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Fate and behaviour of gunshot residue - A review.[1]

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ABSTRACT

A review of the literature concerning the fate and behaviour of gunshot residue (GSR) is presented. A number of concomitant parameters including firearm and ammunition type, plume and GSR material characteristics, travel distances, chemical composition and GSR morphology are critically discussed in relation to their effects on the distribution and deposition, transfer and persistence processes of GSR. The underlying mechanisms associated with such processes are also considered. Knowledge of these processes on GSR materials could provide valuable information concerning scene preservation and subsequent forensic sampling. The number of GSR particles deposited can vary significantly with each firearm discharge, highlighting the potential to produce distinctive data in each individual case. With the continual development and compositional changes of new ammunition types, further evaluation of the effect these processes may have on GSR evidence and their possible influence on the interpretation of the analytical results should be given due consideration.

Keywords

Forensic science, ballistics, gunshot residue, distribution, transfer, persistence, fate and behaviour.

The SWGGSR 2011 guide (1) defines gunshot residue (GSR) as “residues formed during the discharge of a firearm. In the context of [scanning electron microscopy / energy dispersive x-ray spectrometry], GSR is the inorganic and metallic residues largely originating from the ammunition that has been discharged but may include contributions from the firearm and previous ammunitions discharged from the firearm.”

GSR is a chemical cocktail of compounds produced as a result of a series of high-pressure reactions which are intended to force the projectile down the barrel of the gun. Combustion products originating from both the primer and the propellant are produced simultaneously to form a plume of airborne particulates, which escape from the barrel and any other openings in the firearm (2, 3). These particles are rapidly cooled and deposited in close proximity of the firearm (4), including the hands and clothing of the shooter and potentially other nearby persons and surfaces.

The presence of GSR can provide supporting evidence in criminal investigations involving firearms. Forensic scientists may be asked, “Can the shooter of a firearm be distinguished from a bystander based upon GSR counts and distribution?” (5). Despite improvements in GSR detection and analysis, there are still challenges in the interpretation of the presence of GSR particles, based on their distribution when considering the shooter/ bystander question. The level and distribution of GSR present on an individual can be influenced by many factors within the context of any case. Therefore, an understanding of these fate and behaviour processes in relation to GSR is vital when assessing and interpreting any case findings.

Several scientific reviews have previously explored the evidential value of GSR and its analysis, (4, 6-10). This paper assesses the current knowledge surrounding the fate and behaviour of gunshot residues, focussing on inorganic aspects.

Distribution of GSR

Differences in distribution have been noted when using various types of ammunition and firearms, at different muzzle-target distances and at a range of times after shooting. With the exception of a suicide or in cases where a suspect is apprehended immediately following firearm discharge, GSR distribution is likely to be altered due to transfer and/or loss (2, 11, 12).

GSR Deposition

GSR particles deposit onto nearby surfaces via two mechanisms: fallout deposition and impact deposition. Firearm discharge is thought to cause a ’blasting’ of residues into the immediate vicinity of the firearm, also referred to as “trigger blast” (13) and “muzzle blast”(14). Burnett (15) suggested that upon impact with the target GSR may undergo some modification in the form of splattering or flattening. Deposition of GSR particles may also occur due to particle sedimentation of airborne particles. Airborne GSR particles (AGSR) have been shown to take relatively long periods (up to 10 minutes) after discharge to settle (16). While GSR on the shooters hands is likely to originate from impact deposition rather than fallout deposition (12, 13), fallout deposition may account for characteristic particles found on bystanders or individuals entering a scene after discharge (17).

Influence of firearm type

Plume studies and fast speed photography have allowed the visualization of residues both during and following discharge (18). A “GSR plume”, can be defined as “the gaseous formation that exits all openings of a firearm following the discharge of ammunition” (2).

A close relationship between firearm type and the spatial distribution of GSR has been shown (2, 18, 19). Schwoeble and Exline (2) investigated plume development and the areas of heaviest GSR concentrations of 28 different weapons. The authors noted that the location of the cartridge ejection port on certain weapons influenced GSR distribution. Larger calibre revolvers were seen to have a widespread plume as opposed to the more compact plume of larger calibre semi-automatic weapons with ejection ports. Table 1 lists some of these differences, providing descriptive information only on plume formation.

These findings are in agreement with other authors who reported higher particle concentrations on the side of the ejection port at ground level (20). Although the number of GSR particles varied between firings Gerard et al. (21) noted a consistent trend of increased particle numbers to the right of the bullet path, i.e. the side corresponding to the ejection port. As many as 16 additional particles were found on targets placed to the right bullet path than those to the left. Similarly at 4m and 45 degrees right from the shooter, Fojtášek et al. (20) detected over 3000 GSR particles, opposed to just 15 GSR particles 4m and 45 degrees left from the shooter.

