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ORIGINAL ARTICLE

The influence of muzzle gas on the temporary cavity

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Abstract

Shot range, the muzzle-target distance, is a crucial parameter for forensic reconstruction of deaths by firearms. In a large number of cases, especially suicides, the forensic pathologist is confronted with contact or near-contact shots, where muzzle gases play an additional role. This study was conducted to systematically investigate the influence of muzzle gases on the temporary cavity (TC). A total of 72 shots were fired using full metal-jacketed bullets in four forensically relevant calibres from 10-, 5-, 3-, 2- and 1-cm distance and in close contact. Target model was the so-called reference cube (10% gelatine at 4 °C) with 12-cm edge length. The TC was recorded using high-speed video (HSV). Cross-sectional analysis was performed by cutting the blocks to 1-cm slices, which were evaluated by applying the polygon method. The TC of shots from 10 and 5 cm distance had a tubular form. This aspect changed depending on the cartridge with decreasing distance (≤ 3 cm) into a pear-like form, which was typical for contact shots. The cumulated heights of the TC increased with decreasing distance below 3 cm. Contact shots approximately doubled the extension of the TC compared with exclusive energy transfer. Whereas HSV documented an increasingly asymmetric profile with ballooning at the entry side, cross-sectional analysis of cracks in gelatine resulted in convex graphs with only slight asymmetry for contact shots. Additional damage in gelatine was detected for 3-cm distance or less in calibre .357 Magnum and ≤ 2 cm for .32 auto, .38 special and 9mm Luger. The increasing influence of muzzle gas pressure is detectable with decreasing shot range below 3 cm.

Keywords Suicide · Contact shot · Muzzle gases · Wound ballistics · Firearm barrel · Backspatter

Introduction

In European forensic practice, the major part of gunshot wounds is observed in suicidal context. However, the discrimination between suicide and homicide remains a challenging task for the crime scene investigators and the forensic pathologist [1]. One aspect of distinction is the firing distance. In most suicides, the firearm is fired with muzzle contact [2], whereas in homicides the distance is rather variable [3]. Contact shots differ considerably from those fired with distance, because not only the projectile is doing damage but also the muzzle gases [4, 5]. The entry wound may be increased, disrupted, lacerated and sometimes stellate. In autopsy, an important sign of muzzle gas pressure is the evidence of a powder pocket. Soot can be observed within the lacerated subcutaneous layers and even under the periosteum in cranial contact shots [6]. The evolution of the powder pocket could be visualized using high-speed video [7]. However, a previous study on spherical gelatine-filled head models had demonstrated that the influence of muzzle gases extended to the interior part of the model causing increased destruction of the gelatine core in comparison to shots from distance [8]. Unfortunately, it was not possible to visualize this destructive effect because the silicon covered, gelatine-filled plastic [7, 9] or acrylic [8, 10] containers were intransparent. As a consequence, the 12×12×12 cm^3 “reference cube” was developed which allowed for high-speed video recording. The front cover of this gelatine block consisting of an absorbent kitchen wipe is moulded into the gelatine so that even muzzle gas pressure could not extract it from the gelatine [11]. Originally the reference cube was designed to investigate

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staining inside firearm barrels [12]. More and more, this transparent target model was also used for wound ballistic research in studies of the temporary cavity (TC) [13–15]. In this context, a qualitative difference between the huge TC of a deforming bullet shot from distance and the TC of a similar dimension left by a contact shot with a simple full metal-jacketed bullet was noticeable [16]. This study was conducted to analyse the general influence of muzzle gases on the TC.

Material and methods

Gelatine cubes with 12-cm edge length ("reference cubes") were prepared as target models as previously published [11]. Three shots per calibre and per distance were performed using current 4-inch barrelled firearms fired from 10-, 5-, 3-, 2- and 1-cm distance and at close contact. Highest safety precautions were adopted in the shooting range. The shooter unlocked and precocked the loaded firearm and pointed it supported with both hands. The muzzle to target distance was then controlled by direct measuring and corrected if necessary. The effective reproducibility was about ± 2 mm. Only full metal-jacketed (FMJ) bullets in the calibres .32 auto (4.7 g), .38 special (8.4 g), 9mm Luger (8.0 g) and .357 Magnum (10.2 g) were used. The target models were put on a 5-cm high synthetic sponge to allow for full expansion of the TC [13]. The TC was recorded using a SA-X2 Fastcam (Photron ltd., Wycombe, UK) at 40.000 fps and 10 μs exposure time.

