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ORIGINAL ARTICLE

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Trajectory reconstruction from trace evidence on spent bullets

I. Deposits from intermediate targets

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Abstract Contact of a fired bullet with an intermediate target of sufficient resistance commonly causes the bullet to ricochet, fragment or perforate together with a deviation in trajectory. The transfer of intermediate target material to bullets and subsequent detection on the bullet surface after recovery from a bullet collector, were examined using a scanning electron microscope and an energy-dispersive X-ray spectrometer (SEM/EDS). A total of 76 gunshots (9 mm Luger FMJ RN bullets) were fired at various intermediate targets and at combinations of intermediate targets and tissue located in line. Elements already present on unfired bullets and elements from the bullet collector, the jacket, the charge and primer could be consistently detected as a "background". Abundant deposits of "fragile" (brittle) materials such as concrete, flat glass, asphalt and gypsum board could be visualised on every bullet by SEM. The transfer dynamics involved a direct imprint of target material on the bullet surface and thus preferential locations at the tip but also indirect deposition over the entire surface ("powder effect"). X-ray microanalysis demonstrated matching spectra of the elemental composition of these deposits and of the targets contacted. After perforation of "ductile" (flexible) materials such as wood and car body parts, the deposits on the bullets did not show characteristic spectra. If multi-layered car metal targets were hit, few and uncharacteristic fragments were scattered over the bullet surface and titanium indicative of paint-work could be determined on only a minority of bullets. The elemental composition of wood itself was heterogeneous but the fibrous morphology of the deposits was typical. The SEM/EDS findings in gunshots including subsequent perforation of tissue were similar. In particular, the trace evidence primarily transferred to the bullets was not eliminated by secondary contact and the determination of the fragile target materials was not affected. So when a person is killed or injured by a gunshot, the presence of a ricochet and the target material can be determined. This possibility needs to be considered before an evidential bullet is cleaned or contaminated.

Keywords Intermediate target · Trace evidence · Bullet · Trajectory · Ballistics · Ricochet

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Introduction

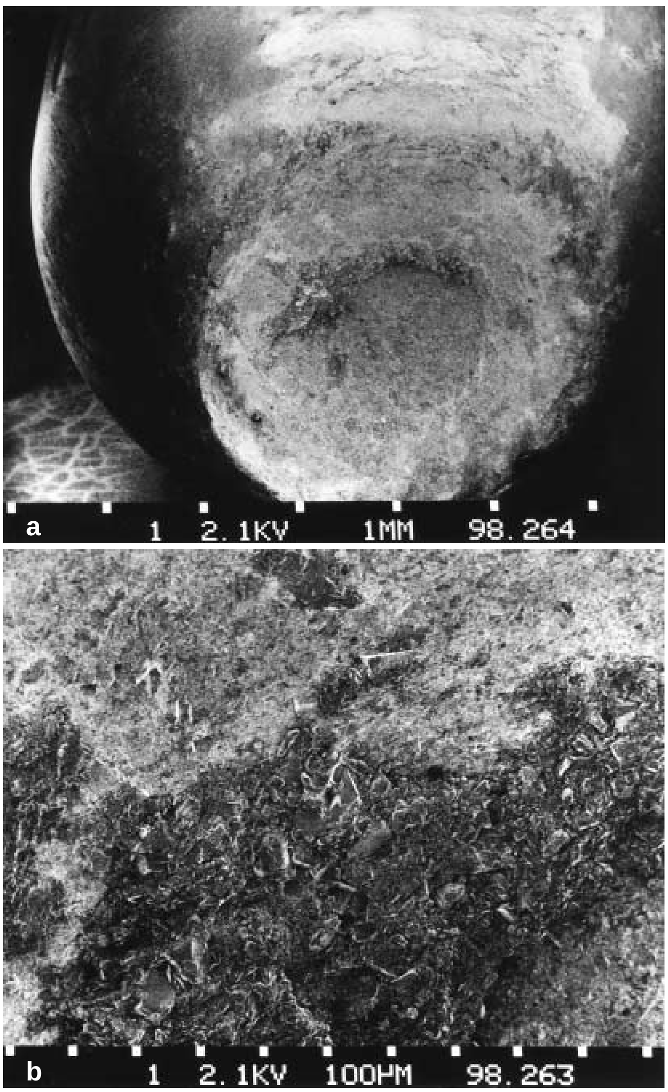
Contact between two objects commonly results in transfer of material. This principle forms the basis of modern trace evidence analysis. Trace evidence may be the decisive factor in reconstruction of the scene of crime and in identifying the persons and objects involved. Some aspects of trace evidence analysis such as fibres (e.g. Coxon et al. 1992; Palenik and Fitzsimons 1990; Siegel 1997) or hairs (e.g. Ogle and Fox 1998; Hühne et al. 1999; Pfeiffer et al. 1999) have been investigated in detail and are used routinely in crime scene investigations. Due to a high velocity resulting in substantial impact forces, bullets striking an object appear to represent favourable conditions for the bidirectional transfer of material but air friction and subsequent impacts may also cause loss of deposits.

