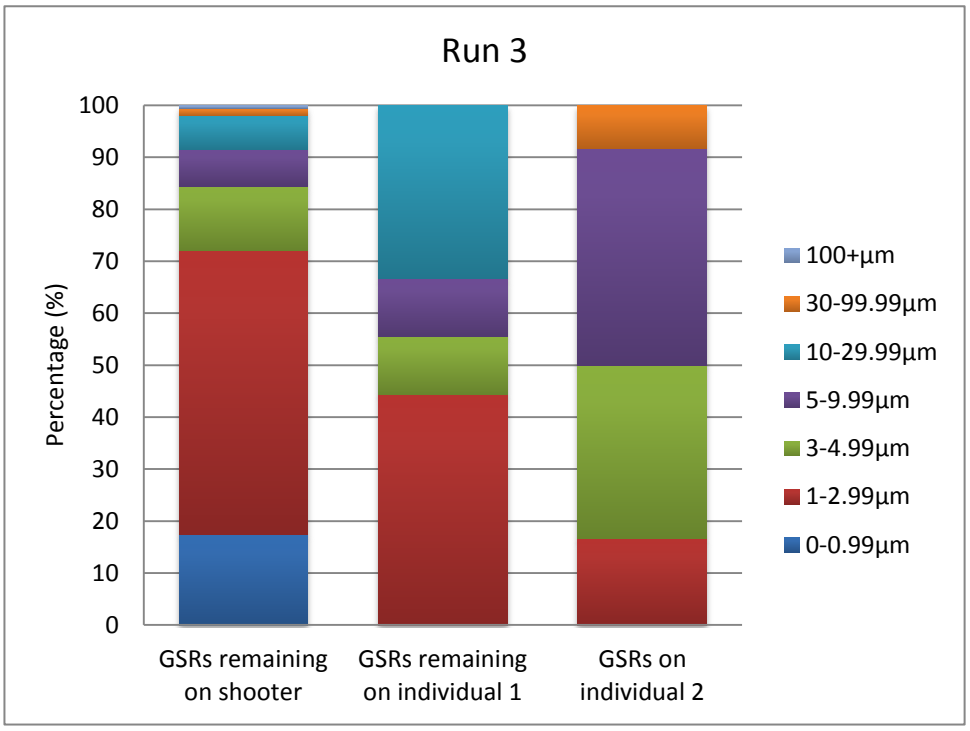


Figure 5.26 Particles per size category following the transfers in run three of scenario four

The data in table 5.36 and figures 5.24-5.26 demonstrate similarities and differences in the proportional distribution of particles among size categories between the donor and recipient samples. The particle size distribution in run two appears to be well replicated across the three samples after the culmination of the transfers. The three samples here clearly correspond and are evidently representative of the same initial population of GSR particles. The largest particles were not transferred from A to B, but particles larger than 10µm were transferred from A to B and then to C. The proportional distributions across the three samples in run two also appear to be representative of the same initial population of particles (and of a similar population of particles to those in run one) (for example, 19.71%, 20.69% and 22.73% of particles on the three samples measured 0-0.99µm). There was some transfer of the largest particles from A to B, but not to C, while particles of 10+µm were transferred from A to B and then subsequently, to C. Finally the replication of the distribution of particles was not observed in run three. While, the particles recovered from the shooter after the transfer exhibited a similar particles size distribution to the samples taken during the previous two runs, the subsequent samples represented a departure from the trend identified for runs one and two. This can be attributed to the absence of sub-

micrometre particles among the secondarily transferred particles, as well as the lack of movement of particles falling into some other classes.

5.4.2c Particle sizes before and after transfer

The change in the size distribution of the particles that were recoverable from the first handshake recipient following a transfer event was assessed. Individual 'B' in the chain received particles via a handshake, before transferring a portion of these onwards to another individual, 'C'. By combining particle size data in the manner outlined in section 5.3, the particles which were initially present on this individual following receipt of a handshake (and prior to giving one) could be approximated. The data was then compared to the corresponding data from the sample taken from individual 'B' following the next handshake, during which some particles had been transferred away (table 5.37).

	Run 1		**Run 2**		**Run 3**	
	GSRs originally on individual	GSRs remaining on individual	GSRs originally on individual	GSRs remaining on individual	GSRs originally on individual	GSRs remaining on individual
0-0.99µm	14	10	11	6	0	0
1-2.99µm	13	6	22	12	6	4
3-4.99µm	8	6	4	2	5	1
5-9.99µm	5	2	9	5	6	1
10-29.99µm	3	1	5	4	3	3
30-99.99µm	1	1	0	0	1	0
100+µm	0	0	0	0	0	0
Total Number of Particles	44	26	51	29	21	9
Average Particle Size (µm)	5.45	3.9	4.5	5.45	7.85	6.56
Largest Particle (µm)	35.47	35.47	29.39	29.39	49.19	16.11

Table 5.37 Pre and post transfer particles per size category on the first handshake recipient for runs one, two and three of scenario four

Despite some between-run variation of the number of particles that were 'lost' from the individual during the second transfer, and despite the variation in the initial average particle sizes across the three runs, the change in average particle size

following a transfer was fairly small - increasing or decreasing by between 1µm and 1.5µm. This confirms that the particles which transferred during the tertiary transfers were representative of those initially on the donor surface. Moreover, rather than involving just small or large particles, the transfers generally involved a full range of particle sizes. It should be noted, however, that the changes in average particle size here were greater than those observed following the secondary transfers from the shooter (see section 5.4.1a). This slight departure was likely to have been a function of the higher efficiency of these transfers compared with the previous transfers and of the smaller numbers of particles involved, which in turn would have meant that the movement of one or two particles of a certain size would have altered the average particle size. In the first two runs of the experiment, the largest particle was not transferred when hands were shaken, yet the particle measuring 49.19µm in run three was transferred.

Proportional pre- and post-transfer particle size distribution data are provided in table 5.38 and are displayed in figures 5.27-5.29 for each run in turn.

	Run 1		**Run 2**		**Run 3**	
	GSRs originally on individual	GSRs remaining on individual	GSRs originally on individual	GSRs remaining on individual	GSRs originally on individual	GSRs remaining on individual
0-0.99µm	31.81%	38.46%	21.57%	20.69%	0.00%	0.00%
1-2.99µm	29.55%	23.08%	43.14%	41.38%	28.57%	44.44%
3-4.99µm	18.18%	23.08%	7.84%	6.90%	23.81%	11.11%
5-9.99µm	11.36%	7.69%	17.65%	17.24%	28.57%	11.11%
10-29.99µm	6.82%	3.85%	9.80%	13.79%	14.29%	33.33%
30-99.99µm	2.27%	3.85%	0.00%	0.00%	4.76%	0.00%
100+µm	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 5.38 Pre and post transfer percentage of particles per size category on the first handshake recipient for runs one, two and three of scenario four

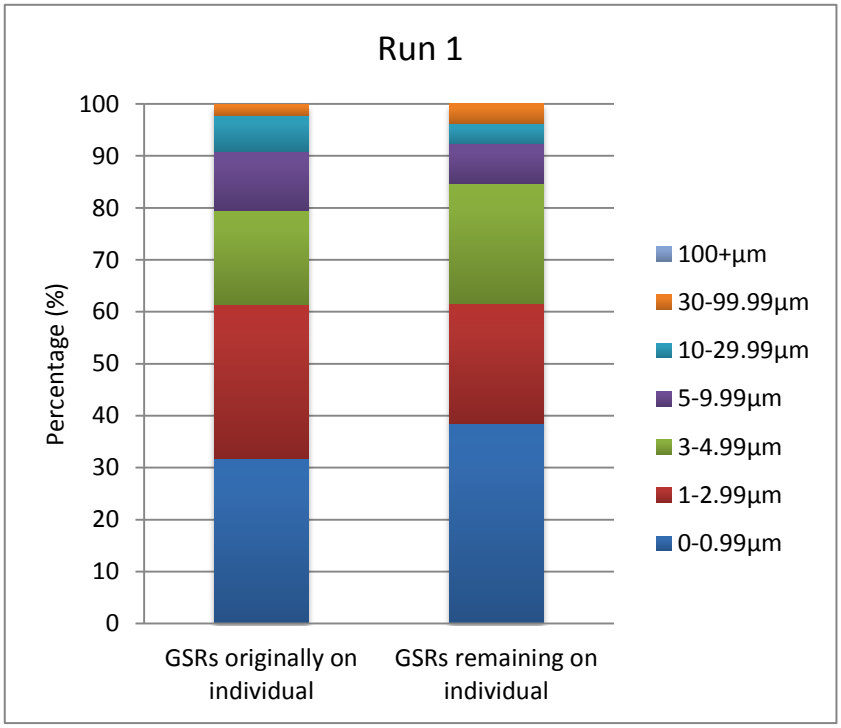


Figure 5.27 Pre and post transfer percentage of particles per size category on the first handshake recipient for run one of scenario four

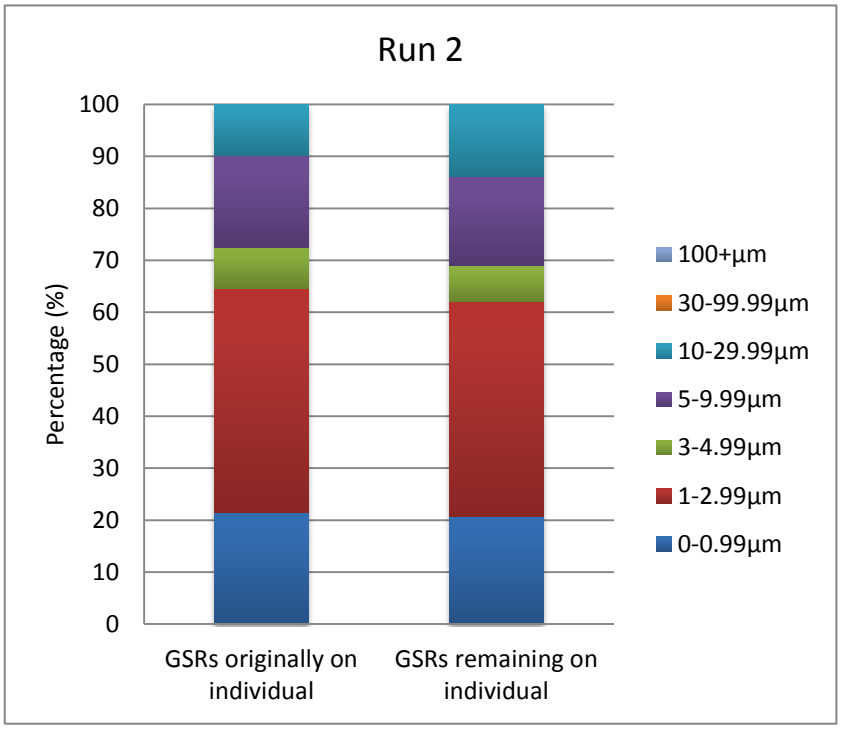


Figure 5.28 Pre and post transfer percentage of particles per size category on the first handshake recipient for run two of scenario four

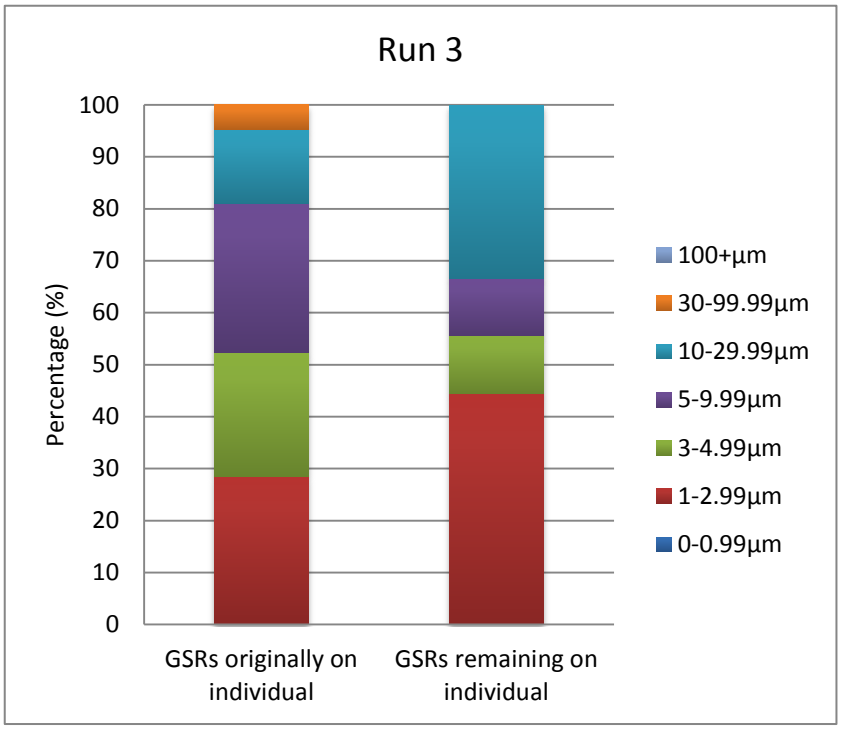


Figure 5.29 Pre and post transfer percentage of particles per size category on the first handshake recipient for run three of scenario four

Given what has been revealed through examination of the data in table 5.36, it is unsurprising that the distribution of particles among the size categories on the individual was, largely unchanged before and after the tertiary transfer in each of the three runs. A 'loss', or donation, of particles resulting from a handshake did not significantly alter the proportional distribution of particles that were recoverable from the second individual in the chain. Proportions of particles were generally maintained, confirming that the number of particles transferred from each size category was representative of the initial proportion in that category. Run three, in some respects, did depart slightly from this trend, although so few particles (nine) remained that it is sufficient to note that most categories which were populated initially, remained populated following the transfer. On the other hand, proportionally, the pre- and post- data for runs one and two are strikingly similar. This is despite transfers of around 41% and 43% of the original particles, respectively.

5.5 Observations

In this section, an account will be provided of some of the observations that were made during the analysis. In particular, a number of notable observations were made regarding particle morphologies, shapes and forms.

5.5.1 Particle shape and morphology

INCAGSR produced a small image of each particle of each feature it identified. However, these images were of insufficient resolution to clearly observe particle shapes and forms. To supplement the particle size analysis presented in section 5.3 a manual survey of a number of samples was carried out in order to identify whether the particle shapes and forms reported in the literature were present. In light of the findings presented by Brozek-Mucha (2011) (see section 3.4.4a), this survey was also carried out to determine whether particle shapes and forms may have been responsible for some of the variation in particle counts that was discussed in section 5.2.

The majority of particles measured <3µm and appeared as small fragments small spheres, or grain-like specks under the SEM. Owing to the limitations of the equipment under the settings required for GSR analysis and detection, imaging and closer inspection of individual features was limited to the larger particles (>c.10µm) encountered during the analysis. Six samples, including both shooters and transfer recipients, which had yielded notable quantities of larger particles were selected for this further survey (see table 5.39).

Scenario/run	Sample stub
Scenario one run 1	Shooter
Scenario one run 2	Shooter
Scenario three run 1	Shooter, post transfer
Scenario three run 1	Secondary transfer recipient
Scenario three run 3	Secondary transfer recipient
Scenario four run 1	Shooter, post-transfer

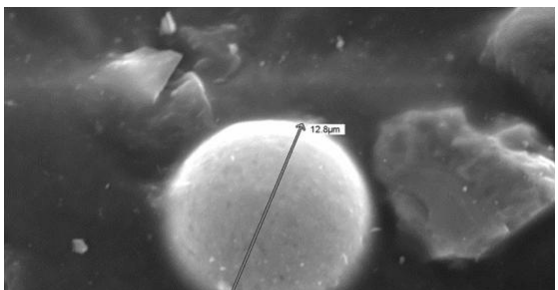
Table 5.39 Samples selected for particle morphology survey

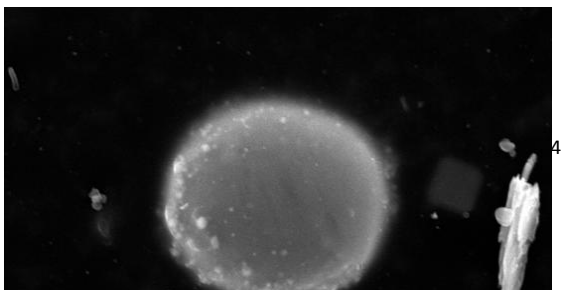
The appearance, morphology and structure of GSR particles produced by different ammunition have been well studied in the literature (see section 3.2.2, Meng and

Caddy 1997, Brozek-Mucha 2007 and Collins et al 2003, for example). However, the novelty of the observations made here is that a number of them relate to GSR particles that underwent secondary transfer. These observations also represent an account of the GSR particles deposited on the shooter when 9mm Luger 95 grain jacketed soft point 9P1 ammunition (manufactured by FEDERAL Ammunition) is fired from a SIG Sauer P226. In establishing the similarity of particle morphologies observed here to those relating to other types of ammunition, the applicability of the experimental findings to other firing scenarios is demonstrated.

Basu (1982) distinguished GSR particle shapes and morphologies according to a number of categories, namely; 'regular spheroids', 'nodular spheroids' and 'irregular spheroids'. In a similar manner, when examining larger particles during the present investigation, recurrent particle shapes were noted. It became clear that, among the larger (c.10µm and above) particles, several labels were appropriate for describing the particle shapes which were commonly encountered, namely; 'spheres', 'irregular spheres' and irregular 'shard-like' forms, or 'plates' (the latter acknowledged by Brozek-Mucha 2007, p.400).

Spheroid GSR particles, measuring from a few micrometres to >10µm, were observed during the analysis phase of this study. Examples of this 'classic' shape were found on samples taken from the shooter, as well as those taken from the transfer subjects. Instances of much smaller (sub-micrometre and 1-2µm in diameter) were encountered but proved difficult to image. However, by no means were GSR particles characterised by this 'spheroid' shape. It could be argued that the 'classic' image of a GSR particle photographed using an SEM is perhaps slightly misleading in that it does not reflect the array of different shapes and sizes of GSR particle that might be deposited during a firearm discharge. Images of a selection of particles that exhibited a 'spheroid' shape are included in figure 5.30.





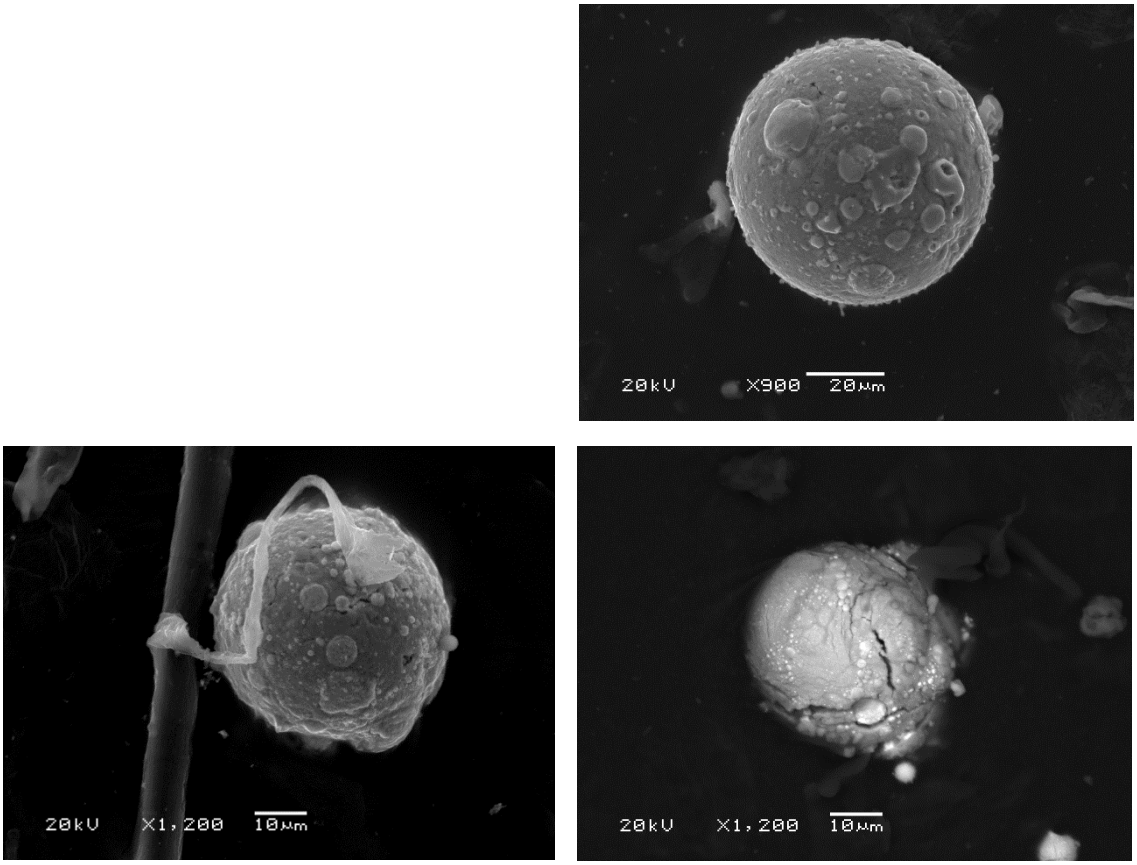


Figure 5.30 Spherical GSR particles detected during the sample analysis

A number of particles were encountered which could be labelled 'irregular' spheres. These particles exhibited much more 'layered', 'pitted', or 'clustered' irregular surfaces, and an elongated, irregular, or 'broken' shape which departed somewhat

from the regular spheres pictured in figure 5.30. The degree and nature of the 'irregularity' varied greatly (figure 5.31) and particles varied in size. They were found not only among the particles that were recovered from the shooters, but also on samples that were taken from transfer subjects.

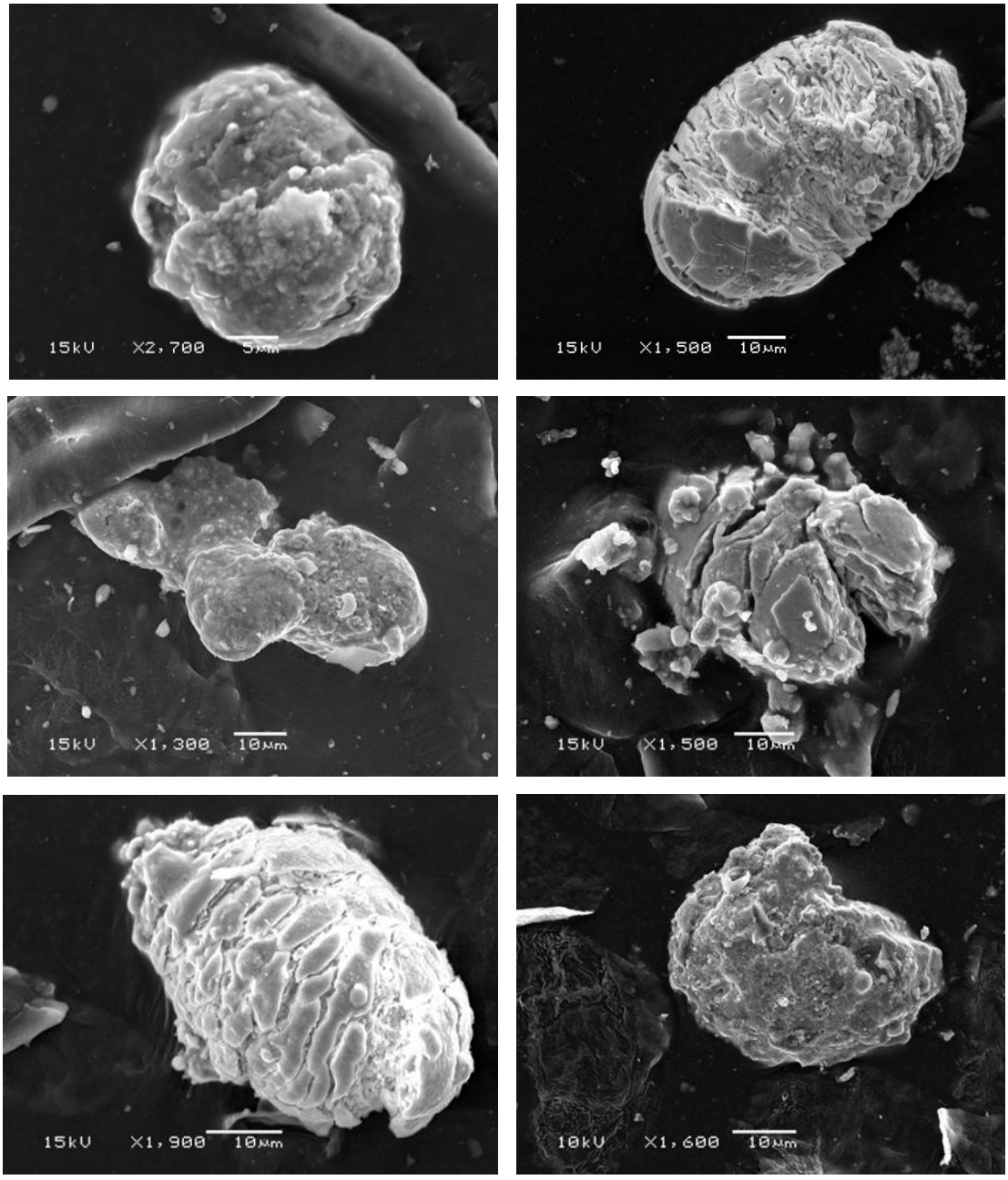


Figure 5.31 Irregular spherical GSR particles detected during the sample analysis

Upon closer examination of the surface of one of the particles in figure 5.29 at a higher magnification, the surface texture was revealed in more detail. Interestingly, small

(<1µm) spheres were found fused to the surface alongside more angular, 'flint-like' forms (figure 5.32).

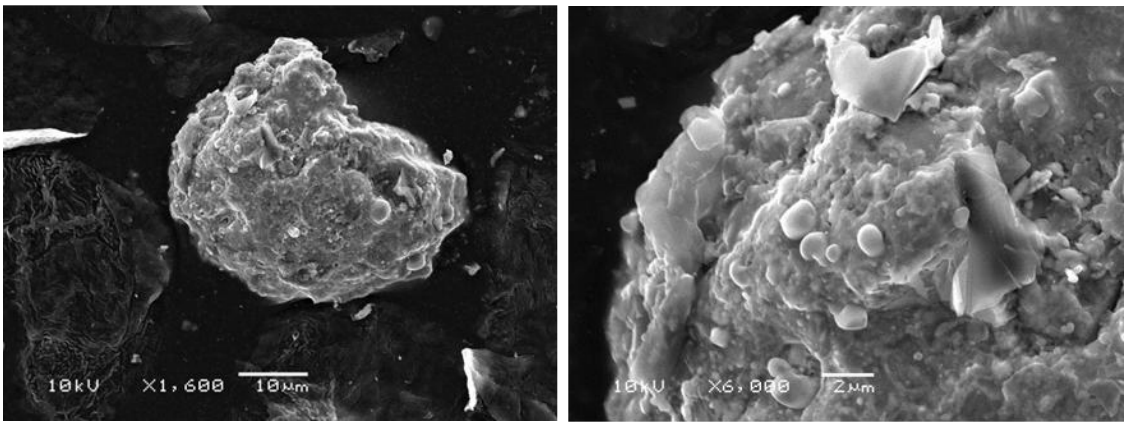


Figure 5.32 An irregular GSR particle and its surface texture composed of sub-micrometre particles and 'flint-like' forms

In contrast to the morphological features exhibited by the particles described thus far, a number of particles were found that were characterised by oblong shapes, the outline of which was angular and irregular. Some of these particles appeared so angular that they resembled shards of glass and were therefore deemed appropriately categorised as angular 'shard' forms or 'plates' (figure 5.33).

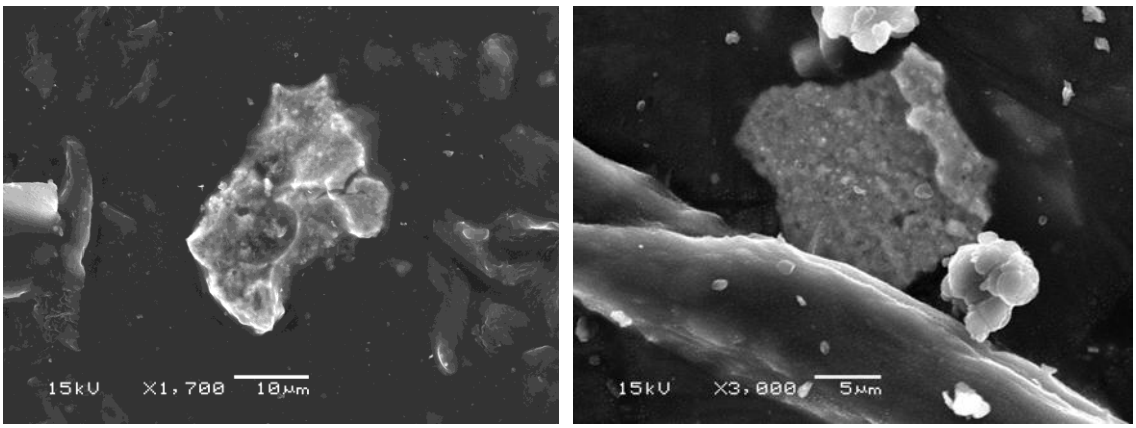


Figure 5.33 'Shard' and 'plate' GSR particles detected during the sample analysis

A large particle detected on one of the handshake recipients in scenario three exhibited both spheroid and angular features (figure 5.34). It featured a spheroid-like 'bulge' in the centre and extended out either side with angular features at the ends. Closer examination of its surface texture revealed it to be peppered with small spheres that were adhered to it. Notably, this was an example of a very large particle

produced during the firearm discharge that was secondarily transferred to the recipient of a handshake from the shooter.

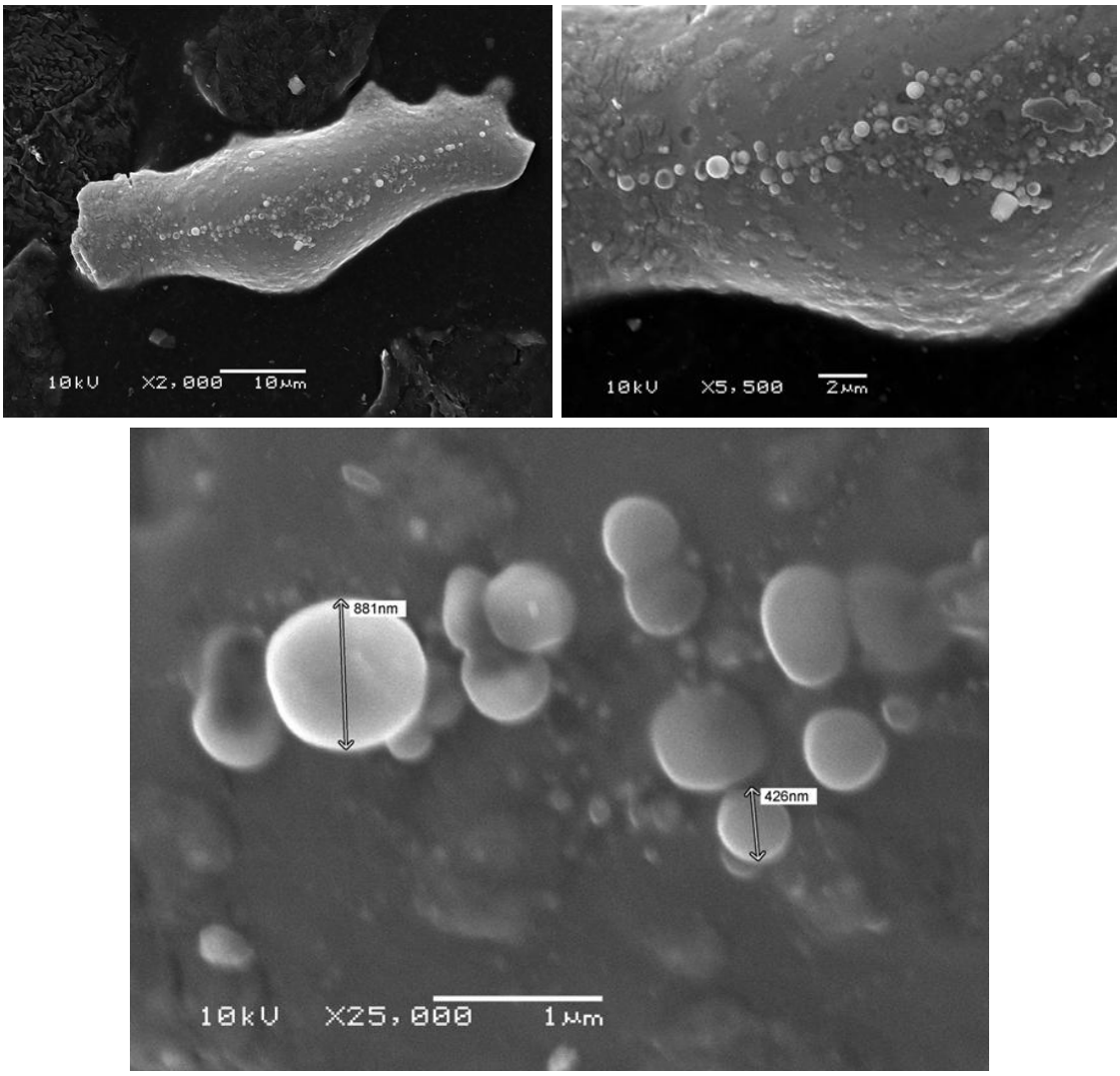


Figure 5.34 Large elongated GSR particle with surface spheres detected during the sample analysis

5.5.2 Concentrations of particles and their effect on particle counts

There were cases when a concentration of large particles in one or more fields contributed significantly to the particle count for that sample, and also to the proportion of those particles that fell into the larger categories. For example, in the first run of scenario four, 45 particles in the 30-99.99 category and five particles measuring >100µm were recovered from the shooter following the transfers. On

closer inspection of this sample, it was found that these particles included a number from the same field. Figures 5.35 and 5.36 depict concentrations and it is clear that, while separations are visible between the fragments, the angular shapes fit together to form what was once one larger piece of material. The degree of separation between particles varied in each case. During the analysis, it was decided that where there was clear separation between the fragments, the particles would be treated as separate entities. This decision was made as it was not clear whether the 'shattering' or 'cracking' that was evident had occurred during its formation, as the particle was deposited, after it had been deposited, or during sampling. Despite the accelerating voltage being set to 20kV, it is suggested that the 'cracking' was not caused by the proximity of the electron beam to the feature as initially the magnification was not high enough (200X) to cause interference with the material which, being composed of heavy metals, was not volatile.

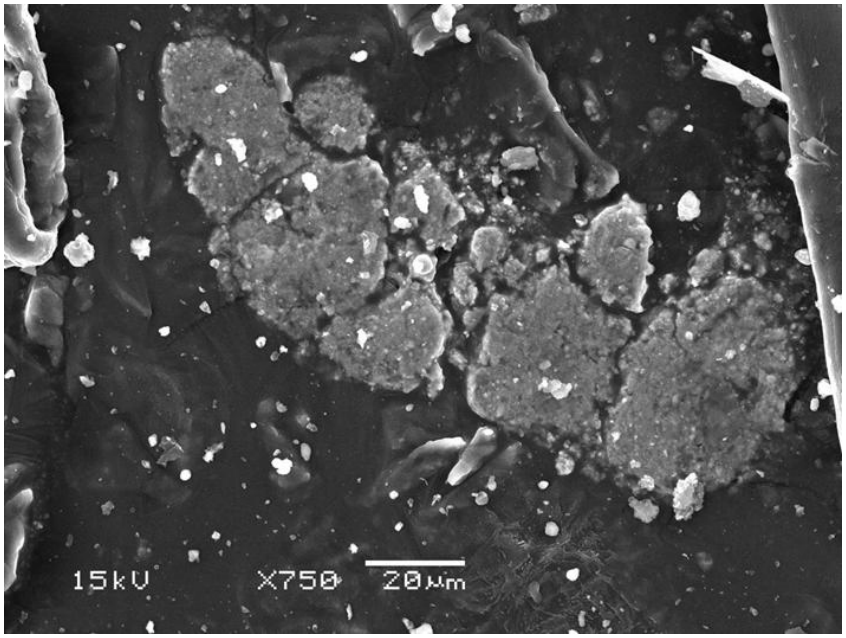


Figure 5.35 Concentrations of large GSR particles exhibiting cracks and fissures

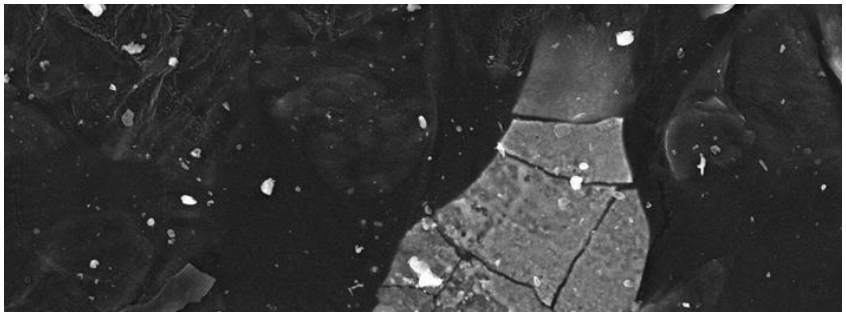


Figure 5.36 Concentrations of large GSR particles exhibiting cracks and fissures

The aggregations of particles shown in figures 5.33 did not only contribute to the counts of particles in the larger size categories, but also contributed significantly to the number of smaller particles present on the relevant sample. On closer inspection, it was clear that the concentration of material also included many smaller, satellite and fragmented particles that were associated with the larger particles. Several examples are shown on the image in figure 5.37.

