The environmental presence of gunshot residue: A case study in the workspaces and hands of employees at a forensic laboratory in Western Australia

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Thesis submitted in fulfilment of the School of Veterinary and Life Sciences

Murdoch University

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Semester 2, 2016

DECLARATION

I declare that this manuscript does not contain any material submitted previously for the award of any other degree or diploma at any university or other tertiary institution. Furthermore, to the best of my knowledge, it does not contain any material previously published or written by another individual, except where due reference has been made in the text. Finally, I declare that all reported experimentations performed in this research were carried out by myself, except that any contribution by others, with whom I have worked is explicitly acknowledged.

Signed: Ashley Le

Dated: 23 December 2016

ACKNOWLEDGEMENTS

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PART I—LITERATURE REVIEW

Abstract

Gunshot residue (GSR) is a type of forensic trace evidence made up of particles that remain after a firearm is discharged, which can assist in determining if someone was involved with or in the vicinity of a fired weapon. A characteristic GSR particle consists of lead, barium, and antimony, although in modern ammunition lead is often absent or replaced with a different element. Although GSR sampling has many potential benefits for investigations, it has often been problematic due to the risk of transfer and contamination of particles from environmental sources; in particular, certain workplaces can have a high probability of containing GSR-like particles. Moreover, there is a potential of secondary transfer of particles from police officers to suspects or other evidence. Determining the source of the particles is crucial for evaluating the strength of GSR evidence. The admissibility of GSR evidence has become stronger in recent times with the development of the ASTM guidelines and the establishment of the Scientific Working Group for Gunshot Residue. However, there is still limited knowledge of the environmental sources of GSR-like particles in local areas and there is a pressing need to investigate differences in specific local environments.

Introduction

As of August 2016, over 35,000 incidents of gun violence occurred in the United States alone [1]. Any crime involving a firearm is treated seriously and requires a full investigation [2]. Gunshot residue (GSR) is a type of forensic trace evidence made up of particles that are left behind after a firearm is discharged, which may be analysed to determine if someone was involved with or in the vicinity of a fired gun. Swabbing for GSR can help establish the probability of involvement of a suspect in a shooting event to the Court. When paired the other fields, GSR analysis may help to assist in determining the sequence of events of a crime. However, GSR sampling can be one of the more difficult fields of forensic firearms casework investigation, as analysing the residue particles and determining their origin is often not a clear-cut process.

The reliability of GSR sampling can sometimes be called into question. For example, if a person of interest is not immediately swabbed at the scene, there is a possibility of secondary contamination of GSR after coming into contact with multiple sources between being brought from the scene to the station. Similarly, if the investigator takes the sample without wearing personal protective equipment, there is a risk of secondary contamination from the investigators themselves. It is important to establish the background presence of GSR and the risk of secondary contamination from environmental sources so procedures can be put into place to ensure the evidence is valid.

The aim of this review is to outline the benefits GSR analysis provides to forensic investigations, as well as the problems that have been encountered in its use. I begin with a general overview of how GSR is formed, as well as the various compounds that have been

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found in GSR and how they have been analysed and reported. I also highlight the variation that has been found in GSR across different calibres and weapons. I provide examples of the use of GSR in court and the problems it has faced, focusing in particular on the current state of GSR in Western Australia. I then move on to explore evidence regarding the risk of secondary contamination of GSR from environmental sources such as workplaces and, crucially, the police force. Finally, I conclude by summarising the current state of GSR use in forensics, and suggest areas that require further research to improve the procedures for analysing GSR evidence.

Discussion

<u>What is GSR?</u>

GSR is also commonly referred to as cartridge discharge residue (CDR), gunfire residue, or firearm discharge residue (FDR). Characteristic GSR consists mostly of lead (Pb), barium (Ba), and antimony (Sb). Other elements are found to be associated with them such as copper, iron, silicon, aluminium, sulphur, potassium and calcium, which may come from various sources. These particles may land on the skin, hair, and clothing of the shooter. The types of particles deposited and the pattern in which they land may give an indication of the position of the person firing and what type of weapon the individual was using. GSRs are made up of propellant powder (unburnt or partially burnt), ammunition primer particles, smoke, lubricants, grease, and metals from both the cartridge and firearm [3-4].

When a firearm is discharged, the firing pin strikes the primer cap, igniting the primer mixture and creating an extremely hot environment while the pressure increases [2-3,5]. The

scolding temperatures melt the primer mixture and GSR particles vaporise and condense into droplets on the liquefied primer surface. The bullet is ejected from the barrel of the gun as the primer mixture ignites the propellant powder, which creates an additional increase in pressure and temperature [5]. The droplets of GSR particles may cool and expand, leaving them to dry in place [6]. An understanding of the origin of GSR particles requires knowledge of various structures involved in firearm discharge; including the cartridge case, primer cup and primer, propellants and the projectile.

Cartridge Cases

The cartridge case of a firearm houses propellant (gunpowder), the primer, and the primer cup, while securing the projectile (bullet) in the neck of the case (Figure 1) [7-8]. A majority of cartridge cases are made up of brass, as it is a strong material that does not rust, while being ductile, flexible, and readily available. Steel may also be used to make cartridge cases [8].

Many strict specifications and quality control procedures are followed during the manufacturing of cartridge cases to ensure the firearm is working to its highest standard when discharged [8]. When a bullet is expelled from a gun, the pressure and temperature rise, causing the cartridge case to expand, preventing any gas from escaping. It is important to have brass that is neither too hard nor soft, as it may jam the firearm or cause the case to crack. Both the base and neck of the cartridge case must be strong enough to make sure that the case expands while the bullet is discharged. The thickness and hardness of the case must

be carefully monitored to ensure the case can handle the amount of stress it receives during the loading, firing, and extraction of ammunition [8].

Primer Cup

The primer cup is usually made of the same type of brass as the cartridge case, which helps it to easily expand, providing a tight seal for gas [8]. Other popular materials include copper, nickel-plated copper or brass, copper alloy, cupronickel, and zinc-coated steel cups. When black powder is used, primer cups must use soft copper due to the weakened firing pin and the low pressures generated by the powder. Smokeless powders, on the other hand, generate higher pressures and are harder to ignite; therefore, a "hotter" primer is needed for a stronger blow from the firing pin [8].

Two types of primers are used in centerfire ammunition—Berdan and Boxer—and the primer cups used for each of these are different [8]. The Berdan primer is popular in European countries and does not contain an integral anvil as part of the cartridge case. The Boxer primer is more popular in the United States and Canada and has its own anvil inserted into the primer cup. The Boxer primer is easily replaceable and therefore the preferred choice of primer [8].

Primers

The primer is composed of various compounds that detonate the propellant by delivering a large volume of hot gases and solid particles [8]. The duration of the generated burst of flames lasts between 650 to 1500 microseconds. Firearms' primers generally consist

of explosives, oxidizers, fuels, frictionators, and compounds that act as sensitizers and binders [8].

Sinoxid primers were traditionally used, which contained lead, barium, and antimony. Currently, Sintox and CCI Blazer® ammunitions, along with other lead-free ammunitions, are commonly used, changing the techniques used to identify GSR particles [9-10].