A bullet ricocheting after contact with an intermediate target is a very important factor: the stability of the bullet will be affected and the trajectory will show a deviation. However, the potential evidential value of trace evidence on spent bullets, for example indicating a ricochet, is not well recognised. Blood, tissue and/or foreign material may be washed from the bullet and loss or contamination may also occur during transportation or storage.

There are only a few case reports dedicated to this field and deposits were only investigated on deformed lead bullets (DiMaio et al. 1987; Petraco and DeForest 1990). However, no experimental investigations regarding the deposition and identification of trace evidence have been

Table 1 Summary of important parameters of the 76 gunshots fired

Number of gunshots	Intermediate target(s)	Target thickness	Bullet collector material	Additional features
5	Concrete	40 mm	Newspaper	Gravel concrete
5	Glass (window pane)	3 mm	Newspaper	Flat glass (lime-sodium-silicate)
6	Asphalt	Ricochet	Newspaper	Bitumen
5	Gypsum board	15 mm (gypsum and cardboard)	Newspaper	Calcium sulfate and cellulose
5	Untreated pine	15 mm	Newspaper	Heterogenous
5	Untreated spruce	15 mm	Cotton	Heterogenous
5	Varnished spruce	15 mm	Cotton	Heterogenous
5	Chipboard	20 mm	Cotton	Formica-coated
15	Driver's door (BMW, yellow)	Paint and bodywork 2.5 mm Panelling 15 mm	Newspaper	Multi-layered paint-work
5	Car wing (VW Golf, metallic blue)	2.5 mm	Cotton	Multi-layered paint-work
5	Gypsum board + tissue	15 mm + 10 cm	Newspaper	Consecutive targets
5	Concrete + tissue	40 mm + 10 cm	Newspaper	Consecutive
5	Car wing + tissue	2.5 mm + 10 cm	Newspaper	Consecutive



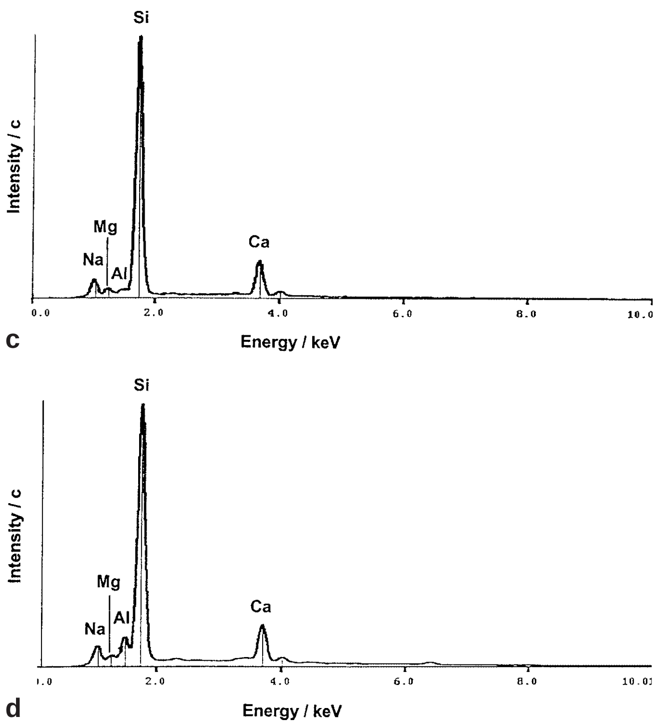


Fig. 1 a–d Perforation of glass. **a** SEM image of the tip of a bullet. The flattening of the tip consists of a shallow hollow including a finely tapered rim. Tiny glass fragment deposits have accumulated in the vicinity of the rim. **b** SEM image of a detail from **a** demonstrating small glass particles. **c, d** EDS spectra of **c** the glass perforated, including the major elements Si and Ca, and **d** the bullet deposits depicted in **b**

published. This study uses the combination of imaging the deposits with a scanning electron microscope (SEM) and qualitative X-ray microanalysis of the deposits with an energy-dispersive X-ray spectrometer (EDS).

