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Fundamental Studies of Gunshot Residue Deposition by Glue-Lift*

REFERENCE: Basu S, Boone Jr CE, Denio Jr DJ, Miazga RA. Fundamental studies of gunshot residue deposition by glue-lift. J Forensic Sci 1997;42(4):571–581.

ABSTRACT: The mechanism of gunshot residue (GSR) deposition and its probing characteristics have been studied by the Glue-Lift collection of GSR and its identification by scanning electron microscopy and energy-dispersive X-ray analysis (SEM-EDX). By blocking alternately muzzle-blast residues and trigger-blast residues of shotguns, it has been shown that, if the firearm is thoroughly cleaned before the firing, the muzzle-blast residues seldom settle from the air onto the shooter's hands. Whereas the trigger-blast residues are literally blasted onto the immediate surfaces of the firearm and on both of the shooter's hands that are on the weapon. Therefore, the hand deposits are mainly the breech deposits. If the firearm is not pre-cleaned the residues of previous firings lodged as fouling in the interior of the gun are blown off rather irregularly through the breeches and the muzzle in the subsequent firings. These residues occasionally overlap with the fresh breech deposits of the shooter's hands. Color tests for residue developed with sodium rhodizonate have confirmed the basic mechanism of GSR escape through the breeches and the ejection mechanism of the close-breech weapons. The forced deposition of the trigger-blast residues is an advantageous as well as limiting process. The contrast of residue deposits on the back of a hand versus the palm, is due to shadowing of the residue particles by the hand grasp on the firearm. But these particles may also be transferred to the nonfiring hand by contact with a fired gun. Whether it is a handgun or a longarm, if the gun is pre-cleaned and the ammunition and the hand grasps remain unchanged, a fixed amount of residues is deposited per firing on the back of the trigger hand. This deposition, which takes into account all deposited particles containing one, two, and three characteristic elements of GSR (e.g., Pb, Sb, Ba), is a fundamental piece of information helpful for the reconstruction of a shooting.

KEYWORDS: forensic science, criminalistics, gunshot residue, scanning electron microscopy and energy-dispersive X-ray analysis (SEM-EDX), muzzle-blast block, trigger-blast block, density distribution

The interpretation of the GSR deposition on a subject's hands requires a clear understanding of the mechanism of GSR deposition and its probing characteristics. Knowing these characteristics is crucial to the reconstruction of shootings (1). The experiments conducted for this report are intended to give a foundation to the simple concept, or the postulate, that when a firearm is discharged, the GSR issuing through the breeches of the firearm is blown instantaneously onto the proximate surfaces of the firearm, and on any hand in contact with, or in close proximity to, the firearm. This "forced deposition" of GSR is essentially a blasting process.

There are two opposite viewpoints concerning the mechanism of GSR deposition (2,3). Wolten et al. (2) first proposed that, "gunshot residue found on a shooter's hand is blasted onto the hand during the firing. Residue settling from the air does not seem to be a factor." Renfro and Jester (3) detected suspended GSR in the air many hours after the firing and they proposed the settling of "airborne" GSR by gravity on the shooter's hand. Matricardi and Kilty (4) also reported the settling of lead aerosols (diameters ≤ 0.42 μm) from air containing gun smoke.

The position of Renfro and Jester (3) is problematic because the settling of GSR from the air would be relatively slow and can hardly be systematic. This hypothesis fails to explain why GSR is usually deposited only on the firing hand and on any hand held in close proximity to a firearm at the instant of discharge (1,2,4–24).

Currently there is also a disagreement about the source of hand deposits. Wolten et al. (2) used handgun firing to suggest that the "hand deposits are mainly breach deposits. Copious amounts of residue also issue from the muzzle, but appear to play a secondary role in the production of hand deposits" (2). (NB. They used the words breach and breech synonymously). Krishnan (22) argues that because the barrels of handguns are short, the firing hand is in the vicinity of the smoke from the muzzle and, hence, both the muzzle-blast residues and the breech residues have the "opportunity" to be deposited on the shooters hands. With regard to "close-breech" weapons Krishnan (22) states, "Since longarms normally have a longer barrel than handguns, GSR from the muzzle-blast does not have much opportunity to deposit on the hands." Neither Wolten et al. (2) nor Krishnan (22) has offered any direct experimental evidence to support their hypothesis.

These issues of the GSR deposition mechanism are addressed in this study by investigating the following hypotheses (1 to 3): 1. The major source of hand deposits can be determined by blocking out the muzzle-blast GSR and then the trigger-blast GSR in alternate series of test firings with the same weapon(s) and ammunition(s) and then determining whether the breech or the muzzle contributed the most to the GSR deposits on the shooters hand(s). 2. Because the primer residues of the trigger-blast are subject to

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the enormous thrusts by the continued burning of gunpowder (23), a "forced deposition" of these residues must be in effect. 3. Because the shooter's hands are behind the muzzle, the muzzle-blast GSR can only settle onto the shooter's hands by a blow-back, or by a backward spread of the gun smoke. If these processes do not exist, or if they are found to be irregular or occasional, then "forced deposition" of the "trigger-blast" residues will be the key mechanism to consider for further investigation of the residue escape, and its deposition characteristics and consequences, such as residue transfer by contact, etc.

The mechanism by which GSR escapes from the "close-breech" weapons and deposits on both hands of the shooter remained unexplored (See discussion with reviewer in ref. 17) Therefore, shotguns and rifles were preferred for the block tests. Preliminary studies have been reported (24–26). These previous studies were undertaken at a time when lead-free primers were non-existent (27,28). Relevance of the present studies with respect to residues of lead-free primers will be discussed.

Materials and Methods

GSR Collection and Search

The glue-lift (1,17) method for GSR collection was used to study the hand deposits. Unless specified, the gun and test-shooter's right and left hands were cleaned prior to each test firing (1,17). Control collections were made from both of the shooter's hands before the firing. The same spots of the hands were sampled immediately after the firing. The sample collection was completed in a few seconds.

The SEM (AMR 1000) imaging in the backscatter mode and elemental analysis with an EDS (EDAX707A) were jointly used to search for and identify GSR particles and, then, to count them on four (4) 1.5-mm diameter circles (total area: 7.1mm^2) (1,17). These particles were identified by their condensate spheroidal shape and by their characteristic elements, namely, lead (Pb), antimony (Sb), and barium (Ba) (2,4,14–17). All GSR spheroids containing either one element, two elements, or all the three elements, were considered. We will refer to this net count as the density (8) of distribution or simply "density distribution."

Muzzle-Blast Block

In this experiment, a plastic screen was used as a barrier to prevent the settling of the muzzle-blast residues onto the shooter's hands (Table 1A, top). If residues were found on the hands after a firing, they would be attributed to the "trigger-blast" residues issuing through the breeches of the weapon and the ejection chamber. The plastic screens, each 1.8 m by 2.7 m (6 by 9 ft), were installed vertically inside a clean firing range. The muzzle of a pre-cleaned shotgun or rifle was inserted about an inch (2.5 cm) through a pre-cut hole on the plastic screen and was sealed to the screen with tape. The screen was then taped to the side walls, the ceiling, and to the floor to prevent leakage of the muzzle gas. Only one round was discharged from the weapon using normal hand positions. The gun was then cleaned, or used unclean, for the next firing depending upon the experimental protocol described in Table 1A (bottom).