After shooting, the gelatine cubes were cut into twelve 1 cm slices, which were scanned with 300 dpi resolution and analysed according to Schyma et al. [17]. The analysis of the TC was performed as previously published [15] using a 12-line grid overlaid on the last frame of the TC's expansion phase in the direction of fire.

Results

TC in high-speed video (HSV)

In all 72 shots, the FMJ bullets passed through the target model so that the rest velocity of the bullet could be measured as published before [14]. Shots fired from 10- and 5-cm distance left a tubular TC (identical height along the whole bullet path) independently from the calibre. The height correlated with the energy deposited as previously published [15]. This aspect began to change at a 3-cm distance. Especially .357 Magnum bullets caused a slightly conical TC which was higher at the entry side than on the exit side. The conical form of the TC was more accentuated at 2 cm for .32 auto, .38 special and 9mm Luger, whereas .357 Magnum provoked a slight asymmetrical ballooning of the TC. Bullets in calibres .38 special and .32 auto caused a pear-like shape of the TC at 1 cm (Fig. 1); 9mm Luger showed a wide cone; and .357 Magnum continued ballooning with vertex in the first third of the bullet path. All contact shots showed a pear-like-shaped TC; .32 auto and .38 special had a more distinct profile than 9mm Luger (Fig. 1) or .357 Magnum.

These qualitative impressions were confirmed by the analysis of the TC height measured at 12 points along the bullet path. .38 special showed a practically horizontal line (tubular TC) for 10- to 3-cm distance, a slightly descending line (cone-like TC) at 2 cm and an increasingly curved profile (pear-like TC) from 1- to 0-cm distance with vertex at 2 to 3 cm into the bullet path and clear decline after 5 cm. Surprisingly, .32 auto (7.65 mm Browning) had practically the same absolute values as .38 special with exception of the 1-cm distance where the TC of the .32 auto was bigger and more curved (Fig. 2). Figure 1 shows shots from 1-cm distance where .32 auto and .38 special caused similar results. When the two pistol calibres are compared, the most important difference is observed at 1-cm distance, where the 9mm Luger (Fig. 3) has a slightly descending line (cone-like) and the .32 auto a curvy, pear-like profile (Fig. 2). The niveau in the first 5 cm of the bullet path is comparable, but for the rest .32 auto is clearly inferior to the 9mm Luger. At 2-cm shot range, both calibres showed parallel descending lines, the .32 auto about 85% of the 9mm Luger heights. For 3- to 10-cm distance, it is not possible to distinguish the graphs.

.357 Magnum shots from 1 cm distance reach 86–96% of the values for contact shots in the first third and up to 99% in the last two thirds of the bullet track. The profile of .357 Magnum TCs is overall higher than that of the other cartridges, but the maximum height of the TC (reached in contact shots) is about 100 mm without significant difference for the calibres (Figs. 1 and 3, Table 1).

The sum of the TC heights $\sum H$ along the bullet path shows best the increasing influence of muzzle gas on the TC in dependence of shooting distance and cartridge (Fig. 4). Table 1 shows an increase of $\sum H$ by factor 1.8 to 2.4 when contact shots are compared with shot ranges of 5 cm and more.

Following the evolution of the TC until its first collapse, a qualitative difference between contact and distant shots was observed. There was much more movement after contact shots. Therefore, the collapsed TC was measured in analogous manner, and the cumulated heights were compared to $\sum H$ of TC (Table 2). The ratio of collapsed TC to TC varied for contact shots, shots from 3 cm distance and those from 5 cm or more distance systematically. After contact shots, the TC collapsed only to about the half (45 to 56%), whereas in distant shots a collapse to a third or less was observed. Obviously, .357 Magnum shots from 3-cm distance behaved like contact shots.

The short or not existing shooting distance prevented measuring the initial velocity of the bullet. Even with 10-cm distance, the muzzle gases hid the bullet in many sequences.