Material and methods

The firearm used was a SIG-Sauer P225 (model P6) pistol (barrel length 98 mm). The 9 mm × 19 Luger FMJ round nose bullets (Geco, DNAG, Troisdorf, Germany) had a mass of 8.1 g and a muzzle velocity of approximately 350 m/s measured by conventional light screen devices (Competition Electronics, Liszt, Austria). The distance from the muzzle to the intermediate target was 1 m and the bullet trap was located 1 m behind the intermediate target. All gunshots were fired inside a large wooden box (55 × 55 × 225 cm) to prevent uncontrolled ricochets.

A total of 76 gunshots were fired at 10 different materials simulating intermediate targets (Table 1). Of these, nine materials including four different types of wood were perforated (angle of incidence 90°) and deflecting ricochets (no perforation) were produced by firing at asphalt at angles of incidence of approximately 20°. In three additional series, the perforation of gypsum board, concrete and a car wing were combined with the subsequent perforation of tissue located 50 cm behind the first target (Table 1).

After perforation of, or ricochet from the intermediate target, the bullet was recovered from the bullet collector at the end of the box. The material for the bullet trap had to be chosen carefully to prevent considerable transfer of this material to the bullet and also deformation of the bullet. Various bullet trap materials were tested in a preliminary study. A total of 35 reloaded rounds (approx. 150–350 m/s) were fired directly into the bullet trap and examined by SEM/EDS. Ordinary newspaper and cotton (laboratory coats without buttons) produced the best results in that the surface areas covered with coat-like deposits were small. Therefore, these two materials were used for the bullet trap. EDS analysis determined the presence of chlorine (Cl), potassium (K), calcium (Ca), silicon (Si), aluminium (Al), phosphorus (P), sulphur (S) and sodium (Na) in the case of newspaper and Ca in the case of cotton.

The bullets were recovered from the bullet collector wearing gloves and transferred to plastic bags. After screening with a stereomicroscope, the bullets were attached to the specimen holder of the scanning electron microscope (Stereoscan S180, Cambridge, UK). Frequently, the deposits on the targets were insulators, therefore, coating with carbon by evaporation was carried out to produce a conducting surface. The accelerating voltage used for imaging and analysis was 2–20 kV, mostly 15 or 20 kV. Secondary electrons were used for the imaging and the incident beam energy for the X-ray microanalysis was normally 15 keV. For the best detection of light elements, analysis with lower excitation energies was also performed. A beryllium window detector (PGT) was used in most instances and as all X-ray lines below Na are absorbed, these EDS spectra do not display carbon or oxygen. In some instances, an X-flash detector (Röntec, Berlin, Germany) was also used.

Results

Unfired bullets

X-ray microanalysis of the jacket material determined the major components to be copper (Cu) and zinc (Zn). Various quantities of pre-existing environmental deposits, mostly in the form of small spheres, were present on the bullets. The EDS spectra showed the major elements to be S, Cl, Ca, Si and Al.

Perforation of glass

The bullets showed a typical hollow in the tip of the bullet 0.5–1 mm in depth including a finely tapered rim (Fig. 1a). SEM demonstrated the presence of numerous minute deposits preferentially located at the tip (Fig. 1b) but glass dust was also present on the sides and the rear portion of the bullets. This is supported by comparison of the EDS analysis of the window pane (Fig. 1c) and of the bullet deposits (Fig. 1d).