TABLE 1A
MUZZLE BLAST BLOCK

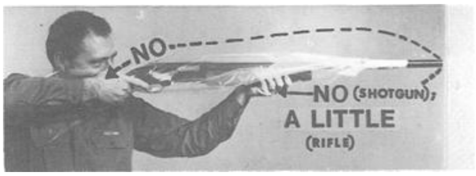
SHOT NO.	CONDITION OF GUN†	TRIGGER HAND BACK #GSR*/4 CIRCLES	MUZZLE HAND BACK #GSR*/4 CIRCLES
1ST	CLEANED GUN-INSIDE & OUTSIDE	8 (3PbSbBa; 2SbBa; 3Pb)	8 (3SbBa; 4Pb; 1Ba)
2ND	NOT CLEANED	12 (4 " ; 4 " ; 4 ")	8 (4 " ; 4 Pb)
3RD	" "	20 (4 " ; - ; 16 ")	- 12Pb
4TH	" "	84 (4 " ; - ; 80 ")	- 100"
5TH	" "	16 (- 4 " ; 12 ")	- 12"
6TH	CLEANED GUN-INSIDE & OUTSIDE	8 (3 " ; 1 " ; 3 " ; 1Sb)	8 (3 " ; 4 " ; 1Ba)

†12 GA PUMP ACTION SHOTGUN

*SPH; DIAM.: 0.2 – 10 μM

INSET ON TOP: "YES" MEANS DEPOSITION

TABLE 1B
TRIGGER BLAST BLOCK



SHOT NO.	CONDITION OF GUN*	TRIGGER HAND BACK # GSR/4 CIRCLES	MUZZLE HAND BACK # GSR/4 CIRCLES
1ST	CLEANED GUN-INSIDE & OUTSIDE	0	0
2ND	NOT CLEANED	0	0
3RD	" "	12 Pb (SPH)**	8 Pb (SPH)**
4TH	" "	0	8 Pb (SPH)**
5TH	" "	16 Pb (SPH)**	0
6TH	CLEANED GUN-INSIDE & OUTSIDE	0	0

*12 GA PUMP ACTION SHOTGUN

** DIAM: 0.1 – 0.5 μM

INSET ON TOP: "NO" MEANS NO DEPOSITION

Trigger-Blast Block

The same shotgun or rifle used in the "muzzle-blast block" was wrapped within a heavy-duty transparent plastic bag (See Table 1B, top). The bag was heat-sealed at one end, the butt end of the gun, and at the other end, the bag was sealed to the barrel within about 0.05 m (2 in.) of the muzzle. The purpose was to trap the breech residues within the bag and determine whether the muzzle-blast residues settle from the air or blow back onto the shooter's hands. The trigger was pulled from outside the bagged firearm. The support hand was in its usual position on the barrel. Fresh plastic bags were used to cover the gun in each test shot. The gun was cleaned as described in Table 1B (bottom).

GSR Capture

The variable emission of GSR was a property of only uncleaned guns (Tables 1A and B). This observation needed confirmation by an alternative means which would not involve hand deposits. Rather, GSR be captured by suitable targets and then analyzed. This was accomplished during the "muzzle-blast block" experiment by positioning two "glue-lift" disks one on either side of the screen. One was placed on the muzzle side of the screen (i.e., the side of the firing range) and the other on the shooter's side of the screen. Both of these disks were at a distance of about 0.15 m (6 in.) from the axis of the gun, or about 0.158 m (6.3 in.) from the exit of the muzzle. The deposits on the muzzle-side disk were due to muzzle-blast residues striking the glue layer at a glancing angle. The deposits on the shooter's side disk were due to trigger-blast residue which have traveled forward axially. With the pump action shotgun (Table 1A) the maximum distance traveled by residues was about 0.9 m (3 ft). This was the distance between the trigger-breech and the screen. The trigger-breech (far left), the ejection chamber (middle), and the sliding action (far right), which appear between the two hands of the shooter in Table 1A (top) were the major breeches of this shotgun.

Gun Leak Test by Residue Color

The purpose of this test was to confirm the leaks at the breech of a weapon. The cleaned gun was covered with a lint-free white cloth from the rear end of the gun up to about 0.05 m (2 in.) from the muzzle end. The gun was wrapped evenly with 1 to 2 layers so that the length of the gun would coincide with a marked line on the outer surface of the test cloth. After sealing the cloth onto the bottom side of the weapon with masking tape, the cloth surface was labeled with sticky "press-on" letters to designate the location of possible leaks. The cloth was removed from the gun after a firing and carefully spread on a clean paper with the residue side of the cloth up. The sodium rhodizonate test of Harrison and Gilroy (5) as modified by Bashinski et al. (29) was performed on the test cloths and color developed due to lead (Pb) residues. This modification consisted of a hot acetic acid treatment which converts the lead (Pb) residues on the test cloth to a form which will then react with the sodium rhodizonate reagent with maximum sensitivity (29). Briefly, this method consisted of: (1) spraying 10% acetic acid onto the test cloth, (2) covering the soaked cloth with a clean paper and/or a clean towel, (3) pressing the overlay in (2) with a hot iron, (4) removing the overlay and then spraying a freshly prepared saturated aqueous solution of sodium rhodizonate onto the test-cloth, and (5) spraying immediately with tartaric acid buffer (pH 2.8)- all in one sequence. Because the acidity of the tartaric acid buffer (pH 2.8) contributes to the fading of colors, the developed colored spots were encircled with a marking pen. Emission leak positions were confirmed by a superimposition of the gun on the marked cloth.

GSR Stopping

The two "block" experiments were performed with thick non-porous plastic sheeting (thickness 0.5 by 10^{-4}m or 0.002 in.) and bags (thickness 1.5 by 10^{-4}m or 0.006 in.) to ensure that GSR particles did not penetrate the plastic. These plastics were also examined in the SEM after the shooting experiments but no pores were detected. If pores in the size range of GSR (diam. 0.2–100 μm) were detected, this could have been strong evidence for hot GSR particles. The following describes the protocol used to investigate this issue.

After each test firing of the "trigger-blast block" group, the shotgun (or rifle) was placed on a clean table top and the plastic bag around the gun was cut out with a scalpel into 0.05 m by 0.05 m (2 in. by 2 in.) pieces from areas facing the suspected leaks (ports) of the gun, e.g., the ejection chamber, hinge, hammer gap, trigger, and magazine, etc. GSR particles were collected from each plastic piece by 5 touches with a glue-lift disk. Both the GSR collectors and the plastics (carbon-coated) were examined in the SEM. Note that GSR had to be lifted from the plastics to search for the pores. The results have shown that the "trigger-blast" residues were, in fact, barricaded by the sealed plastic bags (See the Results section).

Consistency of Density Distribution (ρ)

The block tests using shotguns and rifles revealed that a systematic deposition of the trigger-blast residues takes place with pre-cleaned guns. The purpose of the experiments in this section was to study this subject using handguns because the amount of GSR deposition is usually more with handguns than longarms (17,22). If the muzzle-blast residues do not settle from the air onto the firing hand, a consistent deposition would result from the "blasted" or "blown in" residues of the trigger-blast. This "forced deposition" should not be influenced by the substrate structure. Therefore a comparison has been made between the observed density distributions (ρ's) on a bare shooting hand (coarse surface) and a smooth shooting hand. The smooth hand was a smooth, clean polyethylene glove fitted snugly onto the hand. In these test firings the same collection spots were chosen on both the bare hand and the gloved hand.

