Int J Legal Med
DOI 10.1007/s00414-017-1623-5

ORIGINAL ARTICLE

The influence of the counterfort while ballistic testing using gelatine blocks

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Received: 4 May 2017 / Accepted: 2 June 2017

Abstract In wound ballistic research, gelatine blocks of various dimensions are used depending on the simulated anatomical region. When relatively small blocks are used as substitute for a head, problems with regard to the expansion of the gelatine block could arise. The study was conducted to analyse the influence of the material the gelatine block is placed upon. Thirty-six shots were performed on 12 cm gelatine cubes doped with thin foil bags containing acrylic paint. Eighteen blocks each were placed on a rigid table or on a synthetic sponge of 5 cm height. Deforming bullets with different kinetic energies were fired from distance and recorded by a high-speed video camera. Subsequently, the gelatine cubes were cut into 1 cm thick slices which were scanned using a flatbed scanner. Cracks in the gelatine were analysed by measuring the longest crack, Fackler's wound profile and the polygon (perimeter and area) outlining the ends of the cracks. The energy dissipated ranged from 153 to 707 J. For moderate energy transfer, no significant influence of the sustaining material was discerned. With increasing dissipated energy, the sponge was compressed correspondingly, and the cracks were longer than in gelatine blocks which had been placed on a table. High-speed video revealed a loss of symmetry and a flattened inferior margin of the temporary cavity with energies superior to approx. Two hundred Joules when the blocks were placed on a rigid platform. However, 12 cm gelatine cubes showed material limits by a non-linear response when more than 400 J were dissipated for both rigid and elastic sustainment. In conclusion, the smaller the gelatine blocks and the greater the energy transfers, the more important it is to take into account the counterfort of the sustaining material.

Keywords Wound ballistics · Simulants · Temporary cavity · High-speed video · Energy transfer

Electronic supplementary material The online version of this article (doi:10.1007/s00414-017-1623-5) contains supplementary material, which is available to authorized users.

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Introduction

For many decades, gelatine has been used as tissue simulant in wound ballistic research [1]. Usually, gelatine blocks for ballistic experiments are moulded using a 10% gelatine solution (90% water). The expression "tissue simulant" is rather misleading, because gelatine has no structure, whereas biological tissues are very complex. However, gelatine is a reproducible and reliable substitute for real tissue while posing no ethical problems. Fackler compared bullet tracks in 4 °C cooled 10% gelatine (250 bloom, high viscosity) to those in anaesthetised pigs [2, 3] and elaborated a gelatine preparation method which avoided heat excess in order to ameliorate the reliability of the target models [4], establishing a standard which is internationally accepted and applied by many research groups [e.g. 5–10].

Gelatine is an elastic material with the advantage of transparency, thus allowing to record the bullet interaction with the target medium using high-speed video. The energy transfer of the bullet to the gelatine leads to an acceleration of the latter in

Published online: 14 June 2017

the radial direction, perpendicularly to the bullet track. Thus, for a short time, a cavity is expanded within the gelatine which collapses after a few milliseconds, followed by a decreasing pulsation of the cavity in both the axial direction of the bullet track and perpendicularly to it. After movements have come to an end, gelatine shows a discreet destruction zone corresponding to the bullet path and radial cracks as a consequence of the stretching of the gelatine by the temporary cavity. The cracks in gelatine correlate with the dissipated energy [11, 12].

In practice, the dimension of gelatine blocks used in wound ballistic experiments varies widely, depending mainly on the ammunition used. For deeply penetrating bullets, long blocks or a serial composition of several blocks are necessary to capture the whole bullet path. Expanding bullets (high energy deposit) require more voluminous blocks to avoid the latter being torn up by cracks. Another reason for varying the size and the form of the block is the necessity to simulate different parts of the body, e.g. an extremity [13] or a head [14, 15]. In contrast to large blocks, the bullet path in small target models has a distinctly smaller distance to the bottom. Riva et al. had studied the influence of the distance between the bullet path and the bottom and found no deflection of the non-deforming bullet if the distance was greater than 3.5 cm [16]. Jussila discussed the interaction between the gelatine block and the supporting platform for the formation of fissures and proposed to envelop the gelatine blocks in a shroud [17]. However, so far, it has not been investigated to which extent rigid versus elastic sustainment influences the expansion of the temporary cavity, especially in cases of high energy transfer or muzzle gas action.