Propellants

Black powder was the first major type of propellant used in firearms ammunition; however, it came with many disadvantages [8]. Rust may form due to the moisture that builds following combustion, and the large amount of smoke produced may affect the shooter's view for following shots and gives away his or her position. Black powder has therefore become less common, but continues to be used for specialised purposes, such as baton guns, signal flares, etc.

Smokeless powders are used in commercially manufactured ammunition [8]. These propellants produce much less smoke than black powder and carry less risk of causing the firearm to rust. Smokeless powders may have a single-, double-, or triple-based composition [11-12]. Single-based smokeless powder is made up of nitrocellulose, double-based is made up of both nitrocellulose and nitroglycerine, and triple-based is made of nitrocellulose, nitroglycerine and nitroguanidine.

Projectiles

Many types of bullets are available with varying core and jacket designs, which are designed for a specific purpose [8]. Bullet cores are most commonly made of lead due to its high density and because it is cheap and easy to obtain. This can either be soft lead or lead hardened by tin, antimony, or both, which may be present when analysing GSR.

GSR Compounds

GSRs are comprised of both organic and inorganic compounds. Organic compounds can originate from every part of the ammunition used, but are mostly found in the primer mixture and propellant powder [4]. They take the form of gunpowder particles and some products of their transformation, as well as hydrocarbons. Inorganic compounds primarily come from primer mixtures, and can originate from the cartridge case, primer cap, bullet, and barrel of the gun [6].

Collection of GSR

Any surrounding surface in the vicinity of a shooting event may be used to collect GSR samples. The hair, clothing, and skin of a person believed to be in the area can be sampled immediately, as well as other surfaces including vehicles, doors, and around bullet holes [13]. A range of techniques have been developed to collect GSR particles from these different surfaces.

Vacuum lifts can be used to collect both organic and inorganic GSR from clothing; however, they may lift debris from deeper parts of the clothing rather than just the surface,

making the interpretation of samples more difficult [14]. Glue lifts have been used to collect GSR samples from hands and the evidence so far suggests that these lifts do not collect many additional particles or contain any particles that interfere with the scanning electron microscope (SEM, used to analyse GSR samples) [15]. Swabbing has also been used to collect samples from the hands, but only to collect organic compounds. Hand swab samples may be prone to environmental interference [6]. The swab material is soaked in a specific solvent that maximises the transfer of GSR particles onto it, and collected particles are extracted from the material for examination [6]. Another technique has been developed to collect inorganic GSR from the mucus of the nose. This technique produced samples that were successfully analysed in an SEM over 48 hours after the shooting incident [16]. Other collection techniques have been developed to optimise the extraction of a range of both organic and inorganic compounds [17], although tape lifts are currently the preferred method of choice to collect inorganic GSR from skin, hair, and other surfaces [4]. The advantages of using tape lifts include the low cost, efficient sample collection, and compatibility with SEMs [18]. The disadvantage of using tape lifts is that they require a large surface area to be searched, must be coated with carbon prior to being used, and may collect other particles that mask GSR.

Organic Compounds in GSR

Nitrates and nitrites were the earliest studied organic GSR particles. Currently, particles such as nitrocellulose, nitroglycerine, ethyl centralite, 2,4-dinitrotoluene and others are typically examined [19]. In particular, nitrocellulose is present in all organic GSRs. This

compound, however, can also be found in other environmental sources such as paints, lacquers and heart medication. A method has been developed to distinguish between the lower molecular weight of nitrocellulose from GSR and the higher molecular weight of environmental GSR, but despite this nitroglycerine is currently not considered of high evidential value on its own [19]. The evidential value of nitroglycerine is considered much stronger when found with 2,4-dinitrotoluene. Two of the most characteristic materials of organic GSR are ethyl centralite and 2,4-dinitrotoluene, which are rare in any products apart from firearms and therefore generally not present in environmental sources [6].

Analysing Organic GSR

One of the largest problems with GSR evidence is that the primary characteristic inorganic particles (lead, barium, and antimony) are not always available to analyse. For example, many firearms use lead-free ammunition due to the higher risk of damage to both health and the environment [20]. Therefore, analysing organic GSR along with inorganic GSR can be more informative and increase the value of a sample [21].

Chemical tests were traditionally used to analyse organic GSR, more specifically testing for the presence of nitrates and nitrites. The paraffin test was the earliest chemical analysis technique used, in which paraffin changes colour in the presence of nitrates and nitrites [6]. Other chemical tests were later developed, but these tests have since become replaced by other methods as they are used in a presumptive nature [6, 20].

Currently, the major analytical methods used to analyse organic GSR include gas chromatography and high performance liquid chromatography, while capillary

electrophoresis is an important electrochemical detection test [6, 20]. These methods test for the presence of various constituents of smokeless powder, including nitrocellulose and nitroglycerine, and may be used in conjunction with other detection tests for optimal results [6]. Each of these tests have different advantages and are suited to different situations (Table 1).

Table 1. Methods for analysing organic GSR

Method	Advantages	Disadvantages
Gas chromatography	Coupled with different detectors, GC is able to detect multiple compounds of interest (especially when paired with mass spectrometry [20]	Inability to analyse nitrocellulose; unsuitable for the analysis of stabilisers [20]
High performance liquid chromatography	Can be used to detect both organic and inorganic GSR; suitable for routine analysis of organic GSR; useful in the analysis of compositional variations in smokeless powders [20]	Must be used in conjunction with electrochemical detection in order to analyse nitroglycerine, 2,4- dinitrotoluene, and diphenylamine [20]
Capillary electrophoresis	Provides high-resolution separations of complex mixtures quickly [20]	May require large ammunition samples [20]

Inorganic Compounds in GSR

Lead, barium, and antimony are the most characteristic materials found in GSR [2-5]. Lead and antimony may be present either as chemical compounds from combustion or in the form of free metal from the projectile, while barium is found in the form of a compound [6].

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As previously mentioned, many primers are currently made without lead and other heavy metals, although some manufacturers still produce bullets containing lead [22].

Analysing Inorganic GSR

A variety of different techniques are used to analyse inorganic GSR, including neutron activation analysis (NAA), atomic absorption spectrometry (AAS), inductively coupled plasma (ICP), and scanning electron microscopy (SEM) [21]. Similarly to the methods used in analysing organic GSR, each of these techniques have particular strengths and weaknesses, although currently SEM methods are by far the most popular techniques for GSR analysis.

NAA identifies mostly barium and antimony [23-24], but may also identify other transition metals [25]. The problem with using NAA is that it is a time-consuming and expensive technique, which furthermore cannot be applied to analysing lead [13]. AAS uses two common radiation sources—flame and flameless. Flameless AAS is cheap and efficiently analyses inorganic GSR [21] once particles have been extracted. However, many issues have been highlighted using this technique, including the high percentage of false negative results generated and the ineffective extraction of particles from the collection swabs [26]. ICP is used to analyse minute amounts of the three characteristic materials of inorganic GSR in primer residues [13]. One of the major problems with using ICP is that the levels of association were lowered between residues from the projectile and the cartridge case, since small amounts of lead were present after firing, despite the firearm being thoroughly cleaned [27]. ICP has been successful in differentiating whether samples originated from environmental sources or from GSR [28].