Variations in both the diameter and the distance travelled by the plume, in both the firing direction and the reverse direction between four different firearms have been noted (22). Carreras and Palma (22) suggest that the rifling of a firearm may result in GSR initially acquiring a greater velocity than the bullet due to rubbing of the bullet with the inner surface of the barrel. The increased contact between the bullet and the interior of a rifled barrel is likely to cause a -'shaving' of the exterior of the bullet, and an increased proportion of bullet residues (23).

The burn rate of a propellant may additionally account for some of the differences in the distances travelled and the diameter of the GSR plume seen between different firearms and ammunitions as seen by Carreras and Palma (22).

Ditrich (18) investigated the relationship between plume formation, the corresponding deposition and distribution of GSR particles and the construction of a specific firearm. Variations in plume development and GSR distribution were noted between a selection of pistols, rifles and shotguns. Whilst the distribution pattern from the muzzle was directed predominately towards the target for all firearm types, there were substantial differences seen in the plumes released via the ejection port and the barrel-gun gap.

The barrel length of a firearm may further influence the distribution of GSR particle. When shortening the barrel length of a rifle by 10cm Deinet and Leszczynski (24) found lead to be more sparsely distributed. It is suggested that this was due to a decrease in pressure in longer barrelled firearms.

Influence of ammunition type

Limited data exists regarding particle populations following the discharge of various ammunition types. Repeat firings in apparently identical conditions do not necessarily generate the same GSR particle distribution and quantities. Additionally, progressive firing of the same firearm/ammunition may not necessarily yield progressively increasing amounts of GSR (25, 26). It was suggested by Wolten et al. (12) that simple firing chamber and barrel misalignments, faulty collection procedures and the age and condition of both the firearm and ammunition used might further modify particle counts.

Wallace (11) noted an increase in particle numbers when comparing jacketed to non-jacketed ammunitions for residue collected shortly after discharge (table 2). The increased particle population seen in the round nose lead (RNL) ammunition is largely due to lead particles (rows 1-3). Since a much smaller proportion of the lead bullet is exposed in the jacketed hollow point (JHP) ammunition, bullets that are not jacketed would be expected to produce greater numbers of lead particles. These significant differences in particle numbers between the two ammunition types were not as pronounced in Wallace (27), and a signifiicant increase in Pb particles was not observed (rows 4-6).

Udey et al. (28) also identified differences in elemental concentrations between the two bullet types. Significant increases in both Pb and Sb concentrations were prominent in the non-jacketed ammunition (147,565 µg/g Pb and 5,444 µg/g Sb) compared to jacketed ammunition (6,567 µg/g Pb and 1,732 µg/g Sb). Elements originating from the interior of the gun barrel or the ammunition primers however, were not significantly different in the two bullet types. These discrepancies in particle numbers seen between the two bullet types may be attributed to the coating on jacketed bullets. This thin layer of protection reduces the 'scraping' between the bullet and the barrel, which in turn may reduce the number of corresponding bullet residues.

Brożek-Mucha (29) suggested that the number of particles detected may not provide a meaningful description of particle dispersion upon firearm discharge. The author proposed that analysis of GSR distribution should instead focus upon parameters such as the occurrence of certain classes (e.g PbSbBa), mean parameters and their mean diameters.

Discrepancies in the chemical composition of different batches of the same ammunition have been noted, together with the effect this can have on GSR distribution (12, 20, 30, 31). Fojtášek et al. (20) reported inconsistencies in particle populations during experiments employing the same gun (CZ 85 calibre 9 mm Luger), but using ammunition (9 mm Luger S&B) from different production runs. The general trend of distribution at increasing distances from the muzzle were similar, however, the total number of particles at a distance of approximately 3m in the firing direction differed from several hundred in the first experiment to several thousand in the second. Deinet and Leszczynski (24) also noted varying values for the distribution of GSR from different brands of ammunition.

Botello et al. (32) proposed that an ammunition's composition may influence the maximum distance travelled by the GSR particles. The authors found that as the relative burning rate of the propellant powder improved, the maximum distance of GSR patterns declined. This relationship was attributed to the dropout rate of the powders. Slower burning powders were thought to start to drop out later and persist longer than faster burning powders.

Many modern centre fire ammunitions from the West are very similar in primer composition, making differentiation between ammunitions problematic. However, Eastern Bloc ammunition types have mercury fulminate based primers, opposed to the sinoxid type primers seen in the West (7, 11, 33, 34). Compositional differences seen between the ammunition from the two geographical groups, allows limited ammunition differentiation.