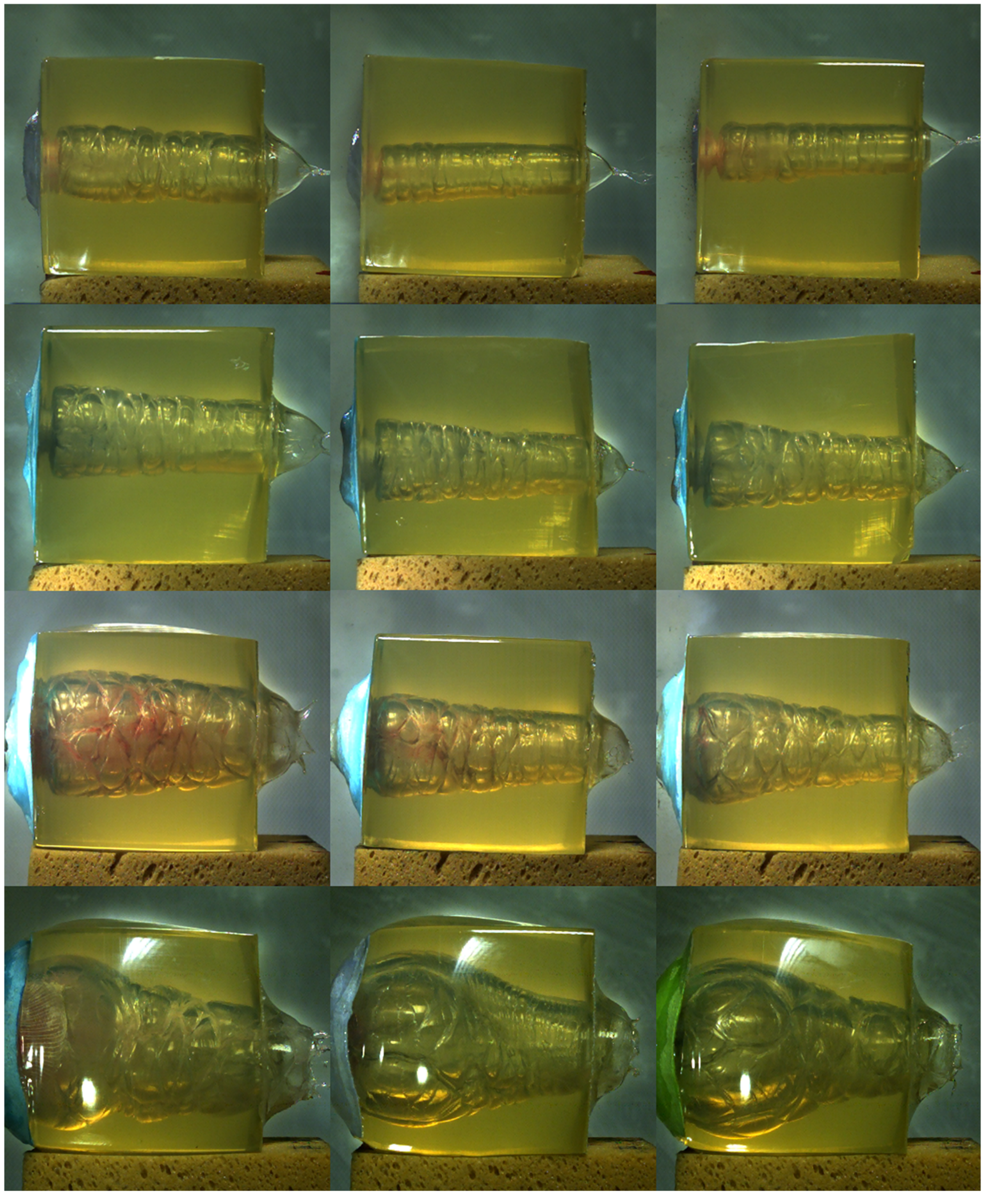

Fig. 1 The temporary cavity of full metal jacket bullets in decreasing shot ranges. First line, 5 cm distance; second line, 2 cm; third line, 1 cm, and last line, contact shots. First column, 9mm Luger; column in the middle, .32 auto; and third column, .38 special. All pictures were adapted to the same scale

