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Three-dimensional visualization of gunshot cavities in ballistic gelatine with computed tomography – A forensic ballistics case study

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ABSTRACT

Three-dimensional (3D) imaging, primarily computed tomography (CT), has proven valuable in the documentation and analysis of gunshot injuries. Explicit visualization of findings may play a pivotal role in judicial settings. This forensic ballistics case study aimed to examine the potential of CT-based 3D reconstruction to digitally visualize gunshot cavities in ballistic gelatine. Three .30 caliber bullets of different types (full metal jacket, soft point, and expanding monolithic) were fired into standardized blocks of 10% ballistic gelatine. The blocks underwent CT scanning with clinical equipment. Gelatine and air were segmented from the CT data using an open-source software. 3D reconstruction views of the segmented gelatine and air components were created. The gunshot cavities were clearly observed in both gelatine and air segmentation. The differences in cavitation between bullet types were evident in both reconstruction approaches, although gelatine segmentation produced higher resolution of small details. The obvious benefit of digital reconstruction was the ability to freely tilt and rotate the 3D images, with the possibility of taking measurements manually or automatically from any plane. Moreover, all the data can be stored for future analysis. This study introduces a preliminary method for digital visualization and documentation of gunshot cavitation in ballistic gelatine, to be fine-tuned and implemented for research purposes and routine practice in forensic institutions.

1. Introduction

Three-dimensional (3D) imaging is highly valuable in the forensic documentation and analysis of gunshot injuries.[1–3] Even though there are an increasing number of modalities available, forensic institutions have widely implemented the use of computed tomography (CT) as a routine method in everyday practice.[1] In individuals with gunshot injuries, CT may reveal pivotal information regarding, e.g., projectile trajectory and fragmentation.[1,4–6] Ideally, the comparison of a victim's CT findings to those obtained in forensic test firing may aid practitioners make inferences about the course of events, or even match or exclude a suspected weapon or ammunition type.

In terminal ballistics, i.e., the study of a projectile entering a target, ballistic soap and gelatine are used as human soft tissue simulants.[3,7–10] One reason for ballistic testing is the inspection of a permanent and temporary cavity, i.e., direct tissue damage along the path of the projectile and stretch damage surrounding the projectile track, respectively.[11] Traditionally, practitioners are required to manually slice open the soap or gelatine blocks to analyze the simulant material. Physical slicing is time and labor consuming, and also brings inaccuracy to the analysis; for example, the process of slicing gelatine after rifle shots is challenging. Once sliced, the blocks are no longer intact nor applicable to a full re-examination.