Perforation of concrete

The deformation was typical. The compressed lead core caused a circular bulge in the mid-portion of the bullets resembling a mushroom (Fig. 2a) but the jacket remained intact and the head of the mushroom always showed fine longitudinal striation and abundant adhering material

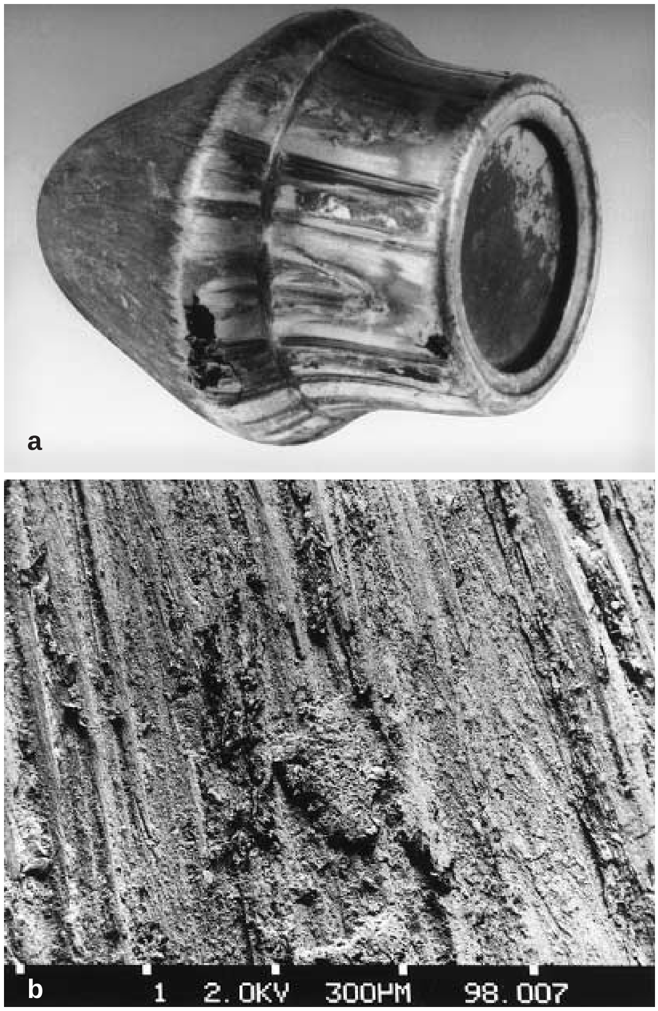
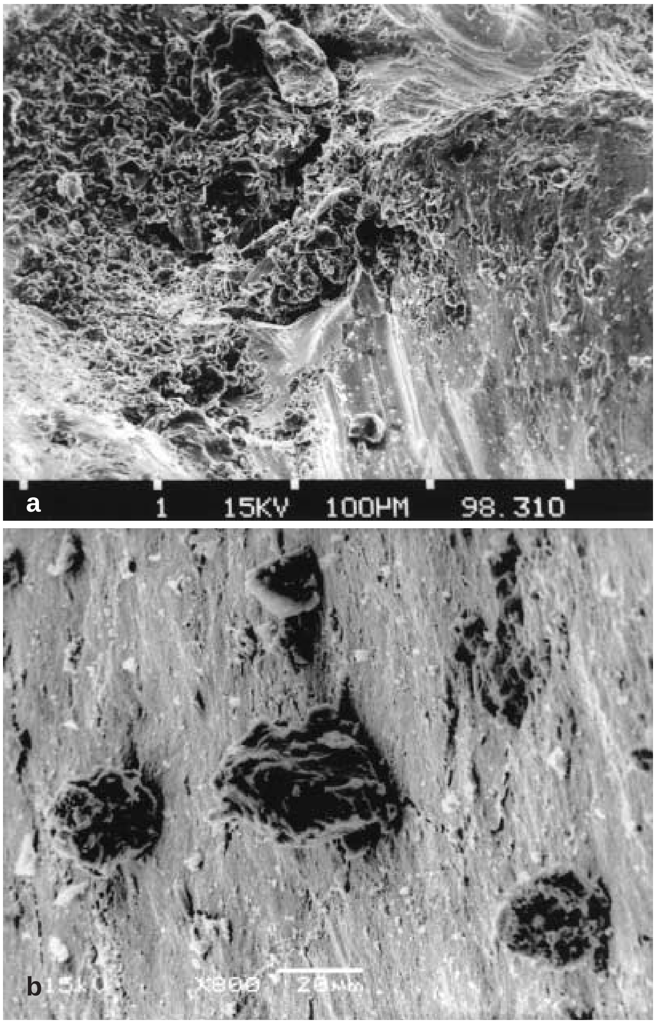


Fig. 2 a, b Perforation of concrete. **a** Typical mushroom shape of the FMJ bullets including bulging and longitudinal striation. The diameter of the striation corresponds to the size of the gravel grains in the concrete. **b** SEM image of the side of the bullet shown in **a** demonstrating striation and concrete deposits