The frequencies of occurrence of certain chemical classes can provide additional features in aiding the differentiation between various ammunition types, particularly where supporting evidence (e.g. spent cases) are not available (31). Brożek-Mucha (31) assessed both visual and statistical evaluations of the frequencies of occurrence of six ammunition types. Visual inspection of the number of particles in individual chemical classes allowed the immediate discrimination of Browning 7.65mm ammunition from the remaining samples. Additional non-parametric statistical analysis allowed for further discrimination; however, this analysis did not provide discriminative power for all samples.

Spatial distribution of GSR

Carreras and Palma (22) hypothesised that GSR from a firearm discharge can be divided into three clear categories - those that are expelled prior to the bullet exiting the muzzle (primary residues); those leaving alongside the bullet (secondary residues) and those leaving after the bullet (tertiary residues). They examined the changes in GSR ejection patterns at various distances and classified the distances at which the shots were made into the following groups:

- Contact wound, the muzzle in contact with the target;
- Close range shots with soiling or blackening/sooting;
- Long distance shots.

At close ranges, the GSR particles reach the target and cause soiling, the extent of which is dependent upon the proximity of the target to the cloud of residues expelled prior to the bullet. At increased distances, only the heaviest particles (e.g. metals and grains from burnt and unburnt propellant as opposed to soot) are expected to reach the target.

An explanation for the spatial distribution of GSR, depending on the weapon used, was also given by Chohra et al. (19). The authors place an emphasis on the proximity of both the hand that operates the firearm to the ejection port, and the hand holding the gun barrel to the exhaust gas locations (35-37). The distribution of residue, especially upon the hand used to fire the gun and the hand holding the barrel of the gun, was shown to depend upon the weapon used and the corresponding areas of plume discharge.

GSR has been identified at distances as far as 18 metres (m) from the shooter (21) (see table 3). As you move away from the shooter, GSR deposition and distribution changes. The highest levels of GSR particles may be detected at several meters from the firearm's muzzle (20). An understanding of the relationship between the distance of an individual or target from the firearm and the corresponding GSR deposition may aid in scene interpretation. Since GSR may be deposited onto individuals who have been shot, or shot at, results must be interpreted with caution (38).

Fojtášek et al. (20) investigated the spatial GSR distribution at floor level in seven directions originating from the shooting firearm. In an open environment, no GSR particles were found at distances further than 6m. In a closed environment, GSR particles were found to travel as far as 10m from the muzzle. The maximum number of GSR particles, (3020 particles), was found at a distance of 4m at 45° to the right of the shooter. Several hundred particles were also found to the right of the shooter and in the firing direction. These results demonstrate that GSR particles may be found on individuals who were up to 10m away from the muzzle during firearm discharge. In contrast, Seamster et al. (39) found the most intense fallout of residue (probably ejected from the barrel) at about 0.9 m (3ft) ahead of the weapon. Although the number of particles detected at these maximum distances has been demonstrated to be low, they may still yield evidential information.

Gerard et al. (21) investigated distances greater than the 10m previously examined by Fojtášek et al. (20). The authors found that the majority of the airborne GSR particles down range were deposited within 13.5m of the muzzle. The authors suggested that GSR travelling down range is in close association to the bullet. This is in agreement with Ravreby (40), who found GSR particles on bullets taken from targets. This widespread distribution of GSR highlights the potential for bystander contamination (38).

Lepik et al. (23, 41, 42) compared the injuries caused by a collection of pistols at distances of 1-100cm. When the distance from the muzzle was increased, the dimension of the zone of GSR particles on the targets also increased, however the density of this zone decreased. At closer ranges from the muzzle the extent of GSR skin impregnation and fabric scorching was increased. At a muzzle to target distance of 100cm, particles were only visible on the skin surface, whereas at 25cm they were found both on the surface and in the outer layers of the epidermis. Variations in deposition were noted between target material and firearm and ammunition types.

Brożek-Mucha (29) investigated the relationship between the shooting distance, GSR chemical composition and particle size. A gradual change in the frequencies of occurrence of the classes PbSb, Pb and Sb as the shooting distance was increased from 10-100cm was noted. The fraction of Sb particles increased from 0.1 at targets 10cm from the muzzle to about 0.9 at 70-100cm. The greatest contribution of larger particles was found on the shooting person. On the samples taken from targets in the direction of shooting, particles >4.5µm were found to account for a greater frequency of the whole population of particles on targets at longer distances (if any were found).

In a similar method, Gerard et al. (21) reported opposing results. The authors noted a decline in the relative occurrence of larger (≥8 µm) GSR particles with increased distance down the range, and none were observed beyond 13.5 m. The number of smaller (≤2.9 µm) particles however increased from 1 at the ejection port to 37 at 13.5m. An increase in particle numbers and a reoccurrence of large particles was observed at 18m, within a few centimetres of the target (17m), thought to be a result of GSR cast off from the bullet.