Material and methods

The experimental work had two phases. In the first part, performed in collaboration with the criminal investigation service of the Police Department Bonn (Germany) in 2012, cubic gelatine blocks of 12 cm × 12 cm × 12 cm were doped with a thin paint pad integrated into the front of the block [12]. Shots were performed from 0.5 m distance using deforming bullets with a wide range of initial kinetic energy. The initial and the rest velocity of the bullet were measured using two light barriers BMC18 (Mehl, Diebach, Germany). Three shots each were performed on a block placed on a table or on a 5-cm high synthetic sponge (Table 1).

Recently, the experimental series was repeated with the reference gelatine cube of 12 cm [15], this time controlled by high-speed video. The gelatine blocks had been doped with a thin foil bag containing a mixture of acrylic paint and barium-sulphate [18]. The procedure was analogous for table and sponge (identical product). To record the bullet velocity before and behind the target [19], a SA-X2 Fastcam (Photron, Wycombe, UK) was used at 40.000 fps, exposure time 10 µs. The high-speed camera allowed to document the deformation of the gelatine block. Expanding bullets with different energy deposit were used as shown in Table 1. The blocks were first imaged as a whole by computed tomography [20] and subsequently cut into 1 cm slices perpendicularly to the bullet path and scanned on a flatbed scanner. Image analysis was performed using AxioVision 4.9 SE64 (Zeiss, Oberkochen, Germany) as published previously [12, 21].

The deformation of the block was measured from the calibrated high-speed video.

Results

Using different kinds of deforming bullets, the series covered a wide range of muzzle energies (170 to nearly 1000 J). The energy transferred to the target model varied from 153 to 707 J. The analysis of the relative (percental) energy transfer per 1 cm slice was very stable which documents a reliable expansion of the bullets in the gelatine (Fig. 1). This characteristic was independent of whether a sponge was used as support or not. The radiological control by computed tomography of the 18 blocks of the second series did not reveal any irregularity. The bullet hit the centre of the target with ±1 cm precision without any fragmentation along the bullet path.

Following previously published recommendations [22], all results are listed shot by shot in Table 1. All measurements were performed by two independent investigators. The reproducibility of all parameters, including velocity and energy deposit, was better than 99%.

The weakest bullet (cal. 32 auto) with a dissipated energy (E_d) from 153 to 162 J did not show a significant difference between a hard and an elastic counterfort (Fig. 2). This was valid for all measured parameters. High-speed video showed a maximal temporary cavity (TC) of approximately 7 cm diameter placed in respect to the height in the middle with 2.5 cm distance each to the hard bottom and to the top. The maximum diameter of the TC did not change when the block was placed on the sponge. Curiously, the energy adjustment—less than 10 J range—resulted in a visible difference (Fig. 3, Table 1).

Medium energy transfer was studied in three shooting series (38 Gold Dot, 38 First Defense and 9 mm Luger Gold Dot) of three shots each with (Supplementary Fig. 1) and without the sponge (Fig. 4). The 38 Gold Dot (Speer, CCI Ammunition, Lewiston ID, USA) has an 8.1 g (125 gr) weighing hollow point semi jacketed bullet with lead core. This ammunition was fired from a revolver with 2.5 in. barrel and E_d 170 to 237 J (median 219 J). The greatest difference between sponge and table was visible in the r_{max} (Fig. 2), the longest crack per slice, followed by the WP (wound profile according to Fackler [23], addition of the two longest cracks per slice), both showing an increase using the sponge as compared to a rigid surface. The perimeter of the polygon (PP)

Table 1 Ammunition used, sustainment of the target model, initial velocity, energy dissipated (E_d) and parameters measured