CT-based 3D analysis of intact blocks may allow obtaining a rapid,

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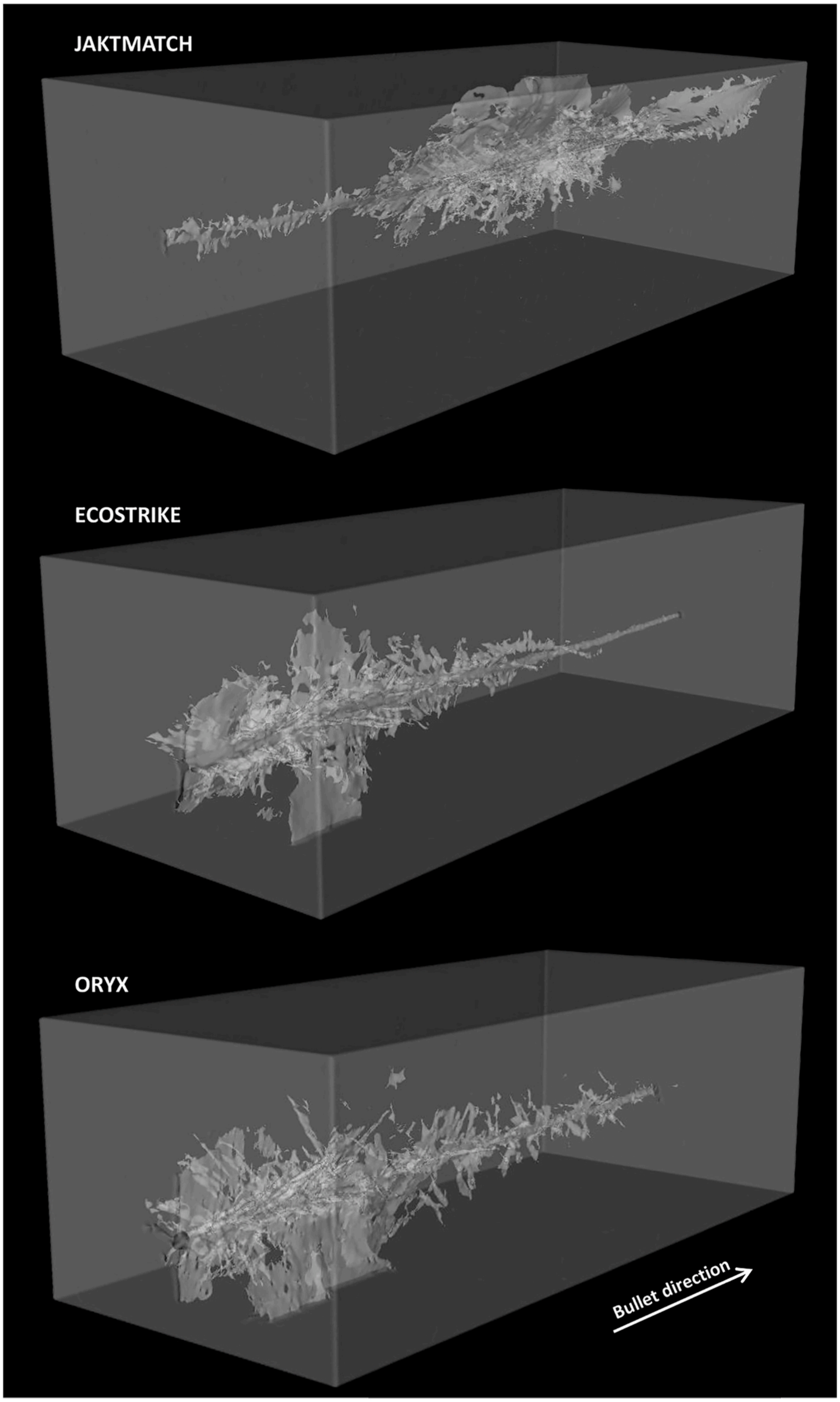

Fig. 1. Oblique view of a three-dimensional reconstruction of gelatine blocks based on computed tomography (gelatine segmentation).

permanent, and accurate digital record of the findings.[3,12] To date, however, most studies that have addressed this entity have concentrated on ballistic soap. The experiments of Burgos-Díez et al.[13] and Gremse et al.[14] suggested that digital 3D reconstruction of gunshot cavities proved clearly superior compared to manual slicing of the ballistic soap blocks. Rutty et al.[3] emphasized that CT combined with 3D analysis created a reliable record of the projectile paths in ballistic soap, allowing rapid analysis of different firearms and projectiles.

It should be noted that ballistic soap and gelatine have fundamental differences in mechanical properties such as tensile strength and plasticity.[10,15] As for ballistic gelatine, the studies of Bolliger et al.,[12] Korac et al.,[16] and Moraitis et al.[10] addressed CT-based digital analysis in terminal ballistics, and the study of Schyma et al.[17] investigated the use of radiocontrast material within a gelatine block. However, there is paucity of studies on the visual 3D reconstruction aspect. Explicit visualization of findings may play a pivotal role in medico-legal and judicial