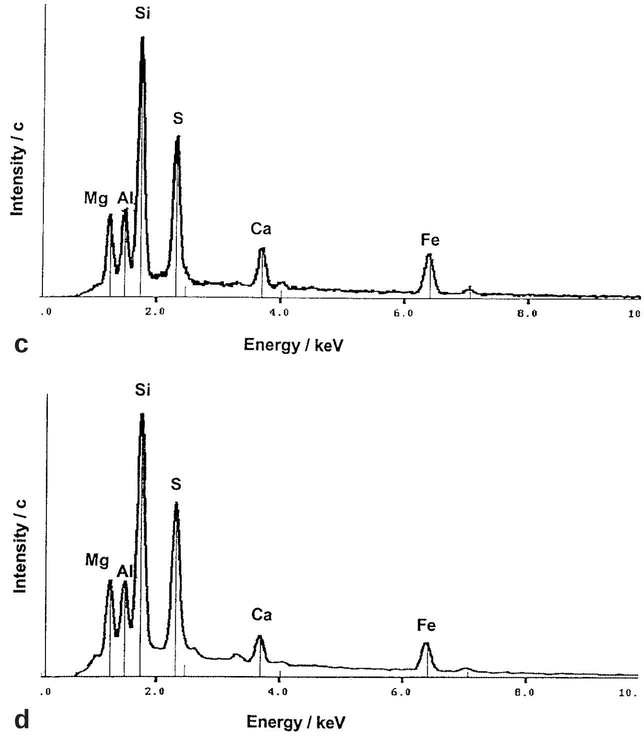


Fig. 3 a–d Ricochet from asphalt. **a** SEM image of asphalt deposits on the furrowed lead core of the bullet. The deposits accumulated in moulds. **b** SEM image of small spherical asphalt deposits in a shielded region of the torn jacket. **c, d** EDS spectra of **c** the asphalt target and **d** the bullet deposits depicted in **a**

(Fig. 2b). EDS analysis demonstrated a spectrum with major peaks typical for Ca and Si, which showed a match to the elemental analysis of the concrete used.

Ricochet from asphalt

The bullet jacket was regularly torn open and separated from the lead core. Jacket fragments were embedded in the lead and also in the asphalt close to the long impact mark of the bullet. The exposed lead core was compressed and deeply furrowed and in the SEM showed dark deposits over the entire surface (Fig. 3a). Smaller spherical deposits could be verified on protected portions of the jacket (Fig. 3b). EDS analysis of the deposits and the asphalt target demonstrated a match for all elements (Fig. 3c, d).

Perforation of gypsum-board

The slightly flattened tip of the bullets was the preferential location of the bullet deposits (cf. Fig. 6a). EDS analysis demonstrated different types of spectra which showed elements characteristic of one of the two target components or of a combination of both. The main elements were S, Ca, Si, K, and Al (cf. Fig. 6b–d).

Perforation of wood

The four different types of wood used essentially showed identical results and the deformation was restricted to minor changes. The tip was slightly flattened and the diameter of most bullets was reduced in one cross-axis, which sometimes resulted in detachment of the bullet base. Typical lengthy and fibrous deposits could be detected on every bullet by SEM (Fig. 4a, b).

EDS analysis determined the main elements to be Ca, Cl, Si, K, S, and Al but characteristic spectra could not be obtained from the bullets or the heterogeneous wood specimens themselves. In the case of Formica-coated chipboard, the coating consisted of the main elements titanium (Ti), S, Si, P, Cl and Ca. Ti and P could be demonstrated on some bullets but again, characteristic spectra were not obtained.

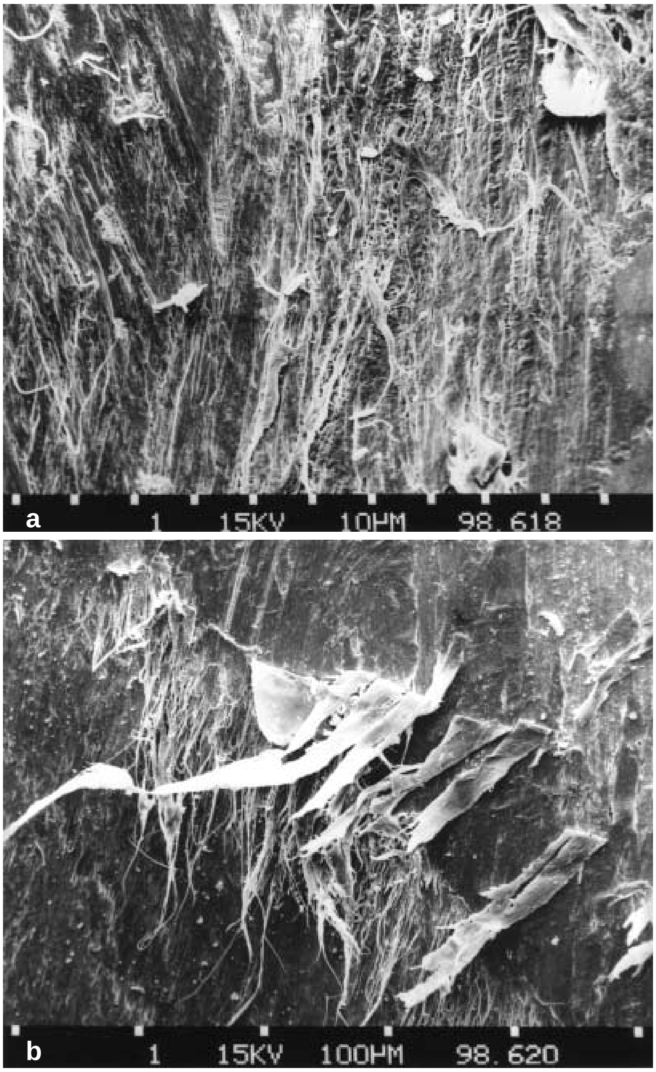


Fig. 4 a, b Perforation of wood. SEM images of bullet deposits after **a** perforation of spruce wood and **b** after perforation of varnished spruce wood. Both microphotographs demonstrate the typical fibrous morphology of the wood deposits

Perforation of car body parts

The driver's door consisted of yellow paint-work, body-work and an interior plastic panelling. The nose of the bullets showed a pronounced flattening and jacket defects were present at the rim in some cases. The yellow paint-work could not be identified on the bullets by light microscopy. A small number of uncharacteristic deposits could be detected on the bullets by SEM. For EDS analysis, the door was disassembled. EDS analysis of deposits from the bullets demonstrated a variety of elements which did not match the door components or single layers. On a few bullets, Ti could be determined probably originating from the paint-work (Fig. 5).

The car wing had a blue metallic paint-work. In addition to a minor flattening of the nose with soft rims, a dish-shaped plug of slightly smaller diameter than the bul-

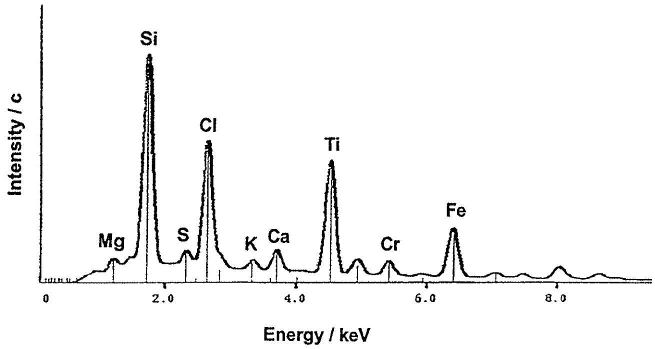


Fig. 5 EDS spectrum of deposits on the surface of a bullet after perforation of a car door. The elements Ti and Cr probably originate from the paint-work

let was punched out and found in the bullet trap. Small amounts of deposits scattered on the bullet surface could be depicted by SEM. X-ray analysis of the deposits demonstrated various spectra which did not match the metal or one of the paint-work layers of the wing. Abundant Cu and Zn from the bullet jacket could be verified around the punched out and indented defects in the target metal.

