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ORIGINAL ARTICLE

Visualisation of the temporary cavity by computed tomography using contrast material

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Abstract The temporary cavity of a missile produces radial tears in ordnance gelatine, which correlate to the energy transfer. Computed tomography is a useful and non-destructive method to examine gelatine blocks. However, the tears give only few radiocontrast by air filling, which decreases with the time past shooting. Therefore, systematically, a radiocontrast material was searched to enhance the contrast. Different contrast materials were amalgamated to acryl paint, and about 7 g was sealed in a foil bag, which was integrated in the front of a standard 10% gelatine cylinder. Shots with Action-5 expanding bullets were performed from a 5-m distance. Gelatine was scanned by multi-slice computed tomography. The multiplanar reconstructed images were compared to mechanically cut slices of 1 cm thickness. It was shown experimentally that iodine containing water-soluble contrast material did not give sufficient contrast and caused diffusion artefacts. Best results were obtained by barium sulphate emulsion. The amount of acryl paint was sufficient to colour the tears for optical scanning. The radiocontrast of barium leads to satisfying imaging of tears and allowed the creation of a three-dimensional reconstruction of the temporary cavity. Comparison of optical and radiological results showed an excellent correlation, but absolute measures in computed tomographic (CT) images remained lower compared with optically gathered values in the gelatine slices. Combination of paint and contrast material for CT examination will facilitate the evaluation of complex ballistic models and increase accuracy.

Keywords Wound ballistics · Temporary cavity · CT · Contrast material · Gunshot energy · Ordnance gelatine

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Introduction

Gunshot injuries show two pathophysiological aspects: permanent and temporary cavity [1, 2], which are both consequences of bullet tissue interaction. The residual wound channel or permanent cavity represents directly crushed tissue which has to be excised by surgery [3]. The temporary cavity is caused by energy transfer of the bullet to the tissue. The tissues surrounding the bullet tract are driven away in a radial direction from the bullet path. This stretching effect can lead to tissue disruption depending on the energy [2, 4]. For many decades, already gelatine is used as tissue simulant in wound ballistics to demonstrate those effects. In order to standardise these experiments, Fackler [1, 4, 5] calibrated gelatine on living tissue and established a procedure on how to prepare gelatine blocks which have to be shot at 4°C block temperature. Usually after shooting, the gelatine blocks are examined by transillumination, which shows the longitudinal extension of the destruction caused by the temporary cavity. Then, the blocks are cut to slices perpendicular to the bullet track. In gelatine, the permanent cavity is easy to detect as a cylindrical defect along the bullet path. The stretching effects by temporary cavity provoke radial tears in gelatine.

The idea was to analyse the entire block by a non-destructive method. Radiology, especially computed tomography, which is regarded to be the gold standard in clinical examination of gunshot injuries [6], seemed to be the most obvious method. Korac et al. [7] were the first to use computed tomography for this purpose to visualise permanent cavity. Bolliger et al. [8] directly examined cracks in gelatine blocks by computed tomographic (CT) analysis but did not compare their findings with the extension of the tears in conventionally, that is, mechanically cut slices. However, if Harcke et al. [9] might have thought that postmortem CT images showed poor differentiation between soft tissues, there is no contrast at all in amorphous gelatine. In difference to the defect of the permanent cavity filled with air giving a radiological contrast, the cracks in gelatine close themselves after the collapse of the temporary cavity. Already some hours after shooting, the cracks are vanishing if only transillumination is used. Only by cutting the block as soon as possible can one find and measure radial tears in their original extension. Therefore, it was necessary to find a method to introduce radiological contrast into the model. We did not try to instil contrast material in the bullet path because analogous tests long time ago using paint had shown poor results. Experiences with paint pads that were put onto the block and were penetrated by the bullet seemed to be better. The acryl paint was soaked into the block by the temporary cavity and even filled the finest cracks [10]. Therefore, we started a systematic study to verify if optical and radiological contrast could be realised simultaneously in gelatine.