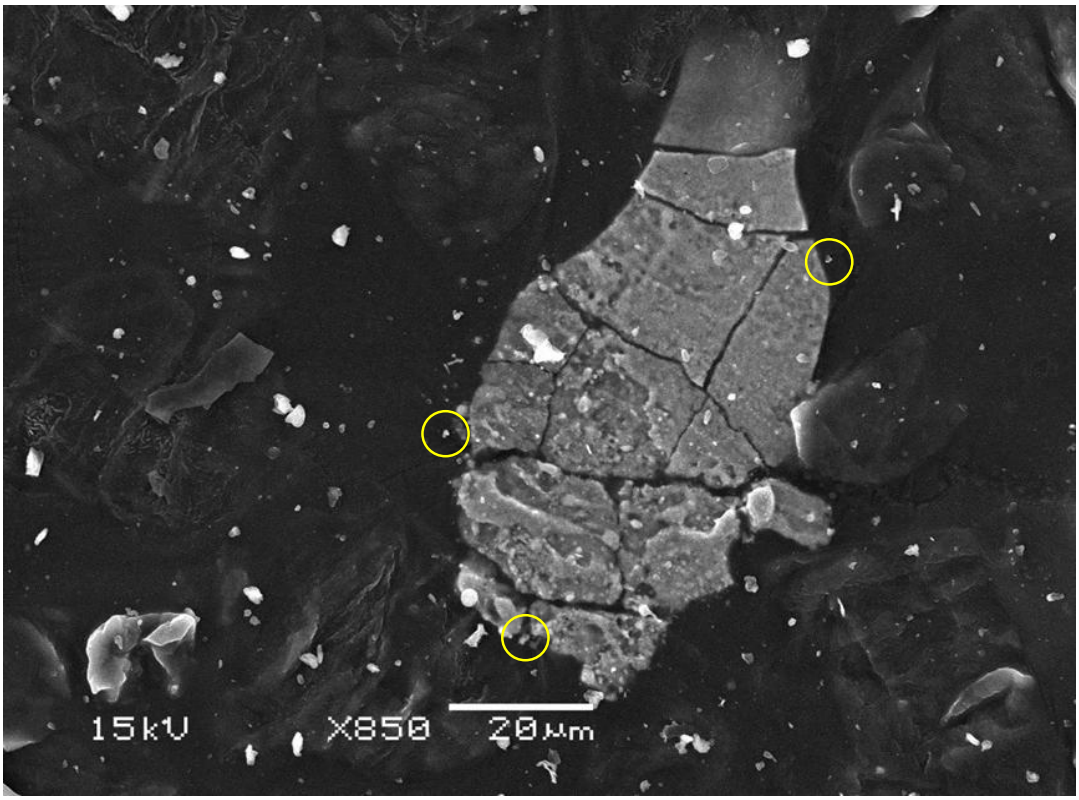


Figure 5.37 Concentration of large GSR particles showing small, satellite GSR particles

The agglomerations of GSR particles shown in figures 5.35 and 5.36 were recovered from the sample which was taken from the shooter in run one of scenario four. Therefore, these structures had remained adhered at the donor surface in this

condition during the handshake and were not entirely transferred from donor to recipient. It is not possible to say whether particles that were recovered from the transfer recipient included a contribution from these agglomerations, although the results in section 5.4.2b suggest that very few, if any, large particles underwent transfer thus suggesting that these structures resisted transfer. While such agglomerations of particles were encountered relatively infrequently, their presence on some samples did contribute significantly to both the particle count and to the numbers of large particles detected on that particular sample. It also meant that a relatively large number of (large) particles in the sample were located in one field, or in two or more fields when there was more than one aggregation of particles or where an aggregation was spread across multiple fields. The implications of this for the analysis and interpretation of samples in casework will be discussed in chapter six.

Chapter 6 A discussion of the experimental findings

6.1 Outline

Following the preceding chapter that reported the results of the experimental phase of the thesis, this chapter discusses the findings in the context of the research questions set out in section 3.7[55]. The findings of the research are considered with reference to the literature on trace evidence and the dynamics of GSR. In addition, the relevance of GSR transfer mechanisms are considered with respect to the various stages of the forensic investigation (set out in 2.2.1), in order to demonstrate the practical ramifications of the experimental findings for forensic casework. A particular emphasis is placed on the interpretative issues that are posed by the findings and this provides a basis for chapter seven, which explores the possibility of reasoning about GSR transfer problems using a Bayesian approach. This present chapter also includes an assessment of the method of sample analysis used for the study, for both casework and research purposes.

6.2 GSR and evidence dynamics

The findings of the experimental study and subsequent analysis represent an important contribution to our understanding of the behaviour and transfer properties of GSR and to the body of literature on evidence dynamics. It is this body of literature and these experimental findings which are referred to when interpreting the presence of trace evidence, in this case GSR, through the assessment of a pair of interpretative propositions (see section 2.2.2). With reference to the research questions that were set out in section 3.7, this section considers the ways in which the experimental findings inform and update our understanding of GSR.

6.2.1 GSR particles

Prior to a consideration of the ways in which the findings from this study inform our understanding of their dynamics, it is important to consider the contribution that the

[55] A selection of the points in this chapter are presented in French et al (2013), see Appendix II

results presented in chapter five make to our understanding the characteristics of GSR particles. During the analysis process, 4070 particles were detected and analysed and thus, the data that were produced provide an opportunity to make a number of observations, particularly regarding particle sizes and forms.

Particle shapes included those which could be described as regular and spherical, as well as those which were much more 'irregular', in accordance with Basu (1982) and Brozek-Mucha (2007), among others (see section 3.2.2). Particles resisted rigid categorisation under shape descriptors or labels, owing to the plethora of particle shapes and to the prevalence of small fragments of material. Nevertheless, certain particle shapes were frequently observed and these captured the distinction between smooth spheroids and more irregular particles and accounted for the existence of 'flint-like' or 'plate-like' features (see section 5.5.1). A number of different surface features were noted including cracking, nodular spheres and smooth surfaces and a further study could examine the formation of these features or their impact on the transfer and persistence properties of GSR. In accordance with Wright and Trimpe (2006) and a number of other sources (Brozek-Mucha 2009, Wolten and Nesbitt 1980, Basu 1982 and Lindsay et al 2011a), terms such as condensed", "rounded", "fused" could be employed to describe the form of many of the particles that were encountered, while the presence of "angular" and "cracked" forms was also noted. In agreement with Basu (1982), "peeled", cracked and cratered surface textures with cavities and holes were identified. In conclusion, to define GSR as consisting exclusively of smooth, spheroid particles will serve to underplay the heterogeneity of particle shapes and forms. While the majority of particles did measure under 10µm (akin to Meng and Caddy 1997, for example) and a significant proportion of these were spherical, not all particles conformed. Particularly in situations that involve manual analysis and detection, failing to acknowledge the myriad forms that GSR particles can take could, conceivably, result in particles being overlooked.

The 4070 particles that were detected and analysed across all experimental sample stubs were sorted into classes according to their size (see tables 5.8, 5.9 and figure 5.2). Regarding the particles produced under the conditions simulated during the experimental work, particle sizes were heavily skewed towards the smaller particle sizes (<10µm). Of all particles that were detected, 90.8% measured under 10µm and

this is a finding that aligns with the observations of various studies, including Basu (1982) Nesbitt et al (1976), Brozek-Mucha (2011), Trimpe (2011), Thornton (1994), Zeichner (2012), Zeichner (2003), Meng and Caddy (1997), Wolten et al (1977) and Lindsay et al (2011), that have all reported that the majority of GSR particles can be expected to measure in the order of between 1µm and 10µm. The modal class of particle was 1-2.99µm and the mean particle size was 4.9µm, statistics which, again, align with the literature on GSR particles which was presented in section 3.2.2, although the mean particle size was slightly higher than the 2.6µm reported by Halim et al (2010) for 9mm ammunition from a semi-automatic pistol. In accordance with Andrasko and Maehly (1977), Basu (1982), Christopher et al (2013), particles measuring in excess of 15, 20, 30 and 40µm were recovered following the firearm discharges and simulated transfers. Notably, a number of very large GSR particles were recovered during the experiments and while the possibility of observing these larger particles has been acknowledged, reports of their detection are not widespread. This can perhaps be explained by the relative absence of catalogues of large numbers of GSR particles such as the one produced during this study, in which only 10 particles measuring >100µm were detected among over 4000 particles – a figure which represents only 0.25% of the total particle count. The detection of particles of this size is an important observation that informs our understanding of the profile of GSR particles. It should be acknowledged that the particle size data relate to the firing of 9mm Luger 95 grain jacketed soft point 9P1 ammunition (manufactured by FEDERAL Ammunition) from a SIG Sauer P226 9mm self-loading pistol and the profile of particle sizes is likely to differ for alternative firearm-ammunition combinations. Nevertheless, these results represent an indicator of the trends to be expected in firings involving ammunition and firearm types that are analogous to those that were employed in this study.

The detection of conglomerates, or concentrations, of GSR particles was also documented in chapter five (section 5.5.2). The sample analysis highlighted how, on occasions, large clusters of GSR particles were deposited and were subsequently recovered during sampling. These clusters, when present, contributed significantly to the particle count for the sample in question and in particular, to the number of large (>10µm) GSR particles. In addition, the clusters were often associated with many

smaller GSR particles. It was noted that in a number of instances many of the particles in these clusters, while visibly separate, appeared to have once been associated as one or more larger pieces of material.

These findings resonate with the observations of Brozek-Mucha (2011, p.975) who identified 'fragmented solid particles' on the hands of shooters following test firings. The 'fragments' or 'sections' in some cases appeared to exhibit a 'physical match' with one another that enabled them to be assigned to a single, larger particle (figure 6.1). According to Brozek-Mucha (2011) the presence of such particles among a population of deposited GSR will contribute to the recoverable particle count and to the variation between the counts which result from different firings. Additionally, in a previous study, Brozek-Mucha (2007) recovered 'plate' and branched GSR structures from the inside of a discharged cartridge (figure 6.2). Similar plate structures were detected during the analysis and were presented in section 5.5.1, suggesting perhaps, that contact with the loading chamber and other parts of the firearm resulted in particles that were formed in the cartridge being deposited on the shooter.

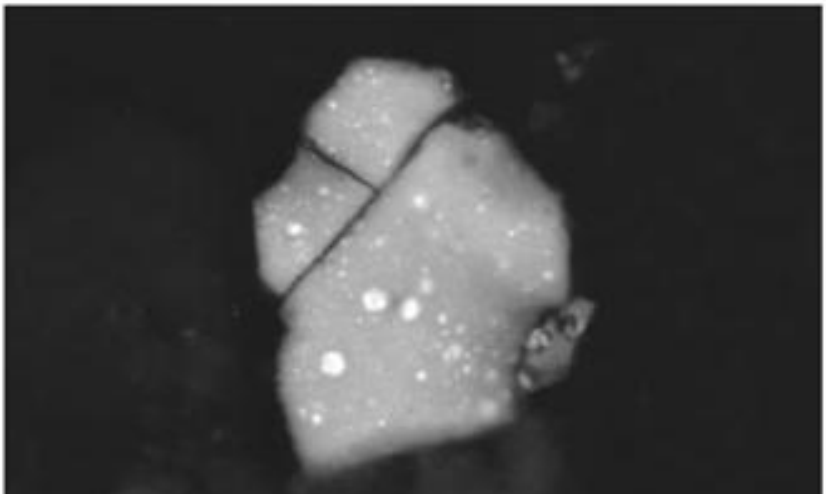


Figure 6.1 'Fragmented solid particle' detected by Brozek-Mucha (2011, p.975)

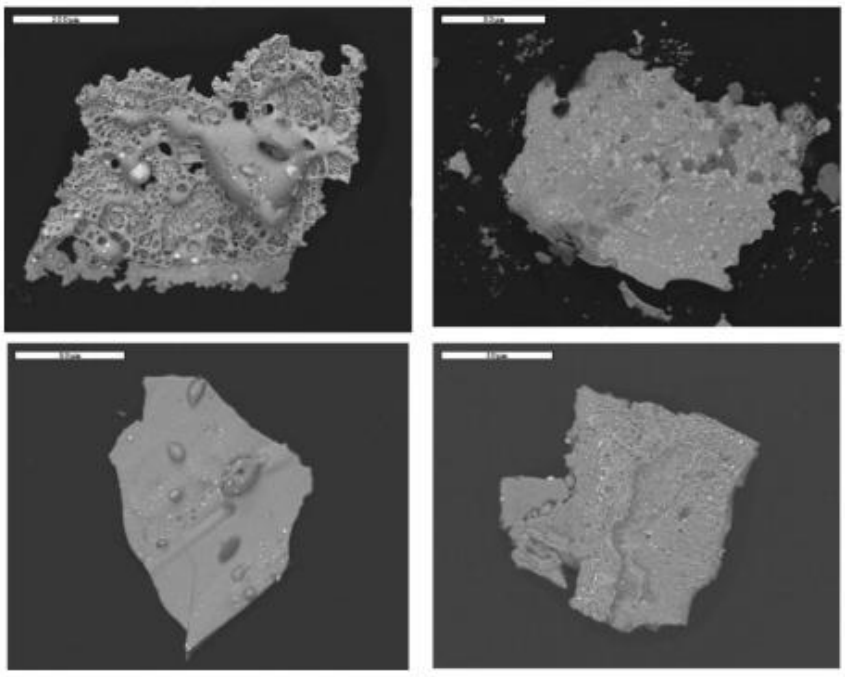


Figure 6.2 'Plate' structures detected by Brozek-Mucha (2007, p.402)

Neither sampling nor beam proximity were deemed likely to have caused the apparent 'cracking', 'shattering' or 'dissociation' of material. It is suggested that these clusters may owe their appearance to the modification of GSR particles that can occur on impact with a surface (see, for example, Burnett 1989), but it is more likely that the cracking occurred along fissures during the rapid cooling of material following its formation under high temperatures (Nag and Sinha 1992, see section 3.2.1). This observation, therefore informs our understanding of the GSR formation and deposition process and is perhaps further evidence of GSR particles that have an appearance consistent with rapid cooling (Wright and Trimpe 2006).

An additional finding regarding the dynamics of GSR which was not anticipated concerned the persistence of GSR during hand-washing regarding GSR. It was identified that two control samples that were taken following hand-washing intended to remove all GSR prior to the start of the experiment (section 5.2). One and five particles were recovered from these samples. This finding resonates with previous findings regarding the persistence of GSR that were reported in section 3.4.4b, particularly Andrasko and Maehly (1977) who reported the resistance of two GSR particles to thorough washing. It should be acknowledged that control samples confirmed that thorough hand-washing was successful in removing large quantities of deposited GSR in the vast majority of cases, corroborating (Andrasko and Maehly

1977, Nesbitt et al 1976). Thus, while GSR particles can persist on hands during thorough hand-washing, they do so infrequently.

6.2.2 Secondary transfer

Establishing whether the potential exists for GSR to undergo secondary transfer following its initial deposition is central to the aim of this piece of experimental research. Such transfers would mean that individuals other than the shooter could acquire GSR following its deposition. Furthermore, the nature of these transfer mechanisms and the quantities of material involved were also of interest. Research questions one and three asked (section 3.7):

- Can GSR particles undergo secondary transfer from a discharged firearm to the hands of an individual who was not present at the scene of a firearm discharge but who handled the firearm afterwards?
- Can GSR particles undergo secondary transfer from the hands of a shooter to those of an individual who was not present at the scene of a firearm discharge?

The results of the experiments provide unequivocal evidence that GSR particles can undergo secondary transfer from their original site of deposition (see, for example, table 5.6). These transfers, as demonstrated by the results of experimental scenarios two and three, can result when the hand of an individual makes contact with the hand of a person who has recently discharged a gun, via a handshake. Additionally, secondary transfer can also result when an individual takes hold of a recently discharged firearm. Crucially, these conclusions are based on the results of experiments in which the recipients of the secondary transfers were not present at the scene of the original shooting – the ramifications of this observation will be discussed in section 6.4. Moreover, owing to the control measures that were put in place (outlined in 4.2.4) and to the results from the control samples[56], it can be concluded that the presence of GSR on the secondary transfer recipient can be attributed to the transfer mechanisms that were simulated. Thus, Research Questions One and Three

[56] In the vast majority of cases, these control samples confirmed the absence of any material that had persisted hand-washing. However, as described in section 5.2 (and throughout Chapter Five), contamination was encountered in a very small number of cases. In these cases, the contribution of contamination to the overall particle count was negligible. Therefore, its impact on the results and on the validity of any conclusions that are made is also limited.

have been answered. That GSR particle evidence was found to undergo secondary transfer in the manner described suggests that other forms of trace physical evidence may behave in a similar manner.

The finding that GSR can be secondarily transferred via interpersonal (hand-to-hand) contacts is a novel one in the literature. Transfer in a similar manner has been reported with respect to other types of trace evidence (see, for example, Lowe et al (2002) and Lowe et al (2003) for LCN DNA and French et al (2012) for trace particulates) and it might thus have been hypothesised that GSR could also behave in this manner. Furthermore, that GSR can be transferred by such contacts has been inferred by several contributions that state that contact with surfaces bearing GSR can result in transfer. However, until now, the possibility of the transfer of GSR via hand-to-hand contact has not been experimentally confirmed, nor has it been quantified in any experimental setting. The principal finding of experimental scenario two, that GSR can be secondarily transferred via contact with a recently discharged firearm is one that corroborates the observations made by Basu et al (1997) and Cetó et al (2012). Moreover, the counts that were recovered are similar to some of those reported by Basu et al (1997) that resulted from simulated contact with the trigger and rear of a fired revolver, (see section 3.5). Akin to the Cetó et al (2012) and Basu et al (1997) studies, GSR particles counts resulting from contact with the firearm were distinguishable from those recovered from shooters in the experimental setting of this piece of research. However, in the Basu et al (1997) study, in line with the principles of evidence transfer (see section 2.3.1), much greater levels of transfer from the firearm to the handler were effected by increased pressure of the contact or by rubbing and brushing the hands on the cylinder/barrel of the revolver. These transfers resulted in greater levels of GSR on the transfer subject when compared to shooters – something that was not observed during the experimental simulations in scenario two.

The quantities of particles that were involved in both types of secondary transfer simulated during the experimental phase of this thesis varied from run to run. This variation was a result of the differing quantities of GSR that were available for transfer from the hands of the shooter or the outside of the firearm, which in turn, was the result of the tendency for the quantity of GSR produced by a firearm discharge to vary from firing to firing (Matricardi and Kilty 1977, Jalanti et al 1999, Schütz et al 2001,

Lindsay et al 2011a, Brozek-Mucha 2011). Goray et al (2012) previously observed inherent variability involved in multi-step transfers, albeit with regard to DNA. Meanwhile, referring to the theories of trace evidence transfer that were outlined in section 2.3.1, variable GSR transfer may have been in part attributable to variations in the pressure of the contacts (handshakes) between runs (see, for example, Pounds and Smalldon 1975a and Robertson et al 1982). In addition, the adhesive properties of the hands of the different transfer subjects (owing to the degree of sweat for example) and the effect of these properties on the efficiency of sampling may also have contributed to the variations in the quantity of transferred material (see Brozek-Mucha 2011). Large 'fragmented' particles of the sort described by Brozek-Mucha (2011) and recovered from shooters during this study (see sections 5.5.2 and 6.2.1) were not recovered from transfer subjects and therefore, did not contribute to between-run variations in the number of particles recovered from the transfer subjects.

The GSR counts that were determined for the samples taken during these experiments relate to transfers and depositions that occurred under a specific set of circumstances and experimental conditions. The results should not be used to infer that these specific counts are indicative of those that can be expected in all scenarios with regard to GSR. Rather, they are indicative of the extent of transfer that may be expected in conditions which are analogous to the experimental conditions or, at the very least, indicative that secondary transfers of GSR might conceivably be observed in alternative circumstances. Importantly, however, steps were taken to approximate real-world casework scenarios that enhance the applicability of the findings to real-world scenarios (see section 4.2.5). The quantities of particles involved in the transfers suggest that forms of contact other than handshakes or grasping the firearm, perhaps fleeting hand-to-hand contact, would also be effective in initiating a secondary transfer.

With regard to the interpersonal (hand-to-hand) transfers, it is significant that GSR particles were transferred in all six runs; in no case did a handshake fail to result in the transfer of particles. An average of 60-61 particles were transferred while a maximum of 129 particles (29.93% of initial particles) and a minimum of 21 particles (9.5% of initial particles) were found to have undergone a secondary transfer. Meanwhile, in the three transfers that resulted from handling the discharged firearm, variable

quantities of GSR were again involved with a maximum of 86 particles and a minimum of 14 particles recovered from the transfer subject. However, the relatively small number of experimental runs means that it is not possible to suggest that these results indicate that the interpersonal contacts resulted in the transfer of more particles than when the subject made contact with the discharged firearm. However, like the hand-to-hand secondary transfers it is notable that no contact with the firearm failed to initiate the transfer of GSR particles. In practice, the quantity of material that is secondarily transferred will be influenced by factors such as the force of contact and the nature of the donor and recipient surfaces (see section 2.3.1, 2.3.3 and 3.4.4). It is conceivable that the amount of transferrable material that is available from the regions of a firearm that a secondary handler may touch might be less than that which may be found on the hands of the shooter, owing to the fact that the hands of the shooter 'intercepted' much of the material that could have otherwise been deposited on the handle and trigger regions. Further research could confirm this.

Of paramount importance in the context of the GSR evidence dynamics literature, and with regard to the interpretative implications that will be explored in section 6.4, is that the amount of particles involved in the secondary transfers tended to be considerable. For example, the 86 particles transferred by handling a firearm in run one of scenario two and the 129 that were particles transferred via a handshake during run three of scenario three appear to run counter to the findings of previous investigations into contamination via the secondary transfer of GSR that cite the possibility and extent of secondary transfers as being minimal (Gialamas et al 1995 and Berk et al 2007). However, it must be noted that these studies are concerned with contamination during arrest and suspect processing, via secondary transfer from officers and police facilities and do not consider the potential for transfer in the period between deposition (firing) and suspect arrest/sample collection. So, while the potential for contamination during and after collection via secondary transfer has been found to be minimal by previous studies, the findings of this study indicate that secondary transfer to hands following a shooting, and prior to collection, is highly possible if contacts have been made. Moreover, in settings analogous to those in this study, these transfers can involve considerable quantities of GSR particles. By extension, if a surface bears sufficient GSR then it may also represent a willing donor

source and a source of contamination via secondary transfer. The investigative implications of this will be discussed in section 6.3.

It must be acknowledged, however, that the transfers that were staged during the experiments represent an "extreme" case, in which the contact between the test subject and shooter/firearm was made in the immediate aftermath of the firearm discharge. This was discussed in section 4.2.2. Consequently, in the absence of a significant window for the decay of material, the population of GSR on the donor surface will have been largely undisturbed. In such conditions, any transfer that takes place can be expected to involve larger quantities of trace material than one that took place one hour after a firearm discharge, for instance. However, when it is considered that an average of 60-61 particles and a maximum of 129 particles were transferred from on hand to another in scenario three, it is reasonable to suggest that even given a delay between initial deposition and secondary contact (that would, in turn, reduce the amount of GSR available for transfer), a detectable transfer can be expected. Despite the generally lower levels of transfer (86, 18 and 14 particles), the same can be said of the possibility of a secondary transfer following the handling of a discharged firearm after some delay. Taking into account the timeframes of trace evidence and GSR longevity that have been reported and that were outlined in section 2.3.2 and 3.4.4b, respectively, it would be reasonable suggest that after a few hours (in the absence of any firearm cleaning or hand-washing etc.), contact with a shooter or discharged firearm could result in the secondary transfer of a detectable number of particles.

In section 5.4.1a, estimates of the efficiency of the hand-to-hand secondary transfers were made. The most efficient secondary transfer involved a little fewer than 30% of particles being transferred from the shooter to the handshake recipient and on average this figure was around 13%. Given that between 21 and 129 particles were transferred during the secondary transfers, it seems reasonable to predict that a measurable tertiary transfer could be expected if a subsequent transfer was made. This was confirmed by the results of scenario four and will be discussed in section 6.2.3.

Addressing research questions one and three also involved a consideration of the sizes of the particles that were secondarily transferred. From the particle size data that

were presented in chapter five a number of observations can be made. It is important to re-emphasise that the particle size data (as well as the GSR counts) concern the GSR that was produced during the particular scenarios, under the specific conditions set out in chapter four and using the specific firearm-ammunition combination. Thus, the extent to which the data can represent an expected dataset following firings in different scenarios and under alternative conditions will be limited to some extent. However, the particle size data can be used to inform our understanding of the dynamics of GSR with respect to the sizes of particles and to provide an indication of what trends can be expected in a different scenario. Meanwhile, conclusions about the tendency for certain sizes of particles to undergo transfer must be made carefully, owing to the limited number of experimental runs, despite the large number of particles that were analysed.

A comprehensive review of the sizes of particles that are involved in secondary transfers has not previously been undertaken and thus, the trends with that have been identified here are as part of an exploratory investigation. Further study, which is enabled by the employment of an automated particle search capability, is needed to examine the reproducibility of these observations. At this stage, preliminary trends and observations, as indicated by the data, are documented.

With regard to the interpersonal (hand-to–hand) transfers, the data that were presented in chapter five clearly demonstrate that, with reference to the overall particle population, a full range of different sized particles underwent secondary transfer. In other words, all particles that are deposited on the shooter during a firearm discharge, from extremely small sub-micrometre to very large (>100µm) particles, can conceivably be transferred if the shooter shakes hands with second individual. Interpersonal secondary transfers of GSR are by no means limited to small particles. That very large (>100µm) particles were recovered from a secondary transfer recipient represents a novel observation regarding our knowledge of GSR evidence dynamics; one which has not been reported in the published literature. This is also a significant finding for our understanding of secondary transfer in the trace evidence literature more generally as it confirms that secondary transfers are not limited to the movement of smaller particulates.

In chapter five, particle size distributions for each sample were produced by sorting particles into size categories. Notably, when compared to the distributions for the 'initial' populations of GSR that were deposited on the shooters, the size distributions of the particles recovered from the handshake recipients were very similar (see tables 5.14 and 5.20). This confirmed that not only did a full range of particles undergo secondary transfer, but also that the resulting populations of GSR particles were representative of the initial population of GSR that was deposited on the shooters, notwithstanding small amounts of between-run variation. That representative groups of GSR particles were transferred to the handshake recipients was confirmed by examining the particle size distributions of reciprocal transfer samples; donor and recipient, following the completion of the transfer (see section 5.4.1b). This was confirmed by the particle size data for the donor surface before and after the transfer, which exhibited the preservation of the proportional distribution of particles among the size categories (section 5.4.1c). In sum, in conditions analogous to those simulated in the experiments, secondary transfer is highly possible and can involve considerable number of particles, large particles, and a population of particles which is representative of that initially deposited on the shooter.

The data indicate that the average size of particle recovered from a shooter and an individual who has acquired GSR via an interpersonal transfer from the shooter may be expected to be similar, assuming that material has not been subject to a significant degree of decay. Meanwhile, mean particle sizes for reciprocal recipient and donor surfaces, following the secondary transfers were similar in some cases. However, the transfer of an unrepresentative proportion of large particles has the potential to limit this similarity.

It has been reported by Andrasko and Maehly (1977) that the larger (>10µm) GSR particles in a population will dissociate most quickly from a surface and that after a few hours, smaller (<3µm) particles tend to remain. As a result, the average particle size of a recoverable population of GSR on a subject will alter over time, while the distribution of particles among the size categories will become skewed towards the smaller size categories. It is likely, at this point, that the particle size data (particularly the particle size distributions) for a sample taken from a shooter and from a secondary transfer recipient would not appear to correspond. This would be attributable to varying

influences on the persistence of material and owing also to the loss of the small number of large particles that were present on the secondary transfer recipient, while at least some large particles may be expected to remain on the shooter.

Noteworthy observations were also made from the particle size data for the samples taken from the subjects who handled the discharged firearms. Interestingly, in comparison to the samples taken from the interpersonal transfer recipients and from the shooters following the initial deposition, particularly particle size distributions were less consistent from run to run when a discharged firearm was handled by a subject. Moreover, there were some differences between the particle size data for these samples and those taken from the shooter and from the interpersonal transfer recipients. For example, the average particle sizes for these runs differed from those calculated for shooters and handshake recipients. Furthermore, fewer particles were recovered that fell into the largest size categories and the size of the largest particles encountered tended to be smaller. However, owing to the fact that the subject handling the firearm would have come into contact with the same areas as the shooter when the gun was being fired, it is unlikely that the initial starting population of GSR that was borne by the firearm would have differed greatly from that which deposited on the shooter. Rather, any discrepancy is likely to be owing to the small numbers of particles that were involved in the secondary transfers from firearm to handler. Alternatively, this could be a function of the different retentive properties of the surface of the firearm in comparison to the hands of the shooter, according to theories of transfer and persistence as outlined in section 2.3, which could be investigated through further experimentation. Indeed, it would be profitable to examine the sizes of particles that are deposited on the firearm during a discharge and also the effect of handling a firearm on the population of particles that remains adhered to the firearm, using the approach that was employed with regard to hand-to-hand transfers in section 5.4.

Despite the relative absence of the very largest particles on the firearm-to-hand secondary transfer samples in these experimental runs, the results do indicate that a secondary transfer initiated by handling a firearm does not involve, for example, exclusively small particles. Rather, particles measuring >10µm (20.35µm, 41.44µm and 18.03µm, for example) were found to undergo transfer by this means, in addition to

sub-micrometre particles and those measuring between 1µm and 10µm. This represents a novel observation in the GSR literature.

6.2.3 Tertiary transfer

Research Question Two was concerned with further transfers:

- Can particles of GSR undergo multiple transfers (i.e. tertiary) from the hands of a shooter to another surface and then be transferred to subsequent surfaces which were not present at the scene of a firearm discharge?

As predicted by the results of scenario three (section 5.2.3), the results of scenario four (section 5.2.4) confirmed that GSR particles that have initially been deposited and subsequently secondarily transferred can undergo a tertiary transfer via another handshake. Again, this represents a novel observation with regard to GSR dynamics, having not been experimentally determined, and until now could only be inferred from statements regarding the possibility of acquiring particles from a surface which bears GSR. The possibility of tertiary transfers of trace evidence is acknowledged by Gaudette and Tessarolo (1987) and has been confirmed experimentally by Taupin (1996) and French et al (2012) with regard to hair and fibres and to trace particulates, respectively, but not to GSR until now. That GSR particle evidence was found to undergo tertiary transfer in the manner described suggests that other forms of trace physical evidence may behave in a similar manner. The quantities of particles involved in the transfers also suggest that forms of contact other than handshakes may also be effective in initiating a tertiary transfer.

It is very significant that all simulated contacts resulted in the tertiary transfer of GSR particles. Importantly, the quantities of GSR that were detectable after the tertiary transfers were not negligible. Rather, the 18, 22 and 12 particles that were transferred in the three runs (representing transfers of 40.91%, 43.14% and 57.14% of particles, respectively) were significantly higher than quantities of particles that may be considered 'trace' quantities, such as between one and three particles. In the same way as explained with regard to the results from scenario three, the tertiary transfers represent an "extreme" case in which secondary contacts were made straight after the initial deposition and subsequently, tertiary contacts were made without delay.

Notwithstanding the fact that this meant the maximum quantities were available at the donor surfaces, the quantities involved in the transfers are, again, suggestive that further detectable transfers from the tertiary recipient may be possible. Indeed, the tertiary transfers were more efficient than those that took place between shooters and the first handshake recipients. In section 5.4.2a, it was calculated that 40.91%, 43.14% and 57.14% of GSR particles were transferred from the secondary recipient to the third subject, representing a notable increase in efficiency compared to the secondary transfer events (note that these quantities represented 2.60%, 4.76% and 5.43% of the initially deposited GSR populations). These more efficient transfers in the third stage of the transfer chain appear to suggest that subsequent transfer would be possible if sufficient particles were present. If these subsequent transfers were similar in efficiency to the tertiary transfers, the recoverable particles along a transfer chain would exponentially decrease and trend towards zero, echoing the two-stage pattern of decrease observed by French et al (2012) along transfer chains.

The particle size data for the samples taken from the tertiary transfer recipients exhibited a number of noteworthy features. Analysis of the data revealed that, owing to the relatively few particles involved in these transfers, the possibility of larger particles being present on the sample was lower. These larger particles, it was demonstrated, had tended to remain either at the shooter or at the first transfer recipient, rather than be deposited for a third time. The resulting particle size distributions for these samples resembled those for the samples taken from shooters and interpersonal secondary transfer recipients and were representative of the same initial populations of GSR particles, apart from a relative absence of particles in the larger size categories. As a result, average particle sizes and the sizes of the largest particles encountered on samples of GSR transferred in this way may be expected to be lower. However, in one of the runs, a particle was recovered from the recipient after a tertiary transfer that measured 49.19µm. Owing to the low number of particles that were transferred as a result of this particular contact, the large particle had the effect of inflating the mean particle size and demonstrated how, when only a few particles are transferred, the movement of one or two particles of a particular size may have a great impact on the particle size data generated for that sample. In addition,

this effect was shown to contribute to between-run variance in terms of the replication of particle size distributions and mean particle sizes.

It is important to stress that the very large in particle in question had, first, been deposited on the shooter during the firearm discharge before being secondarily transferred via a handshake to a second subject and finally, this particle had undergone a tertiary transfer via a handshake with a third individual. This particle was larger than almost 99% of the 4070 particles that were encountered across all of the experiments. Demonstrating that it is possible for large GSR particles to be recovered from the recipient is a novel finding and one that enhances our understanding of GSR evidence dynamics. It is also a noteworthy observation in the context of the trace evidence literature and in particular, that portion of it which is concerned with multiple transfer mechanisms (see, for example, Goray et al 2010, French et al 2012 and Gaudette and Tessarolo 1987). These observations give rise to a number of potential interpretative ramifications that will be explored in section 6.4.3.

It is certainly the case that further analyses of GSR evidence dynamics with a focus on the sizes of particles, which assess the reproducibility of the findings that have been made here, will enhance our understanding of these dynamics. Concurrently, such research will assist in exploring the evidential value of transferred GSR particles of different sizes and the interpretative implications that are involved.

6.2.4 Deposition mechanisms

Research Question Four asked:

- Can GSR particles be deposited on a bystander who was in the vicinity of a firearm discharge?

As stated in section 3.7, while to some extent a positive answer to this question has been provided to this question by previous studies (Lindsay et al 2011a, for instance), this question was addressed using the same methods and procedures that were employed during the other firings. Consequently, the quantities of any deposited particles could be directly compared to the quantities of GSR particles that were deposited or transferred via other mechanisms and thus, Research Question Five could be addressed.

The quantity of GSR particles that was deposited on the hands of the individual standing one metre behind the shooter during the firing of five rounds was similar across the three runs. Counts of 18, 22, 12 particles were recovered and despite the limited number of runs, it could be reasonable to suggest that slightly fewer GSR particles were deposited on the bystanders compared to those that were transferred via a direct contact with the shooter. The results from this study indicate that deposition on the bystanders in this case was less likely to result in the deposition of considerable (>50) quantities of GSR particles. Notwithstanding this, the quantities recovered were significantly higher than a 'trace' quantity of, for example, one or two particles. The results are very similar to those reported by Lindsay et al (2011a) who found that between 0 and 27 particles were recoverable from the bystanders in their experiments, irrespective of their orientation in relation to the firearm discharge. It is notable that in each run GSR particles were deposited on the bystander, unlike the firings reported in the Lindsay et al (2011a) study which in some cases failed to deposit detectable GSR on the bystander.

The Lindsay et al (2011a) study found that in some firings, similar quantities of GSR were recoverable from shooters and bystanders, owing to the variability in quantities of GSR which were deposited. On the contrary, the findings of the experiments in this study revealed markedly divergent levels of deposition on shooters and bystanders. In accordance with previous findings from experimental research, the quantity of GSR that was produced by the firearm discharges and deposited on the shooter varied greatly from firing to firing (Matricardi and Kilty 1977, Jalanti et al 1999, Schütz et al 2001, Lindsay et al 2011a, Brozek-Mucha 2011). It is likely that some of this variation may have been attributable to an accumulation of GSR from previous firings as a result of the 'memory effect' (Rijnders et al 2010, Basu et al 1997, López-López 2013, Charles et al 2011), although the change in levels of deposition in the present study was not simply one of an increasing trend with successive runs, meaning that other variables were influential. A maximum of 834 particles and a minimum of 206 were deposited on the shooter, while the average count was 429 particles. Owing to the consistency of the sampling strategy (see section 4.2.3) it is reasonable to assume that a sampling bias did not contribute to this variation. In all runs, the quantity of GSR that was recovered from the shooter was a great deal higher than that which was deposited on

the bystanders (an average of 429 particles were recovered from shooters compared to 28 from bystanders). The relative consistency in deposition on the bystanders contrasts strongly with the variability in levels of GSR that were deposited on the shooter between firings. In most cases the quantity of GSR that was deposited on the shooter was significantly greater than that which was transferred by any of the other mechanisms being investigated. However, owing to the high degree of variation between firings, in some cases the difference between secondarily transferred counts and the more conservative depositions on the shooter was not quite so great, although even the lowest counts recovered from the shooter were still somewhat higher.