Models of GSR distribution

A number of authors have proposed the use of statistical models for estimating the firing distance based upon GSR distribution. Several techniques have been used in the literature to provide a link between the amount of GSR present and the shooting distance (43-47). Whilst studies investigating the level of GSR on shooters/suspects/cases regularly involve the detection of individual GSR particles using SEM/EDX, the estimation of shooting distance often involves the use of chemical tests on targets and victims to estimate a likely shooting distance.

Historically, Krishnan (48) identified a relationship between firing distance and Sb concentrations. More recently, Santos et al. (49, 50) identified a linear relationship between the firing distance and the natural logarithm of Sb, Ba and Pb content at radial positions from the bullets entrance. The authors identified that it was possible to estimate the firing distance by quantifying Sb, Ba and Pb levels, up to a firing distance of 80cm (depending upon the firearm and ammunition used). A clear decrease in the content of each element at increasing firing distances was observed between 20-50cm. Extrapolation of this model to distances above the detection limit of 80cm however is unreliable. These results were applicable to different firearm and ammunition types; however, the results were very firearm and ammunition specific. In the absence of regression coefficients for the specific gun & firearm, firing distance estimations are not possible.

A number of histochemical techniques have been studied to estimate shooting distance (44, 46, 47, 51, 52). Gradascevic et al. (43) proposed the use of two formulas for determining weapon type (out of the four different weapons studied) and whether a shot is contact or near contact (contact, 5cm or 10cm) dependent upon the distribution of percentages of different elements, using statistical discrimination function. The method was successful in discriminating between the four weapons in approximately 80% of the cases and shooting distance in 60% of cases. The application of this method outside of the studied weapons however is limited.

Two different methodologies for close range and long-range estimations were proposed by Nag and Sinha (53). The authors proposed that a close range model rests mainly on the assumption that the time required by the GSR particles to reach a close range target is smaller than the time needed for development of turbulence. Firing estimations of longer-range shots were less accurate than close range. The need for the development of alternative models to assess long range firing distance estimations was proposed.

Bhattacharyya (54, 55) attempted to explain the distribution of GSR with a Maxwellian model. The authors found that theoretical GSR concentrations calculated using a Maxwellian model were much greater than experimental values (increasingly so at greater muzzle-target distances). Due to the complexity of the processes that GSR particles undergo, the model was concluded as over-simplified for a complex system.

Other factors influencing deposition and distribution.

Environmental conditions may influence the quantity of GSR particles deposited upon a surface. Schlesinger et al. (56) and Basu et al. (13) suggested that since hand deposits emerge mainly from the rear of the firearm, environmental conditions had little or no effect on the distribution of GSR on shooters hands. The authors additionally hypothesized that since the hand deposits are mainly a result of breech deposits, the contribution that the fallout of airborne GSR particles makes to a shooter’s total hand GSR is minimal. Fojtášek et al. (20) however, found that the total number of particles found on floor targets was ten times lower in an open environment than in a closed environment.

Several studies have attempted to identify the handedness of a shooter (13, 39, 57, 58). Basu et al. (13) proposed that "if the gun is pre-cleaned and the ammunition and the hand hold remain unchanged, a fixed amount of residues are deposited per firing on the back of the trigger hand". However, a number of authors (59-61), found that the ratio of GSR on the firing hand to that on the non-firing hand varied unpredictably because of particle loss and/or transfer. Wolten et al. (12) reported that differences between the particle concentrations on the left and right hands of the shooter were within the sample-to-sample variations.

Stance and weapon handling (i.e. whether or not the non-shooting hand is used to support the barrel of the gun during firing and contact with the firearm following discharge) are expected to affect the amount of GSR on a shooter and the areas of contamination. The high contamination of both hands is of particular note when the second hand is used for supporting the shooting stance (18). Kara et al. (35) reported that since the hand holding the barrel of the gun is closer to the muzzle of the gun than the hand pulling the trigger, the non-shooting hand may be contaminated with a greater amount of GSR. It was found that the back of the shooter's supporting hand contained over 30% more GSR particles than the shooter's firing hand. Results may differ for the shooters palm, however, this was not examined in this study.

It was thought that an individual who has GSR on the back of their hands is more likely to have fired a gun than individual who has GSR solely on their palm (11). Although in ideal situations where samples are collected immediately after firing, this may be the case, redistribution and loss of GSR complicates interpretation.