Methods and materials

First step: feasibility study

A 10% standard gelatine was prepared following Fackler's instructions [5]. The gelatine solution was moulded in cylindrical containers with 15 cm diameter in order to simplify subsequent radiological examination by using head support of the tomograph. These cylinders had a length of 10–12 cm.

Three contrast materials were tested.

Gastrografin®: 37 g iodine per 100 ml purified water (atomic number of iodine is 53)
Micropaque® H.D. Oral: 200 g barium sulphate as suspension in 100 ml water (atomic number of barium is 56)
Telebrix® N: 18 g iodine per 100 ml purified water

Six different mixtures of contrast material and green acryl paint were freshly prepared in test tubes using a vortex mixer.

- 4 ml acryl paint 1 ml Gastrografin®
- 4 ml acryl paint 2 ml Gastrografin®
- 3 ml acryl paint 2 ml Micropaque®
- 4 ml acryl paint 2 ml Micropaque®
- 3 ml acryl paint 2 ml Telebrix®
- 2 ml acryl paint 3 ml Telebrix®

About 4 ml of the mixture was sealed between two foils. Those little bags had a dimension of about 5 cm×7 cm and were fixed in front of the 4°C cooled gelatine cylinders with scotch tape. Because the gelatine cylinders only had a length of 12 cm, Action-5 expanding bullets were chosen, which promised to mushroom reliably and dissipate the major part of their kinetic energy in the short bullet track. The gelatine was shot from a distance of 5 m with a SIG Sauer Pistol P225 with 9 mm×19 (Luger) Action-5 ammunition (RUAG). The velocity of the projectile was measured.

Three hours later, the gelatine was scanned with a multi-slice computed tomograph (Philips, Brilliance 16). The scanning was performed with a tube voltage of 120 kV and a tube current of 320 mA. A spiral mode was used with a detector setting of 16×0.75 mm and a pitch of 0.688. Reconstructed slice thickness was 0.8 mm with overlapping slices and a gap of −0.4 mm. A bone filter was found to be the best reconstruction kernel for the delineation for the concentrated contrast medium versus air versus gelatine in the projectile course. To interpret the images, the window width and level were adjusted to the best visual impression according to the contrast medium. To compare the optical images, multiplanar reconstructions with 2 mm slice thickness were aligned perpendicular to the axis of the bullet's trajectory. Single slices were then exported in TIF format.

Second step: improvement of the contrast material

Mixtures of different chemical substances with acryl paint were tested.

- 2 ml acryl paint 2 g lead acetate salt $Pb(CH_3COO)_4$ (atomic number of lead is 82)
- 2 ml acryl paint 2 g tungstic acid H_2WO_4 (atomic number of tungsten is 74)
- 2 ml acryl paint 2 g barium sulphate emulsion $BaSO_4$ (atomic number of barium is 56)

The mixtures were prepared by stirring the components directly. The resulting viscous material was scratched out in a thin layer on the bottom of a container, which was immediately filled with gelatine solution. Forty-eight hours later, the gelatine was scanned by Philips Brilliance 16 tomograph.

Third step: control of the improved radio-colour contrast

The ready-to-use Micropaque® "barium meal" was left for sedimentation for several days.

Three mixtures of acryl paint and Micropaque® sediment were prepared by amalgamating.

- 4 ml acryl paint 2 ml barium sulphate emulsion
- 2 ml acryl paint 2 ml barium sulphate emulsion
- 2 ml acryl paint 4 ml barium sulphate emulsion

The foil bags containing the mixtures were placed on the bottom of a cylindrical container, which was filled with 10% gelatine solution. After 48 h of cooling at 4°C, the solidified gelatine cylinders were removed from the containers, and the bags were found integrated into the surface of the gelatine. The gelatine was shot from a distance of 5 m with a SIG Sauer Pistol P225 with 9 mm×19 (Luger) Action-5 ammunition (RUAG). The cylinder was oriented so that the bullet hit the foil bag before passing the gelatine. Within 3 h, the gelatine was scanned by Philips Brilliance 16 tomograph.