Number	Calibre	Bullet type	Bullet weight		Counterfort	v_0	E dissipated	$\sum r_{max}$	$\sum$ WP	$\sum$ PP	$\sum$ PA	Mean adjusted to E dissipated		
												WP	PP	PA
			[g]	[gr]		[m/s]	[J]	[mm]	[mm]	[mm]	[mm^2]	[mm/J]	[mm/J]	[mm^2/J]
1	32 auto	GD	3.89	60	Table	295	156	185	333	796	3681	1.989	4.850	22.9
2	32 auto	GD	3.89	60	Table	297	159	171	324	785	3553			
3	32 auto	GD	3.89	60	Table	331	203	203	365	916	4636			
4	32 auto	GD	3.89	60	Sponge	297	153	176	325	808	3813	2.126	5.282	25.4
5	32 auto	GD	3.89	60	Sponge	294	156	174	330	792	3356			
6	32 auto	GD	3.89	60	Sponge	297	162	183	346	889	4838			
7	38 special	GD	8.1	125	Table	270	200	197	368	950	5114	1.739	4.617	29.0
8	38 special	GD	8.1	125	Table	289	*214*	198	377	1014	6719			
9	38 special	GD	8.1	125	Table	321	237	199	383	1034	7121			
10	38 special	GD	8.1	125	Sponge	322	170	212	400	1029	6791	2.064	5.207	31.8
11	38 special	GD	8.1	125	Sponge	280	209	235	459	1110	6329			
12	38 special	GD	8.1	125	Sponge	307	*229*	215	376	975	5792			
13	38 special	FD	6.16	95	Table	308	232	240	444	1110	7250	1.778	4.479	31.7
14	38 special	FD	6.16	95	Table	332	269	252	472	1174	7976			
15	38 special	FD	6.16	95	Table	335	288	255	480	1234	9834			
16	38 special	FD	6.16	95	Sponge	324	264	313	539	1295	8840	1.945	4.769	34.0
17	38 special	FD	6.16	95	Sponge	328	265	256	461	1141	7818			
18	38 special	FD	6.16	95	Sponge	330	266	316	546	1355	10,368			
19	9 mm Luger	GD	8.04	124	Table	354	*358*	277	535	1436	14,251	1.441	3.883	37.2
20	9 mm Luger	GD	8.04	124	Table	*355*	*360*	259	502	1367	12,854			
21	9 mm Luger	GD	8.04	124	Table	357	*364*	268	522	1398	13,181			
22	9 mm Luger	GD	8.04	124	Sponge	350	*350*	265	516	1369	12,685	1.514	3.995	39.3
23	9 mm Luger	GD	8.04	124	Sponge	356	*362*	306	556	1454	14,046			
24	9 mm Luger	GD	8.04	124	Sponge	358	*366*	299	561	1485	15,719			
25	357 Magnum	FD	6.16	95	Table	431	432	336	627	1581	14,455	1.294	3.279	32.0
26	357 Magnum	FD	6.16	95	Table	457	496	338	633	1530	13,702			
27	357 Magnum	FD	6.16	95	Table	461	542	329	625	1676	18,843			
28	357 Magnum	FD	6.16	95	Sponge	425	448	313	595	1503	14,246	1.244	3.126	29.2
29	357 Magnum	FD	6.16	95	Sponge	455	513	375	673	1655	14,774			
30	357 Magnum	FD	6.16	95	Sponge	456	530	318	579	1483	14,377			
31	357 Magnum	GD	8.1	125	Table	472	514	284	535	1397	13,186	0.946 *(0.898)*	2.470 *(2.346)*	24.6 *(24.0)*
32	357 Magnum	GD	8.1	125	Table	454	643	281	541	1450	14,059			
33	357 Magnum	GD	8.1	125	Table	464	677	337	646	1647	17,680			
34	357 Magnum	GD	8.1	125	Sponge	463	394	330	644	1706	19,255	1.097 *(0.829)*	2.904 *(2.191)*	30.5 *(21.2)*
35	357 Magnum	GD	8.1	125	Sponge	470	644	270	519	1408	13,708			
36	357 Magnum	GD	8.1	125	Sponge	496	707	313	601	1550	14,961			

Values in italics are estimated as described. Values in round brackets corrected after elimination of two outliers

GD Gold Dot by Speer, CCI Ammunition, Lewiston ID, USA, *FD* First Defense by Magtech, Lino Lakes, USA, R_{max} longest crack per slice, *WP* Fackler's wound profile, addition of the two longest cracks per slice, *PP* polygon perimeter, *PA* polygon area

(Supplementary Fig. 2) which correlates with the WP [21] was slightly bigger with the sponge, whereas the polygon area did not differ. In analogous way to the 32 Gold Dot, the energy-adjusted values turned out higher for the elastic support.