GSR Transfer by Contact

In these studies the gun and both hands of the shooter and the non-shooter were all thoroughly cleaned prior to each test firing. After one firing or three successive firings, the test-shooter placed the fired gun on a clean table and the non-shooter was asked to pick up the weapon by grabbing a specific part of the weapon. The non-shooter was not allowed any activity that may transfer GSR from the palm to the back of the hand. He handled the gun for either 15 s or 1 min in his palm(s) (See also Table 3 for details).

Results

Muzzle-Blast Block and Trigger-Blast Block

The two "block" experiments were performed by 18 to 24 firings with a pump action shotgun and a pump action rifle. The main results were confirmed by additional firings with a single shot double barreled, hinge frame shotgun and a 30-30 caliber lever action rifle. In each firing the test-shooter had a tight grasp of the weapon and the results as obtained with the pump action shotgun (Winchester Model 1200, 12 gauge; ammunition Remington Express 12 gauge; two and three-fourth in. 0-0 buckshot), are shown in Tables 1A and 1B.

The main observation in the "muzzle-blast block" (Table 1A) was that when the gun was pre-cleaned inside and outside, such as in the first firing and in the sixth firing, the GSR deposits on the two hands were almost identical in amount. In the same study (without replicates) when the gun was not cleaned the deposition increased sharply (about 10–12 folds) and then diminished suddenly, for example, in the fifth firing (Table 1A). The majority of these excess particles were Pb particles (See rows for 3rd and 4th firings, Table 1A). This uncontrolled, sporadic GSR emanation suggests that guns could display a self-cleaning property. As Walker (30) has observed, "The residues of previous discharges, lodged as fouling in the gun barrel, are swept out by the bullet." The difficulty is that one does not know at which subsequent firing the contaminant Pb or GSR particles will be swept out and how completely. Presumably, these particles accumulate in piles or layers until a thickness is reached when these are partially blown off by the passage of a bullet. The build-up of residual Pb or GSR particles inside the barrel, the chambers, and the trigger housing of an unclean gun have the potential for carry-over of the deposited metals (Pb, Sb, Ba) (cf. 27,28,32).

With the pre-cleaned gun, however, the elements of GSR do not agree from one firing to another (See for example, 1st and 6th firings, Table 1A). Only their total counts (i.e., density distribution) agree from one firing to another. When the same shotgun was test-fired in a normal manner, i.e., no blockade was used, the same amounts (ρ's) of GSR were obtained from the back of the hands of the test-shooter as obtained in the first and the sixth firings in the "muzzle-blast block" (Table 1A) (Compare: Basu and Ferries (17)).

The main observation during the "trigger-blast block" was that no GSR was deposited on the shooter's hands when the shotgun was pre-cleaned (1st and 6th firings, Table 1B). When the shotgun was unclean and was continually used, a small number of particles were deposited on the shooter's hands; for example, in the 3rd, 4th, and on the 5th firings (Table 1B). These deposits were due to minute (diam. 0.1 μm to 0.5 μm) lead (Pb) particles and their deposition was quite unsystematic.

The trend in results of the "muzzle-blast block" with pre-cleaned and unclean rifles was similar to the previous results obtained with the shotguns (Table 1A). A slight difference was observed in the "trigger-blast block" in which case, whether the rifles were cleaned or uncleaned, a few lead (Pb) particles were consistently found on the muzzle supporting hand of the test-shooter. The trigger hand of the shooter did not exhibit these (Pb) particles.

In the "trigger-blast block" experiments, only the muzzle-blast residues had the chance to deposit onto the shooter's hands but this deposition seldom occurs with pre-cleaned shotguns. The same weapon was used in both "block tests." The hand positions of the shooter were also identical. A comparison of the hand deposits (Table 1A versus 1B) in these two tests supports the view that the GSR on the shooter's hands are mainly breech residues (compare: Wolten et al. (2)). Because very few muzzle residues settled from the air onto the shooter's hand in our experiment, the GSR issuing through the breech mechanism must have struck these hands at the instant of firing.

In retrospect, the results of the "trigger-blast block" experiments have confirmed Krisnan's (22) speculation that with longarms "GSR from the muzzle-blast does not have much opportunity to deposit on the shooter's hands." These results also support the observation of Wolten et al. (2) that muzzle-blast residues "appear to play a secondary role in the production of hand deposits" (2).

GSR Capture

The main results of GSR capture (Tables 2A and B) were two-fold: 1. In the first firing when the shotgun was clean, the captured muzzle-blast GSR (Table 2A) and trigger-blast GSR (Table 2B) was small. The net capture of either kinds of GSR after the 3rd, 4th, and the 5th firings increased several-fold but not proportionately with the total number (three) of shots. The weapon was uncleaned in these firings. 2. The captured trigger-blast GSR were predominantly regular spheroids with rather smooth surface topography (64 out of 74 GSR). Unlike these GSR, the captured muzzle-blast were predominantly irregular spheroids (42 out of 46 GSR).

Again, this observation was indicative of a variable emissive property of unclean weapons. The capture of either kind of GSR can be explained. The main beam of fresh, formed GSR behind the bullet are ejected elastically (no loss of energy) forward. Very few of these muzzle residues will deviate at the muzzle-exit to strike back at the glue layer (disk) at an angle of 90°. Only the stagnant particles of the gun barrel dispersed by the bullet and by the expanding gas mixture can exhibit this blow-back effect (Table 2A). The captured breech GSR suggest that these were perhaps ejected at sharp angles, grazing the barrel of the shotgun (Table 2B). Notice that these particles were predominantly lead (Pb) spheroids e.g., 66 out of 74. The muzzle hand of the shooter had a larger proportion of these lead (Pb) spheroids. This hand of the shooter could have intercepted these lead (Pb) particles. The contrast of the residue morphology in 2 (above) is usually a function of the firearm and the ammunition and it has been used elsewhere to reconstruct self-inflicted shooting deaths (1) (See also Discussion).

GSR Emission Mechanics

The conventional knowledge based upon the discharge pattern of open-breech weapons (e.g., revolvers), is that breech residues spread over the back of the trigger hand because this residue spread is due to a backward thrust on the primer by the exploding gun powder. The same process is expected with shoulder firearms. Four weapons (12 and 20 gauge single-shot double-barreled hinge frame shotguns, 12 gauge pump action shotgun, and a 30.06 Springfield caliber pump action rifle) were used to determine the basic mechanism of GSR escape from the breeches of these weapons. The color test using sodium rhodizonate was used for determination of residues on cloths (5,29). The main observation will be explained with a 12 gauge hinge frame shotgun (Fig. 1).