The most commonly used method to analyse inorganic GSR is scanning electron microscopy combined with energy dispersive X-ray detection (SEM/EDX) [29]. A scanning electron microscope uses a beam of electrons to focus on a sample, rather than visible light [4]. Using this technique enables GSR particles to be analysed both morphologically and chemically. It does not require much sample preparation, is non-destructive, and enables individual particles to be analysed with a high level of confidence [30]. Previously, analyses from SEM took days to months depending on the number of samples, as the operator would have to manually search for inorganic particles within each sample. Moreover, manually searching for GSR particles increases the possibility of the operator becoming distracted and therefore could lead to false-negative results [31]. New software has now been developed, which automatically searches particles of interest and reduces the chance of human error [32]. Given the prevalence of SEM/EDX technology for analysing GSR samples, it is now important for investigators in this field to understand how this technology works to analyse these particles and why it is the most reliable method [20].

Scanning Electron Microscopy with Energy Dispersive X-ray Detection (SEM/EDX)

Before the scanning electron microscope can be used, adhesive stub samples must be prepared. The most commonly used stubs are 12.7mm round aluminium stubs with adhesive sample mounts [30]. The exposure of the stubs must be limited to avoid any other materials from sticking to the surface [33]. If the surface is not already conductive, it should be coated with a conductive material such as carbon. The samples can be placed onto a stage, which can hold multiple samples at once. The stage can move and rotate in any direction, enabling

the samples' surfaces to be visible from almost any direction [34]. Parameters are set on the SEM using the automatic detection system to target particles of high mean atomic number and a diameter of around 0.5µm, which will be seen using a Backscattered Electron (BSE) detector [35].

A scanning electron microscope is made up of an electron gun, a column, and a sample chamber, which are kept under vacuum conditions [34]. The electron gun houses a filament (usually made up of tungsten) that is first exposed to high temperatures to produce free electrons, followed by high voltage to push those electrons down the column [34]. The positively charged anode attracts the negatively charged electrons toward it, pulling them down. The electron beam converges on an area known as the crossover, and the condenser and objective lenses control the size of the beam [34]. The apertures control the focal length of the electron beam and how much of the beam reaches the sample. The objective lens has a pair of coils that deflect the electron beam along the x-axis and another pair that deflects the beam along the y-axis. Scanning the samples is controlled by the application of electrical signals to each pair of coils [34].

When the electron beam strikes a sample on the stage, a number of signals are produced, including backscattered electrons, secondary electrons, and X-rays. Each of these signals is picked up by their own specific detectors, which are located in the sample chamber [34].

Backscattered electrons are those that reflect off of the sample [36]. They are the result of elastic interactions between electrons from the beam and atoms of the sample. The backscattered electrons penetrate the sample and have interactions with multiple atoms

before leaving the sample [34]. Particles with a high atomic mass (such as those lead, barium and antimony) will appear brighter by generating more backscattered electrons, which will then be further analysed by energy dispersive spectrometry (EDS) [35].

Secondary electrons are produced when the electrons that are focused onto the sample create additional electrons that deflect off of the sample [36]. The electron beam strikes an electron orbiting an atom contained in the sample, freeing it and causing it to escape the sample. An inelastic scattered electron from the electron beam travels further into the sample, causing more electrons to become liberated until it runs out of energy [34]. Secondary electrons are beneficial for displaying the morphology and topography of samples [37].

X-rays are produced when electrons from the beam collide with atoms contained within the sample [37]. They are produced by both elastic and inelastic interactions [34]. During an elastic interaction, an electron from the beam moves closer to the nucleus of an atom contained in the sample, losing energy and changing direction. The energy of the electron is lost in the form of an X-ray. The X-rays that form from inelastic interactions are not characteristic of particular elements. During an inelastic interaction, on the other hand, the X-rays that form are characteristic of the elements. An electron from the beam displaces an electron in the inner most orbital, causing electrons from higher orbitals to replace them, and giving off X-ray energy. Detecting these interactions can lead to an interpretation of the elemental composition of the sample, which is dependent on the energy level of the freed electron and the number of orbitals the replacement electron had to travel [34]. This can be

visualised using an EDX spectrum [4]. The X-ray detector provides morphological and analytical data of single particles to a high degree of detail.

In order to search stubs using automated analysis, software functions must be preset [30]. This enables the SEM to communicate with the EDS to do a thorough search of the surface. The system will store all of the information obtained from each run, including the samples identified, the field of analysis, position and coordinates of the stage for each detected particle, the total number of particles detected and how many of those particles are classified as potential GSR. The X-ray spectra of these particles are obtained and stored. The operator must relocate these particles and reanalyse the X-ray spectra to make sure the elements of interest were not confused with other elements [30].

To ensure the instrument is working routinely at an optimal standard, reference samples can be used [30]. These samples have a known particle distribution with a distinct size and location on the stub and can be used to test the accuracy of detecting and classifying particles. It is also important that various procedures be followed, including saturating the filament, centering the filament and aperture, setting the gun controls, correcting for astigmatism, and degaussing prior to setting the instrument's parameters. These procedures ensure the operator gets the sharpest image when the microscope focuses on a particle of interest and prevents any issues with the electron beam when automatically analysing [30].

Reporting GSR

Characteristic GSR particles consist of the elements lead, antimony, and barium. Once exposed to extreme temperature and pressure, they cool and take on a characteristic

spherical, or irregular and non-crystalline morphology. The diameter of these particles ranges from 0.5µm to 5.0µm, with an average diameter of 1µm [3,6]. Throughout the course of GSR analysis, several different methods have been developed to categorise and report these particles.

Wolten and Nesbit (1980) proposed that inorganic GSR particles could be divided into a "primer particles" category and a "bullet particles" category [39]. Oxides, sulphides, and salts were found in primer particles, where oxygen was contained in the anion. The oxidising environment created by the explosion of the primer cannot be expected to reduce the compounds in the primer ingredients to elements. Bullet particles, on the other hand, are the elemental particles that come from the bullet material [39].

Basu (1982) suggested that inorganic GSR particles generated from the primer be separated into three categories [7]. Category I contained smaller target GSR cross-sections with a diameter between 2-10µm, and primer GSR cross-sections with a diameter up to 30µm. The elemental distribution of lead, antimony, and barium was uniform and concurrent, which was also the case for silicon. Category II had an inhomogeneous distribution, a discontinuous distribution, or both. The target GSR had a cross-section diameter between 15-55µm, while the primer GSR cross-sections had a diameter between 22-130µm. Category III had a more layered distribution of elements, where lead was contained around a barium and antimony core. The cross-section diameter was between 10-35µm for the target GSR and 16-74µm for the primer GSR. The author suggested that the larger particles contained in Categories II and III travelled at a slower rate through the front of the ignited propellant and were exposed to an additional increase in pressure and

temperature, therefore subjecting the particles through various unstable states until a stable state is reached [7].