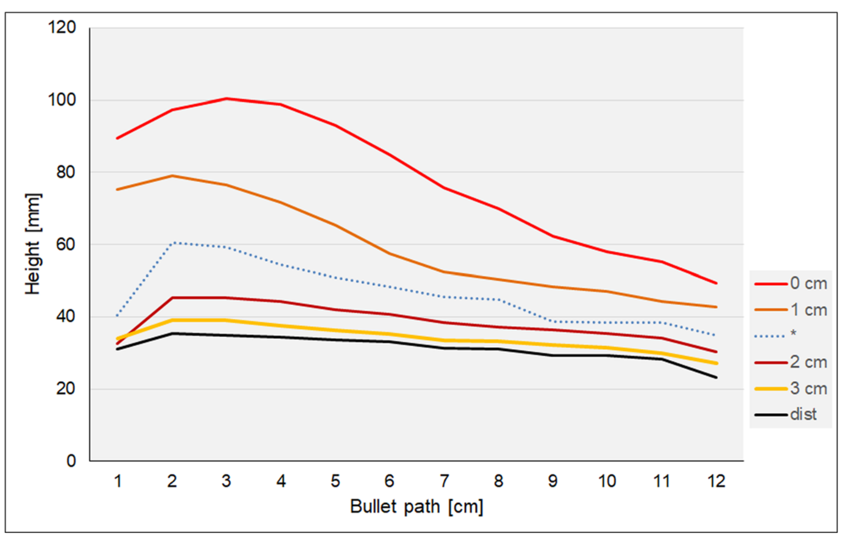

Fig. 2 The height of the TC of the .32 auto (7.65 mm Browning) along the bullet path. The dotted line (*) shows the values for .38 special at 1-cm distance which are weaker

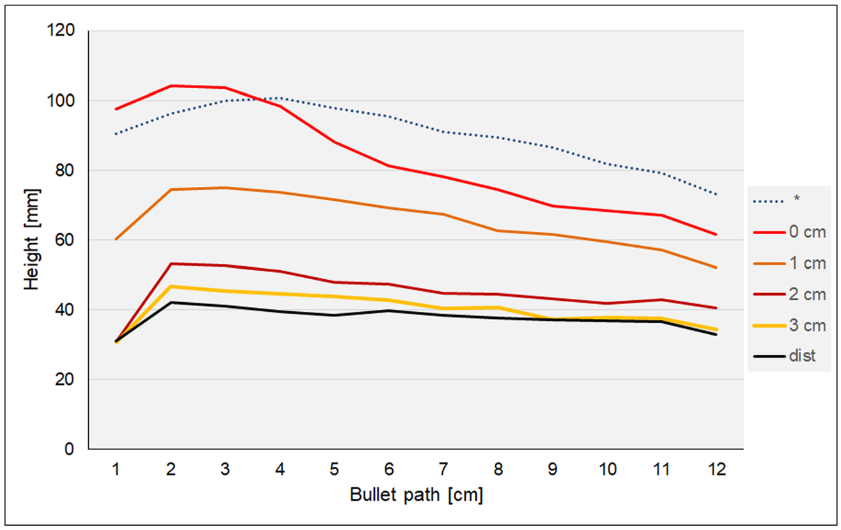

Fig. 3 The height of the TC of the 9mm Luger along the bullet path. The dotted line (*) shows the profile of contact shots with .357 Magnum

However, previously published results allowed for estimating the initial velocity based on the bullet deceleration inside the gelatine cube [14]; the rest velocity of the bullet was easily measured using the HSV method, and its rest energy was calculated. Recordings of 5- and 10-cm distance shots with visible projectiles confirmed that the estimation approximated the actual values with ± 5%. The linear correlation of the sum of the heights $\sum H$ with the initial energy E_0 was confirmed for distant shots (≥ 5 cm; $r^2 = 0.842$) as well as with the rest energy ($r^2 = 0.863$). In contact shots, it was much more difficult to find a relation between energy and TC. A correlation of rest energy and TC seems rather probable ($r^2 = 0.758$).