As expected (Fig. 1A, arrow), the residue color due to lead (Pb) was the strongest at the site encompassing the breech (hinge) and the hammer-gap and, it was the weakest at the trigger-pull. Definite color striations which were slightly less intense were also observed on the test cloth at several unequal intervals along the top surfaces of the double barrel. These striations were oriented perpendicular to the length of the barrel. This pattern was variable from shot to shot but persisted in six single firings with the same shotgun regardless of whether the right or the left barrel was used. Because the barrels exhibited no apparent leak or crack, this residue pattern was positive indication of the residue being tunneled along the valley between the two barrels. The shooter's support hand was under the double barrel and therefore the residue (Pb) flow above the barrel was intercepted by the cloth and this produced the residue striations at irregular intervals. With the pump action shotgun and rifle the residue (Pb) color was the strongest at the ejection chambers. Superimposed on these colors, there was a faint persistent pattern representing several arc-like striations of residue color. These were parallel to each other but perpendicular to the length of the barrel. This pattern was exhibited along the entire length of the barrel. This particular pattern on the test cloth confirms that with closed breech weapons: (a) the trigger-blast GSR escapes the breech at sharp angles grazing the surfaces of the weapon, and (b) these GSR can travel forward a distance of 0.9 m to 1 m (3 ft to 4 ft) up to the muzzle and perhaps beyond the muzzle. Clearly, these are the GSR which struck the "glue-lift" disk on the shooter's side of the screen in the "muzzle-blast block" experiments (Table 2B). Conceivably, these particles can also strike the support hand of the shooter, or any hand in close-proximity of the barrel.

TABLE 2A—*Deposition of muzzle residue at a glancing angle on a glue layered disk on the muzzle side of the screen in "Muzzle-blast block."*

	Number of GSR Particles per Four Circles (7.1 mm^2) Having Different Elemental Compositions (ρ)				
Experiments*,†	Full GSR's (PbSbBa)	Binaries (PbSb/PbBa/BaSb)	Monomers (Pb/Sb/Ba)	Range of Total Diameters (μm)	GSR in 4 Circles
1st shot with a pre-cleaned shotgun	2	1	1	0.5–6	4
2nd shot with the uncleaned shotgun	2	2	1	1–5	5
3rd, 4th, and 5th shots, i.e., total 3 shots with the uncleaned shotgun	42	0	4	0.5–6	46 (4 regular spheroids + 42 irregular spheroids)

*Distance (vertical) of disk from muzzle = (6 in.).
†Shotgun and ammunition same as in Tables 1A and 1B.

TABLE 2B—*Deposition of trigger-blast residues on a glue layered disk on the shooter's side of the screen in "Muzzle-blast block."*

	Number of GSR Particles per Four Circles (7.1 mm^2) Having Different Elemental Compositions (ρ)				
Experiments*,†	Full GSR's (PbSbBa)	Binaries (PbSb/PbBa/BaSb)	Monomers (Pb/Sb/Ba)	Range of Total Diameters (μm)	GSR in 4 Circles
1st shot with a pre-cleaned shotgun	1	0	4 Pb	0.5–1.0	5
2nd shot with the uncleaned shotgun	1	0	5 Pb	0.2–7	6
3rd, 4th, and 5th shots, i.e., total 3 shots with the uncleaned shotgun	8	0	66 Pb mainly	0.2–10	74 (64 regular spheroids + 10 irregular spheroids)

*Distance (vertical) of disk from shotgun barrel = 15 cm (6 in.) (opposite to the disk in Table 2A).
†Shotgun and ammunition same as in Tables 1A and 1B.

The breech GSR on the trigger hand arise from the backward component of emissions from the breech gaps. The residues issuing through the hammer gap contributes significantly to this hand deposit.

GSR Stopping

The plastic bags used in the "trigger-blast block" experiments show that GSR deposited variably onto the interiors of these bags depending upon their proximity to major leaks of the weapon. With the hinge frame shotgun in Fig. 1, these deposits in relation to the leaks were as follow: hinge (breech) and hammer-gap ("hammer-cut"): approximately 180 GSR/4 circles; trigger-pull and under the gun: approximately 60 GSR/4 circles. These GSR were collected by lifting so that the plastics could be examined for any features like pores and punctures which would only occur if the impacting GSR were hot enough to melt the plastic. None of these features were detected. The plastic surfaces exhibited numerous micron size shallow cavities and very few GSR. These cavities were crater like impressions due to GSR embedments and/or impacts. The presence of variable but significant amounts of GSR on the collectors and the finding of no pores in the plastics was a strong indication that trigger-blast residues were, in fact, barricaded by the sealed plastic bags.

Consistency of Density Distribution (ρ)

The "forced deposition" of GSR also prevails in the shooting of open-breech weapons (handguns). If a revolver (.38 caliber Smith & Wesson®) was pre-cleaned and the ammunition and the grasp of the firing hand on the weapon remain unchanged, the same amount of residue was deposited per firing on the back of the firing hand (Fig. 2, line on top). This particulate distribution or "density distribution," which takes into account all deposited particles containing one, two, and three characteristic elements of GSR (Pb-Sb-Ba), changes only slightly (10% or less), when a smooth plastic glove was on the shooting hand (Fig. 2, lower line). This comparison between GSR deposits on the bare hand versus the smooth hand suggests that surface textures of hands have little influence on "density distribution" (ρ). Therefore the forced deposition of GSR must be like a blasting process. The consistency of density distribution (ρ) has been verified by test firing 12 revolvers (0.22–0.45 calibers), 5 pistols, and 7 shotguns (12–20 gauge) (See ref. 1 for a partial list of these weapons). Within each such distribution, the elements (Fig. 3), the morphologies (Fig. 4), and the sizes (Fig. 5) of residue particles vary significantly from one shot to another. The variation in observed morphologies (viz. 15% to 20%) was much less compared to the variations in elements (viz. 50% to 62%) and sizes. Among the observed morphologies with the revolver (.38 cal. Smith and Wesson®) used in Fig.(s) 2–5, regular spheroids ("S") and nodular spheroids ("NS") accounted for 60% to 70% of total GSR counts per shot. The remaining 30% to 40% of GSR counts was due to irregular spheroids ("IS") and peeled-orange spheroids ("POS"). The hollow spheroids ("HS") and hollow peeled-orange spheroids ("HPO") were not detected on the shooting hand with this revolver (For a description of these various GSR morphologies, See Basu and Ferriss (17)).

The regular spheroids ("S," "NS," and "POS") from the shooting hand (hand on trigger) possessed remarkably smooth surface topography, which made them distinct from the irregular spheroids ("IS").