Evaluation

The gelatine cylinders were cut to consecutive slices of 1 cm thickness and scanned with a flat bed scanner at 300 dpi (Epson Perfection 3200). The optical and radiological images were scaled and measured using AxioVision Rel. 4.7 (Zeiss, Germany). In addition, each five radiologic images which represented 2 mm thickness were inverted and superposed using CorelPhotopaint 12 (feature image merging "if darker").

Results

As expected, all the shots were penetrating without leaving any fragments. The velocity of the Action-5 projectiles varied from 377 to 418 m/s. Former experiments with record of the target velocity and the rest velocity of the Action-5 bullets had given an energy transfer of more than 80% (>400 J) in a 10-cm-long gelatine block. All the projectiles recovered showed the typical mushroom-like deformation. In each shot, green acryl paint was soaked into the gelatine cylinders. The intensity of colour was all lower than in blocks endowed with 100% acryl paint pads, which can be explained by the paint's dilution factor of up to 2:1. Another difference to the use of sole paint was the inhomogeneous distribution of the colour in the bullet track. The greatest part of the paint was—apart from the first centimetre of the trajectory—visible in the second half. Finally, all the cross sections of the gelatine showed sufficiently colour contrasted tears. The preservation of the tears was optically and metrically stable for several days like it was already observed with pure acryl paint [10].

The computed tomography showed the permanent cavity as an air-filled cylindrical defect of varying diameter in the gelatine. In the first series, the radial tears were only partly visible because of their air filling. In comparison with the optical slices, the tears in the CT image were shorter and less ramified.

Gastrografin®

It was difficult to mix Gastrografin® with acryl paint. CT showed rests of contrast material on the surface of the gelatine cylinder. However, there was no continuous distribution of Gastrografin® inside the gelatine. Using a low amount (1:4) of Gastrografin®, there was only a touch which seemed to follow the permanent cavity but not the tears. The 1:2 Gastrografin®–paint mix produced a little bit more contrast, leaving a tear in the second half of the trajectory. The detailed image analysis revealed diffusion clouds around the permanent cavity.

Telebrix®

Analogous to Gastrografin®, the water containing Telebrix® could hardly be stirred into the acryl paint. The images showed better distribution of the contrast material along the wound channel which is due to the higher volume (2:3/3:2) parts of the mixture. The major part of Telebrix® was concentrated around the permanent cavity whereas only few tears were slightly contrasted.

Micropaque®

The ready-to-use "barium meal" and the acryl paint was easier to mix than Gastrografin® and Telebrix®. The distribution of the contrast material inside the gelatine was better but not homogeneous enough. In the second half of the bullet track, several tears were contrasted. The contrast material was located only in the gelatine disruption; diffusion however was not observed.

These primary results showed that radiocontrast based on water-soluble substances was neither sufficient nor precise because diffusion artefacts were inevitable. Therefore, further research was needed to find a water-insoluble contrast material which was well mixable with acryl paint. The salts of lead acetate and tungstic acid were directly mixed into the acryl paint and showed a distinct radiocontrast with heavy metals, as already expected. The tungsten mixture caused an unpleasant partial dissolution of the paint into the gelatine. In this regard, lead acetate was unproblematic. The best radiocontrast was produced by barium sulphate emulsion, which was obtained as sediment of the Micropaque® meal. Even in direct contact with liquid gelatine, there was neither diffusion nor dissolution of contrast material or paint.

For that reason, mixtures of Micropaque® emulsion and paint in different proportions were tested using expanding

Action-5 projectiles. The 1:1 mixture showed the poorest amount of paint and radiocontrast because the foil bag was hit to its border. Nevertheless, in all of the slices, there was a fine trace of paint found. Proportionally, the CT images presented slight contrast material, which indicated a more homogeneous mixture.

Best results were obtained by using other preparations, regardless of their mixture proportion. In both gelatine cylinders, the distribution of paint and contrast material was similar with the focal point in the second half (Fig. 1), as was already observed during the first series. However, radiocontrast (Fig. 2) presented a multitude of even finer tears.

Due to high contrast between contrast medium and gelatine, it was possible to create a three-dimensional reconstruction at the work station of the helix of the tears by maximum intensity projection technique (MIP) (Fig. 1). Therefore, computed tomography enabled plastic impression of the temporary cavity.