Despite the relatively small number of runs, some observations may be made about the sizes of particles that were deposited on the shooters and bystanders. These observations inform our understanding of the transfer/deposition properties of GSR evidence and highlight the potential relationships between the size of GSR particles and their dynamics. This relationship could be the focus of future research projects. Taking into account the samples that were taken from the hands of the shooters after firing, the results suggest that from firing to firing, the size profile of the population of particles that is recoverable well replicated. While the specific data (mean particle size, percentage of large particles, etc.) will vary according to conditions and to the firearm-ammunition combination that is employed, the results indicate that where these conditions are maintained, the profile will be maintained from run to run. For example, in most of the runs, the average particle size was between 4µm and 5µm, with only one notable departure (run seven, see table 5.13), while in all runs the modal class of particle was 1-2.99µm. The data indicate that the distribution of particles amongst size categories can be expected to be well replicated between firings and that large (>10µm, >30µm and even >100µm) GSR particles may be deposited on the hands of the shooter. This corroborates previous reports in the GSR literature (see section 6.2.1). The particle size data for the samples taken from the shooters provide the point of comparison for the data derived for the other transfer and deposition mechanisms.

With regard to the GSR particles that were deposited on the bystanders, it is reasonable to conclude that larger particles do not to become airborne and deposit on a bystander one metre from the firing. The largest particles recovered from the

bystanders after the first two firings measured 7.47µm 12.90µm respectively and although a particle measuring 32.35µm was deposited on the bystander in the third firing, proportionally fewer particles in the larger size categories were present on bystanders than on the shooters. The presence of the larger particle in the third firing served to contribute to a fairly high average particle size (7.27µm) of those particles that were recovered from that particular bystander. That the presence of one or two larger articles among a relatively small population of GSR particles (in this case, 28 particles) can impact the mean particle size dramatically was an observation made several times during this study. When considering smaller quantities of particles, the inclusion of a small number of particles in one instance can result in large variations in mean particle sizes between firings and this underscores the importance of considering the distribution of particles among size classes. Notably, the modal class of particles was the same for the bystanders as the shooters, suggesting that the smaller particles that are deposited on the hands of the shooter from the muzzle-blast and breeches are also thrust backwards, behind the shooter following the firearm discharge.

6.3 Implications for the forensic investigation

The importance of demonstrating the utility and applicability of research in forensic science is a central theme of this thesis and one that was introduced in chapter one. According to Mnookin et al (2011), a central tenet of an effective research culture in the forensic sciences is the undertaking of methodologically sound research that informs forensic practice, and the conclusions and testimonies that are made by forensic scientists. Accordingly, this section outlines the implications of the findings of the experimental phase of this thesis for the collection, analysis, interpretation and presentation of GSR evidence. In addition, this discussion will consider the ramifications of the findings for future experimental research into GSR, while considering the research questions that could be addressed when doing so.

6.3.1 The collection of GSR samples

The results of the experiments that were carried out have a number of ramifications for the collection stage of an investigation involving GSR, and for the practices and protocols that are employed as part of this process. Clearly, owing to the reconstructive and probative value that secondarily transferred quantities of GSR might be found to hold, the collection of samples from secondary transfer subjects is recommended. In a situation where a group of individuals might be implicated in a shooting or when claims are made regarding the identity of a shooter, for instance, sampling from as many individuals who may have been implicated as possible is recommended. Moreover, this sampling should be carried out as soon as practically possible and could also involve handled surfaces and objects. The expedience of sampling, ideally at the scene, will ensure that potentially crucial evidence is captured and that it is not 'lost' via decay, nor further disseminated by successive transfers. While all of the samples that may be collected may not all, ultimately, be subject to analysis, this approach does ensure that it is not necessary to return to sampling sites that may become important later in the investigation, by which time material may have been lost or degraded and the window for evidence recovery lost. Conceivably, the evidential and reconstructive value of a quantifiable presence of GSR, or even its absence, on one or more suspects who were sampled in connection with a firearms offence is great. The potential exists to use such samples to make inferences about the likely method of deposition and to assess activity level propositions regarding multiple individuals. This will be developed as a point of discussion in 6.4 and revisited in chapter seven.

Unlike previous studies, such as those undertaken by Gialamas et al (1995) and Berk et al (2007) 'contamination' was not the object of study in these experiments. However, the propensity of significant quantities of GSR to undergo secondary and tertiary transfer, or for GSR to be deposited in the vicinity of a firearm discharge, has ramifications for the collection of evidence and hints at the possibility of contamination via secondary transfer. For example, if the hands of a suspect who had recently discharged a firearm were held during arrest, perhaps to restrain, a transfer of material could take place from the suspect to the officer. This would result in the 'loss' of evidence from the suspect and conceivably, could also mean that the officer was now a potential donor of GSR particles to other surfaces including further suspects who might be detained at the same scene or

subsequently. If multiple suspects are being apprehended, measures could be taken to reduce the opportunities for unwanted transfer. For example, a one-suspect-per-officer policy would limit the possibility of transferring GSR between offenders, via officers.

Meanwhile, the seizure and packaging of exhibits, particularly firearms and spent cartridges represent opportunities for secondary transfer and contamination. For example, if a responding officer chooses to seize or handle a firearm in some way at a scene, a secondary transfer could take place that would result in a 'loss' of GSR from the exhibit and also in a population of GSR on the hands of the officer. These particles could, in turn, be transferred to further surfaces and could potentially represent a source of contamination. While these issues are likely to be guarded against by scene examiners who may arrive at the scene, first responding officers might be less aware of the forensic implications of their actions. Thus, when responding to an incident or attending a scene where a firearm may be recovered, officers should be made aware of the need to avoid handling exhibits and in instances that involve handling surfaces should be followed by thorough hand-washing.

Owing to the potential for multiple transfer, and also to the possibility of fallout from GSR that has been ejected during the firearm discharge, officers should be mindful of the dangers of contamination when entering a scene and should take precautions against any further transfer once they have left the scene. Charles and Geusens (2012) identified an elevated, if still slight, contamination risk posed by firearms officers when making contact with a suspect. The findings of the present study are suggestive of the presence of GSR on the hands of officers who regularly handle and discharge firearms and who come into contact with suspects who have done so. Thus, they may represent a source of secondary transfer and contamination. The suggestion of further research that addresses this issue is reserved for chapter eight.

The results of the experiments, which demonstrated the propensity of GSR particles to undergo transfer upon contact, point to the importance of ensuring that packaging procedures and solutions maintain the integrity of exhibits and samples and prevent the loss or addition of GSR. The sealed SEM sample tubes that were used in the experimental work in this thesis serve to prevent the possibility of cross-contamination and can be easily labelled. However, packaging a firearm in a manner that does not

result in the transfer of GSR to the inside of the packaging conceivably poses a problem. Further research might assess the extent and implications of transfer during packaging and storage, as well as exploring potential solutions to this issue. Owing to the effects of decay from hands, and of the risk of a suspect transferring GSR to surrounding surfaces, it is advisable to sample the hands at the scene. This is reinforced by the fact that bagging of hands, which is intended to arrest further transfer and the loss of evidence, has been shown to effect the transfer of GSR to the inside of the bag (Wolten 1979c). A cautionary note that must be stressed when sampling at the scene is that, particularly if sampling soon after a shooting, is that the sampling site should, if practicable, be established at a sufficient distance from the discharge site so as to avoid the effects of GSR 'fallout' (Fojtášek and Kmječ 2005) – in a similar manner to the experimental set-up in this thesis.

Conceivably, opportunities for contamination through secondary transfer mechanisms also exist in the period following their collection and prior to their analysis in the laboratory. Chains of custody, secure, sealed containment and the careful handling of samples are of central importance in restricting the loss of GSR from, or the addition of particles to, a sample that has been taken from a suspect or other surface. Maintaining a 'GSR-clean' laboratory and cleaning equipment (stub grippers and tweezers, for instance) are essential if the opportunities for post-collection contamination are to be restricted and in line with various authors (see Wright and Trimpe 2006 and section 3.5), regular control sampling of surfaces in the laboratory will assist in monitoring and inhibiting any contamination risks. This is particularly important if the evidential value of trace quantities of GSR, as identified during this thesis, is to be demonstrated effectively. While the risk of contamination within the law enforcement and laboratory environments and the policies that are aimed at limiting it are, to some extent, beyond the remit of this piece of research, the propensity of GSR particles to undergo transfer reinforces the need to safeguard against opportunities for contamination. In the manner described in section 3.5 (see also Wright and Trimpe 2006) establishing areas in which personnel associated with handling firearms cannot enter is an example of a policy that can be effective in curtailing any potential for contamination. In conclusion strategies and procedures for the collection, packaging and processing of GSR should be informed by the findings of

this research, both in terms of identifying and targeting sampling sites to maximise evidential value and in managing the risks of contamination.

The findings of the experiments, and particularly the results of the control samples, may inform the collection procedures and control measures used in future experimental studies involving GSR, as well as informing forensic protocol in casework. While in the vast majority of cases the measures outlined in 4.2.4 were effective in ensuring that hands were free of GSR prior to the commencement of each experiment, there were a very small number of cases in which small quantities of particles resisted attempts at controlling them. In agreement with Andrasko and Maehly (1977) and Wolten and Nesbitt (1980), this finding suggests that some GSR particles may persist through thorough hand-washing or be redistributed during the washing process (see section 6.2.1). Extremely thorough hand-washing, perhaps with the addition of disposable sponges for instance, that is overseen by the researcher is recommended for future studies, along with control sampling as per this piece of experimental research. These observations should also be heeded when scene examiners, responding officers and firearms officers have left a scene. Thorough hand washing will assist in restricting the potential for contamination from one scene to another and control sampling can offer the possibility of demonstrating the effectiveness of this. It is important that studies, where necessary, explicitly consider any degree of contamination in a manner akin to Lindsay et al (2011a) and to the approach taken during the presentation and analysis of results in chapter five of this thesis.

6.3.2 The analysis of GSR samples

The findings of the experimental work and the observations that were discussed in chapter five point to a number of practical considerations for the process of sample analysis in an investigation involving GSR. Moreover, the process of carrying out analysis using SEM-EDX coupled with an automated detection software package has enabled an assessment to be made of the suitability of this approach to analysing multiple samples in order to generate particle counts. The assessment will not only inform the application of this approach in casework scenarios, but also its employment in similar research projects that seek to understand trace evidence dynamics through the detection and quantification of GSR.

Importantly, the step-by step guides to setting up and running the analytical system and filtering and verifying results provided in chapter four, serve as a guide to using such a system in future research projects that involve the GSR analysis. As argued in sections 3.3.2 and 4.3 however, an automated approach to GSR detection using the SEM is not necessarily a straightforward one. Rather, the 'system' (i.e. the coupling of the operating system, the software, the SEM and the detector) is extremely sensitive to variations in its set-up and calibration. Inconsistency in the set-up and operating conditions will affect the performance, and therefore, the outputs of the system. The accurate quantification of the presence of GSR on a sample in research and casework settings demands a meticulous approach to setting up and calibrating the SEM-EDX and automated system. Regular testing of the equipment of the equipment is also advised (Brozek-Mucha 2011, Niewoehner et al 2005 and 2008, section 4.3).

A number of issues that were encountered during the analysis stages of this study centred on the state and performance of the SEM filament. This importance of filament performance was introduced in section 4.3 in the account of the methods and procedures, but owing to the fact that this issue emerged as one of great significance during the analysis, it is appropriate that it is further explored here.

The stage of a filament in its lifetime ('bedding in', normal, 'burning out' and 'burnt out') affected the performance of the SEM and crucially, the brightness of the backscattered image. In turn, this affected the process of calibrating brightness levels against the standard (the process of which was described in 4.3.4). In practice, this necessitated the manual adjustment of the brightness levels to achieve the correct peak heights for the Cobalt, Gold and Rhodium points on the standard. This was routinely fairly straightforward and levels tended to require slight manipulation between analysis runs, owing to variations in ambient conditions and SEM and filament performance. However, a new filament would result in a very bright image that required much adjustment in order to achieve suitable levels of brightness.

Meanwhile, a filament that was approaching the end of its lifetime, the brightness of the image tended to fluctuate and this instability tended to inhibit the pursuit of suitable levels of peaks on the graph. Accordingly, when this was the case, the peaks tended to 'move' and rise/fall when attempting to calibrate. When these fluctuations were experienced, the filament would normally fail within a few minutes, but

occasionally, it would fail during the analysis. The risk of this happening, or of varying filament performance affecting the brightness of the image during the analysis, meant that purely unattended analysis, while possible, was not always desirable. Rather, it was necessary to maintain some degree of supervision of the system to ensure that if a filament blew, or if the backscattered image became bright and as a result a large number of environmental features were unnecessarily subjected to time- consuming elemental analysis, the operator could address the issue. If not, a sample run could be left incomplete or alternatively, could take significantly longer to complete than anticipated, owing to the number of environmental features that fulfilled the brightness threshold. These ramifications could potentially serve to undermine some of the reasons for employing an automated system in the first instance, namely, time-efficient analysis and stability in the conditions for analysis and thus, repeatability of results. It is recommended, therefore, that any analysis project using an automated approach is designed so that analysis runs, where practicable, can be manually overseen. Furthermore, when carrying out analysis for casework or research purposes, the forensic scientist or researcher should be mindful of the effect that the condition of the filament can have on the performance of the system and the accuracy and efficiency of feature search and detection.

Filament degradation is a generic practical problem that is encountered during all SEM work. That filaments are consumable and that their condition can affect the performance of the machine are widely acknowledged, particularly in SEM operation guides (see, for example Dunlap and Adaskaveg 1997 and section 4.3.3b). Accordingly, a number of sources document the common reasons for filament failure and the steps which can be taken to increase filament longevity; operating at low accelerating voltages, increasing accelerating voltage slowly and limiting the switching on/off of the beam (see for example, Chapman 1999). These measures were taken during the analysis of the samples in this thesis and are recommended for use in casework and research investigations, in order to minimise the effects of the problems described above. However, GSR analysis using INCAGSR (and other automated search and detection packages) requires the use of a fairly high accelerating voltage (20kV). This inherently reduces the lifetime of the filament. As mentioned in section 4.3.3b, during this experimental project, as supply of filaments was sourced to account for this and

the process of replacement and re-setting the system could be carried out without delay. In casework and research, this is also advisable if unnecessary delays in generating results are to be avoided. However, a caveat must be added here. Filaments (in addition to operator time) are expensive and potentially, the cost implications of their regular replacement could, in some circumstances, curtail the potential to submit multiple samples for analysis in the manner described in 6.3.1. The cost implications are likely to be easily justifiable in the investigation of a firearms offence. However, the costs that would be incurred when carrying out research projects that involve the automated analysis of multiple GSR samples, in the same manner as this thesis, may serve to stymie the potential for their undertaking. This is a particularly pertinent issue in light of the wider funding and economic context of forensic science research that was outlined in chapter one (section 1.2.2). To this end, it is anticipated that the demonstration of the practical utility of research projects involving automated analysis of GSR will be more crucial than ever and that, in line with the discussion in 1.2. Research projects and studies should be designed with this in mind. Field emission guns (see section 4.3.1) provide an alternative mechanism of beam generation which avoids the problems associated with the heating of a tungsten filament. Therefore, their use for GSR analysis in casework and research settings is recommended.

The automated analysis of samples remains a time consuming process. Notwithstanding the intricate set-up and post-run processing procedures (described at length in 4.3), the analysis 'run' of a single sample was found to require in excess of six to eight hours in cases where the sample was highly populated with both environmental and GSR particles. Moreover in these cases, the post-run filtering, processing and verification procedures (that were outlined in 4.3.5) tended to be extremely time-consuming. To some extent, some of the problems that represented drawbacks for a manual approach to detection using SEM-EDX, namely, the time-consuming nature of the process, are not fully resolved by an automated capability even given increased computer processing power. While using the most modern detector would speed up the acquisition of elemental profiles for individual features and thus, would reduce the overall time taken, the process remains a potentially protracted one. Crucially, however, the length of time taken for analysis, certainly in

the context of this thesis, is of secondary importance. Automated detection and analysis offers the provision of accurate, fully verifiable and repeatable results and GSR particle counts. The significance of this possibility for research and casework purposes is illustrated in this chapter in terms of the research questions that can be answered and the probative value that may be unlocked for GSR evidence.

Measures that might speed up the analysis process, and thus reduce the cost of sample analysis, are desirable, provided they maintain the level of accuracy and repeatability. To this end, it was considered that the comprehensive particle dataset created during this study represented an opportunity to revisit the possibility of a reduction in the search area of a sample when analysing it to quantify the presence of GSR. This issue was originally discussed in section 3.3.2.

With regard to the aims of the analysis that was carried out as part of this thesis, i.e. the generation of accurate quantification of the presence of GSR, the following research questions were identified:

To what extent is it possible to reduce the sample search area and achieve accurate, repeatable estimates of GSR particle counts?

In order to answer this question, the INCAGSR outputs for a number of samples were selected. These data were used in their raw form, as if they had just been imported into Excel not yet subjected to the processing and filtering that yielded the 'clean' data and counts that were reported in the previous chapter. The method was as follows:

1) A list of random numbers was generated in Excel

2) Four samples were chosen at random for the test

3) The list of random numbers was pasted alongside a list of the fields that were analysed for a particular randomly selected sample (i.e. 1-335)

4) A percentage reduction in the field search area was chosen and a number of fields representing this percentage were selected from the top of the sheet

5) The 'dirty' particle dataset for a chosen sample was opened

6) All of the data pertaining to fields not on the list were deleted, as if only the randomly selected fields had been analysed in the first instance

7) The new list was compared to the 'clean' dataset for the fully analysed sample and any instances where particles had been merged/deleted were corrected

8) The list was cleaned so that only GSR particles remained

9) The number of GSR particles was scaled up accordingly to form a 'new' count

10) The 'new' particle count was compared to the original count

The resulting dataset was analogous to that which would have been produced if, during the 'Area Layout' stage of the set-up (see section 4.3.4b), the search area had been set to 'X %' of fields that were to be selected randomly by INCAGSR – a setting which it is possible to select. A 'random' selection of fields would be more appropriate than a set block or line of adjoining fields because the former allows each field the same chance of being selected. In the latter case it could be that sampling was biased towards a region of the stub that came into contact with a cluster of particles or which was pressed onto a particularly GSR-rich area of the sample surface. In this case, there would be a risk that the sample was unrepresentative of the sample as a whole. The results of this supplementary study are provided in table 6.1:

Test	Sample	Percentage search area	Particle count in search area	Scaled-up particle count	Full search area 'true' particle count	Percentage difference of scaled up from full search
1	Scenario 1, run 1	50%	112	224	207	+8% (17 particles)
2	Scenario 1, run 1	25%	52	208	207	+0.5% (1 particle)
3	Scenario 1, run 1	10%	22	220	207	+6% (13 particles)
4	Scenario 2, run 3	50%	7	14	14	0%
5	Scenario 2, run 3	25%	3	12	14	-14% (2 particles)

6	Scenario 2, run 3	10%	3	30	14	+114% (16 particles)
7	Scenario 5, run 2	50%	17	34	36	-6% (2 particles)
8	Scenario 5, run 2	25%	5	20	36	-44% (16 particles)
9	Scenario 5, run 2	10%	3	30	36	-7% (6 particles)
10	Scenario 4, run 1, from shooter	50%	299	598	647	-8% (49 particles)
11	Scenario 4, run 1, from shooter	25%	152	608	647	-6% (39 particles)
12	Scenario 4, run 1, from shooter	10%	76	760	647	+17% (113 particles)
13	Scenario 4, run 3 Control	50%	2	4	5	-20% (1 particle)
14	Scenario 4, run 3 Control	25%	1	4	5	-20% (1 particle)
15	Scenario 4, run 3 Control	10%	0	0	5	-100% (5 particles)

Table 6.1 Results of the supplementary study of the effects of reducing the sample search area

The results displayed in table 6.1 demonstrate that the effect of reducing the sample search area can have a variable impact on the difference between the particle count that is generated and the 'true' particle count. The variation of this impact can be attributed to several factors including the size of the reduction in the search area, the size of the 'true' particle count and the effects of the random selection of fields. 50%, 25%, and 10% search areas were chosen as these would result in a significant reduction in the time needed for analysis, in a way that a 75%, 80% or 90% reduction would not.

In some cases, whether reducing the search area by 50%, 75% or 90%, the difference between the estimated and 'true' particle counts was minimal. For example, in Test 4, when the search area was reduced by 50%, the scaled up particle matched the 'true' count, while in Tests 2 and 9 when the search areas were reduced to 25% and 10% respectively, the estimated and 'true' counts were markedly similar. The most

extreme divergences between counts in terms of the percentage over/underestimation were observed when 25% or 10% of the sample area was searched (see Tests 6 and 8). As well as the effects of random selection of fields, the size of the 'true' GSR count influences the potential to generate a good estimate through the use of a reduced search area. For example, it is more plausible that the random selection will under represent the true particle count when there is a relatively low 'true' count, as in Tests 6 and 8, especially when only 25% or 10% of the sample area is searched. Larger populations (as in Tests 1, 2, 3, 10, 11 and 12) tended to be estimated well, as the overlooking of a few particles and fields did not have a serious impact on the estimated count and its similarity to the 'true' count. Notably, Tests 10, 11 and 12 were carried out using a sample that had a large contribution from a few highly populated fields containing clusters of separate particles (see section 5.5.2). In such cases, the inclusion or exclusion of these fields when randomly sampling has the potential to dramatically influence the accuracy of the scaled-up count. As a caveat, it should be noted that the tests in this investigation were carried out with the benefit of knowing the 'true' particle count and thus enabling the assessment of the method. Clearly, this would not be the case if the method was employed routinely.

If a sample has a very small ('trace') GSR count, say two or three particles, then there is a high risk that a reduction in the search area could generate a false-negative result, particularly if the sample area is reduced to 10% or 25 % of the sample. The interpretative ramifications of this may be severe given that an inference could be made from a negative result that a subject had not been in contact with a surface bearing GSR or had not in the presence of a firearm discharge. The generation of a false-negative becomes statistically less likely as the quantity of GSR particles on the sample is increased. However, when high numbers of GSR particles are present, but especially when medium and low quantities have been collected, there is a significant possibility that, owing to the variables outlined, the scaled-up GSR count could serve to underestimate the 'true' GSR count. The degree of this underestimation could conceivably have ramifications for the process of interpreting GSR evidence. With reference to the interpretative process outlined in 2.2.1, underestimation of the count may lead to a misguided assessment of the probability of observing a given quantity of evidence given that the prosecution and defence propositions were true. Ultimately,

this could manifest itself into the making of inaccurate inferences regarding the activity of a suspect and the mechanism of GSR deposition, of which the consequences could be serious.

On the one hand, reducing the search area does not carry with it the potential for a false-positive detection of GSR presence, given that all particles that could be detected will be captured by a complete search. Conversely, as demonstrated by the data in Table 6.1, there is the possibility that the 'true' GSR count is overestimated. In the same manner described for an underestimation of the GSR count, the consequences of inflating the GSR count for interpretation and inference-making are demonstrably concerning. Particularly if the degree of overestimation was high, the probability that the quantity of evidence aligns with a proposition of firearm discharge may also be overestimated.

The degree of under/overestimation is likely to be generally limited but, owing to chance and to the uneven distribution of particles on a sample in some cases, a major discrepancy could arise and result in a sample with a 'medium' sized GSR population (say, 40 particles) being deemed a 'low' quantity of GSR (8 particles, for example) or, of course, vice versa. In summary, the methodological decisions that are made during sample analysis in casework (and research), and the errors that might be associated with them, will have a bearing on the interpretation of evidence. This resonates with the assertion that the interpretation process is an iterative one and that it spans, and should underpin all stages of an investigation (see Cook et al 1998a) and section 2.2.2).

During research projects (such as this thesis, for instance) and the investigation of casework scenarios that require precise, verifiable and repeatable quantification of the presence of GSR, a reduction in the search area is not justifiable. This conclusion echoes Owens (1990) who argues that using statistical methods in order to limit the necessary search area is, owing to the potential for false-negative results in particular, inherently risky. Other research and casework scenarios may involve verifying the accuracy of a precise particle count, confirming GSR presence, pre-screening for GSR, or estimating whether the population of particles may be 'high', 'medium' or 'low'. In these cases, a reduction in search area could be justified. However, the use of a confidence interval or error rate would be advisable in such cases. If a simple confirmation of GSR presence was required, then a search could be halted on finding

the first GSR particle, yet difficulties will arise when considering the point at which it is appropriate to conclude that a sample has tested negative for GSR? According to Owens (1990) this cannot be concluded with confidence when a portion of the sample is not searched. An alternative option for reducing the length of time taken to analyse a sample would be to propose the use of smaller adhesive surfaces on the SEM stubs. While this would reduce the search area without the need to 'scale-up' the count, the use of ½ inch stubs is something of a standard collection method in research and casework and departing from this would engender problems when attempting to compare counts from different cases and published experimental studies. Notwithstanding this, a smaller adhesive surface would be likely to become saturated with material more readily and would increase the risk of leaving uncollected GSR on the surface being sampled.

In both research and casework settings, if there is a low population of GSR on a sample then the duration of the analysis should not be prohibitively long. Meanwhile, carbon coating and effective setting up of the brightness levels and thresholds will limit unnecessary contributions to the analysis time from extraneous environmental particles. While reducing the search area in certain cases can be a useful tool, its potential impact on the accuracy of results should curtail its application in casework, particularly due to the fact that the accuracy of any results are likely to be the subject of scrutiny if admitted to a courtroom. In keeping with the model of case assessment outlined by Cook et al (1998a), the type and extent of analysis and forensic examination will depend on the questions that are asked of the GSR evidence. For example, a confirmation of positive GSR presence could involve a cursory examination yet, as GSR evidence is likely to be associated with the most serious offences (see section 1.3), casework investigations will require accurate measures that maximise the weight that can be assigned to a particular item of evidence. Notwithstanding the influence on the GSR count that is produced, the effect of reducing the search area and scaling up the result would potentially compromise the ability of the examiner to interpret particle size data. Size data, in addition to particle counts, elemental analysis (via SEM-EDX and/or complementary methods, see Christopher et al 2013, Nakai et al 2009) and surface analysis could assist in discriminating sources of GSR. As will be discussed later in this chapter, the distribution of particles among size categories can

be of potential value, while the presence of one or two large particles may also be informative. These individual particles may remain undetected if the sample area is reduced. Consequently, any attempt to utilise particle size data will necessitate a search of the entire sample stub. Finally, consideration of the entire particle population is necessary when identifying the source of GSR-like material and assessing the potential contribution made by environmental or occupational sources of particles which are similar to GSR (Wolten et al 1979b and Garofano et al 1999). Reducing the search area, therefore, should be undertaken with caution and justified in terms of the aims of the analysis.

6.4 The interpretation of GSR evidence

In demonstrating the practical utility and investigative implications of the findings of the experimental work, it is arguably in the interpretation of GSR evidence that the most significant issues can be raised. Therefore, discussion of the ramifications for the interpretation process has been afforded a section in its own right. This discussion considers the ways in which our updated understanding of GSR dynamics may impinge upon, assist and complicate the framing and assessment of interpretative propositions with regard to GSR evidence. In section 3.4.1 the possibility of using GSR to infer the identity of the shooter was discussed. In essence, the results of the experimental research provide an account of some of the nuances that maybe involved in this process.

6.4.1 The presence of GSR

Of primary importance for the interpretation of GSR evidence is that the results clearly demonstrate that the presence of GSR on the hands of an individual does not necessarily mean that the individual discharged a firearm. Rather, the material may have been acquired via a hand-to hand contact with a shooter, through holding a recently discharged firearm, or by being in close proximity to a firearm discharge. The experiments also confirmed that GSR may even be acquired through hand-to-hand contact within individual who, themselves, had made hand-to-hand contact with a shooter; thus, via a tertiary transfer. Such possible mechanisms of transfer will need to be incorporated into the propositions that are formulated and addressed when interpreting GSR evidence. That the presence of GSR on hands will not necessarily

indicate that the individual discharged a firearm is well established (see sections 3.4 and 3.5 and Matricardi and Kilty 1977 and Lindsay et al 2011a, for example). However, to date the mechanisms of deposition and transfer have not been studied in a systematic fashion with a view to producing a dataset that can inform the process of interpretation and distinguishing between mechanisms of transfer. In light of the results, it is possible to say that rather than indicating that an individual fired a gun, small to medium quantities of GSR recovered from the hands of a suspect may in fact point to an alternative means of exposure to GSR. The fact that GSR particles can be readily transferred in the immediate aftermath of a firearm discharge by the various means described should be acknowledged when attempting to interpret the presence of GSR evidence and when setting about reconstructing an incident involving a firearm.

Without acknowledging the potential for the transfer and deposition mechanisms that have been studied during this piece of experimental work, the possibility exists for misinterpretation. For example, GSR particles that have been transferred to or deposited on an associate, accomplice or unconnected individual could be wrongfully inferred as having been deposited on the hands as that individual discharged a firearm. Subsequently, this misinterpretation could lead to a misidentification and ultimately, incriminate an innocent individual while potentially leaving a perpetrator at large. Thus, when formulating propositions about the activities that may have led to the acquisition of GSR the possibility of innocent, or rather indirect/non-firing exposure to GSR must be incorporated, in addition to possibilities of for example, exposure to GSR-like materials from environmental and occupational sources. A suitable pair of propositions may consider on the one hand, the probability of observing GSR evidence given that the individual discharged a firearm, while an alternative (defence) proposition may consider the probability of observing GSR particles given that the suspect did not fire a gun, or more specifically, given that the suspect was standing in proximity, or shook hands with a shooter. The probability of the second proposition, as demonstrated by the results, is not negligible in some circumstances and further study of its assessment is warranted.

6.4.2 GSR particle counts

chapter five presented GSR counts that were derived by analysing samples taken from the hands of participants who were exposed to GSR in a variety of ways. These counts

may be used to assist in distinguishing different mechanisms of GSR deposition as they providing an indication of the quantities of GSR that can be 'expected' quantities given different scenarios. Despite the measures taken to approximate real-world scenarios and to ensure the validity of the findings (see section 4.2.5), applying the results to the interpretation of GSR in casework contexts involves some inherent limitations. Rather than being repeated throughout the discussion, these caveats are now stated explicitly.

It must be stressed at this stage that, as described in section 6.2.2, the counts produced in this study represent an "extreme" case in which transfers and contacts were made in the immediate aftermath of a firearm discharge, with no opportunity for substantive particle decay. Moreover, there was only a very short delay between the simulated contact and the collection of evidence. As a result, without the influence of any considerable evidence decay, the maximum possible quantity of GSR was transferred and subsequently collected. Consequently, these counts may be higher than the analogous real-world casework situation in which some GSR may have decayed owing, in particular, to a delay between the transfer and the suspect being apprehended and sampled. Thus, the results are indicative of the differences that can exist between GSR counts that have resulted from different transfer mechanisms. In a real casework scenario, the persistence of material and the timeframes involved will have to be incorporated and this will be discussed. Rather than being limited in their applicability to casework scenarios, the results serve to illustrate the interpretation issue that may arise due to multiple transfers. Indeed, every casework situation is unique, with its own 'framework of circumstances' (Cook et al 1998b, p.234) in which interpretations are made and thus, as with all experimental research, extrapolation from the results should be undertaken with caution. Notwithstanding this, the aim of this discussion is not to consider how the findings might impact evidence interpretation in a specific scenario but rather, the interpretative nuances that implicate the formulation and assessment of propositions about GSR evidence are considered more generally. It is also acknowledged that in the experiments five rounds of 9mm Luger 95 grain jacketed soft point 9P1 ammunition (manufactured by FEDERAL Ammunition) were fired using a SIG Sauer P226 9mm self-loading pistol were fired and again, while this may not be analogous to a specific casework scenario,

mimicking a specific scenario was not the intention. Rather, when making observations regarding GSR interpretation and developing a model for the process, the need for case-specific research and data is stressed. Issues regarding the applicability of experimental data were raised in sections 1.2.1 and 4.2.5 (see also Mnookin et al 2011). A case-by-case approach to GSR identification has been recommended (see section 3.2.3 and Dalby et al 2010). The findings of this thesis suggest that this approach may be extended to include transfer and persistence issues.

If a quantity 'X' of GSR was recovered from a suspect, a pair of Level II propositions may be formulated that would consider, first, the probability of observing that quantity given that the suspect fired a gun and secondly, the probability of observing that amount of GSR given some other means of GSR deposition (secondary transfer, proximity deposition, etc.). Assuming that very little time had passed between the deposition and collection of the evidence, the results of the experimental work suggest that the presence of several hundred particles would be much more likely given that the suspect had fired a gun than if particles had been acquired by some other means. The mean number of particles deposited on the hands of the shooter in experimental scenario one was 429, whereas the number of particles acquired by subjects in other experimental scenarios tended to be below 100. However, the variability in the amount of GSR that was initially deposited on the shooter (between 206 and 834 particles - a range of 628 particles) means that if the GSR count was at the lower end of this range, then there is an increased probability that this quantity could be observed given an alternative means of deposition. This is because similar quantities of particles can undergo secondary transfer, as demonstrated by the results of scenario three in which as many as 129 particles were transferred via a handshake. In this manner, it is possible to formulate and assess competing activity level propositions about GSR evidence that reflect explanations for the presence of GSR put forward by the prosecution and defence. Concurrently, claims of secondary transfer or GSR acquisition by other means can be corroborated or refuted and ultimately, this will assist in the reconstruction of an incident. However, uncertainty is inherent when inferring the cause of GSR presence and the assessment of competing propositions is necessarily a probabilistic one. Accordingly, chapter seven will explore an approach to interpreting GSR evidence using Bayesian Networks. Further variables would also need

to be incorporated into the assessment and it is argued in chapter seven that a Bayesian Networks approach can facilitate this.

If a smaller quantity of GSR (30 particles, for example) was recovered from a suspect, once more, a prosecution proposition may involve consideration of the probability of observing that quantity of evidence given that the suspect had fired a gun. On the other hand, consideration of a defence proposition might require the assessment of the probability of observing that the suspect did not fire a gun and this might, in turn, consider the probability of observing such a quantity if a secondary transfer of some sort had taken place, or if the individual had been in the proximity of a firearm discharge. In this case, according to the experimental data, the probability of observing 30 particles given that a mechanism other than discharging a firearm was responsible for their presence is considerable. For example, exactly 30 particles were transferred from a shooter to a second individual via a handshake in one of the runs of scenario three and similar counts were yielded from samples taken from subjects who had handled a firearm, who had been in the proximity of a firearm discharge, and even from those who had acquired GSR through a tertiary transfer. Meanwhile, notwithstanding their variability from firing to firing, the GSR counts recovered from the shooters following firearm discharge tended to be much higher than 30 particles; the lowest was 206 and as many as 834 particles were recovered. Thus, the expected quantity of GSR if the suspect had fired a gun would be significantly higher and the probability of only recovering 30 particles from a suspect who had fired a gun might in fact be fairly low.

As described previously, the figures considered here relate to a very specific scenario in which five shots were fired from a specific firearm, using one ammunition type and in an indoor environment. Therefore, the counts cannot be directly extrapolated to other scenarios or contacts with different variables which would need to be incorporated into the assessment. Nevertheless, they do serve to demonstrate the impact of the existence of secondary transfer and deposition mechanisms on the interpretation of GSR evidence and the way in which case-specific data could be used to assess the likelihood of these alternative means of deposition.

Clearly, cases in which there has been little or no opportunity for GSR to decay from hands, either between deposition and transfer or between transfer and collection, will

be few. Therefore, when interpreting GSR evidence, the timeframes of GSR longevity and the persistence of GSR on hands must be incorporated. The importance of incorporating persistence into the assessment of inferences about trace evidence at the activity level is highlighted by Cook et al (1998b). Without information regarding the timeframes involved, the results of the experiments indicate that it could be possible to wrongly infer that 50 GSR particles, for example, that were recovered from a suspect were the result of a deposition from firing a gun that had been subject to decay over a few hours, when in fact their presence was the result of a recent secondary transfer. Equally, the reverse wrongful inference could be made. While the expected GSR counts for these alternative mechanisms will vary from case to case, the hypothetical example demonstrates the importance of acknowledging the timeframes involved and therefore, incorporating the effects of persistence. Evett et al (2000) also identify the salience of timeframes in formulating Level II propositions, the interpretation of which will be considered by time. The authors note that the role of the scientist is to consider the probability of the evidence given the timeframe of the alleged activity, rather than to offer an opinion of the likely timing of the activity. In the case of GSR, the scientist will need to draw on expertise regarding the transfer and persistence of GSR. The evidence will therefore be interpreted under competing propositions with reference to experimental work on the deposition of GSR on a shooter during firing, on the propensity of GSR to undergo transfer or to be deposited in the vicinity of a shooter and on the persistence of GSR in different settings (see the experimental data presented in chapter five, sections 3.4.4 and 3.5 and Jalanti et al 1999, for example).