Perforation of gypsum board and tissue

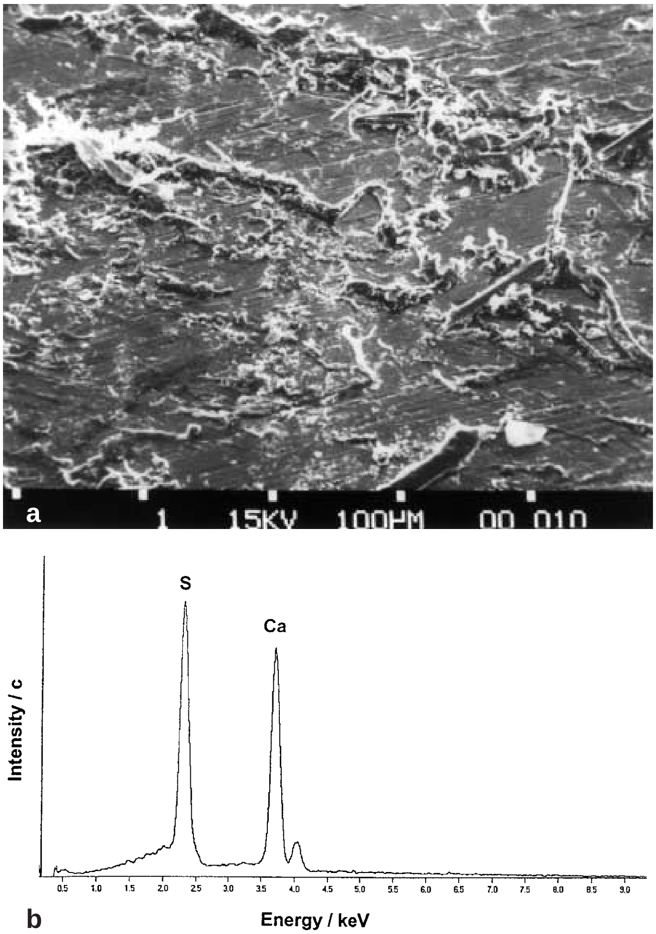
Gypsum board is essentially $CaSO_4$ enclosed by two layers of cardboard. The deposits originating from this two-component target presented as lengthy structures and adhering grainy material (Fig. 6a). The SEM also visualised dried tissue fragments on the bullets. For EDS analysis, the gypsum and cardboard layers were separated and the main elements were S and Ca (Fig. 6b) and Ca, S, Si, and Al (Fig. 6c). In some bullet deposits, the elemental composition of only one of the two target materials could be verified but in other cases, the spectrum indicated the presence of elements characteristic of both materials (Fig. 6d).

Perforation of concrete and tissue

The morphology and elemental composition of the deposits were very similar to the results obtained after gunshots to concrete alone and the EDS spectra of the bullet deposits matched those from the target specimen.

Perforation of car wing and tissue

Dish-shaped plugs were punched out and appeared to ride in front of the bullet tip. Four plugs were recovered from the bullet collector and one was shed off inside the tissue. The SEM depicted dried tissue remnants and small deposits. The morphology of the deposits was not typical and the EDS spectra did not show a match to the wing materials.



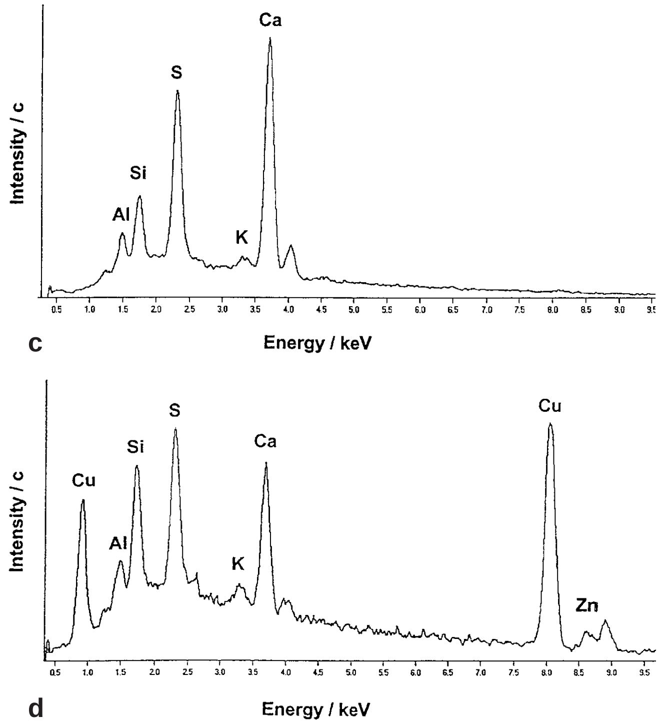


Fig. 6 a–d Perforation of gypsum board and tissue. **a** SEM image of the gypsum board deposits on a bullet. According to the EDS spectrum shown in **d** the long structures represent cellulose and the adhering grainy material is made up from $CaSO_4$. **b–d** EDS spectra of specimens of **b** gypsum material, **c** cardboard layer and **d** the bullet deposits shown in **a**. The elemental composition indicates a combination of the two target materials perforated. Cu and Zn originate from the jacket