Evaluation of the optical and radiological images was performed accordingly to Fackler's wound profile (addition of the two longest cracks) [1] and the polygon method (perimeter of the polygon generated by the ends of the tears) [10]. Figure 3a, b demonstrates the absolute measures of the wound profile. In both test shootings, the tear lengths in CT were lower compared with those in optical scans. Absolute values of the polygon perimeter in the CT also did not reach up to those measured in the colour-contrasted gelatine slices. Finally, the comparison of the relative

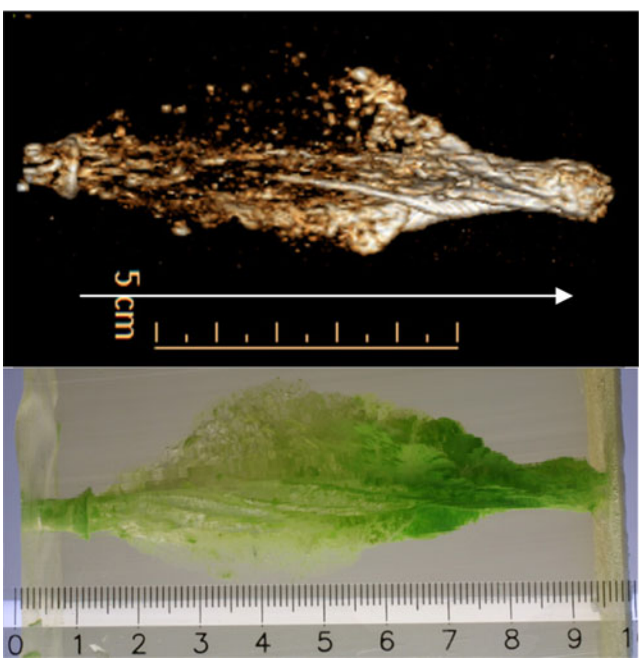

Fig. 1 Multiplanar reconstruction using MIP of shot 1 with Action-5 (barium to paint, 1:2). *Arrow* indicates the shooting direction

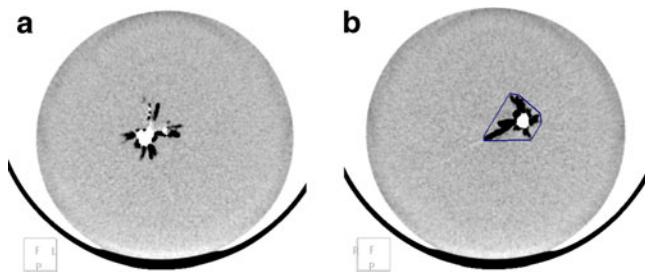

Fig. 2 Inverted pictures of multiplanar reconstructed slices of 10 mm thickness. The contrast material is *dark* and air filling is *white*. **a** Five centimetres after the entry. Ratio of contrast material to paint, 1:2. **b** Seven centimetres after the entry. Ratio of contrast material to paint, 2:1

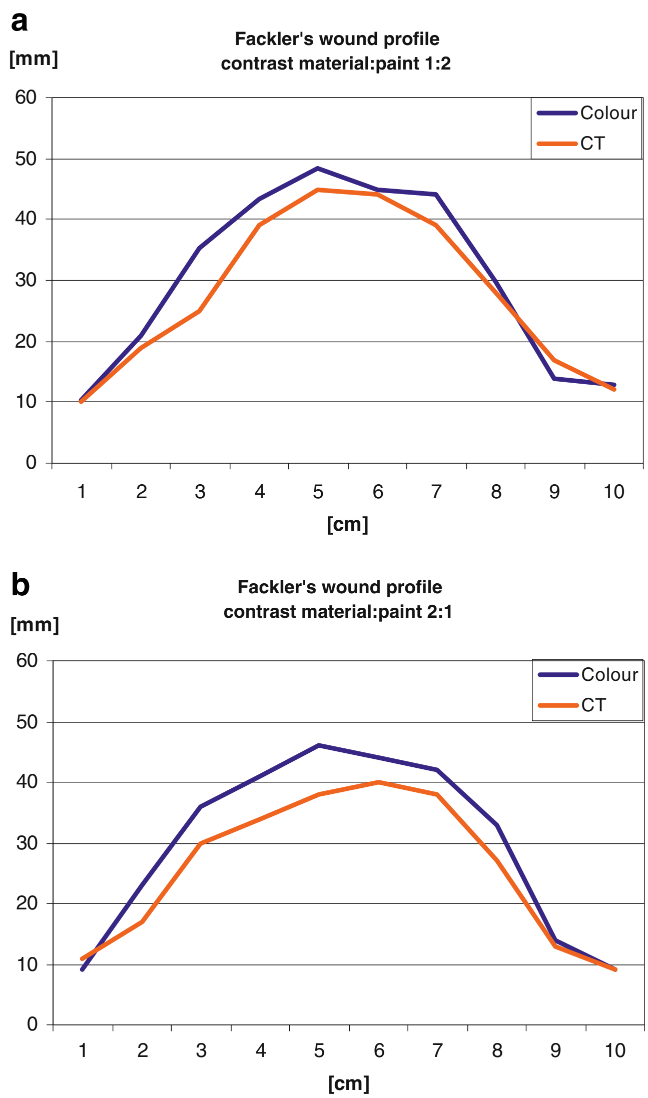

Fig. 3 **a**–**b** Comparison of optically (paint) and radiologically (CT) measured wound profile of Action-5 bullets in 10-cm-long gelatine cylinders. **a** A 2-ml barium sulphate emulsion, 4 ml acryl paint. **b** A 4-ml barium sulphate emulsion, 2 ml acryl paint

profiles of damage (Fig. 4a, b) showed a good correlation of radiological and optical image.

Discussion

In the examination of gunshot injuries, radiological methods have a long tradition and have helped in discovering bullets and bullet fragments in medico-legal routine work [6, 11, 12]. CT analysis is used more and more to reconstruct the bullet path [13] and is even used to detect gunshot residues [14, 15]. The greatest advantage of radiological examination is its non-destructive character. This might be necessary in wound ballistics for complex models like head models where transillumination cannot be performed. Unfortunately, gelatine, the typical tissue simulant, is an amorphous mass without radiological contrast. The disruption of gelatine caused by stretching during formation of the temporary cavity could be shown in CT [7, 8] by contrast of air captured in the tears with gelatine matrix. However, Korac et al. described the difficulty in distinguishing the noise in the CT pictures from the border of the permanent cavity [7]. While radiological analysis of the temporary cavity in soap blocks is reliable [16]—the maximum cavity remains "frozen" in inelastic soap—the temporary cavity in gelatine collapsed immediately after passing the bullet. The radial tears initially filled with air optically vanished with increasing time after shooting. The experience with colour contrast in gelatine proved that resealing of the tears is inhibited by acryl paint, which is soaked into the cracks by the temporary cavity [10]. For radiological imaging, the introduction of paint did not solve the problem because the acryl paint did not bring any radiocontrast and partly substituted the air filling of the tears. Therefore, it was necessary to add a contrast material. The iodine-based water-soluble Gastrografin® and Telebrix® were difficult to mix with acryl paint. After shooting, only a part of the tears was visible and the radiocontrast was inhomogeneous. In addition, cloudy contrast around the permanent cavity and next to the tears suggested the phenomenon of diffusion of the contrast material in gelatine, explicable by a 3-h interval between shooting and radiological imaging.