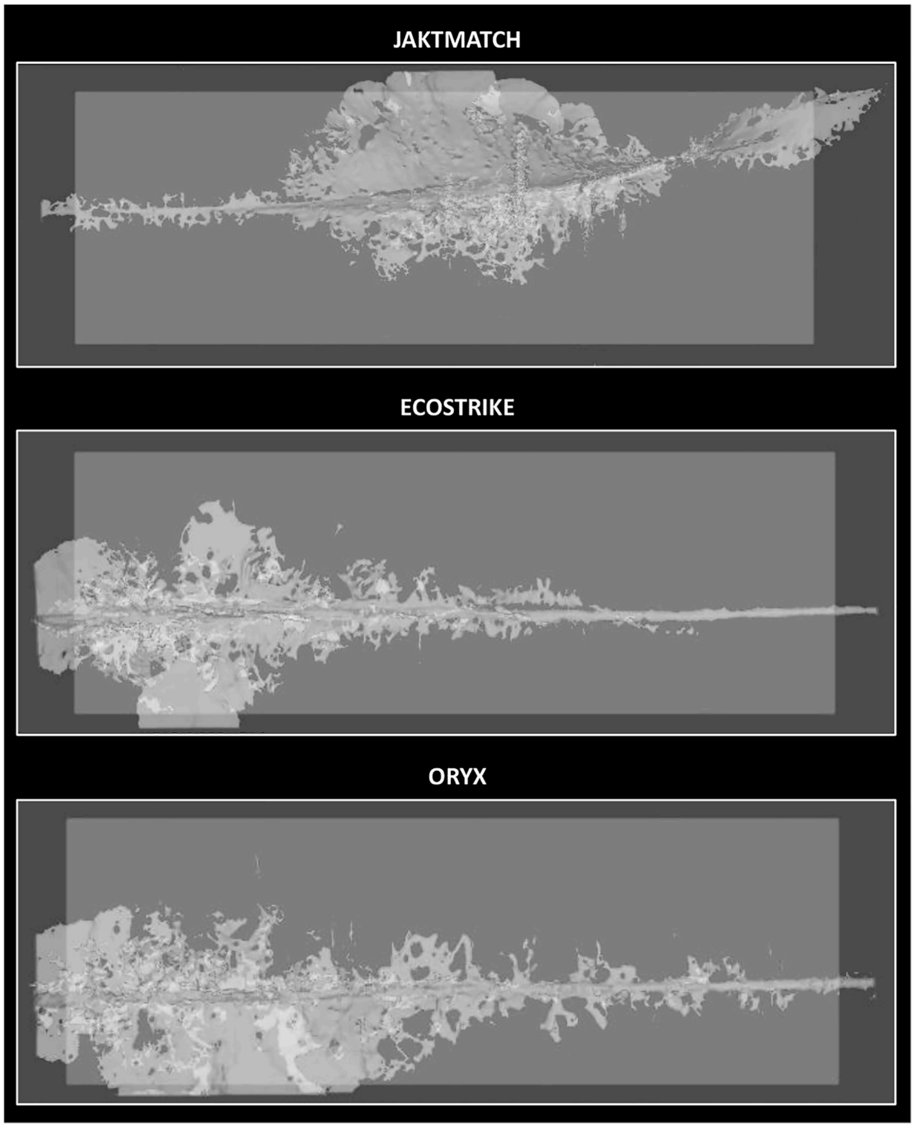

Fig. 2. Lateral view of a three-dimensional reconstruction of gelatine blocks based on computed tomography (gelatine segmentation). Bullet direction was from left to right.

settings.

In this forensic ballistics case study, we aimed to examine the potential of CT and 3D reconstruction software to digitally visualize gunshot cavities in blocks of ballistic gelatine. We utilized three bullet types (full metal jacket, soft point, and expanding monolithic) in the experiment. Our case study introduces a preliminary method for the digital analysis and documentation of gunshot cavitation in ballistic gelatine, to be fine-tuned and implemented for research purposes and routine practice in forensic institutions.

2. Material and methods

2.1. Gelatine blocks

As previously described,[6] three blocks of 10% ballistic gelatine (Gelita, Eberbach, Germany) were prepared in accordance with the guideline of Jussila.[18] The blocks were cuboid in shape with dimensions $25 \times 25 \times 50$ cm (width $\times$ height $\times$ length, respectively). The blocks were prepared 48 h before the test firing in order to allow a 24 h stabilization period at room temperature and a 24 h cooling period in $+4$ °C.