Discussion

Only FMJ bullets were used in this study because the increased resistance to deformation and the smooth surface of this type of bullet offer unfavourable conditions for the transfer and adherence of trace evidence. In contrast, the soft noses of lead and semi-jacketed bullets can carry a considerable amount of target material and layered plugs of textiles inside hollow point cavities can even reflect the target sequence (Smith and Harruff 1988). Nevertheless, impact with hard intermediate targets can cause considerable and also typical deformation of FMJ handgun bullets (Sellier 1971; Rathman 1987; Houlden 1994; Kneubuehl 1999). The mushroom-shape of FMJ bullets together with the longitudinal striation, is typical for perforation of concrete or similar materials and a hollow at the tip including a tapered rim is characteristic for perforation of flat glass.

In impact dynamics, ductile and fragile target media can be distinguished (e.g. Tamagna and Riera 1998; Goldsmith 1999). Ductile material is elastic and can be stretched before perforation whereas fragile material is brittle and will break before any noticeable stretching occurs. The transfer dynamics of the fragile materials concrete, glass, gypsum board and asphalt were two-fold: direct contact between the tip of the bullet and the intermediate target resulted in a violent imprint of material on deformed portions of the bullet and in a pronounced accumulation of material in this area. Almost simultaneously, some of the target perforation zone is shattered by the bullet and a cloud of small particles and dust is accelerated in (and against) the shooting direction (Lamprecht 1959; Thornton 1974; Sellier 1982). When the bullet travels through this cloud of particles, some may become attached. This indirect "powder effect" can explain the presence of deposits on the sides and even the rear of some bullets, especially in the case of glass where the high velocity of the developing fracture lines may contribute to this effect.

In contrast, the complex perforation dynamics of ductile materials involve elastic radial displacement or punching out of a plug, which leads to the separation and crushing of only small amounts of target material. This is detrimental to both the direct imprint of material and the powder effect. In the case of the multi-layered car body parts, transfer seemed to be limited to a few and uncharacteristic fragments of single layers and the EDS spectra of the bullet deposits varied considerably. Elements typical for paint-work such as Ti can supply an indication of the target perforated but could only be demonstrated on a minority of the bullets. In the case of wooden targets, the typical fibrous morphology of the deposits in scanning electron microphotographs can provide evidence for the intermediate target but the results of X-ray analysis varied considerably probably due to the heterogeneous composition of the target material.

It therefore appears that abundant deposits of fragile materials are present on the bullet surface. The reproducible determination of the deposits by concurrence with X-ray microanalysis from the intermediate target is possible. Subsequent perforation of tissue and/or impacts in the bullet trap involving considerable forces, wiping effects and transfer of bullet trap material did not eliminate the deposits. A bullet trap is not of course a realistic set-up but from these results and from case work experience it would appear that a complete loss of fragile trace evidence in subsequent impacts or penetration of a human body does not occur. A longer flight may eliminate some deposits but the effect of air friction should be inferior to that of impacts. A ricocheting instead of a perforating bullet also provides favourable transfer conditions because sufficient material is contacted and crushed for both types of transfer to be effective.

In addition to trace evidence transferred from the intermediate target, a large variety of deposits demonstrating various spectra were present on all bullets. The potential sources of contamination were elements already present on the unfired bullets, material from the bullet collector, elements originating from the jacket, the primer (Pb, Ba, Sb, or Zn, Cu, Ti) or the charge (Ca). The differentiation from relevant trace evidence is assisted by the morphology in SEM images.

In conclusion, the verification of a ricochet by analysis of trace evidence can have considerable legal implications because the intention to kill will not normally be inferred. The determination of fragile target materials is possible by the combined evidence of morphological and analytical findings and a directed search of the scene can be conducted. The intermediate target will show a bullet impact mark/perforation defect, which additionally represents an ideal reference point for trajectory reconstruction. Investigation of the scene is also necessary because contact with an intermediate target may occur before or after a human body is perforated but the sequence of events can usually not be derived from trace evidence on FMJ bullets.

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