Timeframes will necessarily be case-specific but their interpretation may be informed by the findings of experimental studies concerned with the dynamics of GSR. Case-specific research that might address a particular transfer or persistence issue or variable may also be referred to, and these studies should approximate the context of the case while being informed by the methods and experimental design used in studies such as the present one .

Evett et al (2000) (as well as Cook et al 1998b) maintain that the propositions that are formulated will be bound by the circumstantial framework of the case and in particular, the explanation for the evidence that is provided by the defendant. It has

been assumed thus far that the source of GSR has not been disputed – that the particles recovered in the hypothetical examples are accepted to emanate from a firearm discharge and not from some other environmental or occupational source. Meanwhile, the examples have assumed that the explanation offered by the suspect and the defence will have included, for example, being in the proximity of a firearm discharge, or coming into contact with a shooter or a recently discharged firearm. This is distinct from having denied being in the presence of a discharge or making contact with a surface bearing GSR. In this case, the scientist would need to consider the background rate of GSR – i.e. the probability of an individual having GSR on their person if they have not come into contact with firearms (see for example, section 3.5 and Lindsay et al 2011b, Mann and Espinoza 1993, Kotrlý and Turková 2010 and Wright and Trimpe 2006). Clearly, the quantity of GSR will be important in this case and the presence of several hundred particles, for instance, would be very unlikely to have been acquired from background contamination from a non-firearm environment. The data that are presented in chapter five represent a resource with which the forensic scientist may be equipped when interpreting the GSR evidence under propositions that consider the probability of different mechanisms of GSR, particularly in cases where secondary transfer or deposition is put forward as an explanation by the suspect

In multiple suspect cases, the comparison of GSR particle counts taken from different suspects conceivably provides a means to assist in making inferences about the roles of different individuals in a firearms offence. For example, consider an example in which two suspects had been seen leaving the scene of a shooting and were subsequently apprehended. A gun was recovered from one of the suspects and both were sampled for the presence of GSR. Both claimed the other suspect was the shooter and that they merely took the gun from the other suspect and left the scene. A comparison of the GSR counts here may contribute to the accurate reconstruction of events and experimental data such as those presented in section 5.2 for the level of deposition on the hands of a firearm handler and a shooter could be used to support an inference regarding the identity of the shooter. The experimental results indicate that, in settings and conditions analogous to those simulated, shooters may be distinguishable from subjects who have acquired GSR by other means.

The experimental results also indicated that GSR counts may be used to make inferences about the identity of donor and recipient surfaces. However, the results also showed that in some cases the quantity of GSR left at the donor site could be very similar to, or possibly less than, that which was transferred to the recipient following a contact, thus providing the potential for misinterpretation. The consideration of multiple suspects and samples is more complex, particularly given that other variables or items of evidence that relate to one or more of the suspects may come to light and the incorporation of this information can be complicated. Chapter seven will explore the potential for the use of Bayesian Networks to assist in making inferences from GSR evidence when faced with a number of interacting variables and considerations (Dawid and Evett 1997, Evett et al 2002). It will do so with reference to examples involving alternative means of GSR transfer/deposition.

6.4.3 GSR particle size data

A number of observations were made in section 6.2 regarding the trends and patterns that were observed when the particle size data were analysed. Accordingly, a number of insights into the dynamics of GSR were made, with particular reference to the distribution among size classes and the manner in which these distributions appeared to vary, or to be well replicated, according to the mechanism of deposition. It should be re-emphasised that the conclusions made from the particle size data are tentative. While it was possible to unequivocally confirm that GSR particles can undergo secondary and tertiary transfer from the results of the experiments, our ability to infer the repeatability of trends regarding the sizes of particles that underwent transfer is less certain, due to the complex nature of GSR formation and deposition. This is also owing to the relatively small number of repeat runs of each experiment and to conclude that, for example, certain sizes of particle are less likely to be deposited or transferred via certain mechanisms will require further study. Furthermore, the particle size data relate to the firing of five rounds from a particular firearm/ammunition combination, in a particular setting and therefore, the numerical results may not be directly transferrable to other settings. Nevertheless, measures were taken to simulate real-world scenarios and the results pointed to a number of novel findings regarding the dynamics of GSR evidence, which point to a number of interpretative implications if particle size data were to be incorporated into the

formulation and assessment of interpretative propositions. The examination of the particle size data for samples containing GSR has the potential to unlock probative potential that has received limited attention to date. However, from the relatively small scale of the analysis that has been carried out during this piece of research, it is evident that the nuances of this kind or interpretation are manifold.

Hypothetically, a situation could arise in which a sample that was taken from a suspect and analysed was found to contain a number of large (>100µm) particles by the scientist. When assessing the likelihood of observing large GSR particles given alternative hypotheses about the method of deposition, it might be assumed that the probability of finding these large particles as a result of secondary exposure to GSR is low. Therefore, the inference might be made that the presence of large GSR particles on a sample taken from a suspect is indicative of them having fired a gun. On the contrary, the experimental findings have demonstrated that there is a considerable likelihood that large particles may be recovered from an individual given that they have had contact with a shooter, or even from the recipient of a contact with an individual who themselves had previously made contact with a shooter. As described with regard to the particle counts, the influence of persistence and decay would need to be incorporated into the interpretation of particle sizes, particularly as it is known that larger particles tend to decay from a surface most rapidly, leaving only the smaller particles at the surface (Andrasko and Maehly 1977). In a casework scenario in which there was a degree of uncertainty regarding the timeframe involved, and without an appreciation of the possibility that large particles may be secondarily transferred, then conceivably, a sample taken from a secondary transfer recipient could be misinterpreted as being indicative of a deposition on a shooter from a firearm discharge that has been subject to decay over a period of time.

The experimental work has demonstrated that while considerable quantities of GSR that might be expected on the hands of a shooter can be recovered from secondary transfer recipients, similarities may also exist in terms of the particle size data pertaining to the two sampling sites. When a full range of GSR particles is recovered, from sub-micrometre to very large features (>100µm), the experimental results have shown that primary deposition from a firearm discharge is not the only means by which a population of particles representing the overall particle population may have

been deposited on the hands of a subject. Rather, samples that are representative of the same initial population of GSR produced by the firearm, in terms of the mean particle sizes and the distribution of particles among size categories, can be recovered from secondary and tertiary transfer recipients, and also from firearm handlers. It is possible that a secondary transfer recipient may even yield larger particles than those that might be recovered from a shooter. As a consequence, the capacity to differentiate between primary deposition and secondary transfer mechanisms via the sizes of particles involved might prove to be extremely challenging.

The particle measuring 32.35µm that was recovered from an individual who was standing one metre behind the firearm discharge highlights another potential source of misinterpretation. It could be assumed that large particles would be more likely to be recovered if the suspect had fired a gun, rather than if they had been some distance from the discharge. This experimental work has suggested that while lower quantities of particles might be recovered if the suspect was a bystander, the possibility exists that large particles do have the capacity to become airborne and be deposited on an individual in proximity. The results suggest that there may be interpretative potential, despite variability between firings, in the observation that large particles may be less likely to be deposited on bystanders with increasing distance from the discharge. This was indicated by the results of the experiments. However, the relationship between particle size and distance from the discharge has previously been shown to be a complex one by Brozek-Mucha (2009) and further research is warranted which is aimed at enhancing our understanding of this relationship and elucidating the interpretative and reconstructive utility it may hold.

The presence of a concentration of a number of large particles on a sample, in what were termed conglomerates in section 5.5.2, could inform the interpretation of GSR evidence that is recovered from a suspect. These concentrations were found in a small number of cases during the experimental phase of this thesis. Notably, they were found on a sample that was recovered from a shooter. Such concentrations were not recovered from participants who had acquired GSR via any of the other mechanisms the recipient of GSR. Moreover, these concentrations remained at the shooter following a handshake and appeared to resist transfer (see section 5.5.2). This may be attributable to the presence of the concentration on a part of the hand which did not

make contact with the recipient hand during the handshake. In any case, the efficiency of the transfers suggests that if contact was made, one would not expect the entire conglomerate to undergo transfer. Thus, conglomerates may be more likely to be recovered from shooters. This finding may suggest that the likelihood of observing such large clusters of large particles may be low given that the suspect was the recipient of a secondary transfer or had acquired material via a deposition from the firearm while standing some distance from the discharge. Further experimental results are required to determine if this hypothesis is valid, and whether it might apply to, for example different firearm and ammunition types. While they were not observed on samples taken from subjects who handled a firearm following discharge, these conglomerates could conceivably be deposited on the surface of the firearm as well as on the hands of the shooter. Further study could confirm whether this is possible and, as a result, whether the presence of concentrations of large particles could be used to infer that a suspect made contact with the firearm either during or after the firing. In short, further study of conglomerate particles, their dynamics, and their evidential value is warranted.

The possibility of differentiating between a donor and recipient following a transfer is complicated by the fact that the particle size data relating to the material that remains at the donor can be expected to be very similar to that relating to the received material. To this end, it could be possible to infer from such similarities that two surfaces have come into contact (that the GSR comes from the same source or population) and in this way, provide support for claims of secondary acquisition. Perhaps this may also assist in instances where a suspect might deny having fired a gun or having come into contact with another suspect who did. The detection of particles representative of the population of particles that is produced and deposited by a firearm, under conditions relevant to the case at hand, may serve to refute that claim. Once again, the persistence of material and the temporal circumstances of the case will need to be incorporated into such an assessment

Reconstructing transfers by using particle size data to assist in making inferences about the method of deposition will necessarily involve the comparison and interpretation of multiple samples and reinforces the need to sample from all suspects who may have been present, or who could potentially have acquired GSR evidence by some means

(see section 6.3.1). Central to ensuring that the necessary samples are collected is the implementation of sampling strategies and procedures underpinned by an understanding of the mechanisms of transfer and deposition explored in this study (see section 6.3.1). The interpretation of evidence from multiple suspects or individuals is inherently complex. It will be argued in chapter seven that making inferences at the activity level while weighing a number of variables and empirical data in a logical, transparent manner can be assisted by an approach to interpretation based on Bayesian Networks, with the assistance of Bayesian decision support tools.

6.5 The presentation of GSR evidence

The findings of the experimental and analytical work have been discussed with regard to their contribution to the literature on the dynamics of GSR evidence. This chapter has also considered the ways in which the research might inform, impact upon, and be incorporated into the various stages of a forensic investigation. There are also ramifications of this piece of research for the presentation and reporting of evidence in investigations which, in some sense, involve the multiple transfer of GSR or which asses the possibility of secondary exposure to GSR evidence.

An investigation that involves the assessment of the likelihood of observing GSR evidence 'X' given alternative means of transfer/deposition will necessarily involve references to appropriate published experimental work and studies. As recommended by Linacre (2013) (and outlined in section 1.2.1) an effective report of such an assessment and of the inferences that have been made as a result, will demonstrate the way in which the conclusions are supported and underpinned by robust, published empirical and theoretical research on the subject. Evidently, there must also be a distinction, as has been stressed throughout this chapter, between 'reading-off' results produced in specific contexts and being informed, perhaps in combination with case-specific research, by the results and findings of specific studies. Articulation of the reasons for applying research findings to a given scenario, and demonstrating the validity of doing so, are also important.

While contamination may result from secondary transfer mechanisms, care needs to be taken when using the word "contamination" to describe the acquisition of GSR (and other trace evidence) by secondary transfer or passive exposure. The term

"contamination" may serve to invoke the belief that the evidence is in some way compromised. While contamination of GSR evidence could conceivably occur through sampling, during suspect processing or subsequently, in the laboratory, in a situation in which a suspect has handled a firearm, this individual has acquired GSR via a secondary transfer mechanism rather than as a result of "contamination". Thus, making this distinction clear will involve the correct use of terminology and explicit explanation of the proposed mechanisms of transfer. Reporting and justifying inferences made about the likely avenue of GSR deposition may be assisted by diagrams or visualisations of transfer or contact scenarios (as recommended by French et al 2012). In this way, accounting for the presence of GSR on a number of suspects could be explained with reference to a visual, diagrammatic reconstruction of events and transfers.

In section 6.4 it was concluded that formulating and assessing propositions regarding the GSR evidence and the identification of the shooter should account for the possibility of deposition or transfer via a mechanism other than firearm discharge. In formulating a pair of propositions to reflect this, the psychological concept of unpacking should be acknowledged. Van Boven and Epley (2003) indicate that decisions and beliefs can be influenced by the extent to which the detail contained within discrete options is 'unpacked'. Thus, the forensic scientist must be mindful of the persuasive impact of articulating alternative means of GSR transfer and deposition when unpacking a defence proposition regarding the deposition of GSR. Indeed, Tenney et al (2009) have demonstrated the impact the effect of introducing alternative suspects and plausible alternative stories on the likelihood of a not guilty verdict in a legal context.

Chapter seven will consider the potential for an interpretative framework based on Bayesian Networks to assist in the interpretation of GSR evidence. Section 7.4 incorporates the novel empirical findings regarding GSR transfer and deposition into graphical structures to explore the potential to reason about mechanisms of transfer. The presentation of results and inferences based on this approach to interpretation involves a number of contemporary issues, especially in light of recent legal judgments in England and Wales. A discussion of the presentation of inferences made using Bayesian reasoning in this context is presented in section 7.5.

Chapter 7 The interpretation of GSR evidence using Bayesian Networks

7.1 Outline

Chapter six considered the contribution of the experimental findings from this study to the body of literature on evidence dynamics. The implications for forensic investigations involving GSR evidence were discussed, with a particular emphasis on the incorporation of these findings in the formulation and assessment of interpretative propositions about mechanisms of GSR deposition and transfer. This chapter develops this discussion by exploring a Bayesian Network (BN) approach to evaluating GSR evidence under propositions about its transfer and deposition. Thus, this chapter is concerned with further addressing Research Question Six which was set out in section 3.7. It also contributes to the research into models and data for GSR interpretation using Bayesian approaches which is called for by Romolo and Margot (2001). Through the use of illustrative scenarios it will be demonstrated that a BN framework, which incorporates data of the genre presented in chapter five, provides a means of weighing multiple pieces of evidence to make inferences about GSR and the activities that led to its deposition and transfer. A Bayesian decision support tool, AgenaRisk, will be employed in this chapter. While primarily concerned with GSR evidence, the discussion in this chapter is intended to resonate with the interpretation of trace forensic evidence more generally and to contribute to the growing literature on the Bayesian interpretation of forensic evidence. The discussion will also be situated within the context of recent legal judgments and contemporary debates concerning the probabilistic assessment of forensic evidence and will consider the future of probabilistic reasoning in casework and legal contexts.

7.2 Bayesian Networks

Bayesian Networks are graphical structures that represent causal dependencies and probabilistic relationships between variables. A Bayesian Network consists of nodes representing variables of interest, directed arrows that represent dependencies which often correspond to causal relations between the variables, and probability assignments (Taroni et al 2006, Taroni et al 2004, Pearl and Russell 2003, Fenton and

Neil 2012). Conditional probabilities quantify the nature and strength of these links and render it possible to use the graph as an inferential tool[57]. Importantly, an absence of empirical data does not inhibit the use of a graphical approach. Indeed, representing dependencies between variables and inferring the effect of a change to one node on the probability of an event or hypothesis (even though this change will not be quantified) is possible (Lagnado 2011). Reasoning about causal relations and interactions in this way is useful for a variety of problems, including those in the legal and forensic domains.

Bayesian Networks exhibit a number of central features. First, and crucially, a Bayesian Network captures the way in which prior beliefs about the probability of some variable or event are updated by observations and evidence. The capacity to use a Bayesian Network to calculate 'the effect of knowing the truth of one proposition or piece of evidence on the plausibility of others' is noted by Garbolino and Taroni (2002, p.149). Secondly, these network structures can accommodate a number of variables and can capture the interrelatedness of a number of different types of evidence. Bayesian Networks also offer the capacity to examine the effects of different observations and combinations of observations on prior beliefs. Bayesian Networks have been widely applied in a variety of domains to assist in reasoning under conditions of uncertainty (Biedermann et al 2005a, Cowell et al 1999, Jensen 2001).

7.2.1 Bayesian Network Tools

A number of Bayesian decision support tools are commercially available. These software packages enable the construction of networks and the modeling of probabilistic relationships of increasing complexity. In this way, it is not only possible to visualise the causal dependencies, but also to calculate the probabilities of certain outcomes given certain conditions. To articulate these Bayesian calculations by hand can be a very arduous process, particularly if the problem is complex and incorporates a number of interrelated variables. The decision support tool performs these calculations, derived from Bayes' theorem "behind the scenes" using data on prior

[57] Suitable examples are provided for different domains in the tutorials and resources provided with licenses for AgenaRisk (AgenaRisk 2013)

beliefs and probabilities which are entered into the node probability tables (NPTs). Thus, the network becomes an inferential tool through which it is possible to reason about a problem and to calculate conditional probabilities. AgenaRisk (AgenaRisk 2013) was chosen to carry out this study of the interpretation of GSR, owing to the capacity of this software to model continuous variables and in light of previous work that has employed AgenaRisk when considering the evaluation of forensic and legal evidence (see, for example, Lagnado et al 2013, Fenton et al 2013, Fenton and Neil 2012).

7.2.2 Bayesian Networks and forensic evidence

Section 2.2.2 surveyed the process of interpreting forensic evidence. It outlined the process of assessing evidence under a pair of competing propositions that reflect on the one hand, the prosecution stance and on the other, the defence stance (Cook et al 1998a). Assessing the probability of observing a given pattern, quantity or type of evidence, given that first, the prosecution allegation is true and secondly, that the defence allegation is true can involve the incorporation of many variables. For example, knowledge about the background rates of the trace evidence and information relating to the transfer and persistence properties of the material will need to be incorporated. Accordingly, data from published experimental studies will need to be referred to during the assessment. Meanwhile, information about the reliability and error rates of an analysis technique, or data on the level of contamination might also need to be considered. The weighing of a number of variables also takes place at the pre-assessment stage when the expectations of an examination are determined by considering, for example, the quantity of evidence that might be expected if a certain proposition was true (Cook et al 1998a).

Evidently, even in a relatively simple assessment, representing the interpretation problem and modelling dependencies can be challenging. In order to make inferences and to reason about the probabilities the forensic scientist is concerned with, the problem must be formalised in some way. As a result, a number of contributors have proposed the use of Bayesian Networks as a solution to representing, formalising and reasoning about forensic science problems and dealing with uncertainty (Garbolino and Taroni 2002, Taroni et al 2004, 2006, Fenton and Neil 2012). This approach is

advocated for forensic interpretation problems that involve multiple variables (Aitken and Gammerman 1989).

Accordingly, work has followed which is concerned with the application of graphical methods to evaluating scientific evidence (Taroni et al 2004). Puch and Smith (2002), for example, have demonstrated the application of a Bayesian Network system in the pre-assessment and assessment of fibre evidence. The authors demonstrate how the system can be used to train an examiner to reason about uncertainties regarding fibre transfer and retrieval via the BN. Biedermann et al (2005a, 2005b) explore the use of Bayesian Networks in the forensic investigation of fire incidents, while Lee et al (2009) investigate the representation of bodies of digital forensic evidence in a BN framework, citing the capacity to delineate causal relations as a particular advantage of this approach. Furthermore, the use of a Bayesian Network methodology in the evaluation of glass evidence is reported by Zadora (2009).

Considerations of the probabilistic assessment of forensic evidence are not limited to research into the use of Bayesian Networks. The calculation of the likelihood ratio with regard to evidence under competing hypotheses is commonplace in both research and casework settings. The likelihood ratio is calculated by the formula below:

$$\frac{\text{Probability of Evidence (E)} \mid \text{Prosecution Hypothesis (Hp)}}{\text{Probability of Evidence} \mid \text{Defence Hypothesis (Hd)}}$$

The probative value of the evidence is calculated according to the rules below, in a way that quantifies the impact of evidence on our prior beliefs:

LR > 1 : Support for the prosecution hypothesis

LR < 1 : Support for the defence hypothesis

LR = 1 : Evidence (E) has no probative value

The level of support, or otherwise, for the hypothesis can be expressed numerically but is often converted to a verbal scale. The merits and problems associated with this approach will be articulated in section 7.5. Examples of work that considers the interpretation of forensic evidence using the likelihood approach include Morrison et al (2011) for forensic voice comparison, Zadora and Ramos (2010) for glass evidence,

and Taroni et al (2012) for comparative handwriting examination. The use of a likelihood ratio approach is well established in the field of DNA identification and when interpreting from a database search (Stockmarr 1999, Beecham and Weir 2011)[58]. It is worth noting that much research into the assessment of forensic evidence is focused upon source level uncertainty, rather than considering how the evidence may have been deposited at a scene or on a suspect.

While embodying the principles of a Bayesian inference model, the calculation of the likelihood ratio will be afforded less attention in this chapter in favour of a focus on attempts to incorporate multiple variables and pieces of evidence in Bayesian Network structures. It is important, however, to recognise the synergies that exist between the calculation of the likelihood ratio and the use of a Bayesian Network for reasoning and updating. Indeed, it is possible to perform the likelihood ratio calculated from the updated Bayesian Network. Crucially, a graphical approach permits the incorporation of variables and sources of uncertainty that would otherwise render the development of a likelihood ratio formula extremely complex (Biedermann et al 2009).

Bayesian Networks are compatible with, and can facilitate, the model of interpretation which was set out in section 2.2.2. The incorporation of multiple variables and the management of uncertainty are inherent in the processes of assessing the likelihood of evidence under competing propositions and determining what evidence would be expected in certain scenarios. Furthermore, Evett et al (2000) explain that propositions may need to be reviewed or evidence re-assessed in light of changes in the 'framework of circumstances'. Bayesian Networks are ideally suited to accommodate such changes. New nodes can be added should new evidence come to light, hypothesis nodes can be modified to capture a new explanation that is offered by the suspect and data from experimental work that is carried out to resolve a particular issue can be readily incorporated. Thus, graphical approaches facilitate reasoning in a 'flexible and interactive' manner (Biedermann et al 2009, p.26, Jensen 2001, Pourret et al 2008).

[58] The degree to which it is valid to make a distinction between the probabilistic assessment of DNA evidence and the probabilistic assessment of other types of forensic evidence is the source of debate and will be discussed in section 7.5.

A Bayesian Network may also be used to capture the forensic evidence in the wider context of a case. In complex cases involving multiple suspects, witnesses and different items of evidence, a BN approach can assist in representing the dependencies in the case and the manner in which elements "fit" together. In this way, central items of evidence can be identified and the accuracy and reliability of, for example, witness testimonies can be elucidated. A demonstration of the use of a graphical approach to capture the way in which legal judgments are made has been carried out by Lagnado et al (2013) and Fenton et al (2013). Lagnado et al (2013) propose a framework for evidential reasoning in a legal context using causal idioms. These "building blocks" can be used used to capture the relations between complex bodies of evidence in legal cases, and serve to assist the process of reasoning and evidence evaluation (Fenton et al 2013). This framework is also useful for reasoning about forensic evidence and in situating forensic evidence within the context of other aspects of the case.

7.2.3 The Bayesian interpretation of GSR evidence

Before exploring the way in which the experimental findings from this thesis may be incorporated into the interpretation of GSR evidence through Bayesian Networks, it is useful to survey some recent work that has been concerned with the probabilistic assessment of GSR. Through casework examples, Gauriot et al (2013) explored the possibilities and challenges associated with the probabilistic quantification of GSR evidence using Bayesian Networks. The authors present a BN that they used to generate posterior probabilities from recovered quantities of GSR. Data from test firings involving the discharge of a single shot from a .38 revolver were incorporated into the BN and variables such as the level of background contamination (high, medium and low) and the number of shots fired were also included. Through the use of two casework scenarios, the authors demonstrate the challenges associated with discriminating between a shooter and other individuals who may have been involved in some other capacity. The inferences that could be made were found to alter significantly with minor changes to parameters and assumptions. This is an important finding in itself. Echoing Dalby et al (2010) and Romolo and Margot (2001), Gauriot et al (2013) advocate a case-by-case approach to interpreting GSR data and note that likelihood calculation requires experimentation under the same conditions as those involved in the investigation at hand. The authors argue that even with representative

data, the possibility of making probabilistic claims is made difficult by contamination issues such as the prior exposure of a suspect to GSR. It could be countered, however, that weighing these factors in a BN framework can assist in realising the impact of assumptions about prior exposure to GSR in an auditable, transparent and logical manner. This is preferable to a situation in which the assumptions underlying the opinion proffered by the scientist are not made explicit. The authors call for caution when using a statistical approach to make quantitative claims about GSR evidence.

Cardinetti et al (2006) argue that GSR evidence should be assessed and evaluated using likelihood ratios. The authors generated estimates of the GSR counts that might be expected to be recovered from shooters in two different firing scenarios at various intervals following the discharge of a firearm. An estimate of the expected GSR presence on police officers who had not recently handled a firearm was made for comparison. These scenario-specific data were used in the calculation of a likelihood ratio when assessing GSR counts under two competing propositions; (1) that the suspect shot a firearm and (2) that the suspect did not shoot a firearm.

Biedermann et al (2009) developed this investigation by demonstrating the utility of Bayesian Networks in the probabilistic assessment of GSR, for both likelihood ratio calculation and during case pre-assessment. The authors propose a BN framework to accommodate further sources of uncertainty when assessing GSR evidence through the use of a likelihood ratio, namely, the level of background and sample contamination, the relationship between the sampled GSR and the true particle count, and the performance of the analysis. The consideration of these variables would make the calculation of a likelihood ratio very complex but the 'flexibility and capacity' of BNs to accommodate additional variables, as well as empirical and case-specific information is highlighted (ibid.34). In an additional contribution, Biedermann et al (2011) explore a Bayesian approach to parameter estimation for inference-making using experimental GSR particle count data. The capacity of a BN to cope with the complexity resulting from the consideration of multiple variables is cited by Biedermann and Taroni (2006a) during an exploration of the evaluation of firearm mark and GSR evidence. The study focuses on the combination of these two types of evidence within a BN framework that captures the probabilistic relations between parameters and handles the various sources of uncertainty.

Charles and Nys (2010) chart an approach to reporting the results of GSR analysis which is underpinned by Bayesian principles. This approach serves to eschew unscientific opinions by enabling the demonstration the value of GSR evidence to the 'client', having accounted for the relevant theory and sources of uncertainty. In an assessment of its benefits, Charles and Nys (2010) argue that the approach increases the transparency of the interpretation process. The authors argue that databases on parameters assist in the formulation and reporting of the likelihood ratio and that case-specific experimentation can be incorporated, although at present, the relative paucity of empirical data represents a limitation. It should be noted that bodies of hard numerical data are not necessarily required to profit from a BN approach. Rather, as Biedermann and Taroni (2006a, 2006b) argue, such an approach enables the scientist to reason about the parameters that may need to be incorporated during an evaluation. Moreover, subjective beliefs can be revised and updated logically using this methodology. Using a BN in this qualitative sense to carry out meaningful reasoning and to consider qualitative probabilistic relationships and causal relations between variables of interest aligns with Lagnado (2011).

Charles and Nys (2010) identify the need for further research into the use of Bayesian Networks for GSR interpretation and also the importance of experimental data for estimating parameters of interest. The results presented in chapter five of this thesis represent a dataset on the transfer and deposition of GSR via different mechanisms, under a specific set of conditions. Thus, in a similar manner to a number of the aforementioned studies, these data can be used when reasoning about GSR evidence. Importantly, this represents a novel consideration of transfers and depositions of GSR within a Bayesian framework that is underpinned by empirical data. Cardinetti et al (2006) and Biedermann et al (2009) explored the use of particle count data in calculating the likelihood ratio for a pair of propositions regarding whether or not the suspect fired a gun. Crucially, when unpacked, it is revealed that in these examples the framing of the propositions was such that handling the discharged firearm and being in proximity to the firearm were included within the prosecution proposition, 'Hp'. Therefore, no attempt was made to distinguish between the means of deposition; something that the findings of this thesis have suggested may be possible in certain contexts and that, potentially, could assist in determining the roles of suspects in the

reconstruction of a firearms incident. Charles and Nys (2010) use an example to demonstrate how the incorporation of case-specific experimentation regarding an alternative mechanism of deposition (environmental contamination) may be useful when assessing GSR evidence in light of a defence proffered by the suspect. The results of the experimental work in this thesis represent an opportunity to explore the use of a Bayesian Network approach to evaluating GSR evidence under competing hypotheses about the method of deposition. The novel contribution of the following sections lies in the use of experimentally derived estimates of GSR transfer and deposition to carry out this exploration and to consider the potential interpretative impact of these under-researched transfer mechanisms.

7.4 A Bayesian Network approach to interpreting GSR evidence on hands

This section explores the possibility of distinguishing between deposition mechanisms using probabilistic reasoning (thus, further addressing Research Question Six (see section 3.7). Using the experimental results and findings relating to GSR counts which were presented in chapter five and discussed in chapter six, this section will explore the evaluation of GSR evidence under competing hypotheses through a Bayesian Network approach. In a similar fashion to previous research into the probabilistic assessment of scientific evidence (Gauriot et al 2013, Biedermann et al 2009 and Charles and Nys 2010, for example), this discussion will refer to hypothetical and real-world forensic scenarios.

The following discussion contributes to the body of work on the application of Bayesian reasoning to forensic interpretation. Illustrating the way in which a Bayesian Network can provide a framework for reasoning about evidence, for combining items of evidence and for dealing with multiple suspects, will assist in furthering the case for this method of assessment. The discussion will demonstrate the value of a BN approach for making inferences that are of value in the reconstruction of forensic events and in the elucidation of the value of evidence. As will be discussed in section 7.5, this intervention is particularly timely given a number of recent legal rulings in the England and Wales which have questioned the relationship between Bayes and the law. The following sections demonstrate the manner in which the empirical findings of

experimental work in forensic science may be incorporated in reasoning about propositions and how multiple pieces of forensic evidence can be weighed logically. The investigation, with reference to forensic scenarios, further elucidates the interpretative and investigative nuances that were identified in section 6.4 in light of the experimental findings of this piece of research. As a result, it also represents an example of the way that the interpretative ramifications of future experimental studies regarding trace evidence can be explored and considered. Finally, while focusing primarily on the interpretation of GSR evidence, this section will inform the interpretation of trace physical evidence more generally and particularly, cases in which the assessment of a pair of activity level interpretative propositions involves the consideration of alternative means of transfer and deposition.

7.4.1 A simple one suspect scenario

The following causal diagram represents the interpretation of the presence of GSR on a suspect. In this case, there is a piece of evidence (the GSR count) and a pair of mutually exclusive hypotheses about how it came to be recovered from the suspect, which are contained within a single node (figure 7.1)[59].

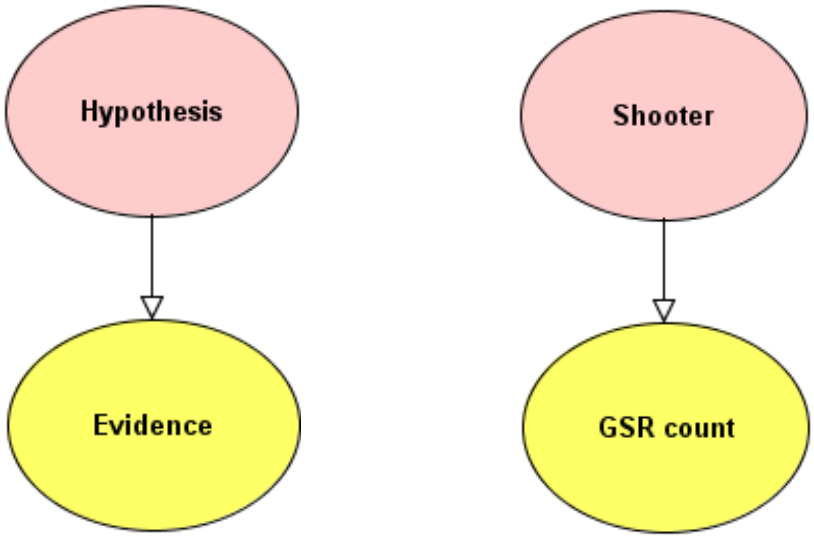


Figure 7.1 Graph showing the causal relationship between the hypothesis and evidence for the one suspect case

In a hypc :ene of a very recent shooting. The hands of the suspect were subsequently sampled at the scene according to the procedure set out in 4.2.3. Five shots had been heard by

[59] All analysis and graph building has been carried out using AgenaRisk (AgenaRisk 2013)

witnesses and cartridges recovered from the scene indicated that 9mm Luger ammunition had been fired. Thus, the results of the experiments produced during the present piece of research were of direct relevance. In the hypothetical scenario, the laboratory result reported a positive result for GSR presence. The suspect, when confronted with this fact, denied having fired the gun or having any previous contact with firearms. A pair of mutually exclusive hypotheses might be formed; that the GSR was acquired through firing the gun, or that the GSR was acquired by some other means of transfer or deposition. Note that the source of the GSR has already been confirmed in this example - it has been determined that the recovered particles did emanate from a firearm discharge rather than from an environmental or occupational source of GSR-like particles (see section 3.2.4). Moreover, it has been concluded that the GSR particles are of an elemental composition that would be expected from the firing of 9mm Luger ammunition.

In order to reason about the quantity of GSR and how it was deposited, it is necessary to consider the probability of observing that quantity of evidence under each hypothesis. The results presented in chapter five can be referred to when making this assessment. Based on the experimental data, three categories of GSR count were formed: Low (0-49), Medium (50-149) and High (150+). It was noted in 7.2.3 that realising the utility of a Bayesian Network approach in reasoning about forensic evidence does not necessarily require hard, accurate numerical data (Biedermann and Taroni 2006a, 2006b, Lagnado 2011). Rather, qualitative causal relationships may be used to carry out useful reasoning.

For the purposes of this exploration, probabilities of observing these different quantities of GSR ('Low', 'Medium' and 'High') under the two competing hypotheses were qualitatively estimated from the experimental data. The precise numerical probabilities are not the primary focus, but rather, are indicative of the probabilistic relationships suggested by the experimental data. For instance, results suggest that the hands of the shooter may be expected to yield several hundred particles and that 'Low' counts are very unlikely. The experimental data also indicated that 'Low' and 'Medium' GSR counts might be expected when sampling from individuals who have acquired GSR via a secondary or tertiary transfer, or via their proximity to a firearm discharge. Meanwhile, 'High' quantities of GSR were not recovered from these

subjects and can, therefore, be considered relatively unlikely. These probabilities also incorporate the possibility of background contamination, although research has shown this to be extremely low particularly when an individual has not recently come into contact with firearms (Kotrly and Turková 2010, Cardinetti et al 2006). Illustrative conditional probabilities that were qualitatively estimated from the experimental data are displayed in the node probability table (7.1).

	Shooter	**Other means of transfer/deposition**
Low (0-49)	0.05	0.6
Medium (50-149)	0.15	0.3
High (150+)	0.8	0.1

Table 7.1 Node Probability Table (NPT) for the one suspect case

The probabilities reflect the apparent tendency for several hundreds of particles to be deposited on the shooter during a firearm discharge under these conditions and also the not insignificant possibility that 'Medium' quantities of GSR may be expected to be involved in secondary transfer events. Three scenarios were run in the simple BN to reflect cases where the laboratory result revealed a 'Low', 'Medium' and 'High' quantity of GSR. The results for the three scenarios are displayed on the graph in figure 7.2. Note that the prior on each of the hypotheses was 0.5 as it is assumed there was no reason to consider one hypothesis to be more likely than the other.

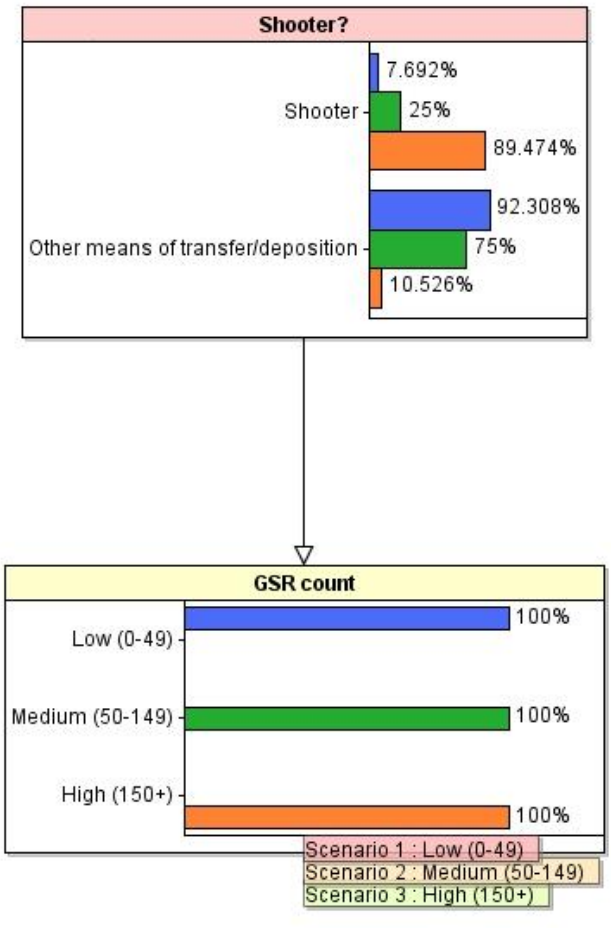


Figure 7.2 Bayesian Network for the one suspect case showing updated beliefs for 'High', 'Medium' and 'Low' GSR counts

The graph shows how the belief about the probability of the two hypotheses changes as a result of the evidence. The potential significance of the experimental findings are made clear in this graph as when a 'Medium' quantity of GSR is recovered, on the basis of the data entered into this particular NPT, it is likely that this quantity of GSR was deposited by a means other than the firing of the gun.