2.2. Test firing

The study utilized three types of .30 caliber hunting/target bullets manufactured by Norma Precision (Åmotfors, Sweden). Caliber .30 was selected for this case study due to its popularity in both military and outdoor use. Calibers .308 Winchester and .30–06 Springfield are globally popular in hunting, target shooting, and military use; other caliber .30 cartridges are also abundant. Norma was selected as a high-quality ammunition manufacturer with a large selection of cartridges in .30 caliber. The bullets were Norma Jaktmatch (full metal-jacketed, non-expanding, 9.7 g), Norma Ecostrike (monolithic, expanding, 9.7 g), and Norma Oryx (soft-point, expanding, 11.7 g). The bullets were weighed using a calibrated digital scale (accuracy of 0.01 g).

Tikka M65 Sporter rifle (Tikkakoski, Finland), in caliber .30–06 Springfield, was used to conduct the test firing. The muzzle-to-target distance was 500 cm. A water tank was placed behind the gelatine block, acting as a backstop. The last author (JAJ), holding a valid firearms license, performed the test firing in a restricted shooting range.

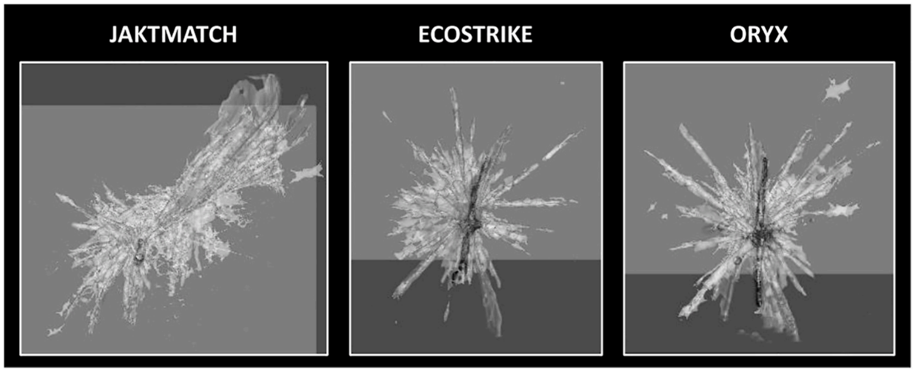

Fig. 3. Perpendicular view of a three-dimensional reconstruction of gelatine blocks based on computed tomography (gelatine segmentation). Bullet direction was away from the viewer.