The size distribution studies (Fig. 5) indicated that the density distribution criterion should not fail unless very large GSR (diameters 10–30 μm, 30–100 μm, etc.) particles were formed. These "very large" GSR particles occupy two out of six (total) size groups (See caption to Fig. 5). These are also produced with uncleaned firearms. Because in most situations (casework) the submitted gun

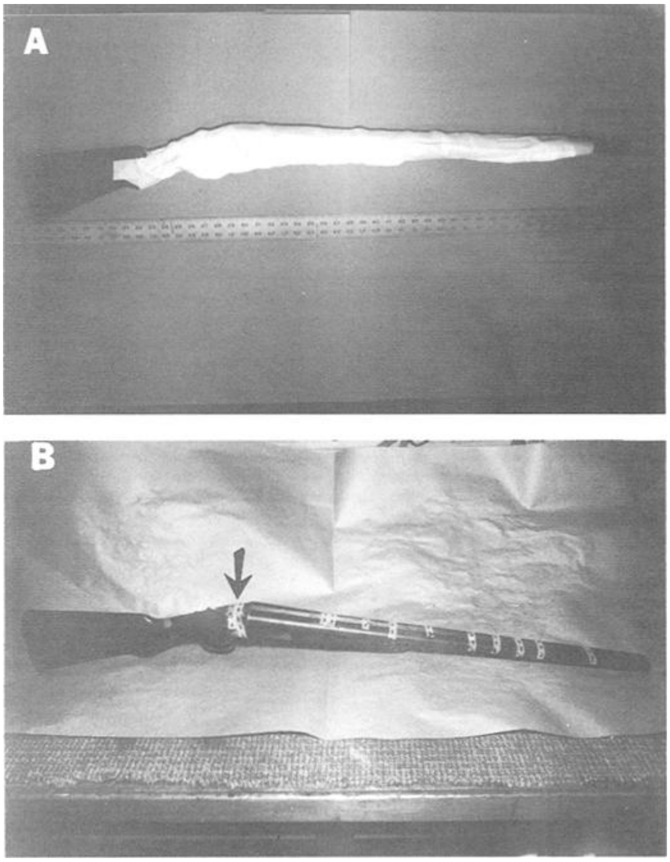


FIG. 1—*Test of GSR leaks of a 12 gauge double-barreled, hinge frame shotgun with sodium rhodizonate (29). One firing with Federal® $2^{3}/_{4}$ in., high power cartridges. A—Shotgun covered with a test cloth before one firing. B—The labeled regions of the gun corresponding to developed colors of the residues on the test cloth after the firing. The arrow shows the region (breech) causing the strongest residue color.*

has to be test fired whether it is clean or unclean in its interior, the probability that very large GSR will occur with firing this gun is 2/6 × 1/2, or 1/6 (i.e., 16.6%). Therefore the maximum probability of the failure of density distribution is 16.6% or one out of six or seven firings. This drawback has been overcome by additional test shots with the pre-cleaned gun (1).

GSR Transfer

The trigger-blast residues are literally sprayed onto the back of the shooter's hand(s). This has the advantage that one can distinguish the shooter from a non-shooter. The disadvantage is that residues are also blown onto the escape ports and other exposed surfaces of the gun. If a non-shooter picks up a fired gun residues are readily transferred to the palm of the holding hand. Two revolvers (each .38 caliber), two semi-automatic pistols (.22 and .25 caliber) and two shotguns (12 gauge and 20 gauge) were used to obtain estimates of transferred GSR to the palm of two non-shooter's hands (one per person) under controlled conditions. These conditions were then varied from experiment to experiment. The variables were the number of firings, the specific area of a gun within the hand grasp, and the number of touches or rubbing activities with increasing time of contact with the surfaces of the gun.

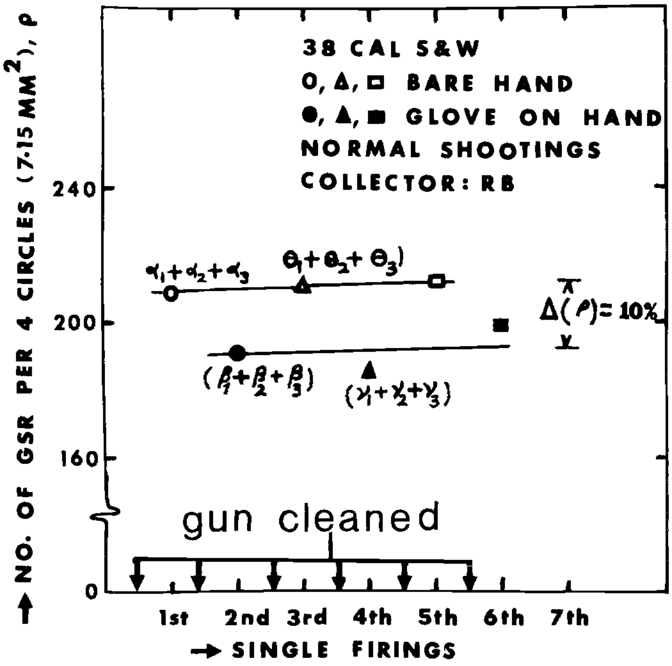


FIG. 2—*Consistency of density distribution (ρ) of GSR on the back of the firing hand in single firings with a pre-cleaned gun. Gun—.38 caliber, Model 10, Smith & Wesson® revolver of a suicide victim; Ammunition—.38 spl. Smith & Wesson jacketed bullets. The density distribution (ρ) on glove (solid) was about 10% less than the density distribution on bare hand (open) of the shooter.*

Table 3 contains representative results obtained with two .38 caliber revolvers. Because no activities of the shooter and the non-shooter were allowed that might cause transfer of GSR from the back of the hand to the palm, and vice versa, the contrast of density distribution (ρ) on the back of hand versus the palm was opposite between the shooter and the non-shooter (compare: Table 3, row 1a and 1b). The degree of GSR transfer was only slight (12%–29%) when the non-shooter picked up the fired gun holding the trigger in the same manner as the shooter normally does to fire a revolver (See Table 3, rows 1b, 2b, and 3b). When the barrel and the cylinder were touched, the transferred residues exceeded the hand deposit of the shooter. Furthermore, when these areas (barrel and cylinder) were deliberately rubbed or touched many times with the palm the yield of GSR increased significantly (compare: Table 3, rows 2c and 3c). The GSR deposits on the back of the hand of the shooter did not increase in proportion with the number firings. It is proposed that a portion of the hand deposits (> 28%) was blown off by the residue blast in the successive firings. Krishnan et al. (9), Guinn (11), and Goleb and Midkiff (12) also observed this effect using other techniques, such as, atomic absorption and neutron activation analysis. Matricardi and Kitty (4) did not take this effect into consideration. The same effect happens with the deposits on the external surfaces of a gun. Some parts of the firearm (e.g., cylinder) retain more particles than the other parts, due to proximity to the escape ports (e.g., cylinder gaps). Remote parts of a gun (e.g., butt) receive very few particles from the trigger blast because the latter is partially blocked by the shooter's grasp of the weapon. Touching this area did not increase the yield of transferred GSR even on multiple firings (compare: Table 3, rows 1b and 2b).

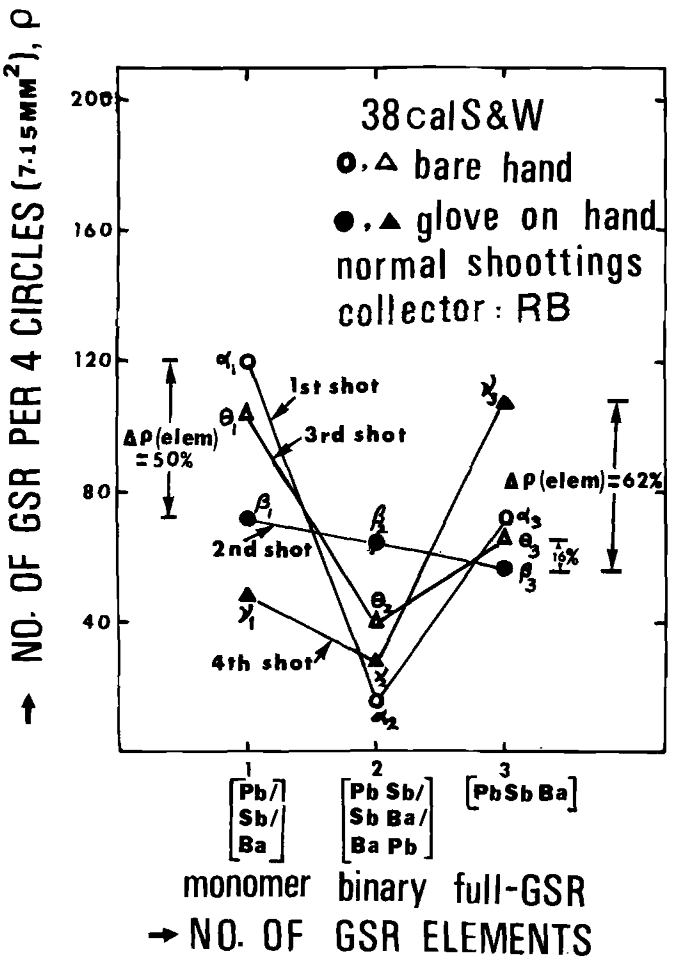


FIG. 3—*Variability of elemental distribution of GSR. The GSR obtained in the first four shots in Fig. 2 (circles and triangles) were arranged into three sub-groups, viz., monomer, binary and full-GSR. See abscissa and Tables 2 and 3, or Basu et al. (1) for explanation of these terms.*

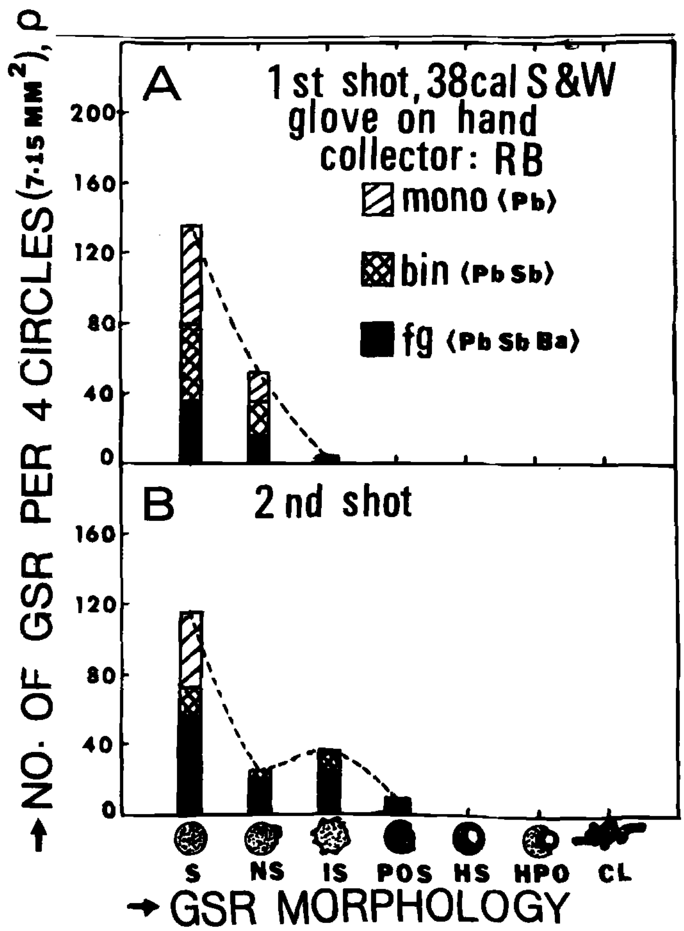


FIG. 4—*Variability of morphologic distribution of GSR. The same variability was exhibited by the GSR on the bare hand. Notations: S—smooth spheroid, NS—nodular spheroid, IS—irregular spheroid, POS—"peeled-orange" spheroid, HS—hollow spheroid, HPO—hollow "peeled-orange's" and CL—cluster (17); mono—monomers; bin—binaries and fg—full GSR(s). The gun and ammunition were the same as in Fig. 2.*

Discussion

The discharge of GSR upon firing a weapon is due to detonation of primer, followed by the controlled burning of gunpowder (23). Because the discharge takes place under high pressure, a forced deposition of GSR is the result. Wolten et al. (2) suggested that GSR may deposit onto the shooter's hands by a blasting mechanism. They also believed that the GSR on the shooter's hands are mainly the breech deposits. Thus Wolten et al. (2) made the first attempt to develop a concept that would link the source of GSR with the mechanism of GSR deposition on the shooting hand(s). The block-tests (Tables 1 and 2), the density distribution tests (Fig(s). 2–5) and the gun leak test (Fig. 1) in the present study offer experimental support for this conclusion. This discussion will highlight this concept, and attempt to resolve many conflicting issues from the past and the present.

The Gulf Atomic General Group presented evidence that wind velocity has no effect on the GSR deposition process (8). This observation is inconsistent with the theory of settling of "airborne" GSR on the shooter's hand(s) (3). Their observation merely suggests that the rate of deposition (i.e., capture) of GSR on surfaces is unaffected by the wind velocity. The results are the same as in our assumption that GSR deposition takes place by a blasting mechanism at the instant of firing. Our tests were conducted inside a firing range where the airflow by air conditioning had no effect on deposition process.

In controlled studies of GSR in the laboratory firing range, GSR particles are usually collected immediately after the firing (1,2,9–17). The rationale for such time controlled standard collection is two-fold: 1. Holding of the shooting hand(s) within the gun smoke for several seconds after the firing did not result in the deposition being appreciably increased. 2. Collection soon after the firing, or during the firing, also avoids any loss of GSR due to any inadvertent activity of the test shooter (13). In the reconstruction of suicides, using handguns, shotguns and rifles, when collections were made at the crime scene, the number of recovered GSR from the victims' hands was equivalent to that resulting from the reconstructive firing (1). A similar observation was made by Wolten et al. (2). Furthermore, in handgun firings, GSR seldom deposit on the non-firing hand of the shooter. Wolten et al. (2) opined that this hand of the shooter and any hand of a by-stander have to be "in the lines of flight of GSR." Both Thornton (20) and Basu (25) reached an identical conclusion that a by-stander's hand has to be in close proximity of a discharging firearm in order to have GSR on it. All these independent lines of evidence suggest that GSR must be blown-in or blasted on the shooter's hand(s).

As Wolten et al. (2) has remarked, a settling mechanism of "airborne" GSR would markedly favor an excess of larger GSR

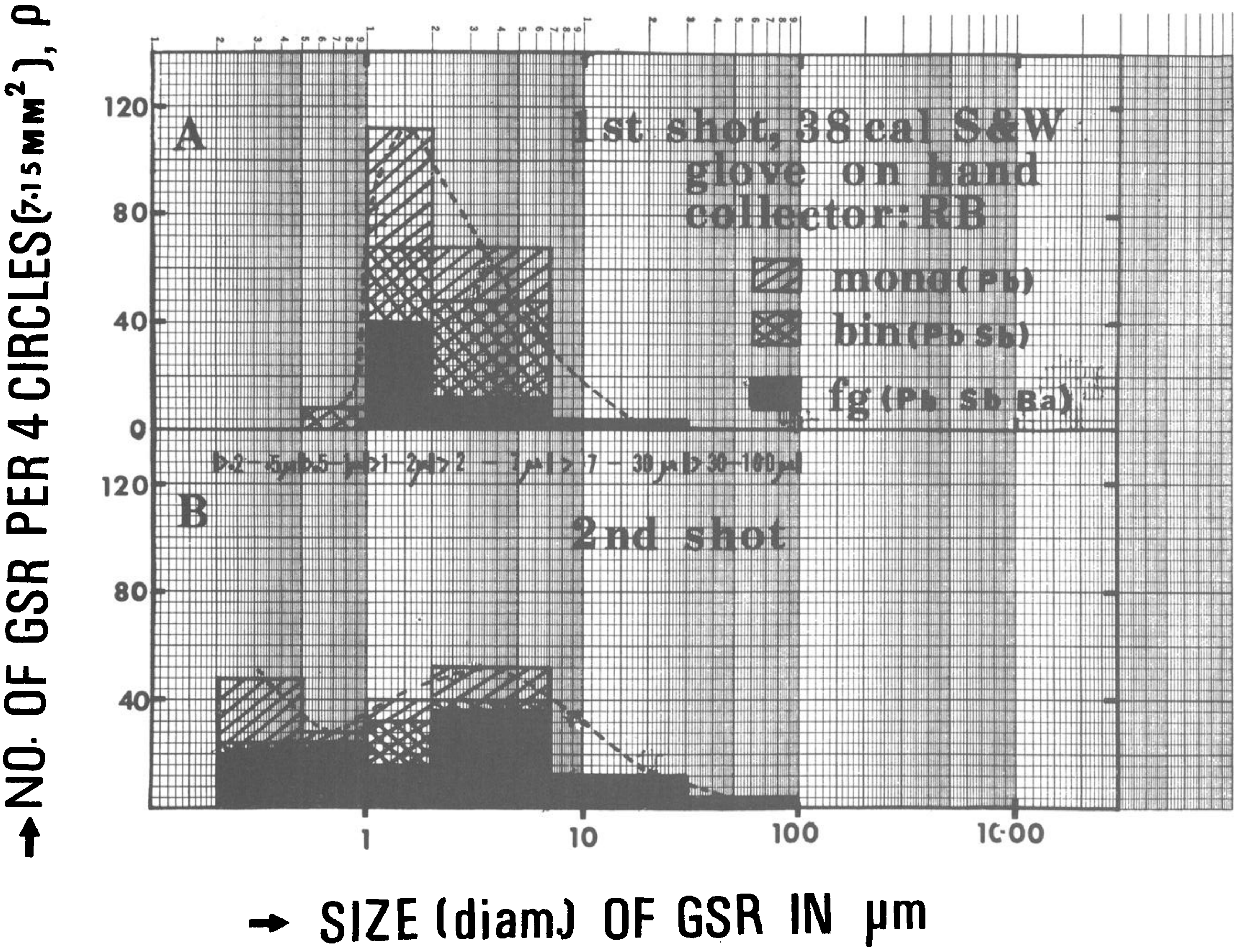


FIG. 5—*Variability of size distribution of GSR. The six size groups were—>.2 to .5 µm, >.5 to 1µm, >1 to 2 µm, >2 to 7 µm, >7 to 30 µm, and >30 to 100 µm. The peak diameters were 1.6 µm in the 1st shot (A) and 3.7 µm in the second shot (B). The gun and ammunition were the same as in Fig. 2.*

TABLE 3—*GSR transfer by contact with a fired weapon.*

		p or # GSR Particles/Four Circles (7.1 mm^2) of R.B.—Right Hand Back; R.P.—Right Hand Palm; L.B.—Left Hand Back and L.P.—Left Hand Palm				Transfer of GSR: Non Shooter's Hand × 100 (%)
Experiment*	Experiment details (shooter/non-shooter)	R.B.	R.P.	L.B.	L.P.	Shooter's Hand
1.	a. Shooter's hand (R), tight grasp, 1 firing with pre-cleaned gun (no barrier at muzzle)	156	0	0	0	
	b. Non-shooter's hand (R), tight grasp on trigger and rear of gun for 15 s.	0	36	0	0	23%
2.	a. Same as 1a except 3 successive firings: gun not cleaned between 2nd and 3rd firings	339	0	0	0	
	b. Same as 1b	0	42	0	0	12%
	c. Non-shooter's hand (R), tight grasp on cylinder and barrel for 15 s.	0	504	0	0	150%
3.	a. Shooter's hands (R&L), one simulative suicide firing, that is, 1 firing with pre-cleaned gun held against a target at muzzle; tight grasp of R-hand on trigger and rear of gun with L-hand support under R-hand (cf. Basu et al., (1)).	88	0	49	2	
	b. Same as 1b and 2b	0	40	0	0	29%
	c. Same as 2c plus rubbing or several touches on cylinder and barrel with palm	0	268	0	0	195%

*Gun and ammunition: For expt. (s) in (1) and (2): .38 caliber Smith & Wesson revolver; Remington 158 gr round-nose.
For expt. (s) in (3): .38 caliber Smith & Wesson revolver; Winchester Western 145 Lubaloy.

particles, which is contrary to the observed results (Fig. 5). The only particles which occasionally deposit from the gun smoke are lead (Pb) aerosols of diameter 0.1–0.5 μm (Table 1B). It is worth mentioning that both Wolten et al. (2) and Matricardi and Kilty (4) had made quite similar observations about these airborne lead particles but their opinions about the settling of "airborne" GSR were diametrically opposite (See Introduction).

During the early 1980s, the issue of the settling of "airborne" GSR was given a new twist. The issue that emerged was that the muzzle-blast GSR may settle from the air onto the shooter's hands by a transfer of the gun smoke toward the shooter's hands (22). The block-tests in Tables 1 and 2 have clearly shown that even this mechanism of GSR deposition does not hold true with pre-cleaned shotguns and rifles. With unclean weapons the lead (Pb) residues of previous firings lodged as fouling in the interior of the gun are blown off irregularly (30) and these are the only residues which may overlap with the fresh breech deposits. These idle residues (Pb) are possibly blown off by the blast waves of first and second precursors which precede the blast wave of propellant gas flow (31). Because these residues are of the size of aerosols (diam. 0.1–0.5 μm) these could be blown backward by the rapidly expanding barrel shock at the muzzle exhaust. Only larger particles which precede the bullet and follow after the bullet can overtake this flow field (31). These will seldom blow back.

The importance of pre-cleaning firearms prior to any shooting for gunshot residue research cannot be over-emphasized (1,17,24–28). There is current evidence supporting this view. The metallic (Pb, Sb, and Ba) residues of previous firings, particularly the lead (Pb) residues lodged as fouling in the gun's interior, can be a major source of mixed composition GSR when different types of ammunition, including the lead-free ammunition (e.g., CCI's Blazer®, Geco's Sintox®, etc.), are subsequently fired using the same firearm (27,28–32).