Firing the 38 First Defense (Magtech, Lino Lakes, USA), a solid copper hollow point bullet, with a 6-in. revolver, an E_d of 264 J in the mean could be obtained. R_{max}, WP and the PP reached higher values if the sponge was placed under the gelatine block. High-speed video revealed an asymmetric TC while the block was put on the table (Fig. 4), while the bottom margin of the TC still had approximately 1.5 cm distance to the table. In contrast, the TC seemed more rounded to

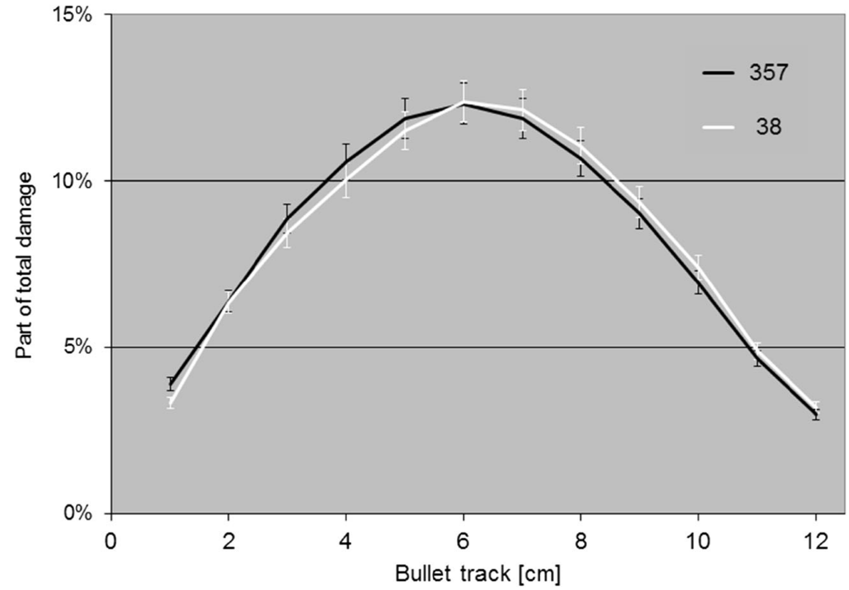


Fig. 1 The analysis of the relative energy dissipation per slice based on Fackler's wound profile for the First Defense bullets in the calibres 38 special and 357 Magnum documents a reliable and uniform expansion and energy transfer

the bottom when the gelatine cube was placed on the sponge. Analysis of the behaviour of the sponge showed a slight compression linked to an enlargement to both sides in the axis of the shot. As for the previous shot series, the energy-adjusted curves for r_{max}, WP (Fig. 3) and PP were distinctly higher with the elastic counterfort, and in this series, the polygon area was slightly greater, too (Table 1).

The very precise 9 mm Luger Gold Dot hollow point bullet had muzzle velocities between 350 and 358 m/s, corresponding to an expected initial energy of 510 J. In a preliminary test (Supplementary Fig. 1), an energy transfer of 71% into a reference cube could be observed. This result was used to estimate a posteriori E_d with 360 J in the mean. The comparison between the two sustaining materials showed higher values for the sponge regarding all parameters, including the polygon area (PA) and the energy-adjusted values (Table 1). The high-speed video documented a huge TC with compression of the sponge. The inferior half of the gelatine block was completely exhausted by the TC (Supplementary Fig. 1). This ammunition showed the most regular pattern of fissures. The overlay of corresponding slices with and without sponge revealed that not one crack alone was longer when using the sponge, but the increase of crack length concerned various directions (Fig. 5).