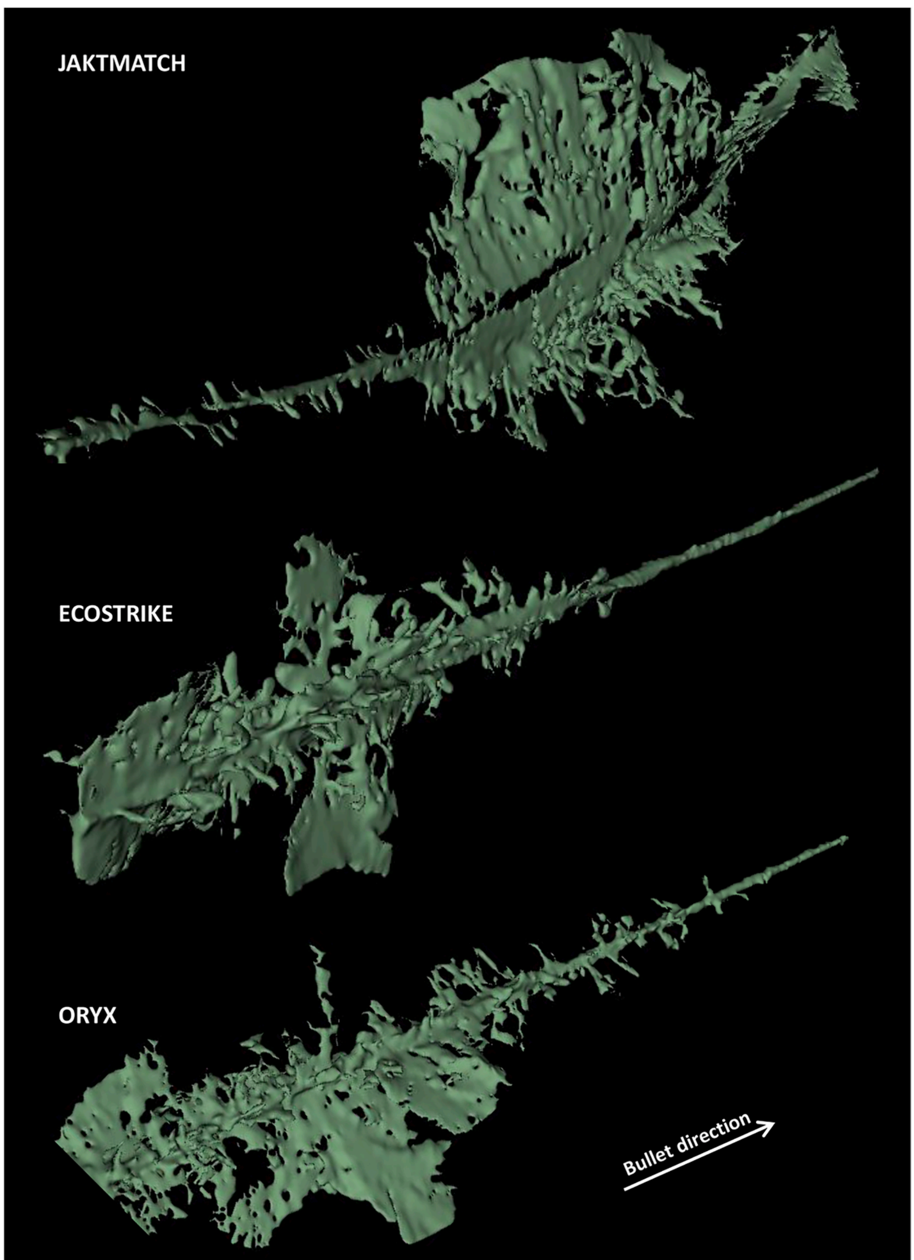

Fig. 4. Oblique view of a three-dimensional reconstruction of gunshot cavities based on computed tomography (air segmentation).