This framework offers the potential to think about the incorporation of other variables of interest. For example, a further piece of evidence such as a witness testimony could be included and its effect on our belief about the hypothesis could be weighed into the assessment. Moreover, the persistence and decay of material could be incorporated if the suspect was apprehended a few hours after the incident. In this case, the data in the node probability table would be adjusted to reflect the loss of material over time. In accordance with previous studies (see, for example Brozek-Mucha 2011, Jalanti et al 1999), the probability of observing 'Low' and 'Medium' quantities of GSR given that a suspect had fired a gun would be higher after a few hours, owing to the influence of decay. Meanwhile, the NPT would reflect that if more than 150 particles were still

recoverable a few hours after the incident, there would be an increased probability that these had been deposited as the suspect discharged a gun.

This framing of the problem is an effective basis on which to start thinking about the effect of certain variables on the recovered GSR count and also on our belief about the activities of the suspect. However, modeling GSR counts in discrete categories is inadequate. In its current state the graph is not sufficiently sensitive to examine the effects of small increases in the number of recovered particles on the resulting posterior probabilities. Moreover, the effect of recovering 150 particles as opposed to 149 means that the boundary between 'Medium' and 'High' has been crossed and our beliefs about the likely actions of the suspect shifts disproportionately. It is suggested that discretization of a continuous variable such as the GSR particle count is unsuitable.

Accordingly, the particles counts that were presented in section 5.2 and figure 5.3 were used to approximate probability distributions for the two hypotheses using the continuous variable modeling capability in AgenaRisk. Clearly, as a result of the relatively small number of runs (nine samples taken from the shooter for instance), the probability distributions that are presented are approximations only. However, they are effective in demonstrating the possibility of incorporating a continuous variable into the BN and of using it to make inferences. Using a distribution fit package, EasyFit 5.5. (Mathwave 2013), a gamma distribution for the number of particles deposited on the shooter was created: Alpha = 3.955 and Beta = 108.47. While the true distribution could not be determined with confidence owing to the limited number of data points, the gamma distribution was chosen for this illustration as it reflects the apparent concentration of counts around the mean (429 particles) and a tailing off towards the higher counts, with a relatively low possibility of recovering less than one hundred particles.

The expected counts from the other means of deposition were calculated by combining the experimental counts for all non-shooting scenarios within the same statistical package. The counts were assumed to be normally distributed about the mean (41.2) owing to the apparent clustering of counts around this mean and the limited possibility of observing extreme counts, as indicated by the experimental data. Therefore, for illustrative purposes, a normal distribution was fitted which was

truncated at the lower bound of zero particles. Its variance was 1156.5. It is stressed that these distributions, calculated from the set of experimental results, are estimates. Moreover, they are intended to reflect only the expected counts for firings and depositions in conditions analogous to those simulated for the experimental settings in this thesis.

These distributions replaced the categorisations presented in figure 7.2 and table 7.1. They were entered as a 'partitioned expression' in the NPT; the gamma distribution representing the number of particles expected if the suspect had fired the gun and the truncated normal distribution representing the expected GSR count given some other means of deposition (incorporating secondary and tertiary transfer mechanisms and deposition on a bystander). Some previous studies (see Gauriot et al 2013 and Biedermann et al 2009) have estimated expected GSR counts on the shooter using a Poisson distribution. Gamma and (truncated) Normal distributions were used in this case as they fitted the values that might be expected in light of the data points produced by the experimental work. Further data points may render an alternative distribution more suitable and the model could be modified to reflect this. However, at this stage the purpose of the discussion is to illustrate the manner in which inferences can be made about the mechanism of GSR deposition by representing expected GSR counts using conditional probability distributions. The new BN is displayed in figure 7.3.

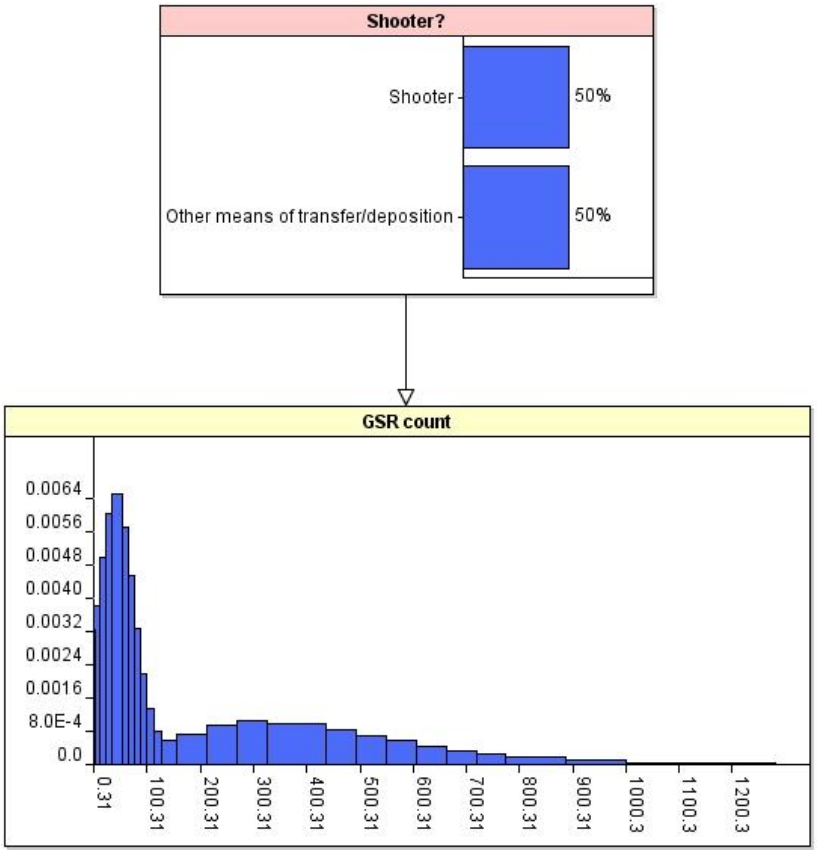


Figure 7.3 Bayesian Network for the one suspect case with expected GSR counts modelled using a partitioned expression

When a value (observation) is entered for the GSR count, the new BN calculates the probability of observing the evidence given the two competing hypotheses. It does so by computing the probability of observing the evidence under the two distributions of expected particle counts, which pertain to the two hypotheses. Figures 7.4 - 7.8 demonstrate the effect of entering a series of different observations for the particle count on the belief about the probability of the two hypotheses, again assuming that our prior belief meant that each hypothesis was initially equally likely.

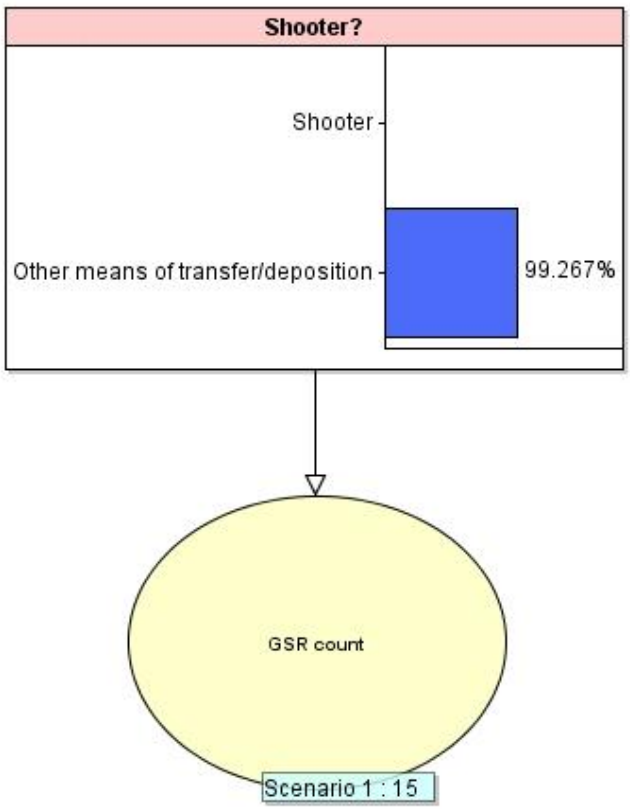


Figure 7.4 Updated Bayesian Network for the one suspect case, 15 GSR particles recovered

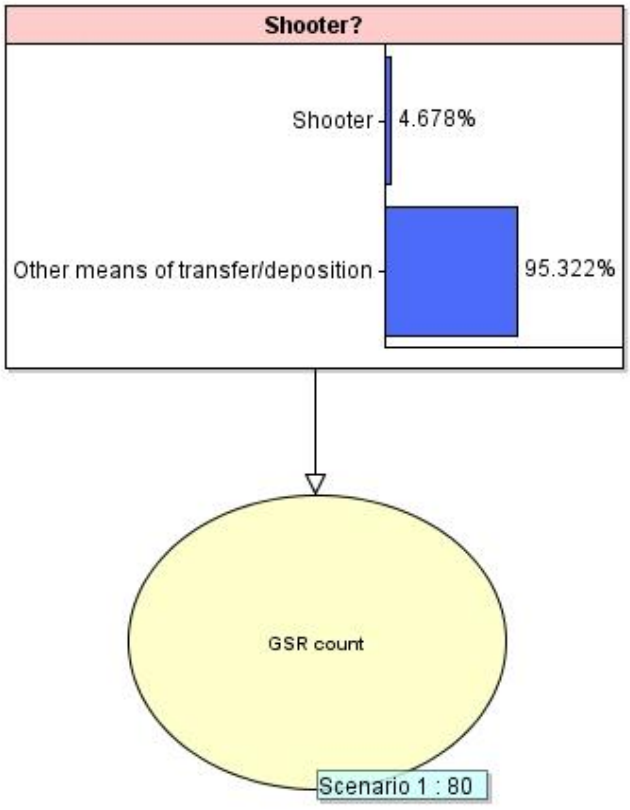


Figure 7.5 Updated Bayesian Network for the one suspect case, 80 GSR particles recovered

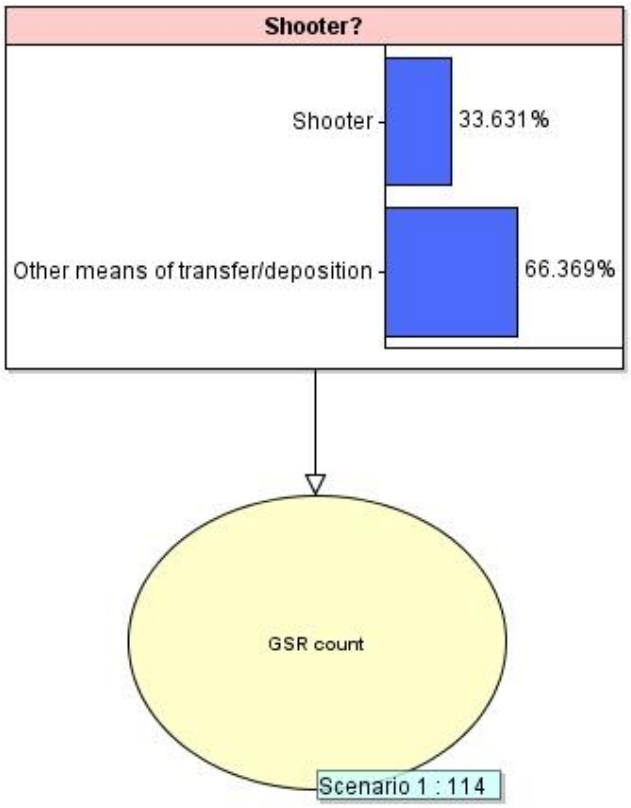


Figure 7.6 Updated Bayesian Network for the one suspect case, 114 GSR particles recovered

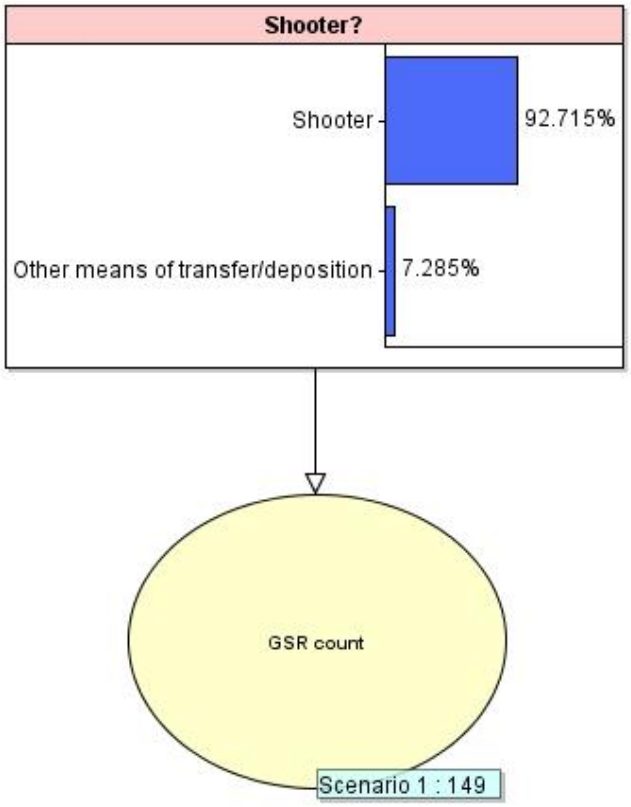


Figure 7.7 Updated Bayesian Network for the one suspect case, 149 GSR particles recovered

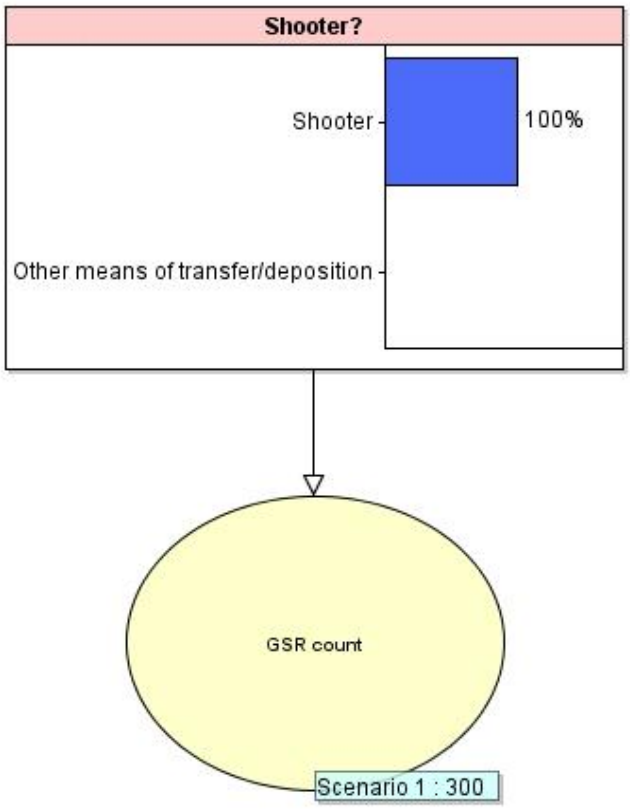


Figure 7.8 Updated Bayesian Network for the one suspect case, 300 GSR particles recovered

Compared to the original BN in figure 7.2, it is clear that modeling the GSR particle count as a continuous variable means that it is possible to capture the effect of subtle changes in the recovered particle count. It should be re-emphasised that the distributions are estimates that have been generated from a very limited number of data points. Indeed, they may not reflect the true shape and form of the population characteristics. Moreover, as explained in chapter six, the data relate to a specific set of firing conditions, namely; five rounds of 9mm Luger 95 grain jacketed soft point 9P1 ammunition (manufactured by FEDERAL Ammunition) fired from a SIG Sauer P226 9mm self-loading pistol, with little or no decay of trace material. Thus, the impact of values on beliefs about the competing hypotheses cannot be extrapolated to other scenarios with case-specific conditions and variables. In these graphs our belief about the activity that gave rise to the presence of GSR on the suspect is only informed by one piece of evidence (a GSR count). In reality, many inter-related pieces of evidence may be involved. However, the example is intended to illustrate the way that the GSR particle count may be modelled as a continuous variable and be used to reason about

the probability of alternative means of GSR deposition. The simple BN may also be adjusted to capture further variables and/or pieces of evidence that may have a bearing on our beliefs about the competing hypotheses.

Figures 7.4-7.8 serve to reinforce the potential significance of the experimental results. While it is widely acknowledged that the recovery of GSR from a suspect may not necessarily indicate that the suspect fired a gun (see section 3.4.), assessments of the quantities of GSR that may result from non-shooting mechanisms and transfers are conspicuous in their absence. The Bayesian Networks presented in figures 7.4-7.8 capture the interpretative ramifications of concluding that, in conditions analogous to the experimental setting, the probability of observing considerable quantities of GSR (15, 80 and 114 particles, for instance) is high. Moreover, the probability that such quantities are observed given that a non-shooting mechanism resulted in the deposition is greater than the probability of observing that quantity given that the suspect fired the gun in some instances. The graphs also reflect that higher quantities of GSR are expected from the shooter, but that these quantities will be observed very infrequently on a non-shooter. It is stressed that these graphs reflect only the data derived during this thesis, but in doing so they re-emphasise the potential salience of the interpretative ramifications of the findings (originally discussed in section 6.4)

The expected distributions could be adjusted to account for the influences of, for instance, persistence and contamination through the addition of further nodes (akin to Gauriot et al 2013[60]). Research into the persistence of GSR suggests that the half-life of a deposited quantity of GSR is approximately one hour (section 3.4.4b and Brozek-Mucha 2011). Thus, if the evidence was being assessed given a timeframe of one hour following the shooting, it is likely that the 'overlap' between the two expected distributions would be greater, potentially meaning that distinguishing between mechanisms of deposition may be more difficult in some cases. However, as discussed in section 6.4, the recovery of several hundred particles from a non-shooter would be even more unlikely and further suggestive of a deposition by firing; our updated beliefs about the probability of the two hypotheses would reflect this.

[60] Although the Gauriot et al (2013) study discretised many of the variables

7.4.2 A multi-suspect case

Section 6.4 considered the potential for making inferences about the mechanism of deposition on the basis of GSR counts. Accordingly, section 6.3.1 highlighted the reconstructive value of recovering multiple samples from suspects who may have been implicated in the transfer and deposition of GSR. Such a sampling strategy, it was argued, should be underpinned by knowledge of potential transfer mechanisms and their extent and evidential utility. However, the weighing of these multiple pieces of evidence may be complex, particularly within the context of a case with multiple lines of evidence and sources of uncertainty. The capacity of Bayesian Networks to capture the relations between multiple pieces of evidence (as discussed in section 7.2) means that they are well suited to provide a method of reasoning and inference-making in multi-suspect cases involving GSR. The example below is used to demonstrate this. The case used in this illustration of the use of a BN framework in a multi-suspect case has been adapted to permit the incorporation of data and findings from the present study. The details of the original case, modified significantly to permit an exploration of the interpretation issues arising from the present study, are presented in: *State of Ohio v. Christopher Latham* (2011).

The Incident:

Mr S, a delivery man, was making deliveries. Having just made a delivery at an address, he noticed three hooded people on the corner. The group approached Mr. S and one of them drew a pistol with the other individuals standing one metre behind him. Mr S handed over the cash he had but believed the trigger was being squeezed so withdrew his torch and smacked the hand holding the gun. The gun remained in the hand of the man and was discharged five times with at least one of the bullets narrowly missing the victim's head. At this point the three men ran around a nearby corner and the shooter fired two shots in the direction of Mr S. The victim gave chase but had been injured during the struggle and gave up. The victim phoned the police.

Police arrived promptly and interviewed the victim and provided police with descriptions before a police dog picked up a scent from the crime scene and tracked it to an address on the same estate. Upon entry to the house, police found three suspects (A, B and C). A 9mm self-loading pistol matching the description of the gun used in the robbery was found concealed in a drawer at the address. All three suspects were brought onto the pavement for identification by the victim. Mr S indicated he was very confident that A, B and C were the three individuals involved.

A BN that captures this problem must represent the GSR evidence relating to each suspect and the possibility that each suspect was either the shooter or a bystander. The BN needs to account for the change in our belief about the role, for example, of suspects B and C, once information has been entered which relates to Suspect A. Finally, as exactly one of these three suspects was the shooter, the graph will need to

constrain the sum of the probabilities of each suspect being the shooter to one. The basic structure of the BN is provided in figure 7.9.

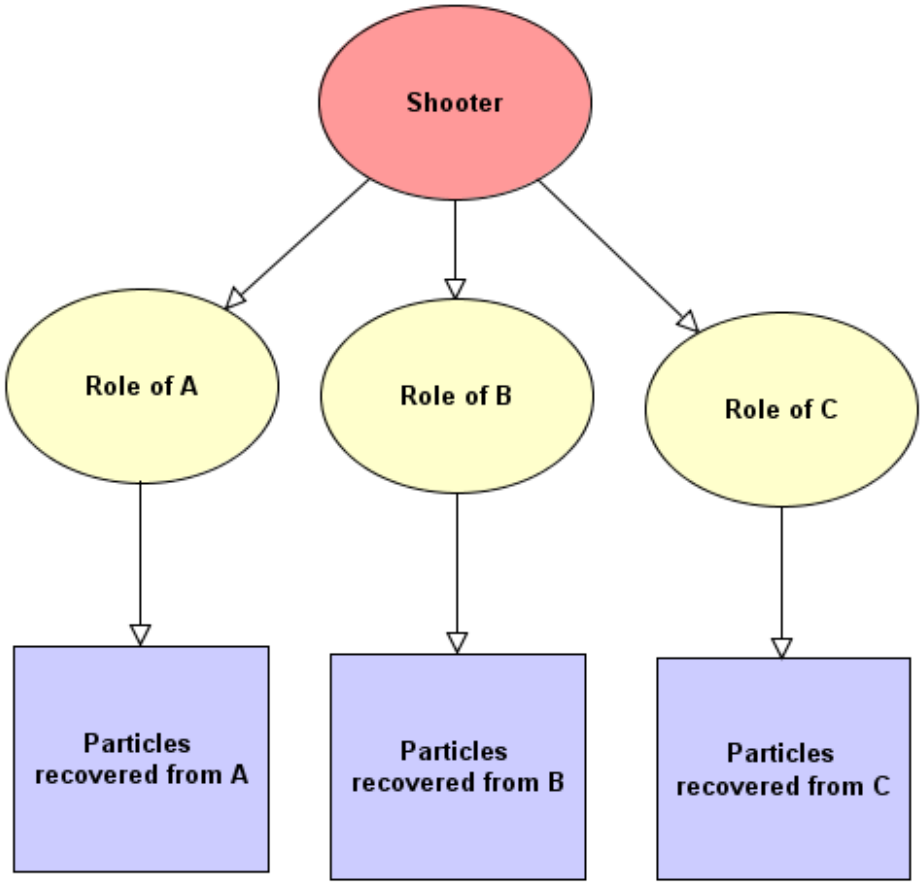


Figure 7.9 Bayesian network for the multi-suspect case

The 'Shooter' node has three states, 'A', 'B' and 'C'. The 'Role' nodes each have two states, 'Shooter' and 'Bystander'. The particle count evidence nodes are modelled continuously using a partitioned expression (in a similar manner to the examples in figures 7.3-7.8). Because we know that the three suspects were the three individuals involved in the robbery (confirmed by the victim as well as the suspects themselves) and that we have no prior indication that any of the suspects was more likely to have been the shooter, the prior belief that each suspect was the shooter is 1/3. In the 'Particles recovered' nodes, the same distribution of expected particle counts for the shooter is used as that which was calculated for the experimental data and presented in figure 7.3. The second part of the expression is represented by a truncated normal distribution, with a mean of 28 and a variance of 1000, which captures the expected values of particle counts that are recoverable from bystanders and accounts for the spread of values that might be expected given further test firings. 28 was the mean

number of particles recovered from the bystanders during experimental scenario five and was deemed appropriate in light of the results reported by Lindsay et al (2011a), who observed similar numbers of particles on bystanders during their simulations. It is important to note, once more, that these distributions are estimates that have been generated from a limited number of data points. However, they are intended to demonstrate first, the potential significance of the findings for interpretation of GSR evidence and secondly, the way that case-specific data may be incorporated into a BN framework. Third, the example serves to illustrate the utility of a BN approach when dealing with multiple-suspect cases involving GSR, or other trace evidence.

Figure 7.10 represents the state of the graph before any observations are entered. The prior belief is that all suspects are equally likely to have been the shooter and we know that there was exactly one shooter. For each suspect, the probability that they were the shooter is 1/3 and the probability that they were a bystander is 2/3. Notably, the BN captures the rationale of proposition formation put forward by Cook et al (1998a,b), Cook et al (1999) and Evett et al (2000) that was presented in section 2.2.2. The framework of circumstances, which include the identification of the three individuals by the victim and the admission of presence by the suspects, have enabled the formulation of pairs of mutually exclusive Level II[61] propositions about the method of deposition for each suspect. The BN framework permits the dependencies between the assessments for each pair to be captured.

[61] The overlap with Level III (offence) is apparent here as the firing of a gun is necessarily a criminal offence, as is involvement in an armed robbery. In essence, via activity level assessments, we are inferring something about the type of offence that each suspect has committed

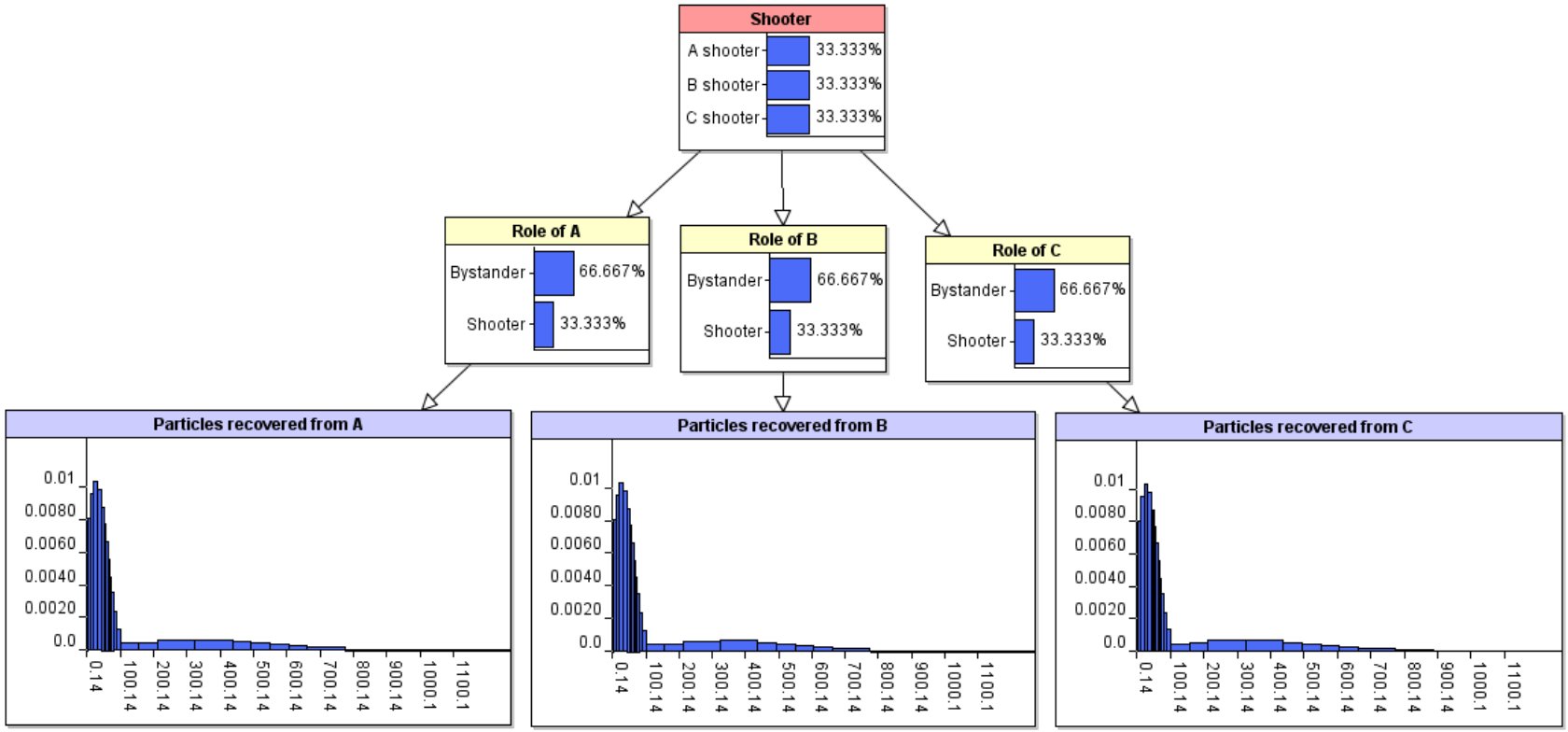


Figure 7.10 Bayesian Network for the multi-suspect case in prior state

Sampling and Results [Scenario A]:

Only one GSR testing kit was available, and the hands of suspect A were sampled.

Sample analysis revealed 320 GSR particles

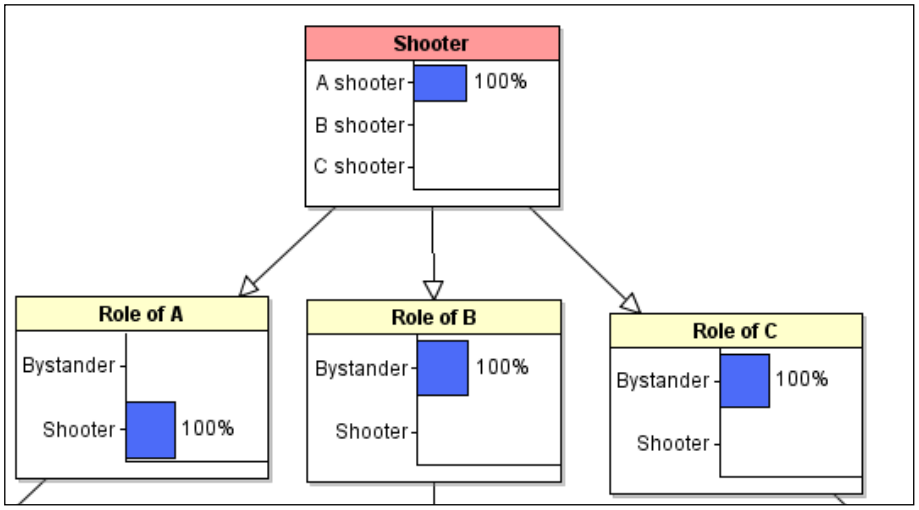


Figure 7.11 Updated Bayesian Network for the multi-suspect case, 320 particles recovered from suspect A, Scenario A

In light of the findings presented in chapter five, in conditions analogous to those simulated in the experimental set-up, the probability of observing 320 GSR particles on a bystander can be considered to be very small. Intuitively, taking into account the GSR evidence only, the probability that A was the shooter will increase markedly on entering 320 as the particle count for suspect A. The updated BN reflects this intuitive conclusion and also accounts for the change in our beliefs about the roles of suspects B and C; the GSR evidence for suspect A strongly suggests this suspect was the shooter and consequently, it is now very likely that suspects B and C were bystanders (figure 7.11).

Sampling and Results [Scenario B]:

Only one GSR testing kit was available, and the hands of suspect A were sampled.

Sample analysis revealed 100 GSR particles

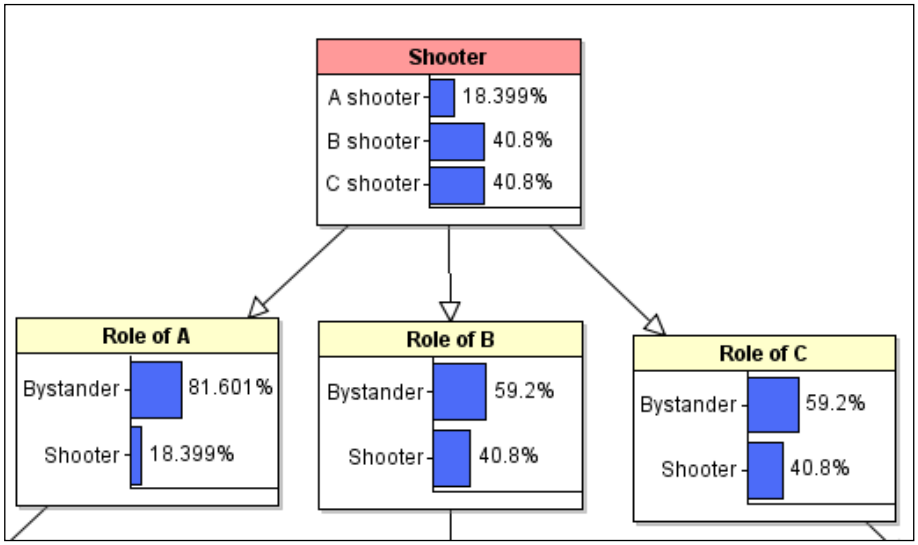


Figure 7.12 Updated Bayesian Network for the multi-suspect case, 100 particles recovered from suspect A, Scenario B

When the observation is entered for suspect A in this scenario, it is interesting to note that the probability that suspect A was the shooter actually reduces (from 0.333... to 0.184...) (figure 7.12). This is because, as indicated by the findings of the experimental results, one would expect to recover several hundred particles from the hands of a shooter in conditions analogous to those simulated in the experimental set-up. This observation serves to emphasise the importance of acknowledging alternative means of GSR deposition and also the possibility of considerable depositions by non-shooting mechanisms. In this example, the presence of a considerable quantity of GSR on a suspect has actually served to reduce the possibility that the suspect were the shooter, while simultaneously raising the probability that one of the remaining suspects was the shooter. It should be noted that the specific values relate to the present study and that the graphs are illustrative of the impact GSR may have on the inferences that are made in specific scenarios.

Sampling and Results [Scenario C]:

Two GSR testing kits were available, and the hands of suspects A and B were sampled.

Sample analysis revealed 100 GSR particles on suspect A

Sample analysis revealed 395 particles on suspect B

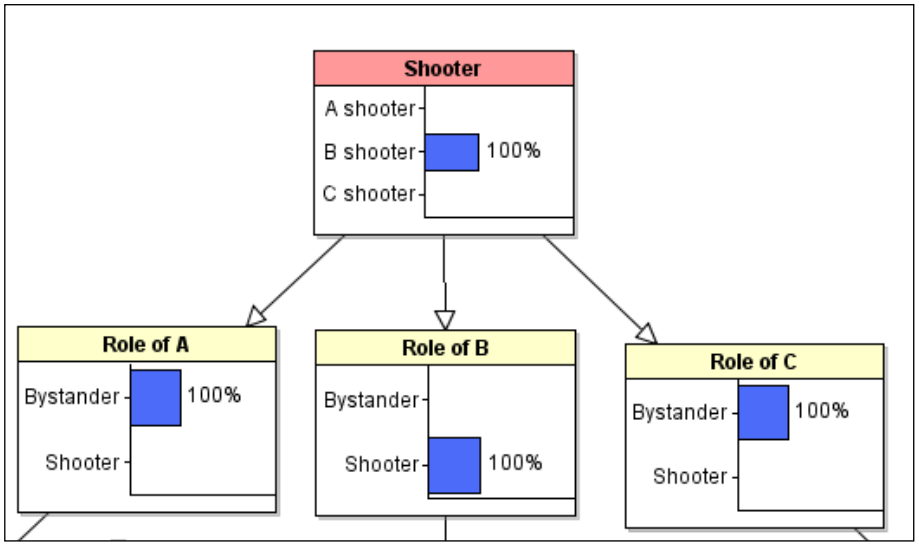


Figure 7.13 Updated Bayesian Network for the multi-suspect case, 100 particles recovered from suspect A and 395 particles recovered from suspect B, Scenario C

In this scenario, 100 particles were observed on the sample recovered from suspect A. When the 395 particles recovered from suspect B are entered, our beliefs about the roles of the suspects differ from the previous scenario. Because we are much more likely to observe 395 particles on a shooter than on a bystander, the BN now indicates that suspect B was the most likely shooter (figure 7.13). Importantly, we are now much more certain that the particles recovered from suspect A resulted from their presence in close proximity to the shooting. The probability that suspect A was the shooter that was calculated for Scenario B (shown in figure 7.12) has been explained away, along with the probability that C was the shooter (despite entering no evidence for suspect C). The value of collecting samples from multiple suspects when making inferences during the reconstruction of an incident is demonstrated.

Sampling and Results [Scenario D]:

Two GSR testing kits were available, and the hands of suspects A and B were sampled.