In a review of developments in the methods for estimating shooting distance, Zeichner and Glattstein (62) emphasised the continuing need for research on the maximum range of GSR particles dependent upon ammunition and firearm types and the accountability of shot to shot variances. The large variation in the amount of GSR from shot to shot was highlighted as a coherent problem in the estimation of firing distance. This, together with other parameters highlighted in this section illustrate that additional factors (e.g. ammunition and firearm type, environmental conditions and time since discharge) need to be considered when assessing GSR distribution patterns and hence the caution needed during the interpretation of GSR results.

Transfer

The presence of GSR on an individual is not exclusively indicative of firearm discharge (63, 64). Investigations have highlighted the possibility for GSR to undergo secondary, and even tertiary, transfer (63) and also the potential for GSR particles to deposit onto an individual walking through a recently contaminated area (17).

Transfer processes

Table 4 highlights the main transfer processes relating to GSR. Differentiation between GSR found due to primary transfer (i.e. on the hands of the shooter) and secondary transfer (i.e. an individual who has not fired a gun but has had contact with a recently discharged firearm), will contribute to our understanding of GSR behaviour and ultimately aid in the interpretation of GSR evidence (63, 65-69).

French et al. (70) demonstrated the importance of considering secondary transfer mechanisms when interpreting trace particulates. The authors demonstrated four scenarios within which trace particulate evidence (not GSR) may be transferred. Direct transfer along a chain of five individuals was possible. As would be expected, decreases in particle quantity along the chain were observed, with only 0.4 -2% of the initial amount being recovered from the final individual. The potential for inert objects to act as an intermediate in transferring trace material was also demonstrated. Transfer from a contaminated individual to a non-contaminated individual was observed when the object was communally used. The transfer of materials was found to take place within both social and contact networks.

Statistical Analysis

For the assessment of the evidential value of GSR, it is important to consider the potential contamination of a neutral individual via transfer processes. It is common practice for forensic evidence to be assessed using liklihood ratios. A number of authors have proposed the use of probabilistic models for assessing the likely origin of GSR particles (65-67, 71, 72).

Models of likelihood ratio procedures, addressing additional sources of uncertainty of GSR evidence, such as analytical performance or contamination, were proposed (66, 73). Using experimental data from Cardinetti et al. (65), likelihood ratios for an observed number of particles were calculated. The adapted approach allows an analyst to address a variety of factors that may influence the evidential assessment (e.g. background presence of GSR particles and analytical performance). This approach offers the possibility of incorporating prior knowledge into statistical evaluation.

Romolo and Margot (7) proposed the use of likelihood ratios for evaluating evidence under opposing hypotheses using a Bayesian approach. The authors stressed that the correct use of statistical assessment can prove valuable where disputes in cases arise. As the use of likelihood ratios and the Bayesian approach is not the focus of this review, we refer the reader to the wide discussion of the topic in the available literature (e.g. (68, 74)).

The vast number of variables possible in GSR casework limits the efficacy of statistical evaluation to GSR analysis. Kaplan et al. (72) stress the importance of choosing the statistical model based upon each individual data set. Empirical data quantifying uncertain parameters, such as those explored by Biedermann et al. (66), would optimise the opportunities to study GSR evidence with statistical evaluation. From a practical perspective however, this would be both time and resource demanding.

Shooter transfer

Although it may be expected that shooters would exhibit a higher abundance of GSR on their hands than individuals observing a discharge at close proximity, this is not always the case. Lindsay et al. (5) demonstrated that in some instances bystanders may have similar concentrations of GSR on their hands to the shooter. Gerard et al. (21) and Fojtášek et al. (20) also commented on the unreliability of distinguishing between a shooter and an individual near the path of the projectile, or a shooting victim using particle numbers alone.

Transfer from shooting to non-shooting hand may occur when a shooter rubs their two hands together (75). Whilst decreases in GSR content over time on the shooters hand are expected, a rise in particle numbers seen on the non-shooting hand at times over t=0 may be seen due to transfer from the shooting hand.

French et al. (69) showed that large quantities of GSR (over 120 particles in one instance) can be transferred to a neutral individual via direct contact with the shooter immediately after shooting. A range of different sized particles were transferred to a subject via a handshake, including particles over 100 µm. Previous studies have only identified the transfer of sub-micron GSR particles to non-shooting subjects (76). Secondary transfer processes may similarly occur via direct contact with a recently discharged firearm (13, 64, 69).

The potential exists for GSR particles to undergo tertiary transfer by means of successive handshakes (63). Handshakes from two individuals who were both absent at firearm discharge resulted in the transfer of considerable numbers of GSR particles (up to 22 GSR particles) (63). The majority of particles that underwent tertiary transfer measured <10 µm.