The Scientific Working Group for Gunshot Residue (SWGGSR) has published a guide for primer gunshot residue analysis using SEM/EDX, which was based on the ASTM standard guide for GSR [29]. This guide includes the criteria on how to report and classify identified GSR particles. Individual particles should be classified as either characteristic of, consistent with, or commonly associated with GSR (Table 2). Characteristic particles have unique compositions that are not usually present in particles from any other source. A majority of characteristic GSR particles originate from Sinoxid primers, which contain lead styphnate, antimony sulphide, and barium nitrate. Particles that are consistent with GSR are composed of particles found in common non-firearm sources with different levels of frequency, which form by various processes, equipment, or other devices. Particles that are commonly associated with GSR are made up of particles commonly found in environmental particles from a number of sources, but can play an important role when present with other particles that are characteristic of and/or consistent with GSR particles, as they increase the probability that the collected sample is GSR [30].

Table 2. The classification of GSR particles, their sources, and elemental profile.

Classification of GSR	Sources of Particles	Elemental Profile
	Ammunition with Sinoxid-type primers	Major/minor trace components include: silicon, calcium, aluminium, copper, and tin

Characteristic of GSR	Ammunition having calcium silicide based primers incorporating a Tin Foil in the primer	Lead, barium, calcium, silicon, and tin
	Tagged ammunition 1) Ammunition manufactured by RUAG Ammotec Ag 2) Ammunition manufactured by MEN GmbH	1) Gadolinium, titanium, and zinc 2) Gallium, copper, and tin
Consistent with GSR	Non-Sinoxid primers based on lead styphnate and other lead compounds that do not contain both antimony sulphide and barium nitrate	▪ Barium, calcium, silicon (with no more than a trace of sulphur ▪ Antimony, barium (little to no trace of iron or sulphur) ▪ Lead (with levels of antimony higher than trace amounts) ▪ Lead, barium ▪ Lead, barium, calcium, silicon (produced by antimony-free, lead styphnate, barium nitrate, and calcium silicide based primers)
	Sintox primers	▪ Titanium, zinc ▪ May include jacketing material (copper or tin), and/or silicon, calcium, and aluminium
	Brands of "environmentally safe" ammunition	▪ Strontium ▪ May also contain copper, aluminium, potassium, calcium, and/or barium
Commonly Associated with GSR	Found in environmental particles from a variety of sources	▪ Lead with trace levels of antimony ▪ Lead ▪ Antimony ▪ Barium (in the absence of sulphur)

The interpretation of GSR particles is important in establishing the presumed origin of those particles [30]. Along with the composition and morphology characteristics outlined above, the chance that a collected sample is GSR increases with the presence of other elements and particles that can form under the specific temperature and pressure environment typical of firearm discharge. If multiple particles are found that are both characteristic and consistent with GSR, there is a greater likelihood that the sample is GSR. It is also important to compare the elemental composition the collected sample to known source samples, such as any firearms recovered at the crime scene [30].

When reporting the results of a GSR examination, it is critical to identify the probability of the detected particle or particles being GSR, rather than identifying the particle as GSR [30]. The number of both the characteristic particles and particles consistent with GSR should be included, as well as the definitions used to describe the composition of these particles. An explanation of how the detected particles are distinguishable from other non-firearm sources with compositions similar to GSR must be given. It is important to highlight whether the particles are consistent with the ammunition or firearm used in the shooting. The interpretations in the report are crucial for presenting the GSR evidence in court.

GSR Evidence in Court

GSR evidence is admissible in court; however, some places choose not to use it for various reasons. For example, in Western Australia, police stopped taking GSR samples in early 2015 due to the low number of crimes involving guns. Mark Reynolds (personal communication, August 23, 2016) explained that Western Australian Police only take samples

in the absence of any other evidence, but this process is triaged heavily to attempt to prevent any contamination. Previously, detectives used it as strong evidence against a suspect if any particle was found. Prior to guidelines being published that documented the acceptable number of GSR particles needed to provide strong evidence in court, the number of particles needed for a conviction varied between agencies and between countries [33]. The establishment of strict guidelines and how they are reported has helped some prior convictions that were based on GSR evidence at the time to become quashed [40]. Here, I highlight an example of such a case.

Barry George v R

In April 1999, Miss Jill Dando was killed just outside of her home by a single shot to the head [40]. One of the suspects was Barry George. A year after the shooting, his home was searched and some items were collected as evidence, including his coat. His coat pocket was found to contain a single GSR particle, which was used to convict him of the crime along with other evidence such as him being in the proximity of the scene hours before the shooting, lying during his interview, and creating a false alibi. Although it was argued that police procedures may have been flawed and contamination could have occurred at any stage before or after victim's death, Barry George was convicted of murder [40].

Following several unsuccessful appeals, a retrial commenced in 2007 based on the argument that the particle may have been deposited due to contamination [40]. In 2006, the Forensic Science Service had released guidelines on how low levels of single particles of GSR should be reported, suggesting that "persons who associate with firearms users might

unknowingly and unwittingly pick up the odd particle of residue." These guidelines helped identify that the probability of the single particle of GSR ending up in Mr George's pocket was the same whether he shot Miss Dando or not. The jury agreed with the fresh evidence and Barry George was released from prison [40].

GSR by Calibre and Weapon Type

Although GSR particles do take on a characteristic shape and morphology, they may vary between calibre and weapon type, as may their pattern of deposition [41]. Andrasko *et al.* (1977) highlighted the quickly GSR particles were lost after firing a gun [42]. Following shooting, particles were found in much lower numbers after hands were rinsed with low-pressure water and dried with a cloth towel. Two hours later, only two three-component particles were found. This study also found that carefully washing hands with soap and water after discharging a firearm has the ability to remove GSR particles completely [42]. Other studies have shown that larger GSR particles are lost at a faster rate than smaller particles, and that they are less commonly found on hands [5].

Using high-speed cinematography, Ditrich (2012) studied the plume formation of different weapon types to determine the effect it had on particle distribution [43]. He found that pistols and revolvers had smoke and particles that moved more slowly out of the firearm than the bullet, and the jet blast intensity depended on the barrel length and type of ammunition. Rifles and shotguns released plumes much more quickly. Most of the particles were found to land on the face, arm, and shoulder region of the person firing. These results showed that there are large differences between firearms in the way particles disperse,

which should be considered when interpreting results for court [43]. Another important factor to be considered is that particles may remain present from previous firings of the same firearm, which is called "the memory effect." Charles *et al.* (2011) studied the memory effect of multiple calibres, discovering that the .22- and .32-calibre had strong memory effects as opposed to the .38, which did not [44].