Sample analysis revealed 100 GSR particles on suspect A

Sample analysis revealed 104 particles on suspect B

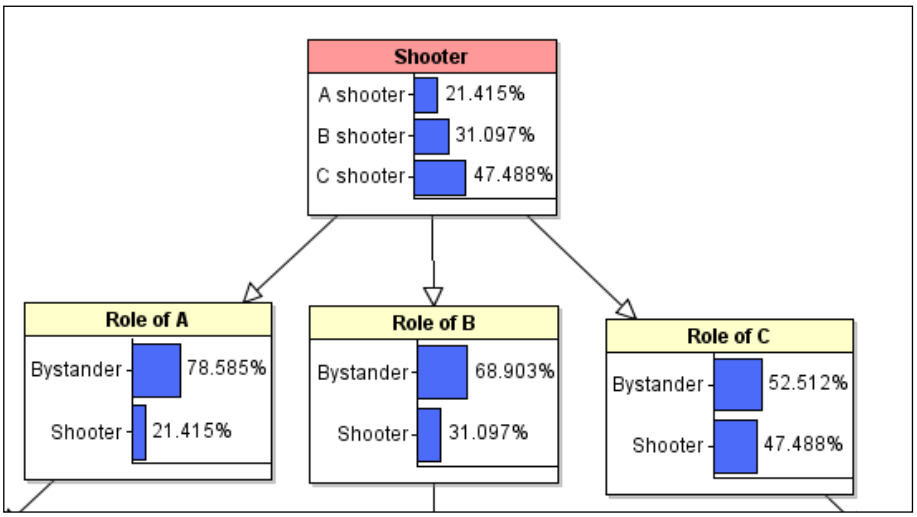


Figure 7.14 Updated Bayesian Network for the multi-suspect case, 100 particles recovered from suspect A and 104 particles recovered from suspect B, Scenario D

When 100 particles are entered for suspect A alongside 104 particles for suspect B, suspect C (from whom a sample was not recovered) becomes the most probable shooter, in contrast to Scenario C. Compared to Scenario B, in which only the value of 100 particles was entered for suspect A, the probability that C was the shooter increases slightly when 104 particles are entered from suspect B. Concurrently, the probability the B was the shooter is reduced and there is a slight increase in the probability that A was the shooter (figure 7.14).

Sampling and Results [Scenario E]:

Two GSR testing kits were available, and the hands of suspects A and B were sampled.

Sample analysis revealed 100 GSR particles on suspect A

Sample analysis revealed 12 particles on suspect B

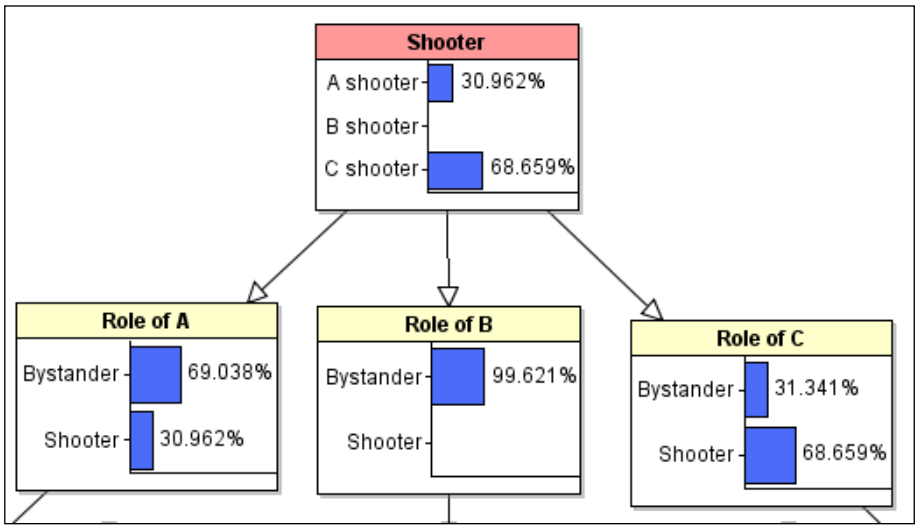


Figure 7.15 Updated Bayesian Network for the multi-suspect case, 100 particles recovered from suspect A and 12 particles recovered from suspect B, Scenario E

In contrast to Scenario D, the evidence entered for suspect B in this scenario means that the probability that this suspect was the shooter is dramatically reduced, with the GSR evidence suggesting that this suspect was one of the bystanders. As a result, the probability that suspect A was the shooter increases slightly, despite the same GSR count (100 particles). It is now most likely that suspect C was the shooter, despite the absence of a GSR sample from this suspect (figure 7.15).

Sampling and Results [Scenario F]:

The hands of suspects A, B and C were sampled.

Sample analysis revealed 100 GSR particles on suspect A

Sample analysis revealed 12 particles on suspect B

Sample analysis revealed 470 particles on suspect C

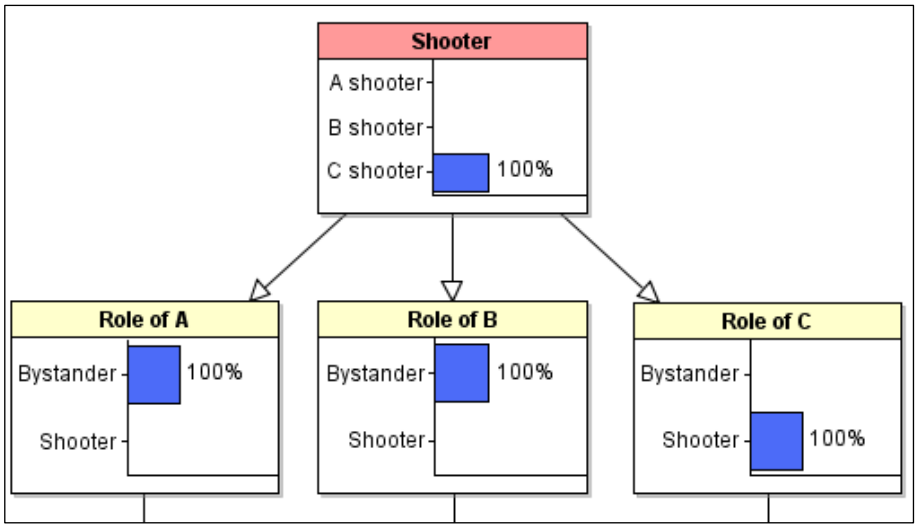


Figure 7.16 Updated Bayesian Network for the multi-suspect case, 100 particles recovered from suspect A, 12 particles recovered from suspect B and 470 particles recovered from suspect C, Scenario F

From the updated graph in Scenario E (figure 7.15), we would expect a sample taken from suspect C to yield several hundred GSR particles. Unsurprisingly, when this is the case in Scenario F (figure 7.16), the results of the three samples are combined to suggest that suspect C was the shooter, while the other two suspects are very likely to have been bystanders.

Sampling and Results [Scenario G]:

The hands of suspects A, B and C were sampled.

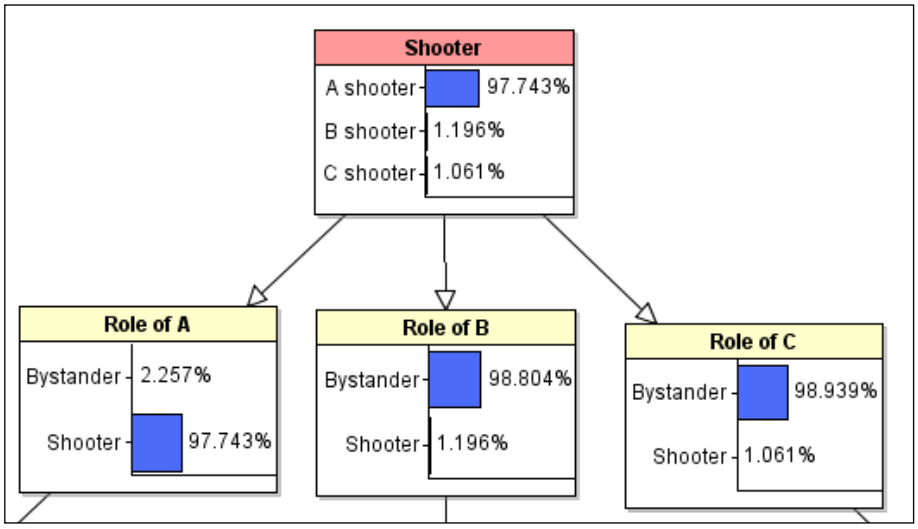


Figure 7.17 Updated Bayesian Network for multi-suspect case, 100 particles recovered from suspect A, 12 particles recovered from suspect B and 18 particles recovered from suspect C, Scenario G

In contrast to Scenario F, the particle count on the sample recovered from suspect C in Scenario G strongly indicates that this suspect was one of the bystanders. Thus, a large amount of the belief we had about suspect C being the shooter in Scenario E (in which no evidence was entered for suspect C) has now been explained away by the GSR sample from this individual. Accordingly, it is now very likely that suspect A was the shooter, despite the number of particles (100) being lower than we might expect in most cases given that an individual has discharged a firearm. It is clear that the same GSR count pertaining to a suspect can be indicative of different mechanisms of deposition, depending on the particle counts obtained from other suspects. Therefore, this example serves to demonstrate the evidential and reconstructive utility of sampling the hands of suspects who may have acquired GSR through mechanisms other than discharging a firearm. These additional samples can assist when making inferences regarding the identity of the shooter by reducing some of the uncertainty

that is inherent in the interpretation process. Moreover, a BN framework can be used to demonstrate how the results of these samples support the conclusions, which themselves are supported by empirical data on rates of GSR transfer and deposition.

The Incident – supplementary information:

Suspects A and B were males and suspect C was female. The victim was sure a male was the shooter and identified suspect A.

A BN can be used to combine forensic and non-forensic evidence. To illustrate the capacity of a BN to incorporate multiple pieces of evidence and the possibility of using it to reason about the identity of the shooter given multiple sources of uncertainty, the BN will now be modified to include the identification of suspect A that was made by the victim. The BN must capture the relationship between the identification and the true identity of the shooter.

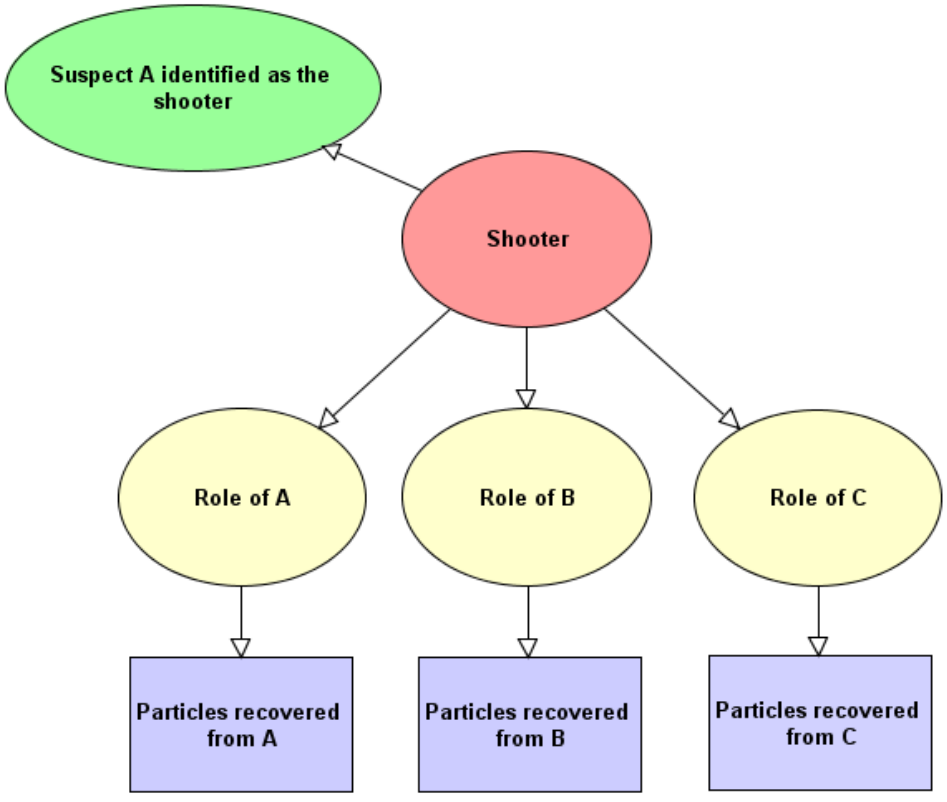


Figure 7.18 Bayesian Network for the multi-suspect case, including identification of suspect A by the victim

With ref[illegible]otions of causal "building blocks" (Lagnado et al 2013, Fenton et al 2013), the reliability of a witness testimony or identification can be captured in a BN. To illustrate this, it is

possible to consider the reliability of the identification given that the robbery took place when it was light, or when it was dark. Intuitively, the identification would have been more reliable if it was light at the time of the incident than if it was dark and faces were obscured at the time. Note that, even in the absence of any numerical data, structuring the problem in this manner is useful for representing the causal dependencies and relations in the case (see Biedermann and Taroni 2006a, 2006b, Lagnado 2011). The NPT might also need to capture an increased possibility of misidentification of suspect A if suspect B was the shooter than if suspect C was the shooter, as the victim indicated that the shooter was male. The new BN and NPT for these nodes are displayed in figure 7.19 and table 7.2. Note that the probabilities are qualitative estimates that serve to illustrate the qualitative causal relationships and their interaction with other variables, rather than precise values derived from an empirical understanding of the accuracy of witness identifications.

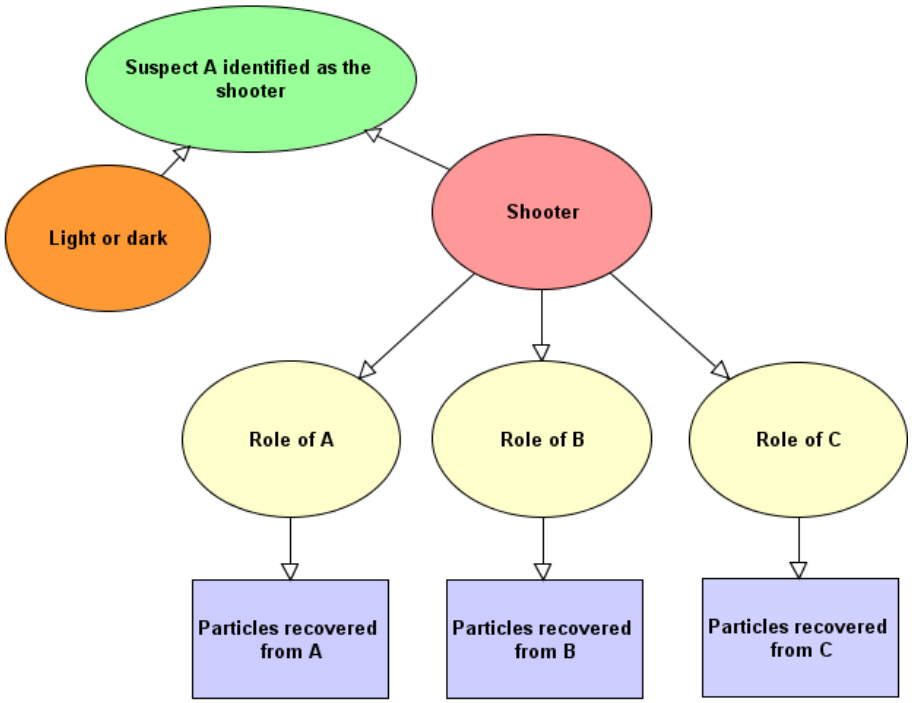


Figure 7.19 Bayesian Network for the multi-suspect case, including identification of suspect A by the victim

Shooter	A shooter	B shooter	C shooter

Light or Dark	Dark	Light	Dark	Light	Dark	Light
A identified as shooter - NO	0.4	0.2	0.6	0.8	0.8	0.9
A identified as shooter - YES	0.6	0.8	0.4	0.2	0.2	0.1

Table 7.2 Node Probability Table (NPT) for the identification node in the multi-suspect case

Sampling and Results [Scenario H]:

Only one GSR testing kit was available and the hands of suspect B were sampled.

Sample analysis revealed 23 particles on suspect B.

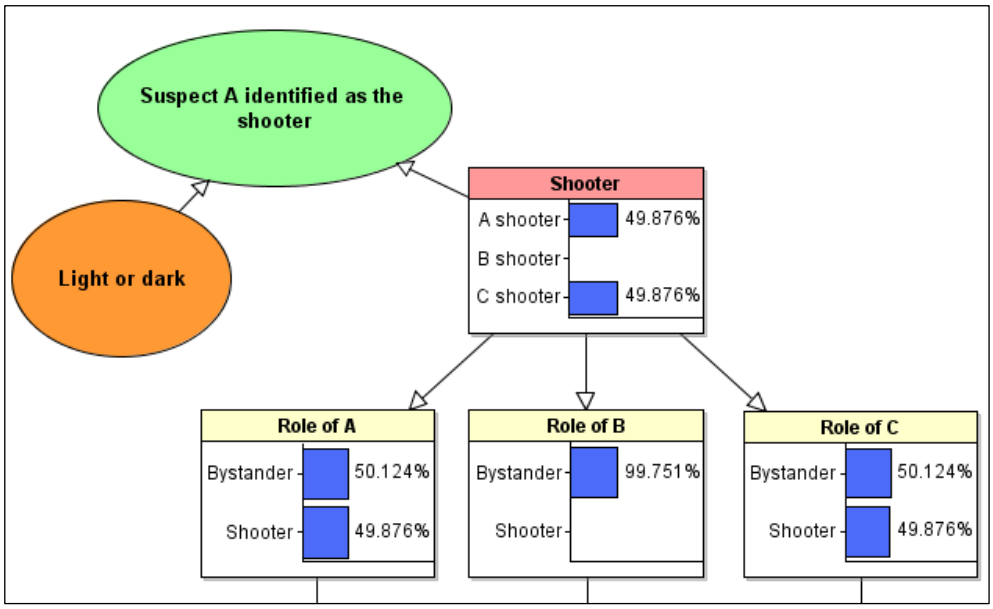


Figure 7.20 Bayesian Network for the multi-suspect case, 23 particles recovered from suspect B, Scenario H

In the absence of a testimony from the victim, a particle count of 23 particles from suspect B means that it was highly likely that suspect B was a bystander (figure 7.20). At this point we have no means of distinguishing between A and C.

Victim Testimony [Scenario H]:

The victim identified suspect A as the shooter and it was light at the time of the robbery.

When the information about the identification is entered (figure 7.21), suspect A is now much more likely to have been the shooter, while much of the probability that C was the shooter has been explained away as a result of the testimony of the victim.

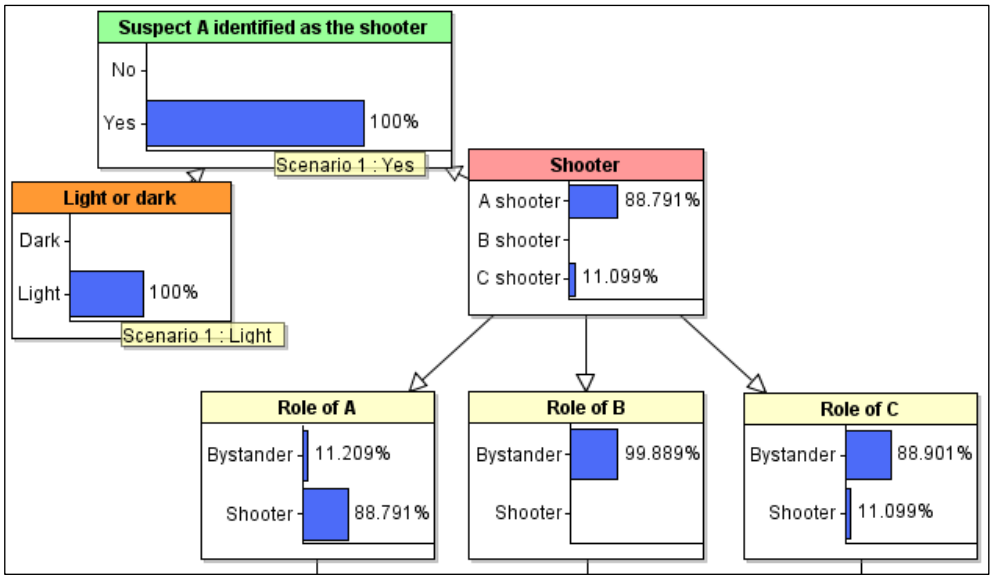


Figure 7.21 Bayesian Network for the multi-suspect case, 23 particles recovered from suspect B, suspect A identified as the shooter and conditions were light

Intuitively, if the robbery was carried out at night in a poorly lit area, then the identification of suspect A could be considered somewhat less reliable. The graph in figure 7.22 reflects this and the result is that less of the probability of C being the shooter is explained away, yet suspect A is still the most likely shooter. Our belief about B remains largely unchanged, with only a negligible increase in our belief that he was the shooter. This demonstrates the use of Bayesian Networks for revising beliefs upon the addition of new evidence and in light of changes to the framework of circumstances.

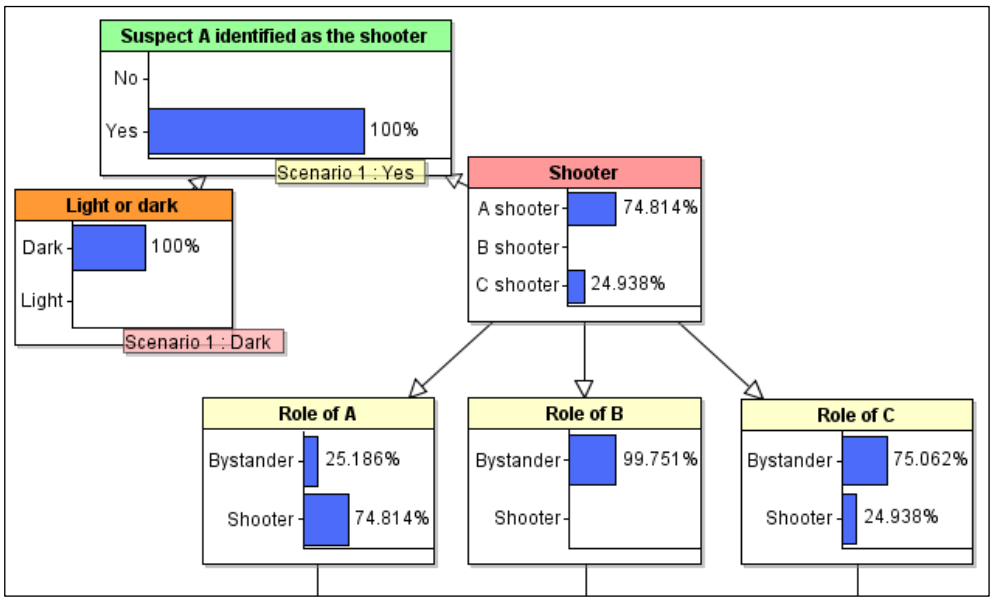


Figure 7.22 Bayesian Network for the multi-suspect case, 23 particles recovered from suspect B, suspect A identified as the shooter and conditions were dark

7.4.3 Summary

Notwithstanding the limitations of the data used in the previous section, both in terms of the number of results and the scenario-specific nature of the counts themselves, the utility of a Bayesian Network approach in evaluating GSR evidence under competing hypotheses about the method of GSR deposition has been demonstrated. Particularly in multi-suspect cases, the capacity of a BN to accommodate and incorporate multiple pieces of evidence is extremely useful. While claims of generally applicability are not made with regard to the data used, a BN represents a suitable means to reason about GSR evidence given alternative activity level propositions. The graphs presented relate to somewhat simplified examples, yet in accordance with Biedermann et al (2009), they offer the potential for further variables such as the persistence of material (given a case-specific timeframe), the number of shots, the error-rate of the analysis technique[34], the extent of any contamination and whether one of the individuals washed their hands. Reasoning about such sources of uncertainty within this causal framework, whether equipped with data or incorporating subjectivities and opinions, is desirable. Indeed, with respect to the examples presented, the approach represents

[34] Which, throughout the illustrative exploration in this chapter has been assumed to be unproblematic

a transparent, auditable and logical method for making inferences about the identity of the shooter in which assumptions are made explicit and in which empirical findings can be logically incorporated. This eschews approaches in which multiple GSR counts are weighed intuitively or in which statements are made regarding the "consistency" of the evidence with a certain hypothesis, with little demonstration of the way in which conclusions are underpinned by empirical and theoretical understanding.

The multi-suspect case in 7.4.2 demonstrated the manner in which GSR evidence from one suspect may inform our belief about the role of another suspect, and how a BN structure can be designed to capture this relationship. Further samples, it has been shown, have the potential to explain away prior beliefs about another suspect and can also reduce the potential for misinterpretation and misidentification of the shooter, thus underlining their value. While enabling the value of particle count evidence to be evaluated, structuring the case in this manner can also be useful in case pre-assessment when considering parameters of interest, sources of uncertainty and valuable samples, and when estimating expected values prior to an examination (in accordance with the process of interpretation proposed by Cook et al (1998a). The example, through the consideration of the witness testimony, also showed how multiple lines of evidence (forensic and non-forensic) can be incorporated, according to the framework for legal reasoning outlined by Lagnado et al (2013). The example also effectively demonstrates the utility of a graphical approach when dealing with evidence from multiple suspects. While the interpretation of GSR evidence may be complex in real cases, with many sources of uncertainty (Gauriot et al 2013), a Bayesian Network approach is well suited to representing and dealing with these complexities.

Importantly, the final BN presented in figures 7.19-7.22 combines qualitative probabilities and values estimated from empirical data. Through the incorporation of qualitative information regarding the identity of a suspect by a witness, the example demonstrates the capacity of a BN to be used to model dependencies that could be intuitively captured but which may be challenging to represent or weigh into the assessment in a transparent manner in the absence of a formal tool. The example also demonstrates the way a BN can be employed in reasoning about legal problems using

qualitative estimates and knowledge, in the absence of, or in combination with, empirical data (Biedermann and Taroni 2006a, 2006b, Lagnado 2011).

With regard to the experimental findings themselves, their incorporation within a probabilistic framework and their application to forensic scenarios serves to capture the potential interpretative ramifications they pose with regard to distinguishing methods of GSR deposition. The possibility that, under certain conditions, considerable quantities of GSR particles may be deposited on hands by mechanisms other than shooting has been further demonstrated. This possibility is likely to be underestimated without reference to empirical data such as those presented in chapter five. The importance of achieving accurate particle counts when analysing GSR evidence is stressed once again. Further empirical research into the relationship between particle sizes, which builds on the initial results and findings presented in chapter five, could also be incorporated into the BN so that two aspects of GSR evidence (particle counts and size data) might be evaluated under the competing propositions. Incorporating the persistence and decay of material would also facilitate reasoning about the method of deposition given alternative timeframes.

7.5 The use of Bayesian reasoning in forensic science: the legal context

An exploration of the application of a Bayesian approach to reasoning about forensic evidence would not be complete without a consideration of the current status of the relationship between Bayes and the law. Current debates stem from a number of recent legal judgments that have questioned the merits of Bayesian reasoning and effectively prohibited its use in legal settings in England and Wales. The most recent debates and concerns centre on the judgment in the Court of Appeal in *R. V. T* (2010)[35] which has been interpreted by many as advocating the exclusion of Bayesian reasoning and statistical weighing of evidence in fields other than DNA evidence. A number of subsequent discussions and commentaries have provided a critical response to the judgment (see for example, Berger et al 2011a, Robertson et al 2011, Fenton 2011,), which is widely considered to represent a backward step for evidence evaluation in legal contexts and a hindrance to the progress of various disciplines of forensic science.

[35] The original judgment should be referred to for a full account

It is argued that the basis of this ruling can be traced to a series of fundamental misunderstandings about Bayesian and probabilistic concepts (Berger et al 2011a Robertson et al 2011, Fenton 2011)[36]. The implication of the ruling is such that probabilistic assessments are eschewed in favour of less formal verbal indications of the level of consistency or support exhibited by evidence in relation to a hypothesis (Robertson et al 2011). While there should be no doubt that underlying assumptions and references to empirical data must be disclosed, as implied by the judgment, this should not be a basis on which to outlaw the use of Bayesian reasoning. Nor should the problems associated with the original evidence in *R. V. T* (2010) (Redmayne et al 2011) or with the use of a verbal scale in expressing the value of evidence (Faigman et al 2011, Facey and Davis 2011, Berger et al 2011b) represent a reason for doing so. The distinction that was made between DNA evidence and other types of evidence may have been overstated in the judgment (Fenton 2011). The incorporation of error rates, random match probabilities, contamination issues, diverging methods of profile generation and subjective probabilities, particularly with regard to Low Copy Number DNA, mean that the implied certainty of DNA identifications may have been overemphasised (Thompson et al 2003).

One difficulty associated with presenting interpretations underpinned by probabilistic assessments is that, as shown throughout this chapter, forensic interpretation problems are rarely simple and often involve many items of evidence and sources of uncertainty. As a result calculations can become extremely complex and it is here that Bayesian Network tools, approaches and concepts (which have been the focus of this chapter) represent a solution, particularly in visually representing the problem at hand (Fenton 2011, Fenton and Neil 2011, 2012). Communicating the utility of Bayesian Networks for logically assessing complex problems involving multiple sources of uncertainty is a contemporary challenge. As a result, research that demonstrates the application of Bayesian approaches to reasoning about forensic evidence in legal contexts has an important role to play. In this sense, the application of Bayesian Networks to reasoning about GSR evidence under activity level propositions which has been presented in this chapter represents a timely contribution and one which confronts the legal status quo.

[36] See Evett (1995) for a discussion of the transposed conditional

Establishing the place of Bayesian reasoning within legal contexts in England and Wales will necessitate an acceptance from legal communities that the data, subjectivities and prior assumptions which are incorporated into an assessment can be the subject of alteration and question, but also that the logical calculation of probability is underpinned by immutable laws (Fenton 2011). According to Fenton and Neil (2011), the fundamental calculations which underpin Bayesian Network tools are logical and should be regarded in the same manner as the micro-level operations performed by an electronic calculator. Communicating this message represents a second challenge and one which appears to be further complicated by the continued confusion regarding basic probabilistic concepts, as demonstrated recently in the judgment in *Milton Keynes Borough Council v. Nulty & Ors* (2013)[37] and in the many fallacious statistical arguments that continue to be observed in legal contexts (Fenton 2011, Fenton and Neil 2011, 2012). Bayesian Networks facilitate the logical assessment of the value of evidence in both case pre-assessment and courtroom settings. Recognising the utility of Bayesian approaches to evaluating forensic evidence arguably offers forensic science with a means of addressing a number of the criticisms presented in reports by the NAS and the Law Commission (see chapter one). Indeed, employing a logical approach to evidence interpretation which is underpinned by research findings from the empirical evidence base represents a departure from poorly founded claims of uniqueness or causality which have been so heavily criticised by the aforementioned reports. The emphasis on incorporating empirical and expert support in the Bayesian interpretation of evidence resonates strongly with calls for a research culture in forensic science (see section 1.2 and Mnookin et al 2011). This will be discussed in section 8.3.

[37] See the discussion at http://understandinguncertainty.org/court-appeal-bans-bayesian-probability-and-sherlock-holmes

Chapter 8 Conclusions

8.1 Outline

This chapter presents an evaluated summary of the research findings, with a particular emphasis on the contribution of the experimental findings to our understanding of the dynamics of GSR evidence and the implications of these for forensic investigations. The limitations of the findings are given consideration, before avenues for further work, which have been alluded to throughout the thesis, are discussed. Section 8.3 then discusses the broader significance of the research findings with reference to contemporary scientific and legal debates regarding forensic evidence and its interpretation.

8.2 A summary of findings

This piece of research was undertaken in order to investigate various means of GSR deposition to hands, including secondary transfers. These mechanisms have, until now, received little attention in the published forensic science literature. Transfer studies have tended to focus on contamination involving law enforcement (Gialamas et al 1995 and Berk et al 2007, for example), rather than transfers and depositions during the period between the discharge of the firearm and the collection of evidence. This piece of research was concerned with addressing this knowledge gap and considering the practical and interpretative implications of the experimental findings for forensic investigations. A series of research questions was formulated in section 3.7 to this end. In order to address the interpretation of GSR evidence in light of the findings, the application of Bayesian Networks to reasoning about means of GSR transfer and deposition was explored.

8.2.1 Evidence dynamics

The results of the experimental scenarios which were presented in chapter five and the ensuing discussion of these findings in chapter six unequivocally identified the potential for considerable amounts of GSR to undergo secondary transfer to the hands of an individual. Importantly, the participants from whom GSR was recovered were

not in the vicinity of the firearm discharge and either held a discharged firearm or shook hands with a shooter in the immediate aftermath of the firing. Meanwhile, the possibility of recovering GSR particles from the hands of a bystander who was standing one metre behind the discharge was confirmed. Finally, the findings highlighted the possibility of tertiary transfer of GSR particles to an individual via a handshake with another individual who had shaken hands with the shooter, following a firearm discharge. That GSR can be transferred in this manner has not previously been reported in the published experimental literature.

The number of particles transferred to, or deposited on, the hands of the subjects under the simulated conditions was considerable. As many as 129 particles were transferred as a result of a secondary transfer via a handshake with a shooter. As many as 22 GSR particles were recovered as a result of a tertiary transfer initiated by a chain of two handshakes. Moreover, the efficiency of these tertiary transfers suggests that further handshakes could initiate further transfers of GSR. Under conditions analogous to the experimental settings that were simulated, several hundred particles can be expected to be recoverable from the hands of the shooter. No alternative mechanism of GSR transfer or deposition resulted in the presence of several hundred particles on a subject.

With regard to the sizes of the particles recovered from the hands of subjects, some initial conclusions can be drawn. The data suggest that, when transfers occur between shooters and subjects via handshakes, the resulting GSR populations are representative of one another in terms of the sizes of particle involved. Meanwhile, large (>50µm, >100µm) GSR particles underwent secondary transfer. This finding is significant in terms of our understanding of transfers of GSR, and for our understanding of multiple transfers of trace evidence in general. The investigation of repeatable trends in the transfer and deposition of different sizes of GSR particles warrants further study that complements these initial insights (see section 8.2.5).

8.2.2 The implications for forensic investigations involving GSR

Section 6.3 considered the possible implications of the experimental findings for forensic investigations involving GSR evidence. With regard to the collection of GSR evidence, the value of sampling from multiple suspects who may have acquired GSR

via one of a number of mechanisms was stressed. A sampling strategy that is informed by knowledge of the possibility of various means of transfer and deposition has the capacity to assist in the reconstruction of a firearms incident. That GSR may be readily transferred from a surface or deposited in the vicinity of a discharge poses contamination risks during a forensic investigation. Conceivably, these could severely impinge on the capacity of the scientist to accurately interpret evidence. Unchecked, these mechanisms could compromise the probative value of the evidence, or could even serve to falsely incriminate an individual. Protocols and procedures that manage the risk of initiating transfers of GSR between suspects, perhaps via law enforcement officers, are advisable. An awareness of the possibility of GSR transfer should also inform the experimental design of future research studies involving GSR. Opportunities for further research into these issues are discussed in section 8.2.5.

With regard to the analysis and examination stage of the forensic investigation, this piece of research has exhibited the capacity of SEM-EDX, coupled with an automated search and detection package, to generate repeatable measures of the GSR population on a sample for reconstruction purposes. Carrying out this analysis and achieving accurate results, however, involves a number of complex processes and procedures. The account of the set-up and analysis processes in section 4.3 represents a guide for employing a similar approach to analysis. It was concluded, in agreement with Owens (1990), that reducing the search area in order to speed up the analysis gives rise to the potential for error in cases that necessitate precise GSR particle counts or a comprehensive catalogue of the sizes of particles. In other cases, that demand an indication of GSR presence or an estimation/verification of the size of a GSR population, reducing the search area is conceivably a viable option.

It is arguably in the interpretation of GSR evidence under competing propositions about its transfer and deposition that the research findings have most significance. The possible interpretative nuances were comprehensively discussed in section 6.4. In summary, the research findings confirmed that the presence of GSR on the hands of a suspect, even in considerable quantities, may not necessarily support the inference that a suspect fired a gun. Conceivably, if this is not fully acknowledged and incorporated into the assessment of (small quantities of) GSR evidence, the possibility of misinterpretation and false incrimination exists. That GSR particles can undergo

tertiary transfer is an extremely significant finding with ramifications for the interpretation of trace amounts of physical particulate evidence recovered from a suspect. Meanwhile, the extent of the secondary and tertiary transfers observed during this study suggests that the possibility of indirect transfer should be considered at the highest level during trace evidence interpretation. It must be stressed that the findings of this study do not undermine the potential to establish links between suspects and forensic events through trace quantities of evidence. Rather, the findings provide the means to accurately assess the possibility of indirect transfer when evaluating evidence under competing propositions, in the pursuit of reliable and empirically-supported interpretations.

No mechanism of GSR transfer or deposition other than discharging the firearm resulted in the presence of several hundred particles on a subject. Incorporating the possibility of secondary transfer (and other mechanisms) into the assessment of GSR evidence will necessitate the incorporation of case-specific variables and the persistence of material in real cases. As a result, the possibility of observing similar quantities of GSR on shooters and non-shooting suspects could, in theory, be more pronounced. Bayesian Networks offer a means of capturing these variables in both a qualitative and a quantitative sense (see section 8.2.3).

If an attempt is made to interpret the sizes of recovered particles, it should be acknowledged that the findings of this piece of research suggest that large (>50µm, >100µm) can be secondarily transferred. Thus, the presence of large particles on the hands of a suspect may not necessarily support an inference that the suspect discharged a firearm. Conceivably, the similarity of two samples in terms of the distribution of particle sizes may be used to support a hypothesis of contact between two surfaces. In real-world cases, case-specific variables such as the timeframes of persistence and the retentive properties of substrates will need to be incorporated. As stated in section 8.2.1, the findings with regard to the sizes of particles involved in transfer result from an initial exploration. Further work aimed at understanding the dynamics of different sizes of particle will assist in realising further the interpretative utility of particle size data (see section 8.2.5).