Additional methods of transfer

It was noted that GSR travelling with the bullet might become deposited on a target (e.g. skin, clothing) (53). It is, therefore, possible for GSR to be transferred to an individual interacting with a victim/target. For example, handling clothing with a close-range gunshot wound may lead to relatively high contamination with GSR (64). Studies on such transfer processes, however, are limited.

The presence of GSR particles, particularly when only small numbers are identified, needs to be interpreted with caution. Similar GSR counts may be seen under a variety of situations. Firearms producing low particle counts, such as a drilled out starting pistols (2), may result in similar particle counts to cases involving the secondary transfer of GSR from an individual who has just discharged a firearm producing a greater abundance of GSR particles. Additional methods of interpretation, for example examination of GSR elemental composition, and where possible matching GSR found on a suspect to ammunition/ firearms may prove invaluable in casework (77).

The GSR transfer processes demonstrated in experimental scenarios represent 'extreme' cases where contact has been made immediately after firearm discharge. In reality, the number of GSR particles undergoing secondary transfer may be influenced by a number of additional factors: these may include the frequency of shooting (64), environmental conditions (20), the passage of time, shedding potential (70), and the material of the substrate (78, 79). Interpretation based upon experimental data should be approached with caution.

Sources of contamination and transfer possibilities

Several studies have highlighted the ease with which GSR particles can be transferred to a variety of surfaces by surface contact, rubbing and particle sedimentation (5, 17, 63, 69, 80). Problems associated with secondary transfer of GSR have been noted during arrest and during police transit.

Personnel entering a crime scene immediately after a shooting may be exposed to GSR due to delayed particle sedimentation. Andrasko and Pettersson (17) highlighted that the movements of individuals following firearm discharge could be more important in GSR distribution than the positioning of individuals during discharge. The authors noted that walking through a particle cloud had a greater influence on the number of particles on a bystander than their distance from the shooter. They also showed that small amounts of GSR may be transferred to 'clean' clothing from a contaminated garment through direct contact. According to Fojtášek and Kmjeé (16), under certain circumstances, this individual may actually be exposed to a greater quantity of GSR than a shooter (especially when the shooter has immediately fled the scene).

An attempt to trace the possible transfer of GSR to a shooter's relatives living in the same home was made by Brożek-Mucha (64). Five families of hunters were examined for the presence of GSR. The risk of shooters contaminating their surroundings and other individuals was found to be closely related to the frequency of shooting and an individual having direct contact with the shooter and the shooter's belongings shortly after shooting.

The capability of law enforcement personnel and facilities to act as potential sources of GSR contamination is well documented. Firearms personnel and police officers carrying firearms may be routinely exposed to high levels of GSR through training and contact with suspects/ samples. Transfer of this GSR may result in false positives leading to possible data misinterpretation. It has been suggested that in cases where samples cannot be taken prior to an arrest, the suspect's hands should be placed into individual paper bags during police transit (81). However, on-scene sampling is always favoured, and using paper bags may only be used as a last resort due to possible contamination from the paper.

Gialamas et al. (82) evaluated the presence of GSR on the hands of non-shooting California police officers at the end of their shifts. Only 7% of the examined samples tested positive for PbBaSb particles. The potential for contamination was considered to be low, as no officer had more than one consistent GSR particle.

Berk et al. (83) investigated the potential contamination of individuals from police vehicles and detention facilities in Chicago, US. They concluded that, although possible, the contamination from these sources is unlikely.

Significantly higher levels of contamination from Swedish police cars and crime scene investigators were reported by Pettersson (84). In about 25% of the samples from the police cars, at least 12 GSR particles were found. Similar findings were reported for Australian operational police (85). The greater levels of contamination seen may be a result of more efficient collection/analysis procedures or sampling of more contaminated areas (85).

Gerard et al. (86) investigated the potential contamination of officers, non-firearms related employees and vehicles in three Toronto area municipal police services. GSR was found on 24% (GSR particles range 1-11) of the clothing and equipment (i.e. sleeves, handcuffs and batons), and 60% of the samples taken from officers' hands (GSR particle range 1-7) collected from the hands of the officers sampled from York Regional Police (n=30). In addition, 25% of the samples collected from the hands of police officers from the Toronto Police Service (n=36) tested positive for GSR particles (GSR particles range 1-15). No GSR was detected on the hands of civilians working in the same building (n=28).

The potential for contamination of suspects during arrest was elevated when special operations officers were used (87). Arrests were simulated under both low and high contamination scenarios, depending upon the amount of special operations clothing worn by the officers. Contamination was most likely during the 'frisking' procedure, with gloves highlighted as the main source of potential contamination of GSR.