The 357 Magnum Gold Dot bullet used in the first part of the study had a bullet weight of 8.1 g and reached nearly up to 1000 J initial kinetic energy when fired with a 6-in. revolver. The E_d in the 12-cm cube varied widely from 394 to 707 J. The r_{max} (Fig. 2), WP and PP showed higher values using the sponge, whereas the area of the polygon did not differ between sponge and table as support of the block. Because of the great differences of dissipated energy (about 300 J range), it was inevitable to adjust the absolute measurements to the energy dissipated. The differences remained after energy-adjusted evaluation. However, when the atypical low E_d were regarded as outlying values (514 J for the table and 394 J for the sponge) and eliminated from the evaluation (reduction of the E_d range to only 64 J in this group), r_{max} was equal for table

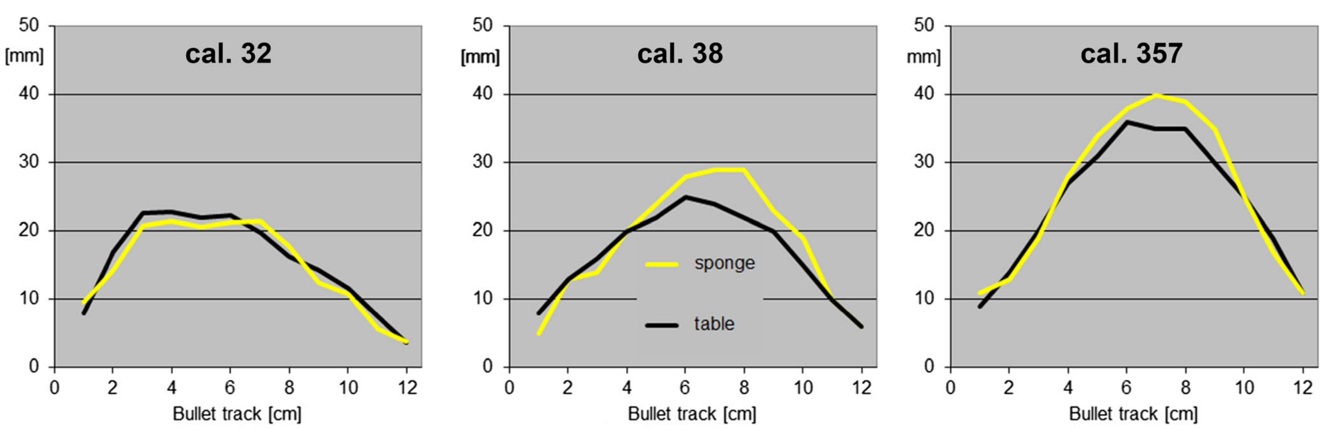


Fig. 2 The graphs show the median of the longest crack (r_{max}) for Gold Dot bullets in the calibres 32 auto, 38 special and 357 Magnum