8.2.3 A Bayesian Network approach to interpreting GSR

Chapter seven demonstrated the utility of Bayesian Networks when reasoning and making inferences regarding GSR evidence, particularly when the means of transfer or deposition may be disputed. Thus, the capacity of using this approach during the assessment of activity level propositions with regard to GSR (and other trace evidence) has been demonstrated. The possibility of incorporating experimentally-derived empirical data within Bayesian Networks was explored. The incorporation of empirical data on the transfer and deposition of GSR within a BN framework represents a novel contribution and one which demonstrated that a BN approach, coupled with empirical knowledge of parameters of transfer and persistence, can assist in making activity level interpretations with regard to trace particulate forensic evidence. The significance of this will be discussed in section 8.3. While the quantitative assessment of the transfer and deposition of GSR (and other) evidence may be challenging, Bayesian Networks provide a means of demonstrating the impact of different variables and assumptions, and can incorporate limited datasets and qualitative causal relationships to enable useful reasoning (Biedermann and Taroni 2006a, 2006b, Lagnado 2011). Chapter seven also considered the findings in the context of ongoing debates regarding the use of Bayesian reasoning within legal settings in England and Wales. Avenues for further research in this field are highlighted in 8.2.5.

8.2.4 Limitations

There are a number of limitations, or caveats, associated with the conclusions drawn from this piece of research which are acknowledged in this section. The issue of validity and the process of applying research findings to real-world scenarios were introduced in section 4.2.5. Accordingly, a number of the limitations that have been identified concern experimental design decisions and their impact on the translation of the research findings into investigative contexts. The experimental results were produced under a specific set of experimental conditions, employing for example, a specific firearm-ammunition combination and involving five rounds of ammunition. These conditions remained constant across all runs of all experimental scenarios in the interest of formulating a coherent body of comparable data on the transfer and deposition of GSR. However, as a result, the precise empirical results (particle counts,

for instance) only represent expected values in a scenario with analogous conditions. They cannot be considered predictive of the rates and patterns of transfer and deposition in alternative forensic scenarios.

However, the aim of this piece of research was to investigate the potential for secondary transfer and other mechanisms to result in the presence of GSR on subjects who have not discharged a firearm. In considering the potential investigative ramifications and nuances the findings may pose, the purpose was not to consider a specific forensic scenario but to consider the implications for interpreting GSR under competing propositions more generally. Morgan and Bull (2007b) warn of the potential dangers associated with extrapolating from published empirical results when interpreting casework samples, owing to the plethora of case-specific variables and conditions that may need to be accounted for. As a result, in concurrence with the approach to GSR analysis proposed by Dalby et al (2010), a case-by-case approach to GSR interpretation is advocated when assessing evidence under activity level, as well as source level propositions. This piece of research has addressed a gap in our knowledge about the dynamics of GSR and the findings may inform the assessment of activity level considerations. In establishing that concepts of multiple transfer and alternative means of deposition are applicable to GSR, the findings of this thesis highlight the utility of further case-specific research into these mechanisms, perhaps with reference to casework material (see section 8.2.5). It was argued in chapter seven that incorporating the findings of this study during the interpretation of GSR evidence, along with case-specific information such as empirically determined estimates of the persistence of material, can be assisted by the use of Bayesian Networks.

Throughout chapter six, acknowledgement was made of instances in which the number of experimental runs limited the potential to infer general trends. Notwithstanding this, a number of conclusions regarding the dynamics, nature and extent of transfers and depositions of GSR were drawn. In addition, the potential ramifications for investigations involving GSR evidence were considered. Avenues for further experimentation are documented in section 8.2.5.

A potential source of error was acknowledged during the presentation of results in chapter five. It was noted that two control samples indicated the presence of a very

low level of contamination on the hands of subjects prior to two experimental runs (see section 5.2 and table 5.1). However, as described in section 5.2, the impact of this contamination on the results and on the conclusions that were drawn is likely to have been negligible. That some particles had persisted on the hands despite thorough washing is a significant finding with potential ramifications for investigative and research protocol (see sections 6.2.1 and 6.3.1).

8.2.5 Avenues for further research

The findings of this research have highlighted a number of areas in which further research is warranted. With regard to GSR, further work should be undertaken which is concerned with the dynamics and transfer and persistence properties under different conditions. Arguably akin to many other forms of trace evidence, research efforts with regard to GSR have been primarily concerned with enhancing our ability to make rapid, accurate source level identifications of minute traces of GSR and distinguishing these from materials with environmental and occupational origins. While the value of such research is great, there is arguably a deficiency in the body of work concerned with issues of transfer, persistence and evidence dynamics, which have been the focus of this thesis. Indeed, it is this body of work that is garnered in order to assess GSR evidence under competing activity level propositions about its method of deposition, and in order to make reliable inference about the activities of a suspect. In a manner that complements the findings of this thesis, experimental research efforts that further investigate multiple transfers of GSR are warranted. These could perhaps address case-specific scenarios and variables such as alternative firearm-ammunition characteristics, varying contact mechanisms, varying sites of deposition (face, clothes, hair, etc.) and the effects of persistence. Further investigation of the transfer and deposition properties of different sized GSR particles may also contribute to revealing the reconstructive potential of examining particle size data. While the findings of this piece of research concern GSR, they highlight the possibility of similar transfer mechanisms with regard to alternative forms of trace evidence and the utility of investigating them.

However, comprehensively addressing each context-specific variable that might impact rates of transfer and persistence in casework settings is clearly not possible. Instead,

investment should be made in ensuring that theoretical concepts and frameworks regarding evidence dynamics are established which can be supplemented by case-specific research. Following the example set out in sections 6.3 and 6.4, it is paramount that future work considers the investigative implications of its findings and the interpretative nuances that might conceivably be posed. Indeed, this is in accordance with the need to demonstrate the practical utility, value and relevance of research within a research culture in forensic science (Mnookin et al 2011, Linacre 2013, see section 1.2.2). This demonstration is also necessary if the funding for such research projects is to be secured.

A further possible study could explore the risks of contamination via secondary transfer mechanisms, which were indicated by the experimental results and discussed in section 6.3.1. In particular, studies that examine these secondary transfer possibilities and contamination risks among law enforcement officers including those within firearms units, in a U.K. context, are currently lacking. Such work could inform forensic practices and protocols. Meanwhile, with reference to the hierarchy of propositions that was outlined in section 2.2.2, a survey of the extent of background environmental contamination risks within a U.K. context would assist in the accurate interpretation of GSR under source and activity level propositions. A survey of this kind would be a crucial resource when interpreting trace quantities of GSR which can, as this study has shown, be deposited through various mechanisms and which can be quantified analytically.

The recovery of 'large fragmented' or conglomerate GSR particles (Brozek-Mucha 2011, p.975) was documented in sections 5.5.2 and 6.2.1. That their existence can serve to inflate the particle count that is recoverable from a shooter has been established (ibid.). Concerted attempts to understand the formation and dynamics of these GSR structures could reveal further evidential value of GSR. For example, if it was found that these structures resist transfer, their presence on the hands of a suspect may support an inference that the suspect discharged a firearm.

Chapter seven demonstrated the value of Bayesian Networks when reasoning about forensic evidence, particularly in situations that involve multiple variables. With regard to GSR evidence, future research might consider further the assessment of activity level propositions regarding the deposition of GSR. As demonstrated in

chapter seven, when supplemented with (empirical) knowledge of the dynamics of GSR, this approach can assist in making inferences about the roles of suspects in a firearms incident. Research might also consider further the combination of GSR evidence with other items of evidence in the wider context of specific legal cases. Such research, it is anticipated, will assist in addressing some of the current misunderstandings regarding the use of Bayesian approaches in legal contexts (section 7.5) and demonstrate their capacity to aid in the logical assessment of the level of evidential support for competing hypotheses. Finally, with regard to GSR, empirical understanding of the dynamics of GSR evidence might fruitfully be combined in Bayesian Networks with recent work that enhances our ability to make source level determinations of the origins of GSR evidence (see for example, Christopher et al 2013, Romolo et al 2013 and section 3.3), in order to formulate a multi-level framework for the assessment of GSR evidence.

8.3 This thesis and the importance of empirical research in forensic science

This piece of research has contributed to our understanding of the dynamics of GSR and considered the implications and opportunities for forensic practice and the interpretation of evidence. Notwithstanding these important interventions, it is also possible to consider the wider significance of the study as a research project in forensic science. Within the context of legal and scientific debates that have been presented throughout this thesis, this section considers the future of empirical research in forensic science.

Linacre (2013) highlights the importance of empirical knowledge that can be cited in support of conclusions that are drawn regarding trace evidence (see section 1.2.1). Notably, the example which is proffered to demonstrate this concerns an activity level dispute about the likelihood of secondary transfer. For Linacre (2013), the example encapsulates the synergy that should exist between research and practice in forensic science. Determining the practical value of research for forensic science is identified as a central tenet of an effective research culture in forensic science (Mnookin et al 2011, Linacre 2013) and has underpinned the approach adopted in the writing of this thesis. Ensuring that empirical bodies of research exist which can underpin practices that are

adopted and conclusions that are made will strengthen the scientific basis of the outputs of forensic science and concurrently, address the concerns and issues that were conveyed by the NAS and the Law Commission in recent reports. In the case of the present piece of research, the empirical findings may be cited in support of inferences that are made regarding the mechanism by which GSR was deposited on a suspect.

This thesis argues that the account of evidence interpretation, and in particular, the 'hierarchy of propositions' presented by Cook et al (1998a, 1998b, p.231, 1999) and Evett et al (2000) (see section 2.2.2), represent a means of ensuring bodies of empirical research exist which strengthen forensic practice. Three levels of proposition exist (source, activity and offence) and within the bounds of the context of the case a pair of opposing propositions is formulated, under which the evidence is assessed. The assessment should involve incorporating (empirical) knowledge regarding, for example, background rates of the material in question, or the transfer and persistence properties of the trace evidence. It is this information that permits the accurate determination of the probability of observing a given quantity or pattern of evidence given prosecution and defence allegations. Rather than being confined to the consideration of the results of an examination, or to the formulation of the forensic report, Cook et al (1998a) argue that the process of interpretation permeates every stage of the forensic investigation (see section 2.2.2). The iterative interpretation process involves considering what might be expected from an examination given alternative propositions that have been formed within the context of a case. This thesis has shown that consideration of indirect transfer mechanisms, for example, should underpin the evidence collection and sampling strategies that are employed. This thesis also argues that this conception of interpretation should be extended so that it underpins and guides the formulation of research questions and research design in forensic research spheres.

Empirical research will address source or activity level issues. Demonstrating which level of proposition a piece of research will help to address, and in what circumstances and case contexts, will ensure that the practical benefit and interpretative significance of the research is made clear. Not only will this increase the likelihood of securing research funding, but in elucidating the value of the empirical research, it will serve to

establish the foundations of an effective research culture in forensic science that is being called for (Mnookin et al 2011, Bono et al 2011, Linacre 2013, Margot 2011). Concurrently, an empirical research base that is clear about the nature of the conclusions it can be used to support will directly address the apparent absence of a robust scientific basis in areas of forensic science which has been identified by the 2009 NAS report (see also section 1.2 and The Law Commission 2009). In addition, crucially, explicit consideration of the interpretative value of findings and acknowledgement of the limitations in terms of the contexts in which they can be applied will ensure that findings are not offered in support of conclusions that lie beyond the scope of the research. These considerations are central to the existence of an effective research culture in forensic science according to Mnookin et al (2011).

Identifying research questions and empirical knowledge gaps can be assisted by consideration of the hierarchy of propositions. For example, in many domains of forensic science, including GSR analysis and interpretation, our ability to address source level considerations has been enhanced by the development of highly sensitive analytical methods. However, our understanding of evidence dynamics, and therefore, our ability to assess activity level concerns are somewhat underdeveloped. The synergy that should exist between casework and empirical research should not only involve the incorporation of empirical findings into casework assessments, but also the identification of empirical knowledge gaps during the assessment of propositions in casework which can feed into research design. This will assist in deciding which level of proposition to address in research. This synergy may be enhanced by collaborations between research and practitioner communities and references to previous casework in research design. Research, therefore, should be carried out to meet case-specific demands but research may also be focused on conceptually establishing principles. Crucially, however, both will be informed by casework concerns.

This thesis argues that the application of Bayesian Networks should be incorporated into this conception of research design. The account of the process of evidence interpretation that was surveyed in section 2.2.2, after Cook et al (1998a) and others, is inherently underpinned by a Bayesian causal logic. That the assessment of evidence under competing propositions in this way involves the calculation of the likelihood ratio is highlighted by Cook et al (1998a,b). It was argued in chapter seven, however

that for complex problems involving a number of variables and qualitative probabilistic information, the scaling up of the likelihood ratio calculation becomes complex. It was argued that Bayesian Networks, and the use of Bayesian Network tools, make it possible to incorporate various sources of (empirical) knowledge. Thus, they are conceptually aligned to a probabilistic approach to interpretation and also represent a means of incorporating information from numerous empirical research efforts in the ultimate assessment of a pair of propositions. Owing to their capacity to be updated according to the emergence of new evidence, other forms of evidence and changes regarding the framework of circumstances in a legal case, they can assist in realising practical benefit of empirical research. Furthermore, this research project has demonstrated the utility of employing Bayesian Networks when assessing activity level propositions, particularly those which involve considerations of transfer and persistence. It has also demonstrated the value of incorporating empirical data (on the transfer of GSR in this case) within a Bayesian framework for reasoning about activity level propositions.

Considerations of the interpretative significance of research findings through the use of Bayesian Networks in a manner akin to this study and demonstrations of the capacity to incorporate empirical findings within Bayesian Networks are well-timed. In eschewing unscientific opinions and 'hunches' (Mnookin et al 2011, p.742) and moving towards probabilistic assessment and empirically-grounded logical interpretations, the use of Bayesian Networks appears to address the legal and scientific criticisms highlighted in the NAS report. This transition is embodied by this thesis and recognised by Bunch and Wevers (2013). Meanwhile, such an approach challenges the status quo advocated by recent legal rulings (see section 7.5) in the pursuit of logically and scientifically robust interpretations of trace evidence.

In demonstrating the existence of multiple transfer mechanisms of GSR and their potential investigative significance, this thesis espouses the connections between research and forensic practice which should underpin research design within the field of forensic science. In light of the findings, the possibility of indirect transfer should be considered at the highest level during the interpretation of trace particulate evidence and its implications for crime reconstruction understood and incorporated into the interpretations made. Furthermore, this process of interpretation and the inferences

that are made should be supported by an empirical understanding of the relevant parameters. This thesis argues that the process of making inferences is inherently probabilistic and involves the incorporation of multiple sources of uncertainty. The forensic community must recognise, therefore, that probabilistic approaches represent a valuable, and perhaps the preferred means of interpreting and presenting the value of evidence. This recognition, coupled with an appetite for carrying out empirical research and establishing concepts and principles rooted in this evidence base, has the capacity to enable forensic outputs to become more scientifically robust, sound and logical interpretations of evidence, which are well placed to serve the legal process.

References

AgenaRisk. 2013. *AgenaRisk.* [Online]. Available from: http://www.agenarisk.com/. [Accessed 4th November 2013]

Aitken, C. 1995. *Statistics and the Evaluation of Evidence for Forensic Scientists.* Chichester: Wiley

Aitken, C. and Gammerman, A. 1989. Probabilistic reasoning in evidential assessment. *Journal of the Forensic Science Society* 29 (5) 303-316

Akulova, V., Vasiliauskiené, D. and Talaliené, D. 2002. Further insights into the persistence of transferred fibres onto outdoor clothes. *Science and Justice* 42 (3) 165-171

Allen, T. and Scranage, J. 1998. The transfer of glass – part 1: Transfer of glass to individuals at different distances. *Forensic Science International* 93 (2) 167-174

Andrasko, J. and Maehly, A. 1977. Detection of gunshot residues on hands by scanning electron microscopy**.** JOURNAL OF FORENSIC SCIENCES 22 (2) 279-287

Ansell, R. 2002. Secondary transfer of seminal constituents. *Journal of the Canadian Society of Forensic Science* 35 (1) 23-27

Archer, M. and Ranson, D. 2005. Potential contamination of forensic entomology samples collected in the mortuary: a case report. *Medicine, Science and the Law* 45 (1) 89-91

Arndt, J., Bell, S., Crookshanks, L., Lovejoy, M., Oleska, C., Tulley, T. and Wolfe, D. 2012. Preliminary evaluation of the persistence of organic gunshot residue. *Forensic Science International* 222 (1) 137-145

Ashcroft, C., Evans, S. and Tebbett, I. 1988. The persistence of fibres in head hair. *Journal of the Forensic Science Society* 28 (5) 289-293

ASTM. 2010. E1588–10e1. *ASTM Standard Guide for Gunshot Residue Analysis by Scanning Electron Microscopy/Energy Dispersive X-Ray Spectrometry*. West Conshohocken, PA: ASTM International DOI: 10.1520/C0033-03

Bailey, M. and Jeynes, C. 2009. Characterisation of gunshot residue particles using self-consistent ion beam analysis**.** *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms* 267 (12-13) 2265-2268

Bailey, M. and Trevorrow, P. 2010. Surface analysis techniques in forensic science. *Surface and Interface Analysis* 42 (5) 339-340

Basu, S. 1982. Formation of gunshot residues. JOURNAL OF FORENSIC SCIENCES 27 (1) 72-91

Basu, S. 1997. Fundamental studies of gunshot residue deposition by glue-lift. *Journal of Forensic Sciences* 42 (4) 571-581

Beecham, G. and Weir, B. 2011. **Confidence interval of the likelihood ratio associated with mixed stain DNA evidence.** *Journal of Forensic Sciences* 56 (SUPPL. 1) S166-S171

Bennett, S., Roux, C. and Robertson, J. 2010. The significance of fibre transfer and persistence – A case study. *Australian Journal of Forensic Sciences* 42 (3) 221-228

Berger C., Buckleton, J., Champod, C., Evett, I., and Jackson, G. 2011a. Evidence evaluation: A response to the Court of Appeal judgment in R v T. *Science and Justice* 51 (2) 43–49

Berger C., Buckleton, J., Champod, C., Evett, I., and Jackson, G . 2011b. Response to Faigman et al. *Science and Justice* 51 (4) 215

Berk, R., Rochowicz, S., Wong, M., and Kopina, M. 2007. Gunshot residue in Chicago police vehicles and facilities: An empirical study. *Journal of Forensic Sciences* 52 (4) 838-841

Biedermann A., Taroni F., Delémont, O., Semadeni C., and Davison A., 2005a. **The evaluation of evidence in the forensic investigation of fire incidents (Part I): An approach using Bayesian networks.** *Forensic Science International* 147 (1) 49-57

Biedermann A., Taroni F., Delémont, O., Semadeni C., and Davison A., 2005b. The evaluation of evidence in the forensic investigation of fire incidents. Part II. Practical examples of the use of Bayesian networks. *Forensic Science International* 147 (1) 59-69

Biedermann, A. and Taroni, F. 2006a A probabilistic approach to the joint evaluation of firearm evidence and gunshot residues. *Forensic Science International* 163 (1-2) 18-33

Biedermann, A., Taroni, F. 2006b. Bayesian networks and probabilistic reasoning about scientific evidence when there is a lack of data. *Forensic Science International* 157 (2-3) 163-167

Biedermann, A., Bozza, S. and Taroni, F. 2009. Probabilistic evidential assessment of gunshot residue particle evidence (Part I): Likelihood ratio calculation and case pre-assessment using Bayesian networks. *Forensic Science International* 191 (1) 24-35

Biedermann, A., Bozza, S. and Taroni, F. 2011. Probabilistic evidential assessment of gunshot residue particle evidence (Part II): Bayesian parameter estimation for experimental count data. *Forensic Science International* 206 (1) 103-110

Bird, D., Agg, K., Barnett, N., and Smith, T. 2007. Time-resolved fluorescence microscopy of gunshot residue: An application to forensic science. *Journal of Microscopy* 226 (1) 18-25

Bisbing, R. 2006. Trace evidence in the real crime laboratory. In: Mozayani, A., and Noziglia, C., eds. *The Forensic Laboratory Handbook: Procedures and Practice.* New Jersey: Humana Press, pp.265-290

Boehm, E. 1971. Application of the SEM in forensic medicine. In: Johari, O., and Corvin, I., eds. *Proceedings of the 4th Annual Scanning Electron Microscopy Symposium, IITRI, Chicago,* pp.553-560

Bono, J. 2011. Commentary on the need for a research culture in the forensic sciences. *UCLA Law Review* 58 (3) 782-788

Brazeau, J., and Wong, R. 1997. Analysis of gunshot residues on human tissues and clothing by X-ray microfluorescence. JOURNAL OF FORENSIC SCIENCES 42 (3) 424-428

Brewster, F., Thorpe, J., Gettinby, G., and Caddy, B. 1985. The retention of glass particles on woven fabrics. *Journal of Forensic Sciences* 30 (3) 798-805

Broeders, A. 2006. Of earprints, fingerprints, scent dogs, cot deaths and cognitive contamination - a brief look at the present state of play in the forensic arena. *Forensic Science International* 159 (2-3) 148-157

Brozek-Mucha, Z. 2002. A gunshot following the stopping of a passenger car by police - A reconstruction of an event on the basis of case files and gunshot residue examinations. *Problems of Forensic Sciences* 51 119-136

Brozek-Mucha, Z. 2007. **Comparison of cartridge case and airborne GSR - A study of the elemental composition and morphology by means of SEM-EDX.** *X-Ray Spectrometry* 36 (6) 398-407

Brozek-Mucha, Z. 2009. **Distribution and properties of gunshot residue originating from a Luger 9 mm ammunition in the vicinity of the shooting gun.** *Forensic Science International* 183 (1-3) 33-44

Brozek-Mucha, Z. 2011. Chemical and morphological study of gunshot residue persisting on the shooter by means of scanning electron microscopy and energy dispersive X-ray spectrometry. *Microscopy and Microanalysis* 17 (6) 972-982

Brozek-Mucha, Z., and Jankowicz, A. 2001. Evaluation of the possibility of differentiation between various types of ammunition by means of GSR examination with SEM-EDX method. *Forensic Science International* 123 (1) 39-47

Brozek-Mucha, Z., and Jarosz, J. 2001. Reconstruction of a crime involving the use of a firearm based on the study of case files and gunshot residue examination. *Problems of Forensic Sciences* 45 109-121

Brozek-Mucha, Z., and Zadora, G. 2001. Frequency of occurrence of certain chemical classes of GSR from various ammunition types. *Problems of Forensic Sciences* 46 281-287

Brozek-Mucha, and Z., Zadora, G. 2003. Grouping of ammunition types by means of frequencies of occurrence of GSR. *Forensic Science International* 135 (2) 97-104

Brozek-Mucha, Z., Zadora, G., and Dane, F. 2003. A comparative study of gunshot residue originating from 9 mm Luger ammunition from various producers. *Science and Justice* 43 (4) 229-235

Bull, P., Morgan, R., Sagovsky, A., and Hughes, G. 2006. The transfer and persistence of trace particulates: Experimental studies using clothing fabrics. *Science and Justice* 46 (3) 182-192

Bunch, S., and Wevers, G. 2013. Application of likelihood ratios for firearm and toolmark analysis. *Science and Justice* 53 (2) 223-229

Burnett, B. 1989. Form of gunshot residue is modified by target impact. *Journal of Forensic Sciences* 34 (4) 808-822

Bydal, B. 1990. Percussion primer mixes. *AFTE Journal* 22 (1) 1-26

Cardinetti, B., Ciampini, C., Abate, S., Marchetrti, C., Ferrari, F., Di Tullio, D., D'Onofrio, C., Gravina, L., Torresi, L., and Saporita, G. 2006. A proposal for statistical evaluation of the detection of gunshot residues on a suspect. *Scanning* 28 (3) 142-147

Casey, E. 2004. Network traffic as a source of evidence: Tool strengths, weaknesses, and future needs. *Digital Investigation* 1 (1) 28-43

Casey, E. 2011. *Digital Evidence and Computer Crime: Forensic Science, Computers, and the Internet* MA: Academic Press

Cecchetto, G., Giraudo, C., Amagliani, A., Viel, G., Fais, P., Cavarzeran, F., Feltrin, G., Ferrara, S., and Montisci, M. 2011. Estimation of the firing distance through micro-CT analysis of gunshot wounds. *International Journal of Legal Medicine* 125 (2) 245-251

Cetó, X., O'Mahony, A., Samek, I., Windmiller, J., Del Valle, M., and Wang, J. 2012. Rapid field identification of subjects involved in firearm-related crimes based on electroanalysis coupled with advanced chemometric data treatment. *Analytical Chemistry* 84 (23) 10306-10314

Chapman, S. 1999. Optimising the performance of a tungsten hairpin. *Scanning Microscopy* 13 (1) 141-146

Charles, S., and Geusens, N. 2012. A study of the potential risk of gunshot residue transfer from special units of the police to arrested suspects. *Forensic Science International* 216 (1-3) 78-81

Charles, S., and Nys, B. 2010. The Bayesian approach to reporting GSR analysis results: Some first-hand experiences. *Proceedings of SPIE - The International Society for Optical Engineering* 7729 no.77291B

Charles, S., Lannoy, M., and Geusens, N. 2013. Influence of the type of fabric on the collection efficiency of gunshot residues. *Forensic Science International* 228 (1-3) 42-46

Charles, S., Nys, B., and Geusens, N. 2011. Primer composition and memory effect of weapons - some trends from a systematic approach in casework. *Forensic Science International* 212 (1-3) 22-26

Chewning, D., Deaver, K., and Christensen, A. 2008. Persistence of fibers on ski masks during transit and processing. *Forensic Science Communications* 10 (3) 1-6

Chisum, W., and Turvey, B. 2000. Evidence dynamics: Locard's exchange principle & crime reconstruction. *Journal of Behavioural Profiling* 1 (1) [no pagination]

Chisum,W., and Turvey, B. 2007. Evidence dynamics. In: Chisum, W., and Turvey, B., eds. *Crime Reconstruction.* Burlington: Elsevier, pp.161-196

Christopher, M., Warmenhoeven, J., Romolo, F., Donghi, M., Webb, R., Jeynes, C., Ward, N., Kirkby, K., and Bailey, M. 2013. A new quantitative method for gunshot residue analysis by ion beam analysis. *Analyst* 138 (16) 4649-4655

Collins, P., Coumbaros, J., Horsley, G., Lynch, B., Kirkbride, K., Skinner, W., and Klass, G. 2003. Glass-containing gunshot residue particles: A new type of highly characteristic particle?. *Journal of Forensic Sciences* 48 (3) 538-553

Cook R., Evett, I., Jackson, G., Jones, P., and Lambert, J. 1998a. A model for case assessment and interpretation. *Science and Justice* 38 (3) 151-156

Cook R., Evett, I., Jackson, G., Jones, P., and Lambert, J. 1998b. A hierarchy of propositions: deciding which level to address in casework. *Science and Justice* 38 (4) 231-239

Cook R., Evett, I., Jackson, G., Jones, P., and Lambert, J. 1999. Case pre-assessment and review in a two-way transfer case. *Science and Justice* 39 (2) 103-111

Coumbaros, J., Kirkbride, K., Kobus, H., and Sarvas, I. 2001. Distribution of lead and barium in gunshot residue particles derived from 0.22 caliber rimfire ammunition. *Journal of Forensic Sciences* 46 (6) 1352-1357

Courts, C., Madea, B., and Schyma, C. 2012. Persistence of biological traces in gun barrels - an approach to an experimental model. *International Journal of Legal Medicine* 126 (3) 391-397

Cowell, R., Dawid, P., Lauritzen, S., and Spiegelhalter, D. 1999. PROBABILISTIC NETWORKS AND EXPERT SYSTEMS. New York: Springer

Curran, J., Hicks, T., and Buckleton, J. 2000. *Forensic Interpretation of Glass Evidence.* Florida: CRC Press

Dachs, J., McNaught, I., and Robertson, J. 2003. The persistence of human scalp hair on clothing fabrics. *Forensic Science International* 138 (1-3) 27-36

Dalby, O., Butler, D., and Birkett, J. 2010. Analysis of gunshot residue and associated materials - A review. *Journal of Forensic Sciences* 55 (4) 924-943

Daly, D., Murphy, C., and McDermott, S. 2012. The transfer of touch DNA from hands to glass, fabric and wood. *Forensic Science International Genetics* 6 (1) 41-46

D'Andrea, F., Fridez, F., and Coquoz, R. 1998. Preliminary experiments on the transfer of animal hair during simulated criminal behaviour. *Journal of Forensic Sciences* 43 (6) 1257-1258

Daubert v. Merrell Dow Pharmaceuticals [1993] 509 U.S. 579

Dawid, A., and Evett, I. 1997. Using a graphical method to assist the evaluation of complicated patterns of evidence. JOURNAL OF FORENSIC SCIENCES 42 (2) 226-231

De Forest, P., Rourke, L., Sargeant, M., and Pizzola, P. 2008. Direct detection of gunshot residue on target: Fine lead cloud deposit. *Journal of Forensic Identification* 58 (2) 265-276

Deedrick, D. 2001. Fabric processing and 'nubs'. In: Houck, M., ed. *Mute Witnesses: Trace Evidence Analysis.* London: Academic Press, pp.1-19

DeGaetano, J., Siegel, A., and Klomparens, K. 1992. Comparison of three techniques developed for sampling and analysis of gunshot residue by scanning electron microscopy/energy-dispersive X-Ray analysis (SEM-EDX). *Journal of Forensic Sciences* 37 (1) 281-300

DiMaio, V. 1985. *Gunshot Wounds.* New York: Elsevier

Ditrich, H. 2012. Distribution of gunshot residues - The influence of weapon type. *Forensic Science International* 220 (1-3) 85-90

Dunlap, M., and Adaskaveg, J. 1997. *Introduction to the Scanning Electron Microscope Theory, Practice, & Procedures*. [Online PDF]. Available from: https://imf.ucmerced.edu/downloads/semmanual.pdf. [Accessed 4th November 2013]

Durdle, A., van Oorschot, R., and Mitchell, R. 2009. The transfer of human DNA by Lucilia cuprina (Meigen) (Diptera: Calliphoridae). *Forensic Science International: Genetics Supplement Series* 2 (1) 180-182

Epstein, R. 2002. Fingerprints meet Daubert: The myth of fingerprint science is revealed. SOUTHERN CALIFORNIA LAW REVIEW 75 (3) 605-657

Erzinçlioglu, Z. 2006. *Forensics: Crime Scene Investigations From Murder to Global Terrorism.* London: Carlton

Evett I., Jackson G., and Lambert, J. 2000. More on the hierarchy of propositions: exploring the distinction between explanations and propositions. *Science and Justice* 40 (1) 3-10

Evett, I. 1995. Avoiding the transposed conditional. *Science and Justice* 35 (2) 127-131

Evett, I. 2002. Interpreting small quantities of DNA: The hierarchy of propositions and the use of Bayesian Networks. JOURNAL OF FORENSIC SCIENCES 47 (3) 520-530

Evett, I., Lambert, J., and Buckleton, J. 1998. A Bayesian approach to interpreting footwear marks in forensic casework. *Science and Justice* 38 (4) 241-247

Facey, O., and Davis, R. 2011. Re: Expressing evaluative opinions; A position statement. *Science and Justice* 51 (4) 212-212

Faigman, D., Jamieson, A., Noziglia, C., Robertson, J., and Wheate, R. 2011. Response to Aitken et al on R v T. *Science and Justice* 51 (4) 213–214

Faigman, D., Kaye, D., Saks, M., and Sanders, J. 2002. MODERN SCIENTIFIC EVIDENCE: THE LAW AND SCIENCE OF EXPERT TESTIMONY. 2nd edition. Saint Paul: West Publishing

Fenton, N. 2011. **Science and law: Improve statistics in court.** *Nature* 479 (7371) 36-37

FENTON, N., and *NEIL*, M. 2011. Avoiding legal fallacies in practice using Bayesian Networks. AUSTRALIAN JOURNAL OF LEGAL PHILOSOPHY 36 114-151

Fenton, N., and Neil, M. 2012. ***Risk Assessment and Decision Analysis with Bayesian Networks.*** **London:** CRC Press

Fenton, N., Neil, M., and Lagnado, D. 2013. **A general structure for legal arguments about evidence using Bayesian Networks.** *Cognitive Science* 37 (1) 61-102

Flynn, J., Stoilovic, M., Lennard, C., Prior, I., and Kobus, H. 1998. Evaluation of x-ray microfluorescence spectrometry for the elemental analysis of firearm discharge residues. *Forensic Science International* 97 (1) 21-36

Fojtášek, L., and Kmjec, T. 2005. Time periods of GSR particles deposition after discharge – final results. *Forensic Science International* 153 (2-3) 132-135

Fojtášek, L., Vaćinová, J., Kolář, P., and Kotrlý, M. 2003. Distribution of GSR particles in the surroundings of shooting pistol. *Forensic Science International* 132 (2) 99-105

French, J., Morgan, R., Baxendell, P., and Bull, P. 2012. Multiple transfers of particulates and their dissemination within contact networks. *Science and Justice* 52 (1) 33-41

French, J., Morgan, R., and Davy, J. 2013. The secondary transfer of gunshot residue: An experimental investigation carried out with SEM-EDX analysis. ***X-Ray Spectrometry*** **43 (1) 56-61**

Frye v. U.S. [1923] D.C. Cir. 293 F.1013

Garbolino, P., and Taroni, F. 2002. Evaluation of scientific evidence using Bayesian networks. *Forensic Science International* 125 (2-3) 149-155

Garcia, J., and Martinez, M. 2000. Case studies in gunshot residue analysis by SEM/EDX. *Scanning* 22 (2) 60-61

Garofano, L. Capra, M., Ferrari, F., Bizzaro, G., Di Tullio, D., Dell'Olio, M., and Ghitti, A. 1999. Gunshot residue: Further studies on particles of environmental and occupational origin. FORENSIC SCIENCE INTERNATIONAL 103 (1) 1-21

Garrett, B. 2008. Judging innocence. *Columbia Law Review* 108 56-142

Garrett, B., and Neufeld, P. 2009. Invalid forensic science testimony and wrongful convictions. *Virginia Law Review* 95 (1) 1-97

Gaudette, B., and Tessarolo, A. 1987. Secondary transfer of human scalp hair. *Journal of Forensic Sciences* 32 (5) 1241-1253

Gauriot, R., Gunaratnam, L., Moroni, R., Reinikainen, T., and Corander, J. 2013. Statistical challenges in the quantification of gunshot residue evidence. *Journal of Forensic Sciences* 58 (5) 1149-1155

Genge, N. 2003. *The Forensic Casebook: The Science of Crime Scene Investigation.* London: Ebury Press

Gerard, R., Lindsay, E., McVicar, M., Randall, E., and Janson, N. 2011a. A survey of primer residues produced by contemporary powder-actuated tool rounds and their relation to gunshot residue. *Canadian Society of Forensic Science Journal* 44 (3) 81-88

Gerard, R., McVicar, M., Lindsay, E., Randall, E., and Harvey, E. 2011b. Long range deposition of gunshot residue and the mechanism of its transportation. *Canadian Society of Forensic Science Journal* 44 (3) 97-104

Gerard, R., Lindsay, E., McVicar, M., Randall, E., and Gapinska, A. 2012. Observations of gunshot residue associated with police officers, their equipment, and their vehicles. *Canadian Society of Forensic Science Journal* 45 (2) 57-63

Germani, M. 1991. Evaluation of instrumental parameters for automated scanning electron microscopy/gunshot residue particle analysis. JOURNAL OF FORENSIC SCIENCES 36 (2) 331-342

Giacalone, J. 2000. Putting the brakes on gunshot residue. *Scanning* 22 (2) 62

Gialamas, D., Rhodes, E., and Sugarman, L. 1995. Officers, their weapons and their hands: An empirical study of GSR on the hands of non-shooting police officers. *Journal of Forensic Sciences* 40 (6) 1086-1089

Gill, P. 2002. Role of short tandem repeat DNA in forensic casework in the UK – past, present, and future perspectives. *BioTechniques* 32 (2) 366-385

Gokdemir, K. 1999. The application of a scanning electron microscope with an energy dispersive X-ray analyser (SEM/EDXA) for gunshot residue determination on hands for some cartridges commonly used in Turkey. *Turkish Journal of Chemistry* 23 (1) 83-88

Goode, S., Dockery, C., Bachmeyer, M., Nieuwland, A., and Morgan, S. 2002. Detecting gunshot residue by laser induced breakdown spectroscopy. In: Sawchuk, A., ed. *Laser Induced Plasma Spectroscopy and Applications.* Vol. 81 of OSA Trends in Optics and Photonics Series. Optical Society of America. Paper FB2-1

Goray, M., Eken, E., Mitchell, R., and van Oorschot, R. 2010. Secondary DNA transfer of biological substances under varying test conditions. *Forensic Science International: Genetics* 4 (2) 62-67