Cross-sectional analysis in gelatine slices

The scanned gelatine slices were analysed using the polygon method. The principal parameters, the polygon perimeter (PP) and the polygon area (PA), provided analogous results. All profiles had a convex graph. As an example, the PP for the .32 auto is shown (Fig. 5) which is strongly correlated with Fackler's Wound Profile [15]. With decreasing firing distance, the kurtosis of the graphs increased. In contrast to the HSV results, the absolute values corresponded with the initial kinetic energy of the projectiles: .357 Magnum > 9mm Luger > .32 auto > .38 special. The difference between .32 auto and .38 special was minimal as described previously [14]. However, the relation of firing distance and damage in the gelatine was analogous to HSV observations; the more the muzzle approached the target, the greater was the damage in the gelatine. In each calibre, the results for 5- and 10-cm distance did not differ significantly and therefore were averaged and subtracted as "base line" (Fig. 6). The graphic indicates additional destruction at 3 cm for .357 Magnum. The values for 9mm Luger and .32 auto could be within a statistical scattering, those of .38 special seem not significant. For 2- and 1-cm distance, the increasing effect of muzzle gases is obvious and depends of the cartridge fired. In contrast, the additional damage by contact shots in absolute values is fairly equal for all the calibres tested. Contact shots using weaker loads caused a relatively higher increase of damage: .38 special + 150%, .32 auto + 120%, 9mm Luger + 100%, and .357 Magnum + 80% (Table 1). Figure 7 shows the correlation of kinetic rest energy and the polygon perimeter PP for contact shots ($r^2 = 0.909$) and for shots from distance (≥ 5 cm; $r^2 =$ 0.859). The shift of the curves corresponds to the effect of muzzle gases. Astonishingly, the slope of both linear function

Table 1 Parameters for contact shots ($n = 3$ per calibre) and shots from distance (≥ 5 cm, $n = 6$ per calibre)

Cartridge	.38 special			.32 auto			9mm Luger			.357 Magnum		
	Contact	Distant	c/d	Contact	Distant	c/d	Contact	Distant	c/d	Contact	Distant	c/d
max. H [mm]	106	39	*2.7*	104	37	*2.8*	107	47	*2.3*	103	57	*1.8*
mean ∑H [mm]	893	376	*2.4*	905	374	*2.4*	993	473	*2.1*	1066	589	*1.8*
mean ∑PP [mm]	1299	521	*2.5*	1281	587	*2.2*	1570	796	*2.0*	1695	952	*1.8*
mean ∑PA [mm^2]	10,453	1266	*8.3*	9680	1832	*5.3*	14,435	3365	*4.3*	17,519	5339	*3.3*

The maximum height of the TC for contact shots is fairly equal, whereas the maximum H of distant shots is increasing with the deposited energy

c/d ratio contact to distance; *H* height; *PP* polygon perimeter; *PA* polygon area

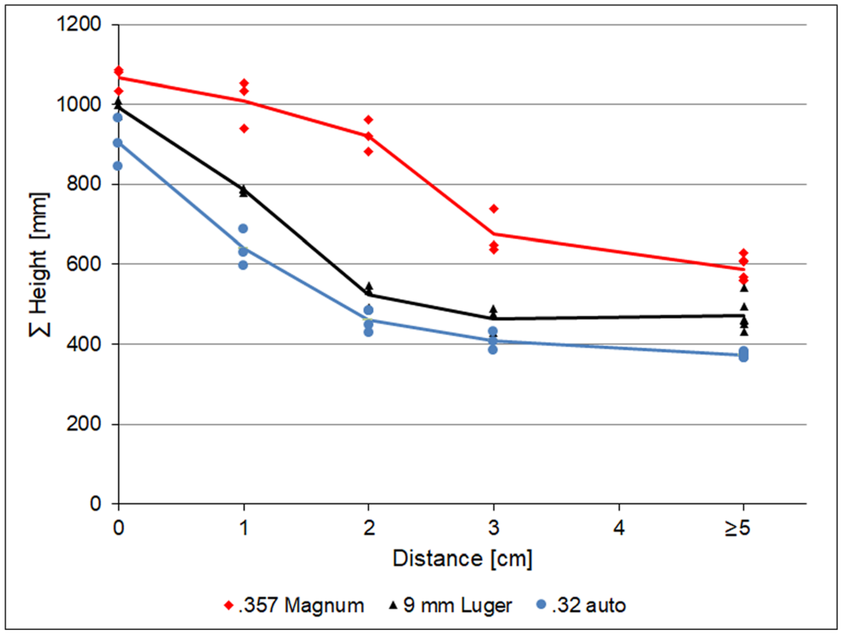

Fig. 4 The cumulated heights of the TC for contact shots and increasing distance. The curve of .38 special is completely overlaid by that of .32 auto

lines is practically identical. There is a strong linear correlation of estimated initial kinetic energy E_0 and PP in contact shots ($r^2 = 0.921$), too. The linear trendline of PP as function of E_0 for shots from distance ≥ 5 cm is shifted parallelly downwards.

Discussion

Gunshot wounds are a classical topic in forensic research. An important question asked of the forensic pathologist is whether the injury was self-inflicted or not. Hence, the determination of the shooting distance is crucial. Close contact shots ("tirs à bout touchant") are mainly observed in a suicidal context and regarded as a characteristic even though a homicide is not ruled out. So-called near-contact shots ("tirs à bout portant") are even worse: a suicidal action is possible, but the suspicion "of a third hand" remains. Although the estimation of the shot range alone cannot solve the addressed question, it remains an indispensable element of the reconstruction [18]. The approach is interdisciplinary. The forensic pathologist describes the wound and its surroundings (muzzle imprint, soot, powder particles, stippling, petechial bleedings). Autopsy may reveal a powder pocket, soot beneath the periosteum [6] or reddish coloration of muscle by CO-myoglobin [19]. Forensic scientists analyse the pattern and distribution of gunshot residues and compare them to results of test firing using the authentic firearm and ammunition [18]. Schyma et al. recommended to inspect the firearm for biological staining inside the barrel before performing test shots. The presence of visible and/or profilable biological traces of the victim was successfully demonstrated for contact shots to the head [20]. For experimentally investigating the origin of the traces, a cubic gelatine target model with 12-cm edge length and 1.7 kg weight, the "reference cube" [11], was introduced to study staining inside barrels and the TC at the same time. Contact shots lead to an impressive expansion of the TC by muzzle gases. When an elastic underlay was used, an asymmetric distortion of the TC was avoided. Whereas the TC in HSV was clearly higher using the elastic underlay, the crack lengths in gelatine did not differ for elastic underlay and rigid counterfort [16]. Yet, systematic research on the influence of muzzle gases on the TC was lacking.

Table 2 Ratio of collapsed TC to maximally expanded TC based on cumulated heights

	∑H coll TC / ∑H TC			
Distance	.38 special	.32 auto	9mm Luger	.357 Magnum
Contact	56%	45%	52%	47%
3 cm	27%	32%	37%	49%
≥ 5 cm	21%	26%	33%	34%

All heights were measured using the overlaid 12-line grid [15]

Previous studies documented the behaviour of deforming projectiles in small target models like the reference cube [14, 15]. This issue was avoided using exclusively form-stable FMJ bullets. The barrel length which is important for gas expansion [7, 21] was kept constant by 4 inch [16]. All calibres tested were known for relevant muzzle gas pressure as observed in forensic autopsies. In order to show the effect of muzzle gases, the muzzle of the firearm was approached more and more to the target. At 10- and 5-cm distance, the results obtained from HSV and gelatine slices did not differ from distant shots (> 20 cm up to few meters) [15] and were

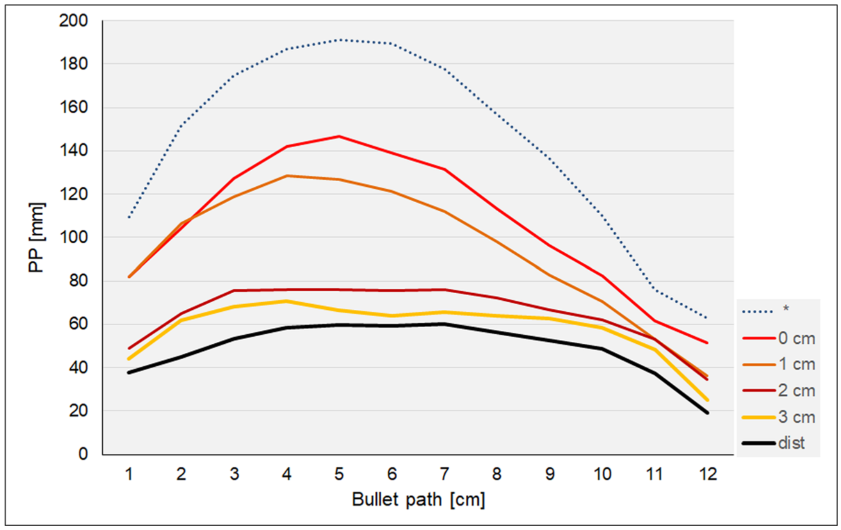

Fig. 5 Cross-sectional analysis of gelatine slices by the polygon method. Results of the polygon perimeter (PP) for shots using .32 auto ($n = 18$). The dotted line (*) gives the profile of the .357 Magnum contact shots as an orientation

correlated to the energy deposited. This confirmed observations that 9mm Luger ammunition fired from 10-cm distance did not deploy additional effects in comparison to shots from far distance [8]. The first difference in gelatine cross sections appeared when the .357 Magnum revolver was fired from 3-cm distance. At the same distance, 9mm Luger and .32 auto showed a slight increase in gelatine damage which, however, was in the range of possible variations within the batch of ammunition. With distances of 2 cm or less, the increasing deformation of the former tubular TC and its higher expansion was visible in HSV for all calibres. Correspondingly, the damage in the gelatine slices increased significantly. The profiles of the destruction parameters were all principally convex as previously published [15]. The distribution of relative damage along the bullet path was identical for all calibres at close contact. Contact shots had the vertex at 5 cm; the rest of the curves were rather symmetric with vertex between 6 and 7 cm. This was in contrast with the obvious form differences of the TC in HSV and brings to mind the issue of deforming bullets which did not leave the profile of damage in gelatine as expected from HSV [15].

The qualitative differences between HSV and damage in gelatine cross sections might be explained by the principal elastic behaviour of the cuboid target as previously discussed [15]. The quantitative observations are more difficult to understand. Four very different cartridges provoked a TC of about maximal 100 mm height at close contact in the phase of maximal TC expansion in longitudinal direction. This point in time was chosen to make the results compatible to the study of the TC in reference cubes [15]. However, this value does not represent the maximum height of the TC which was only reached in the early collapse phase. Therefore, the values for the maximally expanded TC (117 mm for .32 auto, 135 mm for 9mm Luger) published by Schyma et al. [16] differ although the same target model, pistols and ammunition had been used. When

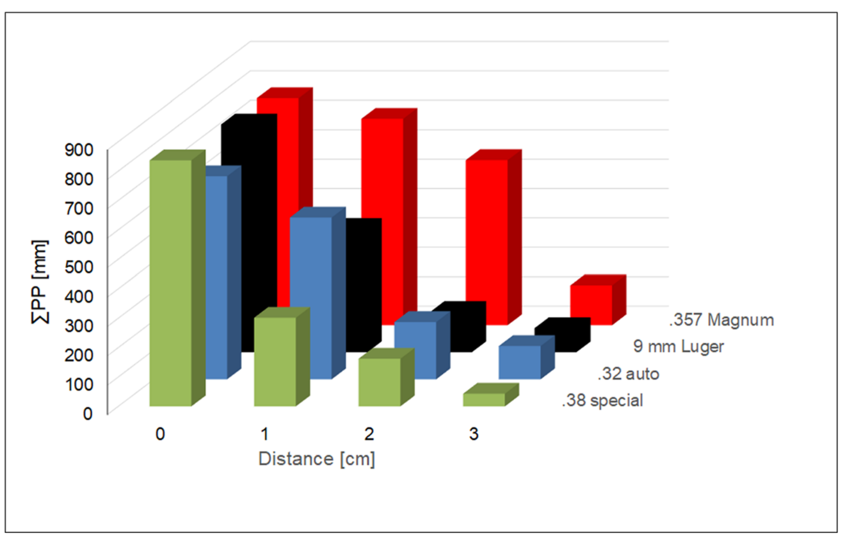

Fig. 6 Additional damage in gelatine measured with the polygon perimeter (PP). The damage caused by energy transfer, averaged for each calibre, was subtracted