The first experiments with Micropaque® "barium meal" showed better radiocontrast. Other substances like lead acetate and tungstic acid offered a similar contrast but had practical disadvantages. Therefore, further experiments were performed with Micropaque®. The barium sulphate emulsion obtained after sedimentation of the "barium meal" contained only some water and was quickly homogenised to the acryl paint. The technique was optimised by sealing about 7 g of the mixture of paint and contrast material into a thin foil bag, which was integrated in the front of the

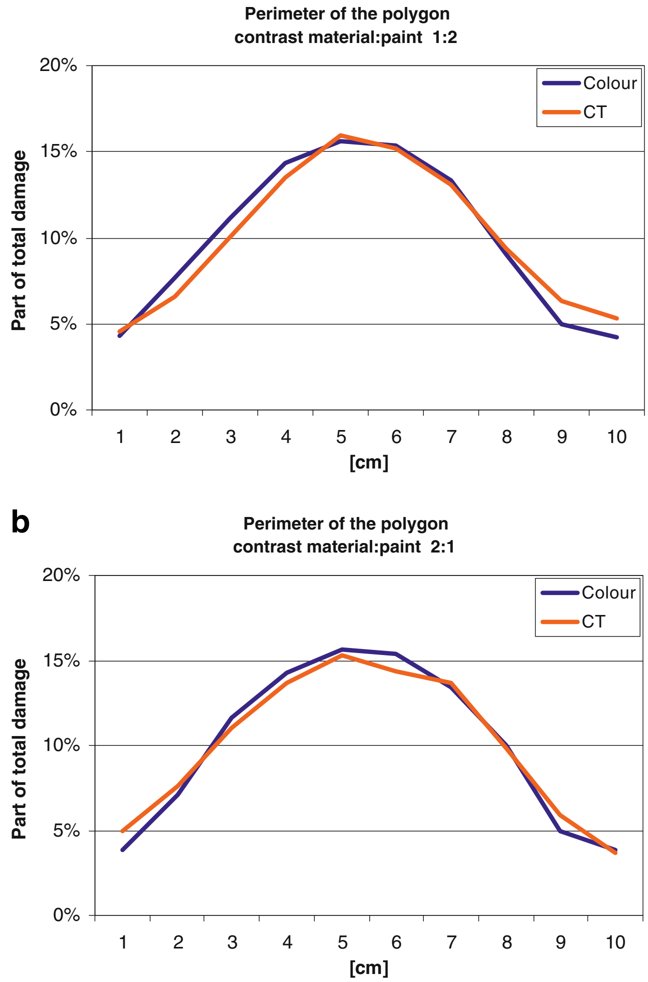

Fig. 4 Qualitative comparison of optically (paint) and radiologically (CT) measured polygonal disruption areas left by Action-5 bullets in 10-cm-long gelatine cylinders. **a** A 2-ml barium sulphate emulsion, 4 ml acryl paint. **b** A 4-ml barium sulphate emulsion, 2 ml acryl paint

gelatine block. After shooting, the distribution of colour in the tears was convincing and the radiological results were satisfying. The comparison of the CT images and the optical results of scanned slices showed good correlation, but the absolute measures in the scaled images differed up to 10 mm in a slice revealing shorter tears in CT images.

Even if the crack lengths in CT images were in a great part only few millimetres shorter than in real slice, the systematic difference has to be discussed. CT images used for measuring resulted from a superposition of each five images representing 2-mm-thick tomographic slices. Despite the improvement of radiocontrast, the principal problem of threshold exposed by Korac et al. [7] is still there. Each image manipulation leads to loss of accuracy. There is also the limited resolution of computer tomography of about 1 lp/mm (line pair per mm) in comparison to X-rays (7 lp/mm). For this reason, the artefact of the partial volume effect has to be considered. The given value in a tomographic volume unit (voxel) corresponds to gelatine if there is only a trace of contrast material, and thus, this point of image is not contrasted. Also, the resolution of resulting images varies a lot: 0.32 mm/pixel for the TIF files of CT images (dimension of 512×512 pixel) whereas optical images used 0.08 mm/pixel. If the difference of measures is related to insufficient radiological image quality, the use of a micro-CT device might be suitable. Recently, Cecchetto et al. even demonstrated the power of micro-CT examination in detection of gunshot residues [15].

Conclusion

The results obtained by using an improved radiocontrast in gelatine suggest that simple CT analysis of gelatine blocks underestimates the real extension of disruption. However, the described method can facilitate the visualisation of disruption in gelatine caused by temporary cavity. By using a contrast material in gelatine, a CT-based three-dimensional reconstruction is possible, which will be useful in the examination of head models.

Conflict of interest None.

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