Ammunition of .22-calibre is commonly encountered in Australia and the characteristics of GSR from this ammunition are quite distinct [45]. Coumbaros *et al.* (2001) studied the primers of this type of ammunition from multiple firearms, which contain mostly lead or lead and barium compounds but not antimony. They found a clear relationship between morphology-composition and size-composition, which is consistent with the fact that particles condense due to the high pressure and temperature environment and increases the reliability of interpreting these results in court [45]. Collins *et al.* (2003) proposed that glass be considered a new type of highly characteristic particle. As .22-calibre rimfire ammunition does not contain the three characteristic GSR particles, meaning it cannot be uniquely classified as GSR under the ASTM standard [46]. However, firearms of this calibre may use glass to sensitise the primer. When analysed using SEM-EDX and time-of-flight secondary ion mass spectrometry (TOF-SIMS), small pieces of glass were found embedded in GSR particles from various firearms in samples taken from hands and close range gunshot wounds, suggesting that these particles may be characteristic and useful for identifying GSR [46].

GSR in the Population and Environment

The utility of GSR for forensic investigation depends on determining the source of sampled particles. It is therefore important to know the prevalence of GSR in the general population. Lucas *et al.* [47] looked at the distribution of GSR particles in the random population in Victoria and South Australia. Samples were collected from the hands of randomly selected volunteers outside of shopping centres and analysed for GSR. Each volunteer completed a survey that contained questions about whether the individual had a firearms hobby, worked with or regularly-handled metals that may be present in GSR, or if the same applied to someone in his or her household. In total, 0.3% of samples from volunteers contained particles of all three elements (lead, barium and antimony), 8% had two-component particles, and approximately 7% had single element particles [47].

Hannigan *et al.* [48] evaluated gunshot evidence by examining the prevalence of GSR on clothing and the frequency of residue types. The cuffs of 100 shirts collected from non-firearm offences were sampled. Of these, 98 did not contain three-component particles, suggesting that these particles are relatively uncommon on clothing (i.e. probability of finding GSR on clothing when firearms have not been discharged is 0.01) [48].

GSR Particles in the Workplace

Some particles from various workplaces may contain barium and antimony, which may be confused as GSR if not analysed further. Therefore, these particles are at risk of giving a false-positive result. In 1999, Garofano *et al.* [49] focused on taking occupational samples from the hands of subjects employed by places where they may have been exposed to heavy

metals, especially antimony and barium. They found that in most cases, occupational samples could not be falsely identified as GSR, but those with jobs related to the automobile industry can be exposed to false-positive particles [49]. Cardinetti *et al.* (2004) proposed an X-ray mapping technique in which GSR particles can be discriminated from those of environmental occupational origin [50]. The preliminary study was able to distinguish GSR particles using this technique as they contain a barium and antimony distribution with lead nodules, while the environmental occupational particles did not [50].

More recently, particles from several other environmental sources have been revealed to be similar to GSR particles. For example, Grima *et al.* [51] assessed the impact that particulate matter from firework displays had on GSR evidence. Of the collected firework samples, 8.5% were very similar to GSR in terms of their elemental profile, shape and morphology. Additional studies have shown that brake pad lining and their wear produce particles that depict elemental profiles similar to GSR [52]. The presence of iron and other elements distinguished these particles from primer-originating GSR, but if iron was found in very low amounts it became more difficult to analyse. These studies suggest there is a need for careful consideration when analysing particles as to whether it is possible that they originate from other sources such as pyrotechnic devices or brake pad lining.

GSR in the Police Force

A critical issue for the use of GSR in forensic investigations is the risk of secondary transfer of GSR particles from the police force. Officers are trained to collect GSR samples as soon as possible following the arrest of a suspect and to wear gloves to avoid contamination,

but different circumstances may arise where the collection of other evidence types is prioritised and therefore GSR sampling is not completed straight away [30].

A number of studies have sampled police officers, police vehicles, and stations to show the possibility of secondary transfer contamination during arrest. Charles and Geusens [53] explored the potential risk of GSR transfer from special units of the police to arrested suspects. Simulations occurred in which members of the special force police unit made arrests in both low and high contamination scenarios. In the low contamination scenario, all participants washed their hands and police officers, dressed in civilian clothes, loaded their guns before arresting the targets, who were wearing single-use Tyvek coats. Samples were taken from both parties and analysed for GSR. In the high contamination scenario, all participants washed their hands but this time officers wore civilian clothes along with a technical vest used during special operations, bulletproof vest, gloves, gun, and handcuffs. The officers loaded their weapons and made the arrest of the targets wearing the Tyvek coats, which were sampled and analysed for GSR. The amount of secondary transfer of GSR during the simulations was not negligible. The cartridge cases used in the training of Special Forces police officers contain titanium (Ti) and zinc (Zn), while the cartridge cases used in the field contain lead, barium, and antimony. In the low contamination scenario, the number of PbBaSb particles was low on the officer's hands, but the number of TiZn particles was high. An average of 1 PbBaSb particle and 1 TiZn was found on the target's hands, while the target's vest averaged 2 PbBaSb particles and 5 TiZn particles, suggesting that transference occurred sometime during the arrest. Similarly in the high contamination scenario, the vests of the targets were on average more contaminated than the hands. The use of highly

contaminated gloves (used during training) may have contributed to the major contamination levels, which suggests that there can be significant risks of secondary transfer of GSR particles from special units officers to arrested suspects [53].

Gialamas *et al.* [54] sampled the hands of non-shooting police officers using adhesive stubs. The hands of 43 officers were sampled and analysed by SEM/EDX. Although the police officers regularly carried and handled a firearm, only three of the police officers had characteristic GSR particles, none of them having more than one particle. Less than half of the officers had particles consistent with or commonly associated with GSR [54]. Berk *et al.* [55] collected samples from surfaces in Chicago police vehicles that shooting suspects' hands may come into contact with following arrest. A minute amount of GSR particles were recovered [55]. Ali *et al.* [56] sampled police stations in Pittsburgh to determine the presence of GSR particles. Of the 70 samples analysed, only one GSR particle was found [56]. Each of these studies shows that the possibility of secondary transfer contamination during arrest does exist; however, the probability of this occurring is relatively low.

Conclusion

In the last decade, the strength of GSR evidence has drastically improved with the development of the ASTM standards and the establishment of SWGGSR. Establishing guidelines has made the process of analysing GSR robust and consistent. We have also come to realise that GSR-like particles are produced by many environmental sources and can be confused as GSR if not analysed in great detail. Furthermore, there is a risk of contamination of samples via secondary transfer of GSR particles from other sources (e.g. from contact with

police officers during arrest), although these findings are inconsistent. It is therefore

important to understand and consider the local environmental conditions when sampling for

GSR. There is a great need for studies to investigate the environmental presence of GSR

particles or GSR-like particles in various local areas where GSR sampling may occur.

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PART II—Manuscript

The environmental presence of gunshot residue on the workspaces and hands of employees at a forensic laboratory in Western Australia

Ashley Le ; Fiona Price, John Coumbaros; and James Speers

ABSTRACT: Gunshot residue (GSR) is produced during the discharge of a firearm, and can serve to prove a relationship between a person and a firearm-related incident. For the probative value of GSR evidence to remain, investigators must demonstrate to the Court that GSR identified on a person of interest may have been the result of the interaction with a firearm, and not from contamination of samples during collection and/or analysis. The aim of this study was to estimate the background levels of GSR in a forensic laboratory by conducting an environmental survey. Samples were acquired from a forensic laboratory environment (n=90) and analysed using scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (SEM-EDS) to determine if any inorganic GSR particles were present. Two particles were found, one 'characteristic' particle on the desk of one of the employees, and one 'consistent with' particle in the arsons and explosives laboratory. Neither of these sampling locations were areas where GSR evidence is processed,. Therefore there is a low risk of secondary transfer of background GSR particles.