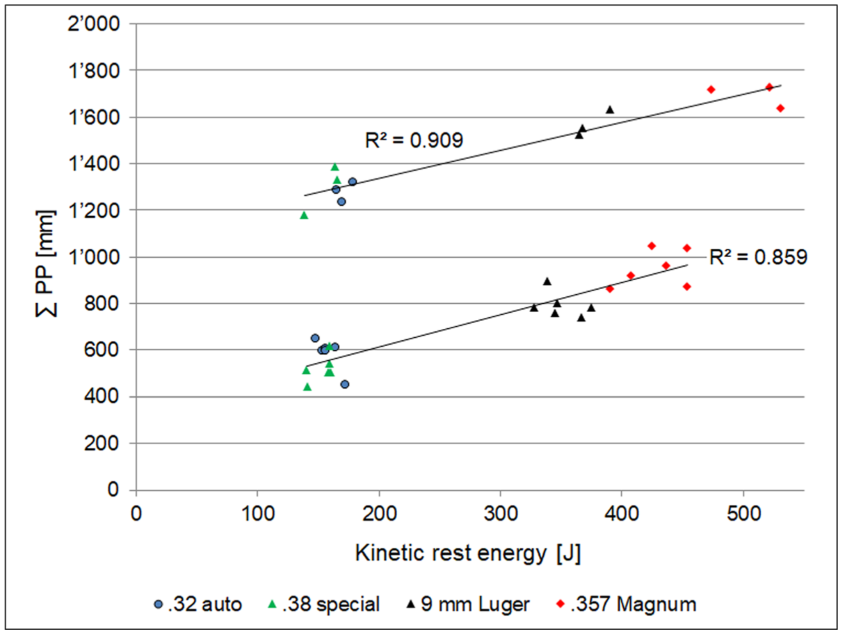

Fig. 7 Correlation of kinetic rest energy and the polygon perimeter PP for contact shots (n = 12) in comparison with distant shot ranges ≥ 5 cm (n = 24)

the TC continues to increase despite its collapse, this might be an indication that gases are still flowing in. Actually, it was demonstrated that muzzle gases blew up the TC, which was caused initially by the energy transfer of the bullet [16]. The analysis of the TC at its first collapse resulted in significant differences between contact and distant shots. This might be an indication that gases were trapped in the TC and prevented a complete collapse at this point in time. In HSV of the 9mm Luger, for example, the inflow of gases after the passage of the projectile is clearly visible. A method to measure this flow of gases in gelatine is not available yet.

Another issue complicating the interpretation of measurements is the unknown initial velocity and in consequence the initial kinetic energy E_0. Based on knowledge of the bullet deceleration in 12-cm long gelatine cubes [14], an estimation of the initial velocity was performed. The essential relation was found between initial energy and damage in gelatine when shots were fired at close contact. This seems logical because the initial energy E_0 reflects the pressure of gases which accelerated the bullet. The energy transferred by the non-deforming bullet which is a stable part of the E_0 in this short target model [14] did not differ significantly for the different shooting distances. Hence, the kinetic rest energy would be related to the initial energy and correlate with the total damage in gelatine. In addition, the kinetic rest energy is a measured and not an estimated value. The resulting linear function for contact shots was shifted upward parallelly to that of distant shots (≥ 5 cm). An analogous result was obtained for the correlation of the rest energy with $\sum H$. The distance between the lines reflects the effect of the full muzzle gas pressure. The results for distances from 3 to 1 cm are distributed in between. However, the "linear" correlation of short shot ranges and damage, respectively, TC should be interpreted carefully because the gas pressure itself was not measured. Further, the present study investigated only standard ammunition in four forensically relevant calibres. The individual increase of muzzle gas effects depending on the cartridge load points to a complex mechanism.

Conclusion

The study was performed on "reference cubes" as transparent head surrogates using HSV to record the TC of FMJ bullets fired from various distances.

- Wound ballistic effects of muzzle gas pressure are detectable from 3-cm distance or less.
- With decreasing shot range, the influence of muzzle gases increases.
- Muzzle gases deform the TC pear-like with blowing up the entry side and finally lead to a ballooning of the TC.
- Contact shots can approximately double the extension of the TC.
- In contact shots, gases appear trapped in the TC until its first collapse.
- Depending on shot range and ammunition, muzzle gas pressure causes damage in gelatine, which exceeds the results of energy transfer by the bullet.
- The 12-cm long target model reacts as a whole to the influence of muzzle gases.

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Compliance with ethical standards

Conflict of interests The authors declare that they have no conflict of interests.

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