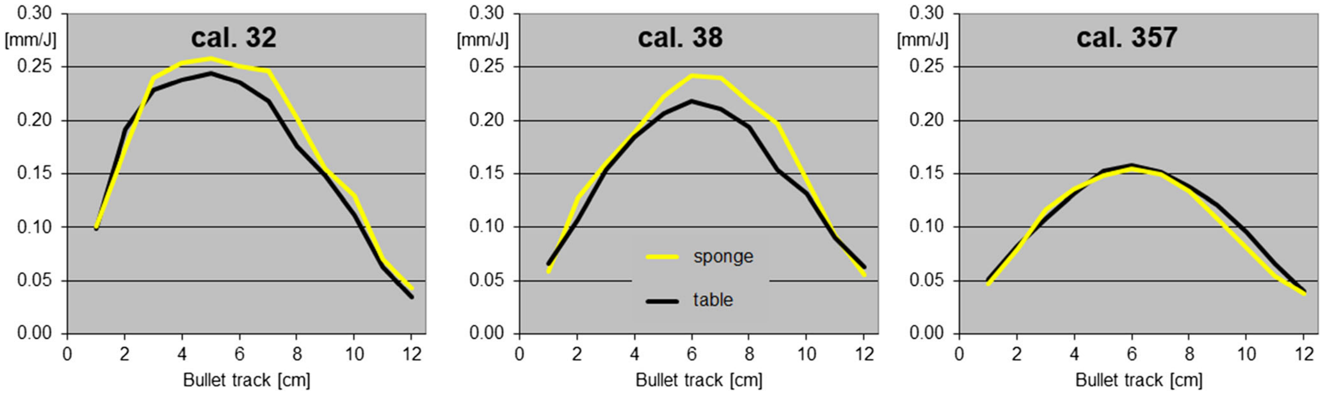


Fig. 3 The graphs show the energy-adjusted mean of Fackler's wound profile (WP) for the 32 auto Gold Dot bullet and the First Defense bullets in the calibres 38 special and 357 Magnum

and sponge, and the other parameters (values in brackets in Table 1) were even lower for the sponge than for the rigid support. As an example, the energy-adjusted polygon area was 24.0 mm^2/J for the table versus 21.2 mm^2/J for the sponge.

Wishing to diminish the variation of E_d in the second series, 357 First Defense ammunition was chosen. To reduce the initial kinetic energy, the bullets were fired by an only 4-in. barrelled revolver. Effectively, the energy transfer ranged between 432 and 542 J which lead to an impressive TC with obvious compression of the sponge (Fig. 6). With this experimental setup, absolute measurements and energy-adjusted values (Fig. 3) did not show a significant difference for the sustaining material (Table 1).

For all energy levels used in the various experimental series, an increase of absolute r_{max} with increasing energy dissipated was observed. In contrast, the energy-adjusted values—here WP as a representative example (Fig. 3)—were similar for low and moderate energy transfer but decreased with increased deposited energy. In consequence, the measurements of the polygon perimeter were displayed in dependence of the E_d (Fig. 7). For energy deposits up to 400 J, a linear correlation with the PP could be statistically confirmed. Beyond 500 J, none of the parameters indicated a linear correlation between energy transfer and gelatine destruction anymore.

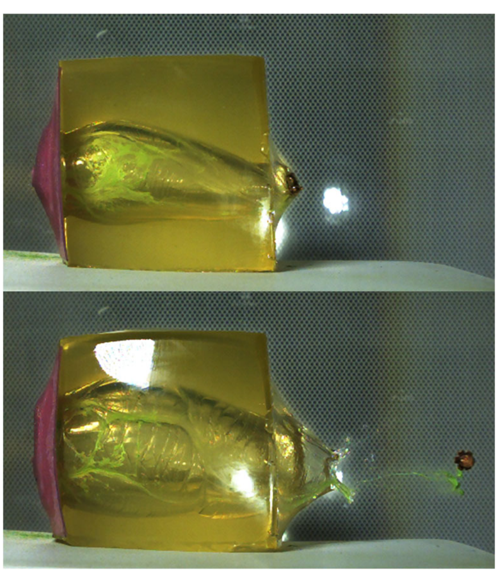


Fig. 4 Shot no. 15 using cal. 38 special First Defense, 0.8 ms time between the two images. Asymmetrical formation of the temporary cavity while the block is placed on the table

Discussion

In the research project funded by the Swiss National Science Foundation, the origin of staining inside firearm barrels had to be investigated. First, silicone-coated boxes or PET-bottles were used as targets for contact shots [20, 24]. Although these target models had a small volume (up to 1 l), the positioning

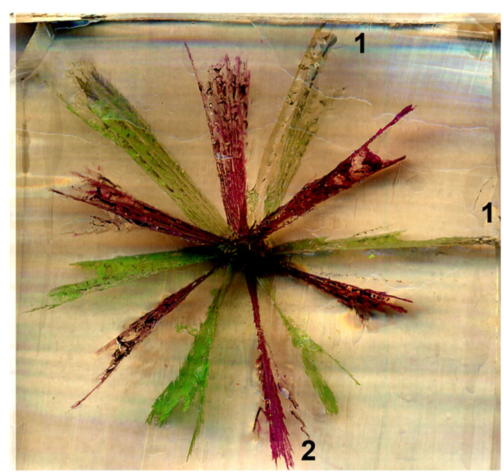


Fig. 5 Overlay of two gelatine slices of shots using the 9 mm Luger Gold Dot. Both images are oriented according to how the block had been placed and show the destruction in 8 cm depth of the block. The brighter (*green*) coloured cracks occurred using the sponge (shot no. 24), the darker (*magenta*) coloured cracks without sponge (shot no. 20). Please note the longer cracks (1) due to the sponge are orientated to top and side, while a relatively long crack (2) points to the bottom, although this block was placed on the table