Goray, M., Mitchell, J., and van Oorschot, R. 2012. Evaluation of multiple transfer of DNA using mock case scenarios. *Legal Medicine* 14 (1) 40-46

Goswami, J., Davis, M., Andersen, T., Alileche, A., and Hampikian, G. 2013. Safeguarding forensic DNA reference samples with nullomer barcodes. *Journal of Forensic and Legal Medicine* 20 (5) 513-519

Grieve, M. 1987. Glitter particles – an unusual source of trace evidence?. *Journal of the Forensic Science Society* 27 (6) 405-412

Grieve, M., Dunlop, J., and Haddock, P. 1989. Transfer experiments with acrylic fibres. *Forensic Science International* 40 (3) 167-277

Grima, M., Butler, M., Hanson, R., and Mohameden, A. 2012. Firework displays as sources of particles similar to gunshot residue. *Science and Justice* 52 (1) 49-57

Haag, L. 2005. Physical forms of contemporary small-arms propellants and their forensic value. *The American Journal of Forensic Medicine and Pathology* 26 (1) 5-10

Halim, M., Ahmad, U., Yew, C., and Jasmani, H.. 2010. Analysis of gunshot residue deposited on cloth target. *2010 International Conference on Science and Social Research (CSSR), 5-7 December 2010,* pp.1212-1217. [Online]. Available from: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5773720&tag=1. DOI: 10.1109/CSSR.2010.5773720. [Accessed 4th November 2013]

Hankins, R., Uehara, T., and Liu, J. 2009. A comparative study of forensic science and computer forensics. *SSIRI 2009 - 3rd IEEE International Conference on Secure Software Integration Reliability Improvement 2009*, article no. 5325371 pp.230-239. [Online]. Available from: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=5325371. DOI: 10.1109/SSIRI.2009.42. [Accessed 4th November 2013]

Harris, A. 1995. Analysis of primer residue from CCI Blazer lead-free ammunition by scanning electron microscopy/energy dispersive X-ray. *Journal of Forensic Sciences* 40 (1) 27-30

Harrison, H., and Gilroy R. 1959. Firearms discharge residues. *Journal of Forensic Sciences* 4 184-199

Havekost, D., Peters, C., and Koons, R. 1990. Barium and antimony distributions on the hands of nonshooters. JOURNAL OF FORENSIC SCIENCES 35 (5) 1096-1114

Heard, B. 2008. *Handbook of Firearms and Ballistics: Examining and Interpreting Forensic Evidence.* 2nd edition. Chichister: Wiley

Hicks, T., Vanina, R., and Margot, P. 1996. Transfer and persistence of glass fragments on garments. *Science and Justice* 36 (2) 101-107

Hillier, E., Dixon, P., Stewart, P., Yamashita, B., and Lama, D. 2005. Recovery of DNA from shoes. *Canadian Society of Forensic Science Journal* 38 (3) 143-150

Howarth, J., Coulson, S., and Newton, A. 2009. Simulating transfer and persistence of a chemical marker powder for Lycopodium clavatum spores. *Forensic Science International* 192 (1-3) 72-77

Jackson, G., and Cook, R. 1986. The significance of fibres found on car seats. *Forensic Science International* 32 (4) 275-281

Jalanti, T., Henchoz, S., and Gallusser, A. 1999. The persistence of gunshot residue on shooters' hands. *Science and Justice* 39 (1) 48–52

Jensen, F. 2001. BAYESIAN NETWORKS AND DECISION GRAPHS. New York: Springer

Jones, P., and Nesbitt, R. 1975. A photoluminescence technique for detection of gunshot residue. JOURNAL OF FORENSIC SCIENCES 20 (2) 231-242

Kamodyová, N., Durdiaková, J., Celec, P., Sedláčková, T., Repiská, G., Sviežená, B., and Minárik, G. 2013. Prevalence and persistence of male DNA identified in mixed saliva samples after intense kissing. *Forensic Science International: Genetics* 7 (1) 124-128

Kee, T., and Beck, C. 1987. Casework assessment of an automated scanning electron microscope/microanalysis system for the detection of firearms discharge particles. JOURNAL OF THE FORENSIC SCIENCE SOCIETY 27 (5) 321-330

Kenna, J., Smyth, M., McKenna, L., Dockery, C., and McDermott, S. 2011. The recovery and persistence of salivary DNA on human skin. *Journal of Forensic Sciences* 56 (1) 170-175

Kilty, J. 1975. Activity after shooting and its effect on the retention of primer residue. JOURNAL OF FORENSIC SCIENCES 20 (2) 219-230

Knechtle, P., and Gallusser, A. 1996. La persistance des résidus de tir sur les mains selon l'activité du tireur. *Revue Internationale de Criminologie et de Police Technique* 49 (2) 228-246

Koons, R. 1998. Analysis of gunshot primer residue collection swabs by inductively coupled plasma-mass spectrometry. JOURNAL OF FORENSIC SCIENCES 43 (4) 748-754

Koons, R., Havekost, D., and Peters, C. 1987. Analysis of gunshot primer residue collection swabs using flameless atomic absorption spectrophotometry: A reexamination of extraction and instrument procedures. JOURNAL OF FORENSIC SCIENCES 32 (4) 846-865

Koons, R., Havekost, D., and Peters, C. 1988. Determination of barium in gunshot residue collection swabs using inductively coupled plasma-atomic emission spectrometry. JOURNAL OF FORENSIC SCIENCES 33 (1) 35-41

Kotrlý, M., and Turková, I. 2010. **GSR particles and their evidential value.** *Proceedings of SPIE - The International Society for Optical Engineering* 7729 no.772919

Krishnan, S. 1974. Detection of gunshot residue on the hands by neutron activation and atomic absorption analysis. JOURNAL OF FORENSIC SCIENCES 19 (4) 789-797

Krishnan, S. 1977. Detection of gunshot residues on the hands by trace element analysis. JOURNAL OF FORENSIC SCIENCES 22 (2) 304-324

Krishnan, S. 1982. Detection of gunshot residue: Present status. In: Saferstein, R., ed. *Forensic Science Handbook.* NJ: Prentice Hall, pp.572-591

Krishnan, S., Gillespie, K., and Anderson, E. 1971. Rapid detection of firearm discharge residues by atomic absorption and neutron activation analysis. JOURNAL OF FORENSIC SCIENCES 16 (2) 144-151

Krüsemann, J. 2000. Latest developments in analytical forensic SEMs. *Scanning* 22 (2) 75-76

Kuhn*, T. 1962. The Structure of Scientific Revolutions. Chicago: University Press*

Ladd, C., Adamowicz, M., Bourke, M., Scherczinger, C., and Lee, H. 1999. A systematic analysis of secondary DNA transfer. *Journal of Forensic Sciences* 44 (6) 1270-1272

Lagnado, D. 2011. Thinking about evidence. In: Dawid, P., Twining, W., and Vasilaki, M., eds. *Evidence, Inference and enquiry.* Oxford: University Press, pp.183-224

Lagnado, D., Fenton, N., and Neil, M. 2013. Legal idioms: A framework for evidential reasoning. *Argument and Computation* 4 (1) 46-63

Lebiedzik, J. 2000. Can gunshot residue indicate the type of ammunition fired?. *Scanning* 22 (2) 61-61

Lebiedzik, J., and Johnson, D. 2002. Handguns and ammunitions indicators extracted from the GSR analysis. *Journal of Forensic Sciences* 47 (3) 483-493

Lee, H., ed. 1995. *Physical Evidence.* Enfield, CT: Magnani & McCormick

Lee, H., and Ladd, C. 2001. Preservation and collection of biological evidence. *Croatian Medical Journal* 42 (3) 225-228

Lee, R., Lang, S., and Stenger, K. 2009. From digital forensic report to Bayesian network representation. *ISI'09 Proceedings of the 2009 IEEE International Conference on Intelligence and Security Informatics*, pp.303-306. [Online]. Available from:

http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5137330. DOI: 10.1109/ISI.2009.5137330. [Accessed 4th November 2013]

Leintz, R. 2011. **Using bluestar forensic to detect shoe movement transfer of cleaned up blood.** *Journal of Forensic Identification* 61 (5) 468-476

Linacre, A. 2013. Towards a research culture in the forensic sciences. *Australian Journal of Forensic Sciences* 45 (4) 381-388

Lindsay, E., McVicar, M., Gerard, R., Randall, E., and Pearson, J. 2011a. Passive exposure and persistence of gunshot residue (GSR) on bystanders to a shooting: Comparison of shooter and bystander exposure to GSR. *Canadian Society of Forensic Science Journal* 44 (3) 89-96

Lindsay E., McVicar, M., Gerard, R., and Randall, E. 2011b. Observations of GSR on the hands of employees at firearms manufacturing facilities. *Canadian Society of Forensic Sciences Journal* 44 (3) 105-109

Liu, J., Lin, W., and Nicol, J. 1980. The application of anodic stripping voltammetry to forensic science. II. Anodic stripping voltammetric analysis of gunshot residues. FORENSIC SCIENCE INTERNATIONAL 16 (1) 53-62

Locard, E. 1930. The analysis of dust traces (in three parts). *American Journal of Police Science* 1 (Part I) 276-298; (Part II) 401-418; (Part III) 496-514

López-López, M., Delgado, J., and García-Ruiz C. 2013. Analysis of macroscopic gunshot residues by Raman spectroscopy to assess the weapon memory effect. *Forensic Science International* 231 (1-3) 1-5

Lowe, A., Murray, C., Whitaker, J., Tully, G., and Gill, P. 2002. The propensity of individuals to deposit DNA and secondary transfer of low level DNA from individuals to inert surfaces. *Forensic Science International* 129 (1) 25-34

Lowe, A., Murray, C., Richardson, P., Wivell, R., Gill, P., Tully, G., and Whitaker, J. 2003. Use of low copy number DNA in forensic inference. *International Congress Series* 1239 799-801

Lowrie, C., and Jackson, G. 1994. Secondary transfer of fibres. *Forensic Science International* 64 (2-3) 73-82

Luce, R., Buckle, J., and McInnis, I. 1991. Study on the backward fragmentation of window glass and the transfer of glass fragments to individuals' clothing. *Canadian Society of Forensic Science Journal* 24 (2) 70-90

Lucena, M., de Sá, G., Rodrigues, M., Alves, S., Talhavini, M., and Weber, I. 2013. $ZnAl_2O_4$-based luminescent marker for gunshot residue identification and ammunition traceability. *Analytical Methods* 5 (3) 705-709

Mann, M., and Espinoza, E. 1993. **The incidence of transient particulate gunshot primer residue in Oregon and Washington bow hunters.** *Journal of Forensic Sciences* 38 (1) 23-27

Margot, P. 2000. A question of time. *Science and Justice* 40 (2) 64-71

Margot, P. 2011. Commentary on the need for a research culture in the forensic sciences. *UCLA Law Review* 58 (3) 795-801

Martiny, A., Campos, A., Sader, M., and Pinto, M. 2008. SEM/EDS analysis and characterization of gunshot residues from Brazilian lead-free ammunition. *Forensic Science International* 177 (1) 9-17

Mathwave. 2013. *EasyFit 5.5 Professional*. [Online]. Available from: http://www.mathwave.com/help/easyfit/index.html. [Accessed 4th November 2013]

Matricardi, V., and Kilty, J. 1977. Detection of gunshot residue particles from the hands of a shooter. *Journal of Forensic Sciences* 22 (4) 725-738

Matte, M., Williams, L., Frappier, R., and Newman, J. 2012. Prevalence and persistence of foreign DNA beneath fingernails. *Forensic Science International Genetics* 6 (2) 236-243

Mejia, R. 2005. Why we cannot rely on firearm forensics. *New Scientist* 23 November 2005 2257 6-6

Meng, H., and Caddy, B. 1997. Gunshot residue analysis - A review. JOURNAL OF FORENSIC SCIENCES 42 (4) 553-570

Milton Keynes Borough Council v. Nulty & Ors [2013] EWCA Civ. 15

Mnookin, J., Cole, S., Dror, I., Fisher, B., Houck, M., Inman, K., Kaye, D., Koehler, J., Langenburg, G., Risinger, M., Rudin, N., Siegel, J., and Stoney, D. 2011. The need for a research culture in the forensic sciences. *UCLA Law Review* 58 (3) 725-780

Molina, D., Martinez, M., Garcia, J., and DiMaio, V. 2007. Gunshot residue testing in suicides: Part I: Analysis by scanning electron microscopy with energy-dispersive X-ray. *American Journal of Forensic Medicine and Pathology* 28 (3) 187-190

Montani, I., Comment, S., and Delémont, O. 2010. **The sampling of ignitable liquids on suspects' hands.** *Forensic Science International* 194 (1) 115-124

Morgan, R., and Bull, P. 2006. Data interpretation in forensic sediment geochemistry. *Environmental Forensics* 7 (4) 325-334

Morgan, R., and Bull, P. 2007a. The philosophy, nature and practice of forensic sediment analysis. *Progress in Physical Geography* 31 (1) 43-58

Morgan, R., and Bull, P. 2007b. The use of grain size distribution analysis of sediments and soils in forensic enquiry. *Science and Justice* 47 (3) 125-135

Morgan, R., Wiltshire, P., Parker, A., and Bull, P. 2006. The role of forensic geoscience in wildlife crime detection. *Forensic Science International* 162 (1-3) 152-162

Morgan, R., Freudiger-Bonzon, J., Nichols, K., Jellis, T., Dunkerley, S., Zelazowski, P. and Bull, P. 2009a. The geoforensic analysis of soils from footwear. In: Ritz, K., Dawson, L., and Miller, D., eds. *Criminal and Environmental Soil Forensics.* Netherlands: Springer, pp.253-269

Morgan, R., Cohen, J., McGookin, I., Murly-Gotto, J., O'Connor, R., Muress, S., Freudiger-Bonzon, J., and Bull, P. 2009b. The relevance of the evolution of experimental studies for the interpretation and evaluation of some trace physical evidence. *Science and Justice* 49 (4) 277-285

Morgan, R., French, J., O'Donnell, L., and Bull, P. 2010. The reincorporation and redistribution of trace geoforensic particulates on clothing: An introductory study. *Science and Justice* 50 (4) 195-199

Morgan, R., Allen, E., King, T., and Bull, P. 2013a. **The spatial and temporal distribution of pollen in a room: Forensic implications.** *Science and Justice* Article in Press DOI: 10.1016/j.scijus.2013.03.005

Morgan, R., Flynn, J., Sena, V., and Bull, P. 2013b. Experimental forensic studies of the preservation of pollen in vehicle fires. *Science and Justice* Article in Press DOI: 10.1016/j.scijus.2013.04.001

Morrison, G., Zhang, C., and Rose, P. 2011. An empirical estimate of the precision of likelihood ratios from a forensic-voice-comparison system. FORENSIC SCIENCE INTERNATIONAL 208 (1-3) 59–65

Mosher, P., McVicar, M., Randall, E., and Sild, E. 1998. Gunshot residue-similar particles produced by fireworks. *Canadian Society of Forensic Sciences Journal* 31 (3) 157-168

Murdock, J. 1984. The collection of gunshot residues. *AFTE Journal* [no issue] 136-143

Nag, N., and Sinha, P. 1992. A note on assessability of firing distance from gunshot residues. *Forensic Science International* 56 (1) 1-17

Nakai, I., Ono, Y., Li, Q., Nishiwaki, Y., Tanaka, K., and Nakayama, S. 2009. Capability of a TES microcalorimeter SEM-EDS system for forensic analysis of automotive paint and gunshot residue. *Surface and Interface Analysis* 42 (5) 402-410

National Academy of Sciences (NAS). 2009. Strengthening forensic science in the United States: A path forward. *Committee on Identifying the Needs of the Forensic Sciences Community*. [Online PDF]. Washington, D.C: National Academic Press. Available from: https://www.ncjrs.gov/pdffiles1/nij/grants/228091.pdf. [Accessed 4th November 2013]

Nelson, E., et al [anon]. 2000. Murder or suicide—in-depth investigation finds the truth. *Scanning* 22 (2) 76-77

Nesbitt, R., Wessel, J., and Jones, P. 1976. Detection of gunshot residue by use of the scanning electron microscope. JOURNAL OF FORENSIC SCIENCES 21 (3) 595-610

Nesbitt, R., Wessell, J., Wolten, G., and Jones, P. 1977. Evaluation of a photoluminescence technique for the detection of gunshot residue. JOURNAL OF FORENSIC SCIENCES 22 (2) 288-303

Niewoehner, L., Andrasko, J., Biegstraaten, J., Gunaratnam, L., Steffen, S., and Uhlig, S. 2005. Maintenance of the ENFSI proficiency test program on identification of GSR by SEM/EDX. JOURNAL OF FORENSIC SCIENCES 50 (4) 877-882

Niewoehner, L., Wenz, H., Andrasko, J., Beijerm R., and Gunaratnam, L. 2008. Continuity of the ENFSI proficiency test on identification of GSR by SEM/EDX. JOURNAL OF FORENSIC SCIENCES 53 (1) 162-167

Office for National Statistics (ONS). 2013. *Crime Statistics, Focus on: Violent Crime and Sexual Offences, 2011/12.* [Online]. Available from http://www.ons.gov.uk/ons/rel/crime-stats/crime-statistics/focus-on-violent-crime/index.html. [Accessed 4th November 2013]

Osterburg, J. 1969. *EVALUATION OF PHYSICAL EVIDENCE IN CRIMINALISTICS: SUBJECTIVE OR OBJECTIVE PROCESS.* JOURNAL OF CRIMINAL LAW AND CRIMINOLOGY *60 (1) 97-101*

Owens, A. 1990. A reevaluation of the aerospace corporation final report on particle analysis - When to stop searching for gunshot residue (GSR)?. JOURNAL OF FORENSIC SCIENCES 35 (3) 698-705

Oxford Instruments, U.K. 2007. *INCAFeature Instructions manual: INCAGSR*. [PDF]. [Provided with software licence]

Palmer, R., and Banks, M. 2005. The secondary transfer of fibres from head hair. *Science and Justice* 45 (3) 123-128

Palmer, R., and Burch, H. 2009. The population, transfer and persistence of fibres on the skin of living subjects. *Science and Justice* 49 (4) 259-264

Palmer, R., and Polwarth, G. 2011. The persistence of fibres on skin in an outdoor deposition crime scene scenario. *Science and Justice* 51 (4) 187-189

Pearl, J., and Russell, S. 2003. Bayesian Networks. In: Arbib, M., ed. *The Handbook of Brain Theory and Neural Networks.* 2nd edition. Cambridge: MIT Press

Pearson, E., May, R., and Dabbs, M. 1971. Glass and paint fragments found in men's outer clothing – a report of a survey. *Journal of Forensic Sciences* 16 (3) 283-299

Perdekamp, M., Arnold, M., Merkel, J., Mierdel, K., Braunwarth, R., Kneubuehl, B., Pollak, S., and Thierauf, A. 2011. GSR deposition along the bullet path in contact shots to composite models. *International Journal of Legal Medicine* 125 (1) 67-73

Phipps, M., and Petricevic, S. 2007. The tendency of individuals to transfer DNA to handled items. *Forensic Science International* 168 (2-3) 162-168

Plattner, T., Kneubuehl, B., Thali, M., and Zollinger, U. 2003. Gunshot residue patterns on skin in angled contact and near contact gunshot wounds. *Forensic Science International* 138 (1-3) 68-74

Port, N., Bowyer, V., Graham, E., Batuwangala, M., and Rutty, G. 2005. How long does it take a static individual to contaminate the immediate environment. *Forensic Science, Medicine and Pathology* 2 (3) 157-164

Pounds, C., and Smalldon, K. 1975a. The transfer of fibres between clothing materials during simulated contacts and their persistence during wear: Part I – fibre transference. *Journal of the Forensic Science Society* 15 (1) 17-27

Pounds, C., and Smalldon, K. 1975b. The transfer of fibres between clothing materials during simulated contacts and their persistence during wear: Part II. *Journal of the Forensic Science Society* 15 (1) 29-37

Pounds, C., and Smalldon, K. 1975c. The transfer of fibres between clothing materials during simulated contacts and their persistence during wear: Part III – a preliminary investigation of the mechanisms involved. *Journal of the Forensic Science Society* 15 (3) 197-207

Pounds, C., and Smalldon, K. 1978. The distribution of glass fragments in front of a broken window and the transfer of fragments to individuals standing nearby. *Journal of the Forensic Science Society* 18 (3-4) 197-203

Pourret, O., Naïm, P., and Marcot, B. 2008. BAYESIAN NETWORKS: A PRACTICAL GUIDE TO APPLICATIONS. Chichester: Wiley

Poy, A., van Oorschot, R. 2006. Trace DNA presence, origin, and transfer within a forensic biology laboratory and its potential effect on casework. *Journal of Forensic Identification* 56 (4) 558-576

Pretty, I., and Sweet, D. 2001. The scientific basis for human bitemark analyses - A critical review. SCIENCE AND JUSTICE 41 (2) 85-92

Raymond, J., van Oorschot, R., Gunn, P., Walsh, S., and Roux, C. 2009. Trace evidence characteristics of DNA: A preliminary investigation of the persistence of DNA at crime scenes. *Forensic Science International Genetics* 4 (1) 26-33

Redmayne, M., Roberts, P., Aitken, C., and Jackson, G. 2011. Forensic science evidence in question. *Criminal Law Review* 5 347–356

Reed G., McGuire P., and Boehm, A. 1990. Analysis of gunshot residue test results in 112 suicides. *Journal of Forensic Sciences* 35 (1) 62-68

R. v. Reed and Reed; R. V. Garmson [2009] EWCA Crim. 2698

R. v. T [2010] EWCA 2439

Reid, L., Chana, K., Bond, J., Almond, M., and Black, S. 2010. Stubs versus swabs? A comparison of gunshot residue collection techniques. *Journal of Forensic Sciences* 55 (3) 753-756

Renfro, W., and Jester, W. 1973. Collection and activation analysis of airborne gunshot residues. JOURNAL OF RADIOANALYTICAL CHEMISTRY 15 (1) 79-85

Rijnders, M., Stamouli, A., and Bolck, A. 2010. Comparison of GSR composition occurring at different locations around the firing position. *Journal of Forensic Sciences* 55 (3) 616-623

Robertson B., Vignaux, G., and Berger, C. 2011. Extending the confusion about Bayes. *Modern Law Review* 74 (3) 444–455

Robertson, B., and Vignaux G. 1995. *Interpreting Evidence: Evaluating Forensic Science in the Courtroom.* Chichester: Wiley

Robertson, J. 2011. Forensic science research-where to in the future?. *Australian Journal of Forensic Sciences* 43 (4) 213-215

Robertson, J., Kidd, C., and Parkinson, H. 1982. The persistence of textile fibres transferred during simulated contacts. *Journal of the Forensic Science Society* 22 (4) 353-360

Romolo, F., and Margot, P. 2001. Identification of gunshot residue: a critical review. *Forensic Science International* 119 (2) 195-211

Romolo, F., Christopher, M., Donghi, M., Ripani, L., Jeynes, C., Webb, R., Ward, N., Kirkby, K., and Bailey, M. 2013. Integrated ion beam analysis (IBA) in gunshot residue (GSR) characterisation. *Forensic Science International* 231 (1) 219-228

Rosenberg, M., and Dockery, C. 2008. Determining the lifetime of detectable amounts of gunshot residue on the hands of a shooter using laser-induced breakdown spectroscopy. *Applied Spectroscopy* 62 (11) 1238-1241

Roux, C., Huttunen, J., Rampling, K., and Robertson, J. 2001. Factors affecting the potential for fibre contamination in purpose-designed forensic search rooms. *Science and Justice* 41 (3) 135-144

Roux, C., Langdon, S., Waight, D., and Robertson, J. 1999. The transfer and persistence of automotive carpet fibres on shoe soles. *Science and Justice* 39 (4) 239-251

Ruch, R., Buchanan, J., Guinn, V., Bellanca, S., and Pinker, R. 1964. **Neutron activation analysis in scientific crime detection – some recent developments.** *Journal of Forensic Sciences* 9 (1) 119-133

Rudzitis, E., Kopina, M., and Wahlgren, M. 1973. Optimization of firearm related residue detection by neutron activation analysis. *Journal of Forensic Sciences* 18 (2) 93-100

Rutty, G. 2002. An investigation into the transference and survivability of human DNA following simulated manual strangulation with consideration of the problem of third party contamination. *International Journal of Legal Medicine* 116 (3) 170-173

Saferstein, R. 1982. *Forensic Science Handbook.* 2nd edition. NJ: Prentice Hall

Saks, M. 1998. Merlin and Solomon: Lessons from the law's formative encounters with forensic identification science. HASTINGS LAW JOURNAL 49 (4) 1069-1141

Saks, M., and Koehler, J. 2005. The coming paradigm shift in forensic identification science. *Science* 309 (5736) 892-895

Saks, M., and Koehler, J. 2008. The individualization fallacy in forensic science evidence. *Vanderbilt Law Review* 61 (1) 199-219

Salter, M., and Cook, R. 1996. Transfer of fibres to head hair, their persistence and retrieval. *Forensic Science International* 81 (2) 211-221

Schütz, F., Bonfanti, M., and Desboeufs, S. 2001. Evaluation of parameters influencing GSR's retention on shooter's hands. *Problems of Forensic Sciences* 47 380-386

Schumacher, R., Barth, M., Neimke, D., and Niewohner, L. 2010. Investigation of gunshot residue patterns using milli-XRF-techniques: First experiences in casework. *Proceedings of SPIE - The International Society for Optical Engineering* 7729 no.772917

Schwartz, R., and Zona, C. 1995. A recovery method for airborne gunshot residue retained in human nasal mucus. *Journal of Forensic Sciences* 40 (4) 659-661

Scott, H. 1985. The persistence of fibres transferred during contact of automobile carpets and clothing fabrics. JOURNAL OF THE CANADIAN SOCIETY OF FORENSIC SCIENCE 18 (4) 185-199

Scott, R., and Skellern, C. 2010. DNA evidence in jury trials: the CSI effect. *Journal of Law Medicine and Ethics* 18 (2) 239-262

Simons, A. 1986. Hair evidence on laundered items. *Crime Laboratory Digest* 13 (3) 78-81

Singer, R., Davis, D., and Houck, M. 1996. A survey of gunshot residue analysis methods. *Journal of Forensic Sciences* 41 (2) 195-198

Smith, J., and Puch, R. 2002. FINDS: A training package to assess forensic fibre evidence. *MICAI, Lecture Notes in Computer Science* 2313 420-429

State of Ohio v. Christopher Latham [2011] Court of Appeals C-100442

Steffen, S., Otto, M., Niewoehner, L., Barth, M., Brozek-Mucha, Z., Biegstraaten, J., and Horváth, R. 2007. **Chemometric classification of gunshot residues based on energy dispersive X-ray microanalysis and inductively coupled plasma analysis with mass-spectrometric detection.** *Spectrochimica Acta - Part B Atomic Spectroscopy* 62 (9) 1028-1036

Stockmarr, A. 1999. Likelihood ratios for evaluating DNA evidence when the suspect is found through a database search. *Biometrics* 55 (3) 671-677

Stoney, D. 1991. What made us ever think we could individualize using statistics?. JOURNAL OF THE FORENSIC SCIENCE SOCIETY 31 (2) 197-199

Taroni, F., Biedermann, A., Garbolino, P., and Aitken, C. 2004. A general approach to Bayesian networks for the interpretation of evidence. *Forensic Science International* 139 (1) 5-16

Taroni, F., Aitken, C., Garbolino, P., and Biedermann, A. 2006. *Bayesian Networks and Probabilistic Inference in Forensic Science.* Chichester: Wiley

Taroni, F., Marquis, R., Schmittbuhl, M., Biedermann, A., Thiéry, A., and Bozza, S. 2012. The use of the likelihood ratio for evaluative and investigative purposes in comparative forensic handwriting examination. *Forensic Science International* 214 (1-3) 189-194

Taupin, J. 1996. **Hair and fiber transfer in an abduction case - Evidence from different levels of trace evidence transfer.** *Journal of Forensic Sciences* 41 (4) 697-699

Tenney, E., Cleary, H., and Spellman, B. 2009. Unpacking the doubt in beyond reasonable doubt: plausible alternative stories increase not guilty verdicts. *Basic and Applied Social Psychology* 31 (1) 1-8

The Fingerprint Inquiry Scotland. 2011. *The Fingerprint Inquiry Report Published on behalf of The Fingerprint Inquiry by APS Group Scotland.* [Online]. Available from: http://www.thefingerprintinquiryscotland.org.uk/inquiry/3127-2.html. [Accessed 4th November 2013]

The Law Commission. 2009. *The Admissibility of Expert Evidence in Criminal Proceedings in England and Wales: A New Approach to the Determination of Evidentiary Reliability.* Consultation Paper No. 190. [Online PDF]. Available from: http://lawcommission.justice.gov.uk/docs/cp190_Expert_Evidence_Consultation.pdf. [Accessed 4th November 2013]

Thompson, W., Taroni, F., and Aitken, C. 2003. How the probability of a false positive affects the value of DNA evidence. JOURNAL OF FORENSIC SCIENCES 48 (1) 47-54

Thornton, J. 1994. The chemistry of death by gunshot. ANALYTICA CHIMICA ACTA *288 (1-2) 71-81*

Tillman, W. 1987. Automated gunshot residue particle search and characterization. *Journal of Forensic Sciences* 32 (1) 62-71

Torre, C., Mattutino, G., Vasino, V., and Robino, C. 2002. Brake linings: A source of non-GSR particles containing lead, barium and antimony. *Journal of Forensic Sciences* 47 (3) 494-504

Trimpe, M. 2011. The current status of GSR examinations. *FBI Law Enforcement Bulletin* May 2011. [Online]. Available from: http://www.fbi.gov/stats-services/publications/law-enforcement-bulletin/may_2011/The%20Current%20Status%20of%20GSR%20Examinations. [Accessed 4th November 2013]

Twibell, J., Turner, S., Smalldon, K., and Higgs, D. 1984. The persistence of military explosives on hands. *Journal of Forensic Sciences* 29 (1) 284 -290

Ueyama, M., Taylor, R., and Noguchi, T. 1980. SEM/EDS analysis of muzzle deposits at different target distances. *Scanning Electron Microscopy* 1 367-374

Vacca, J. 2005. *Computer Forensics: Computer Crime Scene Investigation.* Hingham: Charles River Media

Van Boven, L., and Epley, N. 2003. The unpacking effect in evaluative judgments: When the whole is less than the sum of its parts. *Journal of Experimental Social Psychology* 39 (3) 263-269

van Oorschot, R., and Jones, M. 1997. DNA fingerprints from fingerprints. *Nature* 387 June 1997 767

van Oorschot, R., Ballantyne, K., and Mitchell, R. 2010. Forensic trace DNA: A review. *Investigative Genetics* 1 (14) 1-17

van Oorschot, R., Phelan, D., Furlong, S., Scarfo, G., Holding, N., and Cummins, M. 2003. Are you collecting all the available DNA from touched objects?. *International Congress Series* 1239 803-807

van Oorschot, R., Treadwell, S., Beaurepaire, J., Holding, N., and Mitchell, R. 2005. Beware of the possibility of fingerprinting techniques transferring DNA. *Journal of Forensic Sciences* 50 (6) 1417-1422

Vinokurov, A., 2001. **Machine washing or brushing of clothing and its influence on shooting distance estimation.** *Journal of Forensic Sciences* 46 (4) 928-933

Wallace, J. 2008. *Chemical Analysis of Firearms, Ammunition, and Gunshot Residue*. Florida: CRC Press

Wallace, J., and Keeley, R. 1979. A method for preparing firearms residue samples for scanning electron microscopy. SCANNING ELECTRON MICROSCOPY 2 (2) 179-184

Wallace, J., and McQuillan, J. 1984. Discharge residues from cartridge-operated industrial tools. JOURNAL OF THE FORENSIC SCIENCE SOCIETY 24 (5) 495-508

Walsh, K., and Horrocks, M. 2008. Palynology: Its position in the field of forensic science. *Journal of the Forensic Sciences* 53 (5) 1053-1060

Warshauer, D., Marshall, P., Kelley, S., King, J., and Budowle, B. 2012. An evaluation of the transfer of saliva-derived DNA. *International Journal of Legal Medicine* 126 (6) 851-861

White, R., and Owens, A. 1987. Automation of gunshot residue detection and analysis by scanning electron microscopy/energy dispersive X-ray analysis (SEM/EDX). JOURNAL OF FORENSIC SCIENCES 32 (6) 1595-1603

Wickenheiser, R. 2002. Trace DNA: A review, discussion of theory, and application of the transfer of trace quantities of DNA through skin contact. *Journal of Forensic Science* 47 (3) 442-450

Wiegand, P., Heimbold, C., Klein, R., Immel, U., Stiller, D., and Klintschar, M. 2011. Transfer of biological stains from different surfaces. *International Journal of Legal Medicine* 125 (5) 727-731

Wiggins, K., and Houck, M. 2001. Introduction. In: Houck, M., ed. *Mute Witnesses: Trace Evidence Analysis.* London: Academic Press, pp.xi-xxxi

Wiggins, K., Emnes, A., and Brackley, L. 2002. The transfer and persistence of small fragments of polyurethane foam onto clothing. *Science and Justice* 42 (2) 105-110

Wilkinson, M., and Linacre, A. 2000. The detection and persistence of cannabis sativa DNA on skin. *Science and Justice* 40 (1) 11-14

Wolten, G., and Nesbitt, R. 1980. On the mechanism of gunshot residue particle formation. JOURNAL OF FORENSIC SCIENCES 25 (3) 533-545

Wolten, G., Nesbitt, R., Calloway, A., Loper, G., and Jones, P. 1977. Final report on particle analysis for gunshot residue detection. *Aerospace Report* No. ATR-77 (7915) -3 CA: El Segundo

Wolten, G., Nesbitt, R., and Calloway, A. 1979a. **Particle analysis for the detection of gunshot residue. I: Scanning electron microscopy/energy dispersive X-ray characterization of hand deposits from firing.** *Journal of Forensic Sciences* 24 (2) 409-422

Wolten, G., Nesbitt, R., Calloway, A., and Loper, G. 1979b. **Particle analysis for the detection of gunshot residue. II: Occupational and environmental particles.** *Journal of Forensic Sciences* 24 (2) 423-430

Wolten, G., Nesbitt, R., and Calloway, A. 1979c. **Particle analysis for the detection of gunshot residue: III: The case record.** *Journal of Forensic Sciences* 24 (4) 864-869

Wright, D., and Trimpe, M. 2006. Summary of the FBI laboratory's gunshot residue symposium, May 31–June 3, 2005. *FBI Forensic Science Communications* 8 (3). [Online]. Available from: http://www.fbi.gov/about-us/lab/forensic-science-communications/fsc/july2006/research/2006_07_research01.htm. [Accessed 4th November 2013]

Yañez, J., Farías, M., Zúñiga, V., Soto, C., Contreras, D., Pereira, E., Mansilla, H., Saavedra, R., Castillo, R., and Sáez, P. 2012. Differentiation of two main ammunition brands in Chile by regularized discriminant analysis (RDA) of metals in gunshot residues. *Microchemical Journal* 101 (1) 43-48

Zadora, G. 2009. **Evaluation of evidence value of glass fragments by likelihood ratio and Bayesian Network approaches.** *Analytica Chimica Acta* 642 (1-2) 279-290

Zadora, G., and Ramos, D. 2010. **Evaluation of glass samples for forensic purposes - An application of likelihood ratios and an information-theoretical approach.** *Chemometrics and Intelligent Laboratory Systems* 102 (2) 63-83

Zeichner, A. 2003. Recent developments in methods of chemical analysis in investigations of firearm-related events. *Analytical and Bioanalytical Chemistry* 376 (8) 1178–1191

Zeichner, A. 2012. Firearm discharge residue: Analysis of. In: *Wiley Encyclopedia of Forensic Science.* [Online]. Chichister: Wiley. Available from: http://onlinelibrary.wiley.com/doi/10.1002/9780470061589.fsa342.pub2/full. DOI:10.1002/9780470061589.fsa342.pub2. [Accessed 4th November 2013]

Zeichner, A., and Levin, N. 1993. Collection efficiency of gunshot residue (GSR) particles from hair and hands using double-side adhesive tape. *Journal of Forensic Sciences* 38 (3) 571-584

Zeichner, A., and Levin, N. 1995. Casework experience of GSR detection in Israel, on samples from hands, hair, and clothing using an autosearch SEM/EDX system. JOURNAL OF FORENSIC SCIENCES 40 (6) 1082-1085

Zeichner, A., Levin, N., and Springer, E. 1991. Gunshot residue particles formed by using different types of ammunition in the same firearm. *Journal of Forensic Sciences* 36 (4) 1020-1026

Appendix I List of experimental materials

All materials provided by TAAB Laboratories Equipment Ltd, U.K.:

Adhesive Carbon discs – C249/N 12mm Ø

Disposable gloves - V050 Vinyl gloves

SEM stub storage tubes - T350 Single SEM pin stub storage tube for ½" (12.5mm) stub

SEM stubs - S081 ½" Pin type stub (with groove)

Tweezers for removal of carbon discs – T096 Tweezer type AA – stainless steel

Tweezers for stub handling - T137 Tweezer for ½" stub

Appendix II Research papers

The first pages of the research papers are provided. Please refer to full text versions:

Appendix III SEM-EDX analysis data

Please refer to attached data CD below: