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ORIGINAL ARTICLE

GSR deposition along the bullet path in contact shots to composite models

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Abstract In contact shots, all the materials emerging from the muzzle (combustion gases, soot, powder grains, and metals from the primer) will be driven into the depth of the entrance wound and the following sections of the bullet track. The so-called "pocket" ("powder cavity") under the skin containing soot and gunpowder particles is regarded as a significant indicator of a contact entrance wound since one would expect that the quantity of GSR deposited along the bullet's path rapidly declines towards the exit hole. Nevertheless, experience has shown that soot, powder particles, and carboxyhemoglobin may be found not only in the initial part of the wound channel, but also far away from the entrance and even at the exit. In order to investigate the propagation of GSRs under standardized conditions, contact test shots were fired against composite models of pig skin and 25-cm-long gelatin blocks using 9-mm Luger pistol cartridges with two different primers (Sinoxid® and Sintox®). Subsequently, 1-cm-thick layers of the gelatin blocks were examined as to their primer element contents (lead, barium, and antimony as discharge residues of Sinoxid® as well as zinc and titanium from Sintox®) by means of X-ray fluorescence spectroscopy. As expected, the highest element concentrations were found in the initial parts of the bullet tracks, but also the distal sections contained detectable amounts of the respective primer elements. The same was true for amorphous soot and unburned/partly burned powder particles, which could be demonstrated even at the exit site. With the help of a high-speed motion camera it was shown that for a short time the temporary cavitation extends from the entrance to the exit thus facilitating the unlimited spread of discharge residues along the whole bullet path.

Keywords Contact shot · Gunshot residues · Primer elements · Composite model

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Introduction

The majority of gunshot wound misinterpretations result from the erroneous assumption that the exit wound is always larger than the entrance wound [3, 11, 23, 25, 31]. Investigators tend to confuse entrances with exits especially in contact shots with stellate wounds located in body regions with a bony support [2]: In such cases, the tears radiating from the bullet entry hole may be much longer than the diameter of the tissue severance at the exit site. Therefore, one should never differentiate between entrance and exit by simply comparing the wound dimensions.

If a questionable wound exhibits the features of a contact shot, the presence of the respective signs can be regarded as

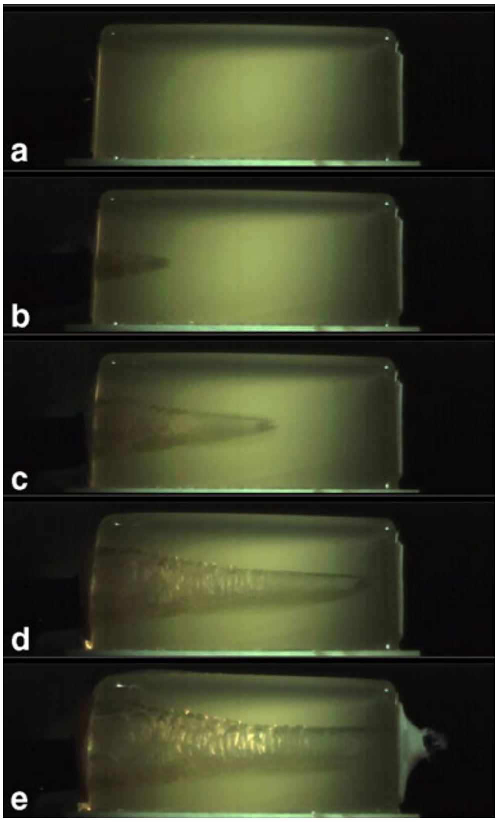


Fig. 1 **a–e** High-speed motion camera documentation showing the formation of the temporary cavity

evidence of a bullet entrance caused by a discharge with the muzzle held against the body. In this context, some authors claimed that a contact (entrance) wound can be identified on the basis of the local deposition of soot [31] and/or propellant particles [11]. According to Spitz [32], the likelihood of soot or gunpowder in tissues near the exit wound is "remote", even if the gun was pressed tightly against the body. As an exception, some gunpowder and even soot may be found when a thin part of the body such as the hand is involved [32]. Di Maio [3] admitted that "on occasion" carbon monoxide and ball powder can travel through the body, but he never saw flake powder or soot at the exit site.

In order to investigate the propagation and deposition of gunshot residues along the bullet path, we fired contact shots to composite models of gelatin and skin-simulating soft tissue targets.

Materials and methods

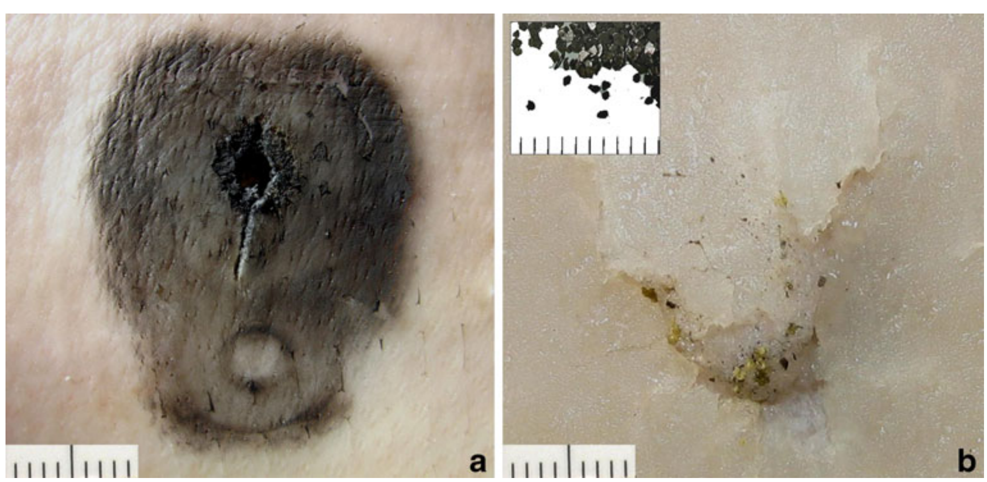
Gelatin blocks measuring 25×12×12 cm (length of the bullet path 25 cm) were prepared in accordance with the recommendations for ballistic gelatin in a 10% concentration [7, 8, 10, 13, 28, 34, 35]. Skin pieces from the belly region of freshly slaughtered pigs were fixed to the front ends (12×12 cm in size) of the gelatin blocks with dental instant glue (Renfert, Hilzingen, Germany) in the areas of the later entrance and exit site.

The shots were fired from a pistol (Heckler & Koch USP Compact Pistol), caliber 9×19 mm, using cartridges with 9-mm Luger full-jacketed bullets manufactured by Dynamit Nobel (Troisdorf, Germany). The bullet mass was 8 g, the average muzzle velocity amounted to 350 m/s. The igniters contained either Sinoxid® with lead styphnate and barium nitrate as main constituents (test shots 1–5) or Sintox® consisting of zinc and titanium-based priming compounds (test shot 6). To ensure unchanged pressure of the muzzle at the moment of discharge, the pistol grip was fixed in a rack whereas the composite model was drawn against the barrel with a tensile force of 8 N (indicated by a spring scale).

The test shots were video-documented by means of a high-speed motion camera (Photon FastCam APX RS, 2,000 fps) from a 90° side view. After each discharge, pictures were taken of the bullet entrance and exit holes in the pig skin and the lateral aspects of the gelatin blocks.

After firing the shots, the gelatin blocks were laminated in 1-cm-thick layers and then the area of the bullet track

Fig. 2 **a** Contact bullet entrance in pig skin, **b** bullet exit with deposition of mostly unburned powder particles and amorphous carbonaceous material; the image in the *left upper corner* shows graphite-coated unburned flake powder particles from the propellant of the cartridge



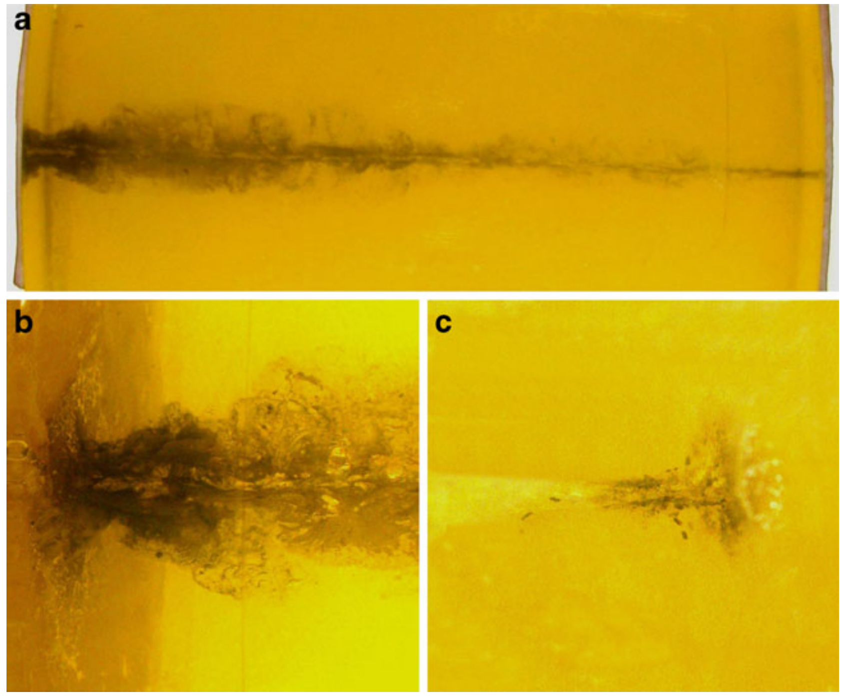


Fig. 3 **a** Transmitted light print of the 25-cm-long bullet track, **b** initial section with intense blackening, **c** final section containing powder particles

was cut out of each slice as already described in other papers [7, 10, 34, 35]. The excised gelatin pieces had a volume of approximately 500 µl. They were liquefied at 50°C, and the particulate matter was filtered (maximum pore size of the filter paper 1 µm, Macherey-Nagel, Düren, Germany) by applying sub-pressure with the help of a water-jet vacuum pump (MTC Haldenwanger, Waldkraiburg, Germany). The resulting sediment was first scrutinized with a stereo microscope at a 25-fold magnification (OPMI 11, Carl Zeiss GmbH, Jena, Germany) and then forwarded for primer element analysis.

The filter papers were covered with a transparent membrane and placed in 34-mm-wide metal cylinders, which were positioned in the energy dispersive X-ray (EDX) spectroscopy device (S4 Pioneer, Bruker AXS GmbH, Karlsruhe, Germany) and analyzed automatically. The skin samples had to be dried before because water vapor would have interfered with the x-rays. In each analysis the elements Pb, Ba, Sb, Ti, and Zn were measured. The results were recorded in counts per second (c/s).

Results

In the high-speed video-documentation the formation and extension of the temporary cavitation could be visualized (Fig. 1). In all test shots, the projectiles passed through the whole length of the composite model. The temporary cavitation had its largest volume in the initial third of the bullet path where the pressure of the inrushing muzzle gases obviously had lead to an additional release of energy resulting in an increased lateral displacement of the simulant (Fig. 1c–e). This first section was characterized by a spindle-like expansion. The following sections of the cavity had a smaller diameter and a cylindrical (tubular) shape [14]. For a short period (starting about 3 ms after the shot), the temporary cavity extended from the entrance to the exit site (Fig. 1e). After the primary expansion, the cavity partly collapsed in an anterograde direction.

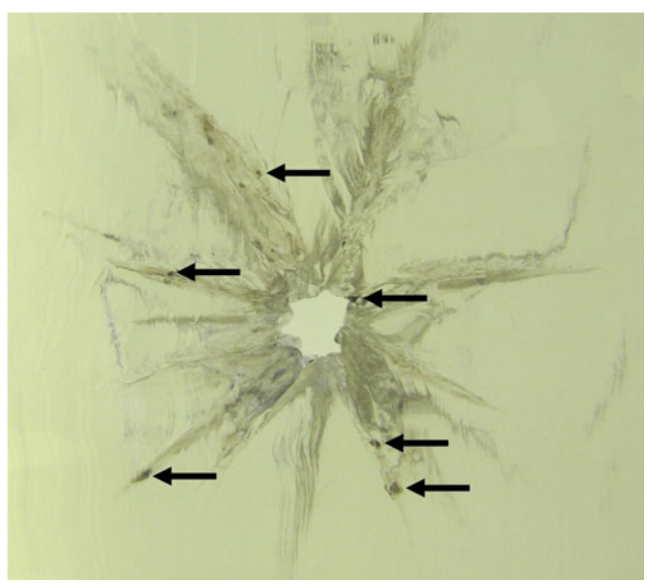


Fig. 4 Axial view of the permanent bullet track with radiating cracks containing soot and gunpowder particles (*arrows*)

The entrance hole was surrounded by a wide zone of powder soot deposition mirroring the muzzle plane of the weapon (Fig. 2a). In spite of the absence of a bony support, the roundish entrance defect was often accompanied by short radial tears. The bullet exits were mostly slit-like without a real loss of tissue. At close-up view, the skin margins of the exits were spotted with unburned and partially burned particles of flake powder (Fig. 2b) and sometimes even with amorphous sooty material.

When looking at the lateral aspect of the gelatin block, one could clearly see the longitudinal bullet path already before dissection (Fig. 3a). The initial third of the track had a fusiform shape with a maximum diameter of about 3 cm (Fig. 3b). The width corresponded with the lengths of the radial cracks and indicated the size of the temporary cavity. Due to the dispersion of amorphous grayish-black material in the permanent channel and within the radiating tears, the temporarily overstretched target material clearly contrasted with the unaffected and therefore still transparent gelatin. The dark discoloration was most intense along the first few centimeters where it appeared as a nearly homogenous blackening. In the following section, the depositions were less dark and rather cloudy. In the terminal third, the bullet's trajectory (Fig. 3c) was still discernible as a grayish line extending to the exit hole without any interruption.

The cross-sections of the laminated gelatin blocks allowed a direct look at the permanent bullet channel and the radiating cracks which were clearly discernible due to their grayish-black lining by soot (Fig. 4). Within the tears, a great amount of powder particles could be recognized, especially in stereomicroscopical view. Corresponding to the findings in the video-documentation and on the side-view photographs, the crack lengths had their maxima in the first section close to the entrance. In this part also, the blackening was most intense.

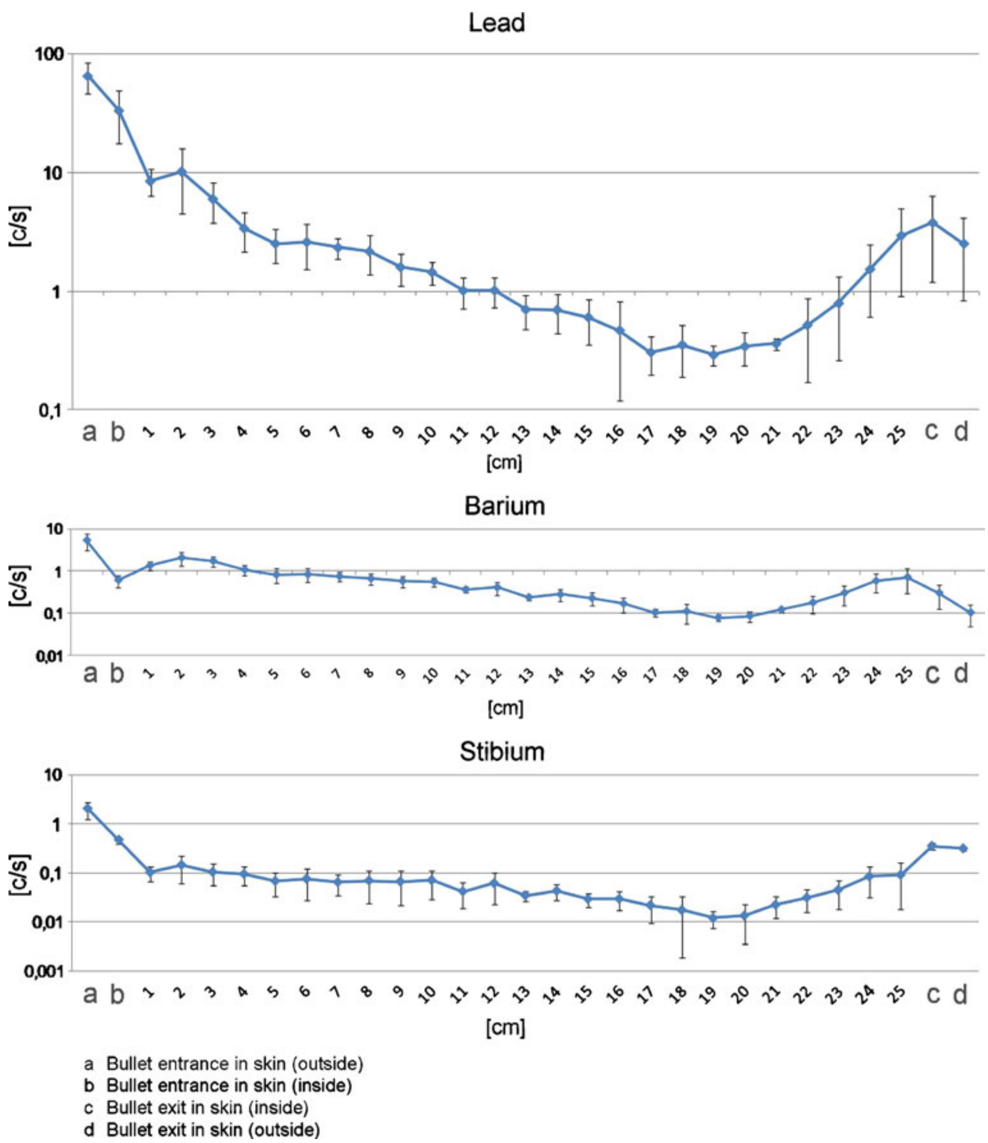


Fig. 5 Quantification of the primer elements Pb, Ba, and Sb along the bullet track (outer and inner surface of the skin at the entry site, 1-cm-thick slices of gelatin, inner and outer surface of the exit site) by means of X-ray fluorescence spectroscopy: mean values of five test shots (cartridges with Sinoxid® primer)

In all samples investigated by EDX, the primer elements were within the range of detection. The individual measurement values are indicated in Figs. 5 and 6.

Discussion

On the discharge of a firearm, a large volume of gun smoke emerges from the muzzle consisting of unburned and partially burned propellant, amorphous sooty material, hot gases including carbon monoxide, primer residues, and often volatilized lead from the bullet [11, 12, 17, 33]. In hard contact shots, all these combustion products enter the target, unless the weapon is fitted with a flash suppressor [3, 6]. The inrushing powder gases expand in the initial section of the wound track causing pocket-like undermining. The entrance region is bloated and ballooned backward against the barrel, so that the contours of the muzzle are imprinted on the skin.

Consequently, the following morphological features are regarded as typical of a contact entrance wound: (1) a patterned muzzle imprint mark, (2) the existence of a powder cavity underneath the skin (containing soot and gunpowder particles) often in combination with a cherry-red discoloration of the surrounding tissue (due to the formation of carboxyhemoglobin (COHb) and carboxymyoglobin), and (3) the facultative occurrence of skin tears radiating from the entrance hole resulting in a stellate wound of entrance (mainly in body regions having a bony support under the skin).

In 1890, Paltauf [21] was the first to recognize that in contact and close-range shots the “chemical effect of the powder gases” may lead to the formation of carboxyhemoglobin causing the tissue to assume a bright red color. In 1908, Meyer [20] demonstrated that smokeless nitro powder produces similar findings as black powder. Since then, the presence of COHb in the vicinity of the entrance wound is considered as indicative of a contact or close-range shot [2, 19, 37]. Bakonyi et al. [1] thought that comparative quantitative determination of carboxyhemoglobin might be a test for distinguishing the entrance from the exit wound—based on the idea that the concentration would diminish along the bullet track [27]. Di Maio [3] urged caution and referred to observations showing an opposite relation with a higher concentration of carboxyhemoglobin at the exit. Under special circumstances, it is even possible to demonstrate high concentrations of COHb in vascular areas away from the wound track [22, 26].

In contact shots, the high-pressure combustion gases ejected from the muzzle enter the entrance wound and still expand in the initial sections of the bullet track. The energy transferred to the local tissue can be visualized by test shots to ballistic soap showing that the cavity volume in the first part of the bullet path depends on the gas pressure at the muzzle [9]. If gelatin is used as simulant, direct determination of the temporary cavitation is not possible, but the total length of the cracks occurring transverse to the trajectory is proportional to the energy released per path unit [15, 30]. As the cracks may be difficult to discern, Schyma [28] developed a method which enhances the contrast of the tears by applying acryl paint to the front of the gelatin block. In our experimental contact shots, the original extent of the “powder cavity” was indicated by grayish-black soot staining which clearly contrasted with the transparent gelatin (cf. Figs. 3 and 4). The same phenomenon has already been demonstrated by Lieske et al. in contact shots with black powder ammunition [18].