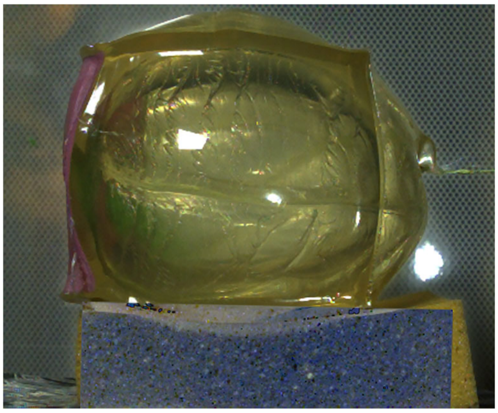


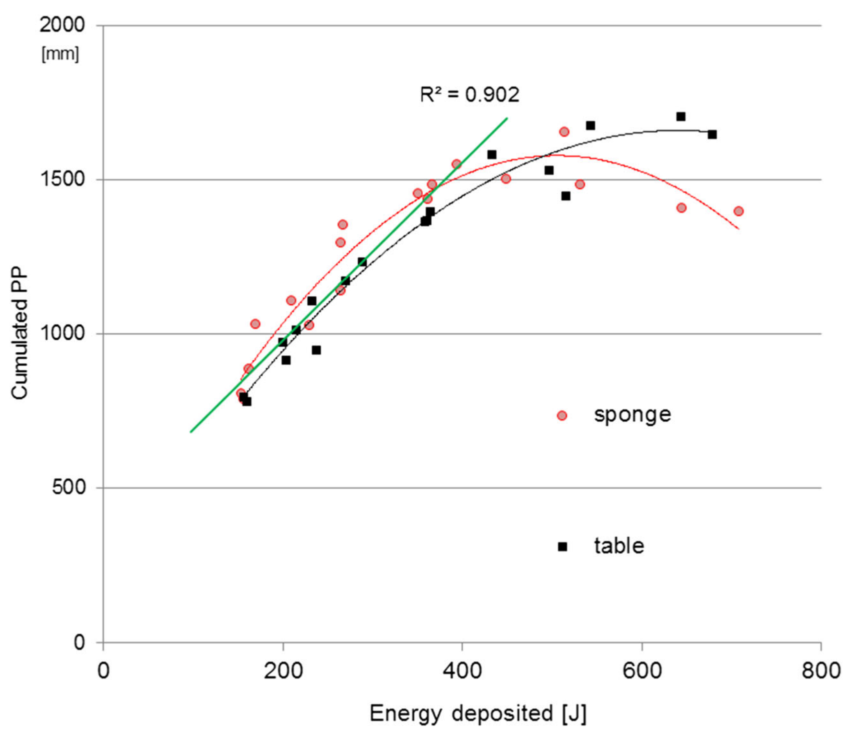
Fig. 6 Shot no. 30 using cal. 357 Magnum First Defense. The original position and form of the sponge had been overlaid to demonstrate the deformation of the sponge

on a table seemed unproblematic, because the gelatine was confined in a container. However, in the course of the development of a transparent target model without an enveloping container—the 12-cm reference cube [15]—the question arose how to correctly place this relatively small gelatine block. The search for a sustaining material which allows for an unrestricted expansion of the gelatine block began in the year 2012, and the first results showed that a synthetic sponge placed under the gelatine block lead to greater crack lengths. This experience was now applied and in the second part of the study controlled by high-speed video. The second part confirmed the first series in all aspects, despite the fact that other brands of expanding bullets had been used.

Several findings were of interest. It was expected that the influence of the sustaining material was dependent on the dimension of the TC. Effectively, for low energies (<200 J), no difference was observed because, as documented by high-speed video, the TC did not deform the gelatine cube. Nevertheless, the energy-adjusted values, especially the longest crack per slice (r_{max}), were higher for the elastic support (Fig. 2). The greatest effect of the counterfort could be observed for energy deposits between approximately 200 and 400 J. This difference was most pronounced in the middle of the block where the greatest expansion of the TC could be observed, whereas the less stretched zones, the beginning and the end of the bullet path showed similar values for both types of sustainment.

Astonishingly, the differences were decreasing when higher energies than approximately 400 J were dissipated. The analysis of the energy-adjusted values revealed a decrease of the destruction parameters per Joule, which was accentuated above 400 J energy transfer (Fig. 3). This indicates a non-linear response of the target medium (Fig. 7), as it had been discussed previously [12]. Jussila discussed both the influence of the supporting platform and the size of the gelatine block for asymmetric formation of the TC [17], too. In fact, the small size of the 12-cm reference cube could be a limitation for wound ballistic analysis of high energy transfer. The comparison of the results with 357 First Defense (mean energy deposit 494 J) and 357 Gold Dot (mean E_d 597 J) reveals arising problems. At first appearance, both bullets seemed to show different energy-adjusted destruction parameters depending

Fig. 7 Correlation of the energy dissipated E_d and the cumulated perimeter of the polygon (PP). The linear trend line refers to shots with E_d < 400 J



on the support used. After mathematical elimination of the two suspiciously weak Gold Dot shots (mean E_d 454 J) as outliers, the behaviour of the two bullets was estimated comparable, showing that the outliers had distorted the curve. Their elimination revealed that for both kinds of bullets, the extremely high energy transfer (First Defense mean E_d 494 J, Gold Dot $\text{mean}_{\text{corr}}$ E_d 668 J) could not be cushioned by the sponge. This can be interpreted as a signal that the sponge as well as the system of the 12-cm gelatine cube had reached their maximum capacity.

High-speed video has shown to be a suitable instrument to control the formation of the TC in respect to possible asymmetry and to avoid misinterpretation. In contrast, the crack analysis is not reliable to retrospectively detect a suspected asymmetry in the formation of the TC. Six shots performed with the very regularly expanding 9 mm Luger Gold Dot ammunition showed six-branched stellate fissures (Fig. 5). The three shots using the table as platform had shorter crack lengths than those using the sponge, but the reduced fissuring seemed to be symmetrical. Further studies have to be conducted to investigate the mechanism of how exactly fissures are formed in gelatine.

Another point of discussion is the choice of an appropriate parameter to estimate the energy transfer. In the comparison of the rigid and the elastic support, the maximum crack length ($r_{\max}$), followed by Fackler's WP and the polygon perimeter—which correlates with the WP [21]—were found to be sensitive. This would be compatible with the concept that the length of the cracks correlates with the expansion possibility of the block. By contrast, the polygon area covering the entire destruction zone showed rather small differences between the different platforms used. By implication, the PA or the TCL (total crack length method [11]), which has a similar characteristic with the PA [12], could be a more robust approach to estimate energy transfer in small gelatine models.

Conclusion

- Energy transfer up to 400 J causes longer cracks in gelatine when using an elastic support of gelatine blocks than with a rigid platform.
- Unrestricted expansion of the gelatine block leads to an increase of crack lengths overall without specific direction in comparison to gelatine models on a rigid platform.
- A compression of the sustaining material depending on the size of the TC could be documented by high-speed video.
- High-speed video is a suitable technique to discover asymmetrical formation of the TC.
- Beyond approximately 400 J energy deposit, the 12-cm gelatine cube approaches material limits with obvious limitation regarding wound ballistic considerations.

Acknowledgments This research work was funded by the SNF (Swiss National Science Foundation, project 310030E-147628/1). We wish to thank Michael Ziege and his colleagues (Grenzschutzgruppe 9, Federal Police, Hangelar, Germany) as well as Frank Gredig (Criminal Investigation Service, Police Department Bonn, Germany). The radiological assistance of Nicole Schwendener (Institute of Forensic Medicine Bern) is also gratefully acknowledged.

Compliance with ethical standards

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

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