KEYWORDS: forensic science, gunshot residue, inorganic gunshot residue, trace evidence, scanning electron microscopy, backscatter electron detector system, energy dispersive X-ray spectroscopy, secondary transfer

Gunshot residue (GSR) is a type of forensic trace evidence consisting of particles that are produced once a firearm is discharged, and serve to demonstrate a relationship between a person and a firearm-related incident. Increases in temperature and pressure during the discharge of a cartridge produce GSR, which includes burnt and unburnt propellant, primer residue, and metals from the bullet, the cartridge case, and the firearm itself (1-4). GSR is therefore a combination of organic and inorganic residue, with organic gunshot residues (OGSR) mainly originating from the propellant, whilst inorganic gunshot residues (IGSR) primarily originate from the primer (5). IGSR is the most common form of GSR evidence, with

a three-component particle containing lead (Pb), barium (Ba), and antimony (Sb) considered characteristic of IGSR (6).

Wolten *et al.* (6) were the first to propose a classification scheme for inorganic GSR. Spheroidal particles are typically between 0.5 and 5.0 μ m in diameter (6). The remainder of particles are irregular in shape and can be a range of sizes (6-7). Particles are typically characterised using scanning electron microscopy paired with energy-dispersive X-ray spectroscopy (SEM-EDS), which can analyse individual particles both morphologically and chemically (7). SEM-EDS enables the analyst to determine if an individual particle is 'characteristic', 'consistent', or 'commonly associated' with GSR (7). GSR particles should not be considered in isolation, and if a potential GSR particle is found with similar particles that are not consistent with GSR, then the individual particle cannot be considered 'characteristic'.

For GSR evidence to have probative value, it must be demonstrated that GSR identified on a person of interest (POI) may have been the result of his or her interaction with a firearm, and not from the secondary transfer of samples during collection and analysis. Knowledge of the prevalence of GSR in the general population, the police environment, and forensic analytical facilities is vital when considering the value of GSR as forensic trace evidence. For example, if it is found that there is a high prevalence of GSR in the wider population, the probative value of GSR may not be sufficient to demonstrate a potential relationship between the accused and a firearm in a court of law. Some studies have demonstrated that there is a low chance that a randomly selected member of the public in the general population with no knowledgeable contact with firearms can return a

positive GSR result (8-9). However, secondary contamination from other sources could be more of a risk. French and Morgan (10) concluded that GSR can be directly and indirectly transferred, meaning there is potential for GSR to contaminate exhibits and suspects during their handling and processing.

Several studies have shown that there is a small possibility of secondary transfer from police officers, who regularly handle firearms, to arrested suspects (11-14). However, no published studies have investigated the possibility of secondary transfer from within a forensic laboratory. Forensic laboratories are involved with the processing and handling of a large range of evidence taken from crime scenes, and it is necessary to determine the potential for GSR to be secondarily transferred onto items of evidence throughout the examination and analysis procedures. It is therefore important to determine the prevalence of 'environmental' GSR in a forensic laboratory.

Here, we investigate the potential for secondary contamination of inorganic GSR particles in a forensic laboratory in Western Australia that provides chemical and forensic science services for the state (15). When evidence from a crime scene is collected, it is packaged and brought to the forensic laboratory for further analyses. Some of these evidence types include firearms evidence, drug and toxicology samples, and arson and explosives samples. The aim of this study is to determine whether GSR is environmentally present, and if so whether secondary transfer of particles onto evidence brought into the forensic laboratory is likely.

Materials and Methods

12 mm aluminium stubs (ProSciTech, Queensland, Australia) containing adhesive carbon tape were prepared prior to sample collection and stored in their holders until sampling to avoid any inorganic GSR collection. The hands of workers, their desks, and various areas of the laboratory were sampled (see Appendix 1 for specific areas and number of samples acquired). Gloves were worn by the investigators when acquiring samples and changed between every nine to ten samples (n=8) to avoid any potential cross contamination. The gloves were sampled before changing to determine if any environmental GSR particles present had adhered to the gloves and ascertain the extent of cross-contamination (if any).

Hands and Desks of Workers

Samples were collected on a voluntary basis from people employed at the forensic laboratory. Samples were collected from individuals with various occupations, including chemists, laboratory managers, and laboratory administration officers (n=26; Appendix 1). Each person completed a questionnaire prior to sampling to establish if the person or someone in the person's household had potentially come into contact with potential sources of GSR (e.g. firearms, etc.) or GSR-like particles (e.g. solder, etc.) within the previous seven days (Table 1). One sample was collected from the front and back of the left hand and one sample from the front and back of the right hand using an extensive dabbing motion focused on the thumb and forefinger area. A further sample was taken from the desk area of each person.

TABLE 1—*Results of the questionnaires completed by subjects prior to sampling. Where respondents answered "no", cells are left blank*

	Subject Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Contact with a firearm in last 7 days				Yes									Yes
Live with person who has been in contact with a firearm in last 7 days													
Shoot recreationally	Yes			Yes									
Make own fishing sinkers													
Work on automobiles				Yes		Yes							
Come into contact with heavy metals													

Laboratory Areas

Multiple areas of the forensics laboratory were sampled, with priority on the exhibit storage room (n=8), the search room (n=3), and SEM room (n=7; Appendix 1), as these are the rooms in which items of evidence that potentially contain GSR are stored, initially examined, and analysed.

Scanning Electron Microscopy with Energy Dispersive X-ray detection

Each stub was coated with carbon prior to analysing. Particle analysis was performed using a CamScan CS3400LV Scanning Electron Microscope with a Camscan Robinson backscatter detector (Camscan Electron Optics Ltd, Cambridge, UK) connected to an Oxford INCA EDX analyser (Oxford Instruments Analytical, High Wycombe, UK). The accelerating voltage was set at 25 kV, the probe current at 1.62 nA, and a working distance of 30 mm was used. The automated particle search was conducted at a magnification of 396. A positive control containing antimony lead particles was used, along with a standard containing cobalt for quantitative optimization. At the end of each automated run, a manual review was conducted of particles that were classified as characteristic and/or consistent with GSR. Any particles of interest were analysed manually, specifically assessing the morphology and chemical composition before being excluded or confirmed as GSR.

Results and Discussion

Glove Controls

No particles of interest were present on the glove samples. Environmental lead is commonly associated with GSR, and was found in majority of the samples. However this was insignificant as the ASTM standard states that Pb particles alone are not considered to be associated with a firearm (9).