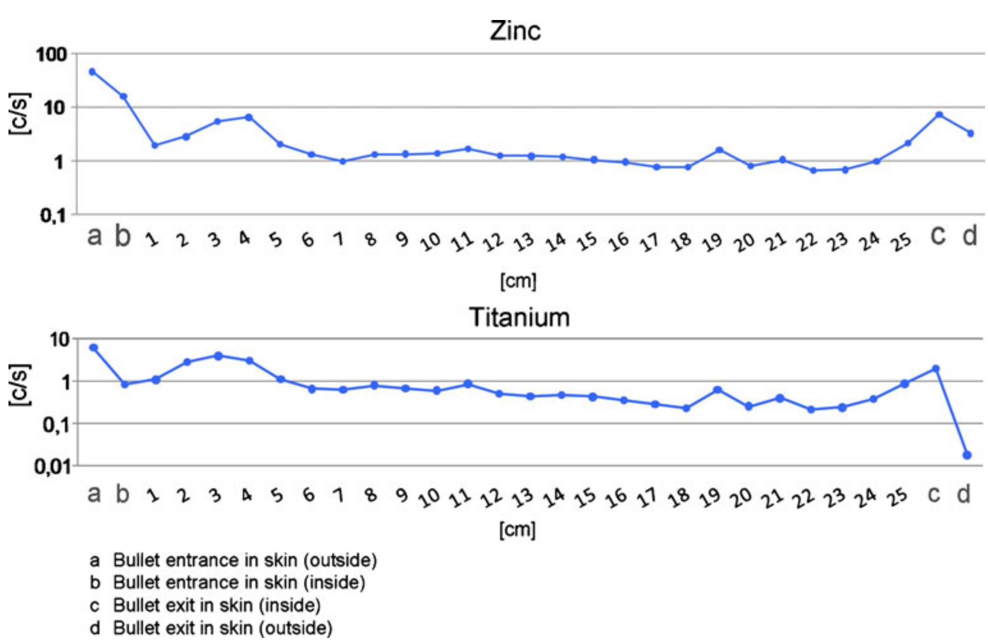


Fig. 6 Quantification of the primer elements Zn and Ti along the bullet track (outer and inner surface of the skin at the entry site, 1-cm-thick slices of gelatin, inner and outer surface of the exit site) by means of X-ray fluorescence spectroscopy in a test shot using a cartridge with a Sintox® primer

The presence of soot in the depth of a gunshot wound is one of the typical signs of a contact or near-contact range discharge. Spitz [32] recommends a layer-wise dissection to reveal deposits of black soot in the "pocket" under the skin. Flecking or staining with soot may be seen in the subcutaneous tissue, on the penetrated muscles [16], the outer surface of perforated bone [24, 32], the underside of the detached periosteum [5] and even on the dura mater [32]. Only few authors mention the possibility of soot staining in tissues near the exit wound, e. g., in shots to thin body segments such as a hand or in the case of a tangential shot [32]. In his famous monograph on gunshot wounds, Di Maio [3] emphasizes that he has never personally seen soot at the exit. According to our own experiments, fine carbonaceous material could be demonstrated in decreasing intensity along the entire bullet track including the exit. Due to the transparency of gelatin, the soot was visible to the naked eye even by transmitted light (cf. Fig. 3 and [18]).

Apart from soot, unburned and partly burned powder grains are driven into the contact entrance wound where they can be identified with the help of a dissecting microscope [3]. As already stated with reference to carboxyhemoglobin, grains of ball powder, and cylindrical powder particles occasionally travel completely through the victim's body, so that they may be found at the exit. According to Di Maio [3], this does not apply to flake powder. Nevertheless, the test shots fired in our experimental setting proved that even flake powder particles may reach the exit hole (cf. Fig. 2b). Analogous to the soot depositions, all sections of the 25-cm-long bullet track contained gunpowder particles either lodged in the geometric bullet path or—more often—at the end of radiating cracks (cf. Fig. 4).

Nowadays, GSR analysis is mainly based on the detection of metals originating from the priming compounds on discharge of a cartridge [4, 29, 36]. In Germany, the most common primer formulations are Sinoxid® (containing lead styphnate, barium nitrate, antimony sulfide, calcium cilicide, and tetrazine) and the lead-free Sintox® (a zinc and titanium-based priming compound). When cartridges equipped with a Sinoxid®-primer are fired, particles composed of Pb, Ba, and Sb are considered as unique for GSR [36].

In contact shots, these primer elements are forced into the bullet track together with the other combustion products. Therefore, one would expect that the concentrations of primer-generated GSR metals diminish with increasing distance from the entrance. To the best of our knowledge, this obvious assumption has never been checked in an experimental set-up. The results obtained by us prove that in contact shots the primer elements are detectable not only in the "powder cavity" close to the bullet entrance, but also in the distal sections of the missile track up to the exit. In most test shots, the metal concentrations were slightly higher again in the terminal part (at the inner surface of the skin covering the exit side of the gelatin block).

As already outlined before, the presence of primer elements along the entire bullet track can be explained (1) by the invasion of combustion products from the muzzle being in contact with the target and (2) by the fact that the formation of a temporary cavitation extending from the entrance to the exit enables the spread of all discharge residues along the whole bullet track.

Conclusions

1. In handgun contact shots to composite models simulating soft tissue targets, the discharge residues consisting of soot, powder particles, and primer elements could be found in all sections of the 25-cm-long bullet tracks.
2. Therefore, the mere presence of GSR does not rule out an exit wound in contact or near-contact shots.

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