Contact with the surfaces on which firearms are handled may not always result in the transfer of GSR. Lindsay et al. (88) found that working in a factory in which firearms are made did not result in the transfer of high GSR particle counts to all employees. The number of particles on employees from a handgun factory who had not handled a completed firearm on the day of sampling ranged from 0-23. However, one individual who had handled a firearm that had been test fired had 424 GSR particles on their hands.

The random presence of characteristic GSR among the general public is thought to be negligible. Brożek-Mucha (64) investigated the levels of GSR on individuals declaring no contact with firearms. Of 100 samples collected from individuals of varying occupations, only a single spherical PbBaSb particle was found on one individual. Lucas et al. (89) similarly observed characteristic PbBaSb particles in only 0.3% of samples collected randomly from volunteers in two Australian jurisdictions and PbSb particles in 8%. The probability of finding one or two 3-component particles on clothing by chance may be as small as 0.02% (90).

The occurrence of environmental particles similar in composition to GSR has been reported in the literature. Particles similar in shape, size and elemental profile have been identified in brake linings and their wear products (91), firework particles (92, 93), and welding fume particles (94) (please note: none of the particles presented in (94) are consistent with Modern Western ammunition types, unless heavy metal free). Environmental and occupational origins need to be considered when interpreting the significance of GSR particle detection, particularly when only small populations are found.

The potential contamination issues surrounding GSR evidence highlights the importance of understanding the transfer dynamics of GSR. Parameters and procedures put in place to minimise the contamination of GSR evidence such as clean rooms (95), reduced contact between suspects and law enforcement personnel and vehicles are essential to minimize GSR transfer and contamination processes (96).

Persistence

The persistence of GSR following a firearm discharge was investigated as early as 1959 by Harrison and Gilroy (100). A number of authors have highlighted the impact that every day and subconscious actions may have on the level of persistence of GSR on individuals’ hands and clothing (59, 90, 97, 98). GSR on shooters hands, hair and clothing is finite. Studies into the persistence of GSR aim to establish a link between the time since discharge and particle deposition.

GSR detection window

The literature reports a wide range of times up to which GSR has been detected, from as little as 1 hour (99), up to 24 hours (100) and potentially over 5 days (101). The persistence of gunshot residue depends largely upon a number of variables (e.g. firearm and ammunition type, collection and analysis technique, environmental and skin conditions (33, 59, 99, 101, 102)). It is therefore difficult to generalise the longevity of GSR, as irreproducibility in particle counts over time is often seen (59).

Jalanti et al. (59) sampled shooters hands immediately after firing one shot, after two hours, four hours and six hours. The shooter was instructed to carry out normal desk activity but not to wash their hands. In each case, most of the GSR was found on the firing hand in samples taken at time=0. At all other intervals however, the ratio of GSR found on the firing hand compared to that of the non-firing hand varied unpredictably. Most of the characteristic particles are thought to be lost within the first 1-2 hours since discharge (59, 61, 99, 103). However, Jalanti et al. (59) found notable numbers of 2-111 characteristic particles both on the shooting and non-shooting hand up to 6 hours after discharge.

Rosenberg and Dockery (101) suggested that the detection window for GSR is days rather than hours. The authors used Laser Induced Breakdown Spectroscopy (LIBS) to determine the period of time that a shooter will test positive for GSR. Tape lifts were taken from shooters hands in day long intervals up to a maximum of 9 days. Detectable amounts of GSR were identified on the shooters hands over 5 days after discharge.

Schwartz and Zona (104) also looked at the persistence of GSR over longer periods. AGSR retained in human nasal mucus was extracted and characterised using SEM/EDX. The technique recovered GSR in samples taken 48-hours post-firing with 500 AGSR particles being recovered. The efficiency of this technique however, will vary between individuals' dependent upon factors such as, heath and the time of year.

It has been noted that the type of substrate being tested for GSR can significantly influence the retention properties of GSR. Zeichner and Levin (61, 105) were able to demonstrate positive results for GSR on hair and clothing even when hand samples were negative. It was noted that GSR may be found on hair samples up to 24 hours post discharge, in cases where the hair had not been washed. In casework samples, the average time lapse for positive GSR samples on hair was 3.3 hours, opposed to 2.7 hours on hands.

Brożek-Mucha (106) also reported notable differences in longevity of GSR on a variety of materials. Samples collected simultaneously from the shooters hands, face and hair, and clothing were taken in nine time intervals over 0-4 hours. The greatest number of particles were observed on the hands immediately after firing, with an average of 1,695 PbSbBa particles being identified. Within the first 30 minutes, this number decreased considerably to an average value of 72. The author reported the estimated half-life of samples taken from hands to be less than 1 hour. A similar decline was seen in the samples taken from clothing. As for the face and hair, the initial numbers were lower. However, this lower level was maintained for a greater period, with an estimated half-life of 2-3 hours. These findings indicate that although hands are the most commonly sampled area, GSR particles are lost from the hands at a faster rate than the hair, face and clothing.