Hands and Desks of Workers

No particles 'characteristic' of or 'consistent with' GSR were present on the samples taken from the hands of the 13 subjects. Studies have shown that GSR can be readily removed from hands within four to five hours after a shooting event through actions such as hand washing, wiping hands against towels or clothing, or placing hands in clothing pockets (15-17). Therefore, it was not unexpected that the samples were negative for GSR, even for the subjects that had declared contact with a firearm within seven days prior to sampling. Two of the subjects sampled had Pb particles, present on both hands. However, in the absence of other particles that are 'characteristic' or 'consistent with' GSR, these particles could have originated from a multitude of sources that are unrelated to a firearm (7).

One three-component characteristic (SbPbBa) GSR particle was found on the desk of Person 13 (Image 1, Figure 1), who primarily undertakes administrative duties and is only
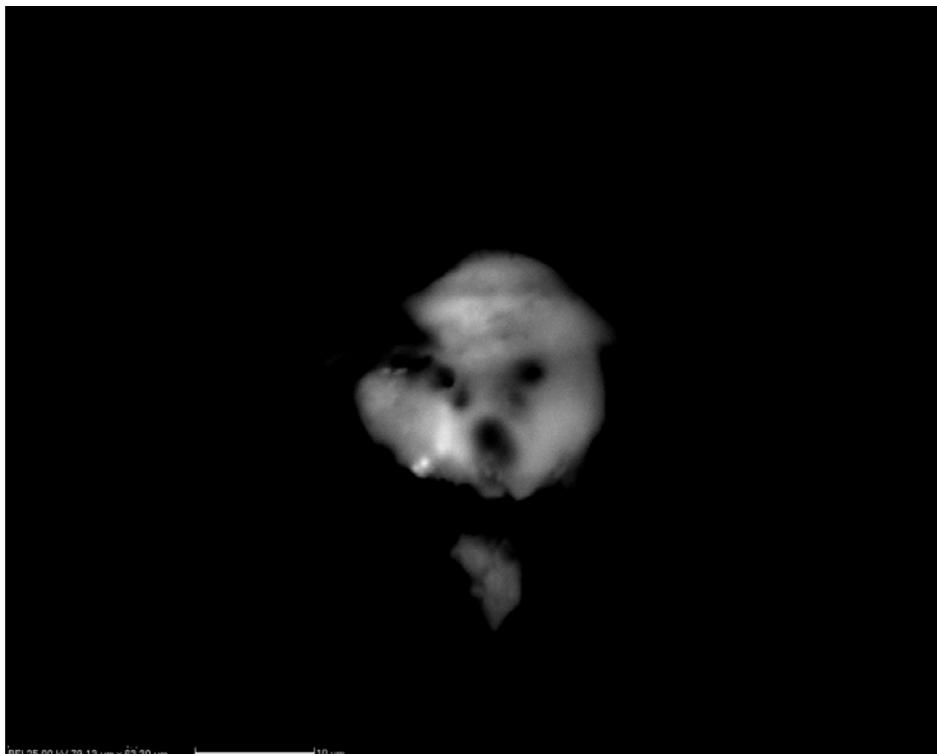

IMAGE 1—*The backscatter image of the three-component particle found on the desk of Person 13. Note the irregular and spherical shape of the particle.*

infrequently in the laboratory. This person indicated in the questionnaire that they had come

into contact with a firearm in the previous week. However, this single particle was the only

potential GSR particle found on this particular sample. As mentioned previously, in the

absence of other particles consistent with GSR, a single particle does not constitute strong

evidence. According to the ASTM E1588-10e1, very little interpretation can be applied to

finding such a small amount of particles (7). Moreover, the lack of other particles from this

person's desk and hands suggests that the probability of secondary transfer within the

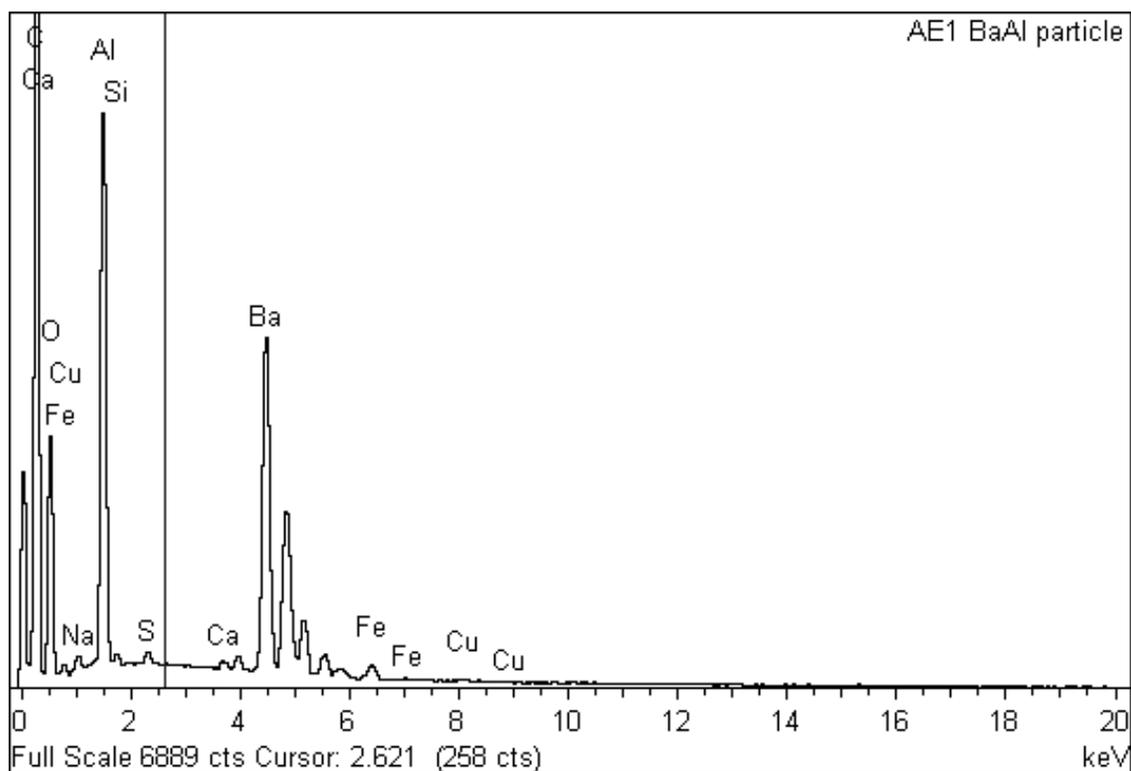laboratory is in this case unlikely.

FIGURE 1—*The spectrogram of the elemental composition of the three-component particle found on the desk of Person 13*.