Krishan (22) had made a serious effort to suggest that the backward spread of the muzzle-blast can increase the GSR found on the non-firing hand and the trigger hand during tests with longarms (See Table 11–2 in ref. 22). His data can also be explained by the lodging of residues in the gun's interior. As each cartridge is spent a portion of the primer residues is always retained as deposits on the walls of the barrel, gun chamber, and the trigger housing (1, 28,30–32). The remainder escapes *via* the breeches and the muzzle. The retention of residues inside the gun increases with the increase of barrel length. Thus if the same cartridges are spent in a regular barrel shotgun and one with a sawed-off barrel, more hand deposits will occur with the sawed off barrel than with the regular barrel. Contrary to Krishnan's (22) belief, it will be shown that only the breech residues are subject to a backward thrust, not the muzzle-blast residues (1).

The results of the block-tests (Tables 1 and 2) and the gun leak test by residue color with sodium rhodizonate (Fig. 1) show that the breeches of the shotguns and rifles used, are not necessarily leak-proof to the micron-size GSR. Even Krishnan (2) believes that "Individual guns, however, may leak at this point (breech) due to peculiarities in the gun or the condition of the weapon." Whether the shotguns and rifles used in the block-tests (Tables 1 and 2) had some peculiarities or not, the tests with these weapons have established that breech residues contribute the most to the GSR deposition on both hands of the shooter of a longarm. Because this is true for "close-breeches" which may have only minute leaks, it must also be true for "open-breech" weapons (e.g., cylinder gaps, gaps of hammer cut, etc., of revolver) (cf. Wolten et al. (2)).

It follows that the block-tests can be applied to handguns as well. With handguns (e.g., .38 spl S & W revolvers) it has been shown in one laboratory by a different technique (sound-strobe illumination photography) that the gaseous discharge of trigger-blast spreads over the back of the trigger hand whereas the muzzle-blast is directed forward from the muzzle (personal communication: Elemental Analysis Unit, FBI Lab., Washington, D.C.). The two blast patterns seldom overlap (1).

There is no doubt that the breech residues (trigger-blast) deposited on the support hand of the shooter. This hand of the shooter for the most part in Table 1A or 1B (top) is under the barrel and it has no chance to have residues settled from the air. The data in Table 2B shows that breech residues can even strike the "glue-lift" disks on the "muzzle-blast" block screen which is farther than the support hand of the shooter. This evidence (Table 2B) and the hand deposits (Table 1A) suggest that the primer gas mixture issuing through the breeches of a longarm are subjected to both backward and forward thrusts.

Several independent sources of evidence indicate that breech GSR are subject to a backward thrust resulting in instant deposition of GSR on the exposed surfaces of the shooter's hands and the forward facing surfaces of the shooter's body, including his/her forehead, nose, mustache, and eye-brows, all of which coincide with the axis of the shooting weapon (Wolten et al. (2), Metropolitan Police Forensic Science Laboratory (33), and Basu, unpublished). Recently, Schwartz and Zona (34) have recovered GSR particles retained in nasal mucus of the shooter several hours after the firing. Although these authors (34) have characterized the detected GSR as "airborne" GSR (AGSR) these could be the blown-in residues of trigger-blast, which the shooter inhaled during the firing. If the subject in their study was a non-shooter who had entered into the firing range after the firing and remained there for 3 min, then, the detected GSR in his/her nasal mucus could be safely attributed to "airborne" GSR. These studies are lacking in Schwartz and Zona (34). Furthermore GSR deposits on the mustache and nose could accompany the nasal discharge of mucus as these are blown onto a surface in their method.

The "blasting mechanism of GSR deposition" is often difficult to understand for a perceptual reason. This has to do with the rapidly cooled down states of semi-solid GSR as these particles strike the exposed surfaces of the shooter's body. On the one hand, the impacting GSR do not seem to burn the skin of the shooting hand, or the plastic glove of mannequin hands in suicide reconstructions (1). On the other hand, if the shooter's hand obstructs the open breech (e.g., cylinder gap) of a revolver during the firing, the trigger-blast scorches the skin while the issuing breech GSR embed into the skin (1). These two observations of an earlier report (1) and the frozen morphologies of GSR (23) together gave clues to the possibility that these particles cool down extremely fast. Additional evidence has been obtained in the block-tests. The crater-like impressions on the plastics used for "trigger-blast block's" were evidence that the impacting breech-GSR were not even hot enough to melt these plastics. Therefore as these particles reach farther, they are not expected to have any heat to transfer and to cause burning. Only the momentum of GSR is delivered to the skin of hands and the face of the shooter.

This forced deposition of GSR with a pre-cleaned, well-conditioned weapon is usually systematic. This is analogous to deposition of metallic and non-metallic vapors in vacuum evaporation in which the deposition rate is influenced mainly by the vapor pressure of the evaporant gas molecules and by the input material. Thus, density distribution of GSR is less variable than other distributions based upon GSR elements, sizes, and morphologies (Fig(s). 2–5). At present, this density distribution of GSR (1) and the spatial distribution of GSR on the firing hand (18) are the criteria to reconstruct a shooting crime using the SEM-EDX technique. Density distribution (ρ) is not perfect by itself. This criterion fails only in one firing out of perhaps six, when the large size GSR are formed at the expense of smaller fluid-GSR. This drawback can be overcome by additional test shots with the pre-cleaned gun.

The blasting process of GSR deposition gives rise to the residue (density) contrast on the back of hand versus the palm and vice versa. This contrast distinguishes a shooter from a non-shooter (Table 3). The disadvantage of the blasting process is that a heavy amount of GSR could be transferred to a non-shooter's hand due to physical contact with the most contaminated areas of the fired weapon.

The block tests can be accessory to interpretation of certain crimes. For example, if no GSR is detected on the back of hands, despite that GSR collections have been made at the crime scene, then possible blockades of "trigger-blast GSR," such as gloves, towels, cloths, and handkerchief, etc., should be found at the crime scene. The "muzzle-blast GSR" are often irregular and accompany a large distribution of bullet-derived GSR, bullet particles (Pb) and bullet fragments which are determined by their association with non-GSR metallic elements like copper (Cu), zinc (Zn), nickel (Ni), and iron (Fe), etc., which originate from the bullet coating and/or casing. These characteristics have been used in the interpretation of combined homicide-suicide cases.

The experiments in this report had to be limited to only single firing tests, so that the deposition mechanism of GSR can be revealed. Whether any difference in conclusion should be found in multiple firing situations, would have to be determined. The residues on multiple firings do not necessarily add up or increase with the number of discharges (Table 3, row 2) (cf. Krishnan et al. (9), Guinn (11), and Goleb and Midkiff (12)).

Conclusion

When a firearm is discharged, the GSR issuing through the breeches of the firearm are blown at once on the immediate surfaces of the firearm, including any hand in contact with, or in close proximity to, the firearm. This forced deposition is essentially a blasting mechanism in which the rapidly cooled down GSR impart only momentum but no heat energy to the surfaces these strike. Thus the hand deposits of the shooter are mainly the trigger-blast residues. The rate of deposition of these residues is not influenced by the substrate surface characteristics. If the gun is pre-cleaned and the ammunition and the hand grasp on the firearm remain unchanged, a reasonably constant amount of residues is deposited per firing on the back of the firing hand. This density distribution of GSR is the most practical criterion required to reconstruct a shooting crime, and for such reconstruction the gun must be pre-cleaned (See ref. 1 for this determination).

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