The sheddability of a fabric may influence the number of GSR particles detected over time. Charles et al. (78) noted that the collection efficiency of GSR was more efficient for smoother fabrics such as leather, due to the rate at which the substrate saturated the sampling tape. At t=0 a strong relationship between the sheddability of a fabric and the collection efficiency of GSR was found, with the collection efficiency found to be five-fold higher for leather, compared to wool. The persistence of GSR remained good on both fabrics, even when shaking the fabric vertically ten times. Such behaviour however, may differ at increased target to muzzle distances (107). At target to muzzle distances above 10cm, the more complex fabric structure of cotton, may provide greater adhesive properties than leather (107).

Lindström et al. (108) reported a faster rate of GSR loss in samples, which were submerged in seawater than those, which were not submerged. The environment that GSR is in may therefore influence its persistence. GSR particles have been found to survive temperatures up to at least 800°C even in cases of charred tissues (109).

It is evident that the amount of GSR on hands and other surfaces can vary, dependent upon firearm and ammunition type (see distribution section). Table 5 highlights the impact that the firearm type, analysis technique, the number of shots, the type of surface and the activity level can have upon the times up to which GSR particles are detectable on a surface. Poor reproducibility in both particle counts and particle distribution between samples taken using the same ammunition and firearm has been reported (29, 78, 106, 110). The difficulty of generalising the period of GSR retention is apparent (6).

The data from table 5 indicates that although the detection window can be governed by the sensitivity of the analysis technique, generally under 'normal' activities, GSR can still be detected on samples in the region of 4-10 hours post discharge.

Post firearm discharge activities

A number of activities conducted following a firearm discharge may influence the persistence of GSR. Rapid decreases in particle counts have been identified following activities such as hand and hair washing, rubbing or wiping hands, handcuffing, machine washing and brushing clothes (33, 59, 75, 98).

Kilty (75) demonstrated that washing hands with soap and water and drying hands with a paper towels effectively removed all detectable GSR. Rinsing hands under low pressure water for three seconds and wiping hands on clothing resulted in the removal of significant amounts of residue, however not all. Similarly, transference from one hand to the other occurred when hands were rubbed together. However, even very vigorous treatments may not remove all GSR deposits around a target.

Vinokurov et al. (98) observed that although machine washing and brushing of cloth targets significantly decreased the number of GSR deposited around the entrance wound considerably, not all particles were removed for close distance shots. Machine washing was found to be significantly more effective in removing GSR than brushing. As the shooting distance increased the extent of removal also increased.

Since activity after discharge is thought to be a leading cause of GSR particle loss, an individual at rest, or totally undisturbed (e.g. suicide victims) may exhibit a greater persistence of GSR. On undisturbed suicide victims, GSR has been found up to 5 days after firearm discharge (12). Douse and Smith (111) reported GSR identification on the hands of suicide victims up to 48 hours after discharge. Further evidence for this was reported by Zech et al. (112) who found GSR on the deceased's hand an estimated 3-6 days after self-inflicted death. GSR has also been identified on a decomposing pig up to 60 days post discharge in the winter period (113) and Sb has been identified in putrefied pig skin around a gunshot wound up to 16 weeks after firearm discharge (114).

Molina et al. (115, 116) studied 116 cases with a known self-inflicted gunshot wound over a 4-year period. At least one characteristic GSR particle was found in only 50% of cases when analysed by either or SEM-EDX or inductive coupled plasma-atomic emission spectrometry (ICP-AES). In the absence of loss and/or transfer, this would tend to suggest issues with sampling and recovery.

Increased GSR persistence has also been noted for undisturbed clothing. GSR was detectable on a cotton sheet placed 1m away from the muzzle up to two months after being shot when left undisturbed (111). Organic GSR was also found on undisturbed clothes the following day by Jane et al. (117) as opposed to just 6 hours when the clothing remained on the subject.

Summary

Advances in both quantitative and qualitative determinations of GSR materials have aided our understanding of their fate and behaviour both during and after the discharge of a firearm. This review highlights the parameters and potential variables that can have a subsequent effect on the fate and behaviour of GSR materials. Knowledge on the distribution, transfer and persistence of GSR may also inform any issues surrounding scene preservation and subsequent forensic sampling. The continuing development of new ammunition types, such as changes to the primer and propellant composition, together with the move towards the use of lead –free ammunition may alter our current understanding of the fate and behaviour processes of GSR. Further work assessing these processes on both inorganic and organic GSR is required.

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