Laboratory Areas

No 'characteristic' or 'consistent with' GSR particles were found in any of the laboratory areas where GSR evidence is encountered. However, one 'consistent with' GSR particle was found in the arson and explosives room. The automated software identified it as a barium and aluminium particle and after manual examination of the elemental profile, a trace amount of iron was present as well (Figure 2). The secondary electron image revealed that it was a very small spheroidal particle (<10 μ m). Although this particle did not contain antimony or lead, it is still considered 'consistent with' GSR, according to the ASTM standard (7; Image 2). This specific particle was found on the sample taken from an empty evidence box, where stored arson and explosive samples are brought into the room for analysis.
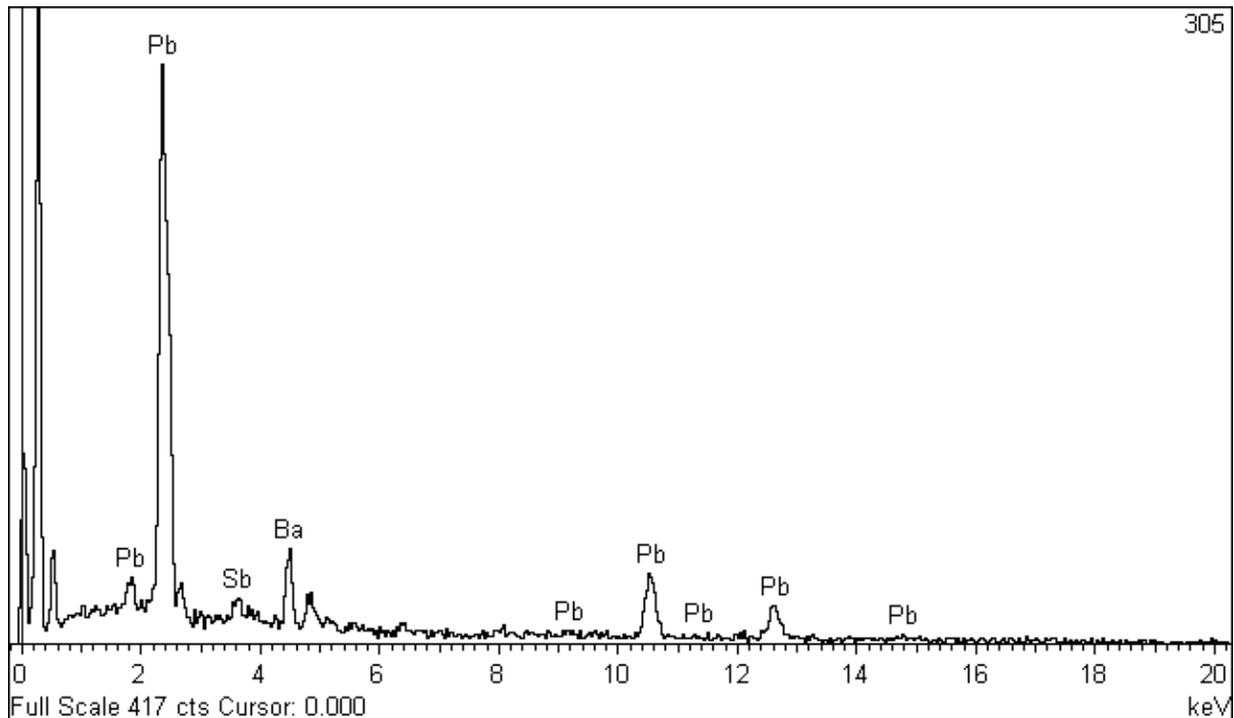

FIGURE 2— *The spectrogram of the elemental profile of the barium (Ba) and aluminium (Al) particle found in the arsons and explosives room. Note the trace amounts of iron (Fe) found in the sample.*

Particles similar to GSR can derive from a number of sources, including brake pad lining and particulate matter from fireworks displays (18-19). Grima *et al.* (19) found that 8.5% of the collected firework samples were very similar to GSR in terms of their elemental profile, shape and morphology. Given that the 'consistent with' GSR particle was found in a room where this type of evidence is likely to be encountered, the probability of it originating from a firearm is much lower.

A majority of particles from all the other laboratory samples were made up of environmental lead and antimony. The lack of 'characteristic' or 'consistent with' GSR particles suggests that the risk of secondary transfer is very low.

IMAGE 2—*The secondary electron image of the BaAl particle found in the arson and explosives room. Note its very small size (<10 μ m) and spherical shape.*

Conclusion

The results of this study demonstrate that there is a low environmental presence of GSR in this forensic laboratory. Whilst one 'characteristic', and one 'consistent with' particle were recovered from the desk of Person 13 and the Arson and Explosives room respectively, the absence of other GSR particles from these samples decreases their significance. Furthermore, these particles were recovered from areas of the laboratory that are not involved in sample preparation or analysis for GSR, which suggests that the potential for these particles to be secondarily transferred to a forensic exhibit is minimal. To strengthen the value of GSR evidence, it would be important to sample the chain of forensic evidence in Western Australia, such as where the evidence is collected and packaged, transferred, and stored prior to arriving at the forensic laboratory. Sampling police stations, officers and vehicles would be beneficial, as these types of environments are often exposed to firearms. Previous studies have demonstrated that secondary transfer of GSR in the police environment is possible (11-14). Understanding the baseline levels of GSR in both the forensic laboratory and police environment could provide information about the baseline levels of GSR and the possible routes by which GSR could contaminate a sample prior to analysis, allowing sample collection , analytical procedures, or cleaning procedures to be rectified. This could strengthen the probative value of GSR evidence, particularly if environments are shown to be GSR-free, as it will demonstrate to the Court that samples taken for GSR analysis are not being contaminated due to exposure to the police or forensic laboratory environment.

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Appendices

APPENDIX 1—*Areas sampled for GSR and rationale for sampling.*

Sampled Area	Reason it was Sampled	Specific Areas Sampled (Number of Samples)	Total Number of Samples (n)	Particle of Interest Present?
Hands of workers	To ensure that GSR particles are not present to rule out secondary transfer	Right hand (13), left hand (13)	26	No
Workers' desks	To ensure GSR particles are not present to rule out secondary transfer	Desk space of each worker (13)	13	Yes (1)
Exhibit room	Area where evidence dropped off by police is stored	Desk area (1), computer (2), five trays at random kept on the shelves (5)	8	No
Scanning Electron	Where stubs are coated with carbon	Left and right bench areas (4), coating area	7	No

Microscope room	and samples are analysed using the scanning electron microscope	(1), scanning electron microscope (1), computer area (1)		
Arsons and explosives room	Where arson and explosives evidence is examined prior to analyses	Evidence tray (1), bench area (1), fumehood (1)	3	Yes (1)
Microscope room	Where forensic exhibits are examined and analysed	Comparison microscope and bench (1), slide box (1), infrared microscope and bench (2), polarising microscope (1), computer and desk area (3)	8	No
Search room	Where forensic exhibits are initially examined	Polilite area (1), microscope and computer area (1), empty bench (1)	3	No
Reception area	Where forensic exhibits are received from police	All counter areas of reception (4), meeting area (1)	5	No
Drugs room	Where illicit drugs are analysed	Tray (1), empty evidence box (1), bench area (1)	3	No
Other areas	Where various items, forensic and other, are examined	Coroner's exhibit bench (1), illicit drugs area (1), metallurgy benches (2), toxicology benches (2)	6	No
Glove controls	To ensure GSR was not being transferred from person collecting samples	Left and right gloves of persons collecting samples (8)	8	No
TOTAL			90	