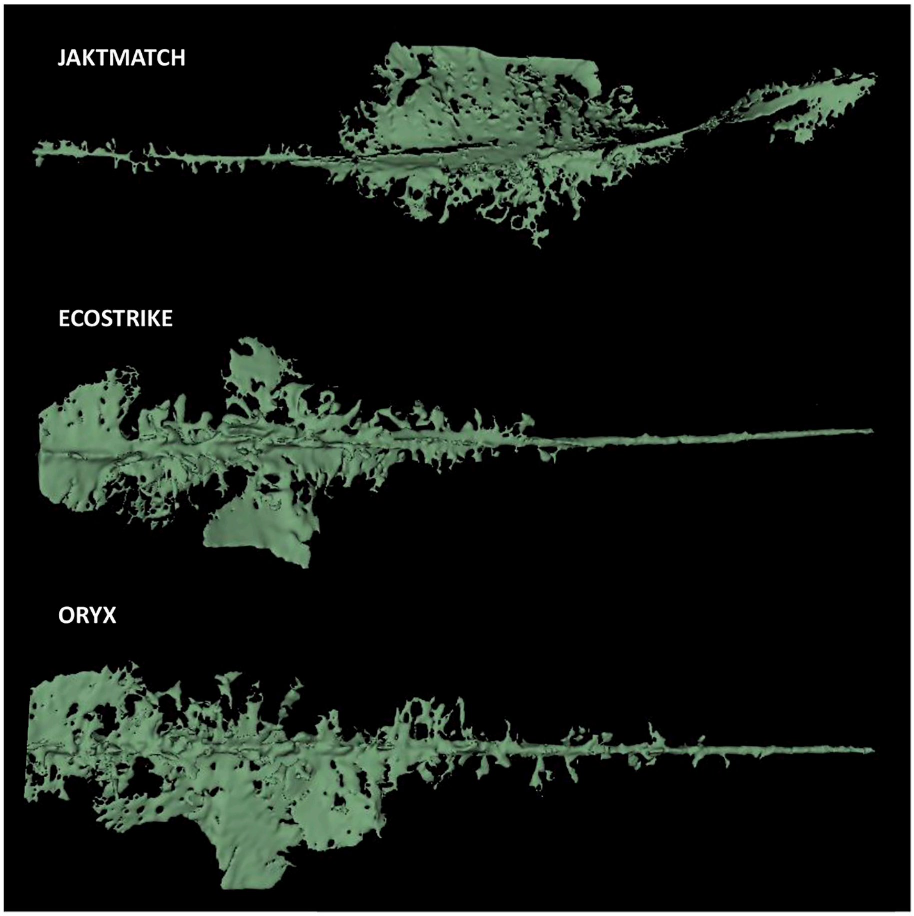

Fig. 5. Lateral view of a three-dimensional reconstruction of gunshot cavities based on computed tomography (air segmentation). Bullet direction was from left to right.

2.3. Computed tomography

The gelatine blocks underwent CT scanning in the Department of Radiology, Oulu University Hospital, Oulu, Finland, within 16 h from the firing.[6] The scans were obtained using clinical dual-source equipment (Somatom Definition Flash, Siemens Healthcare, Forchheim, Germany). All scans were dual-energy CT (DECT) acquisitions with the following parameters: rotation time 0.5 s, pitch factor 0.3, collimation 40 × 0.6 mm, tube kilovoltage (kVp) 80 kVp and 140 kVp. An additional 0.4 mm tin filter was used for the tube operating at the higher kVp. The reference mAs values were 350 mAs and 338 mAs for the 80 kV and 140 kVp acquisitions, resulting in a total volumetric CT dose index (CTDIvol) of 23.4 mGy, and a dose-length product (DLP) of 1295.5 mGy × cm. The data were reconstructed into a voxel size of 0.72 × 0.72 × 0.60 mm using the soft tissue B30f kernel with the filtered back projection algorithm. As the projectiles are strongly attenuating, the extended Hounsfield Unit (HU) scale and metal artifact reduction (MAR) algorithm were used.

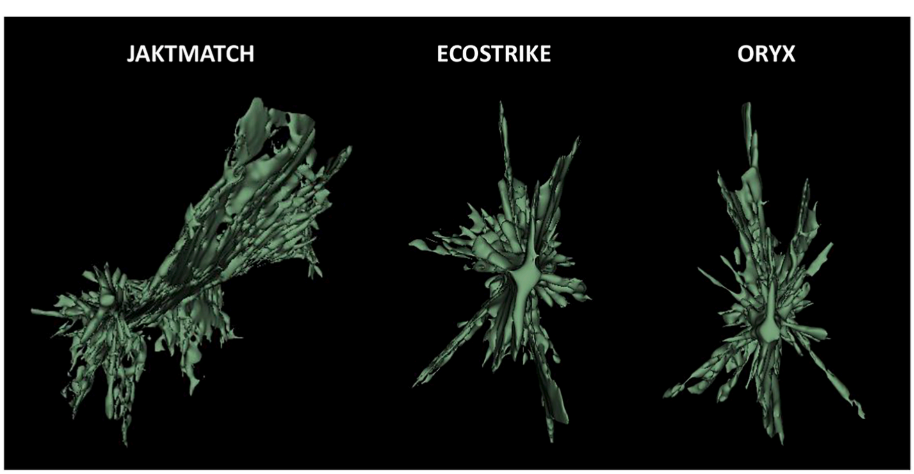

Fig. 6. Perpendicular view of a three-dimensional reconstruction of gunshot cavities based on computed tomography (air segmentation). Bullet direction was away from the viewer.

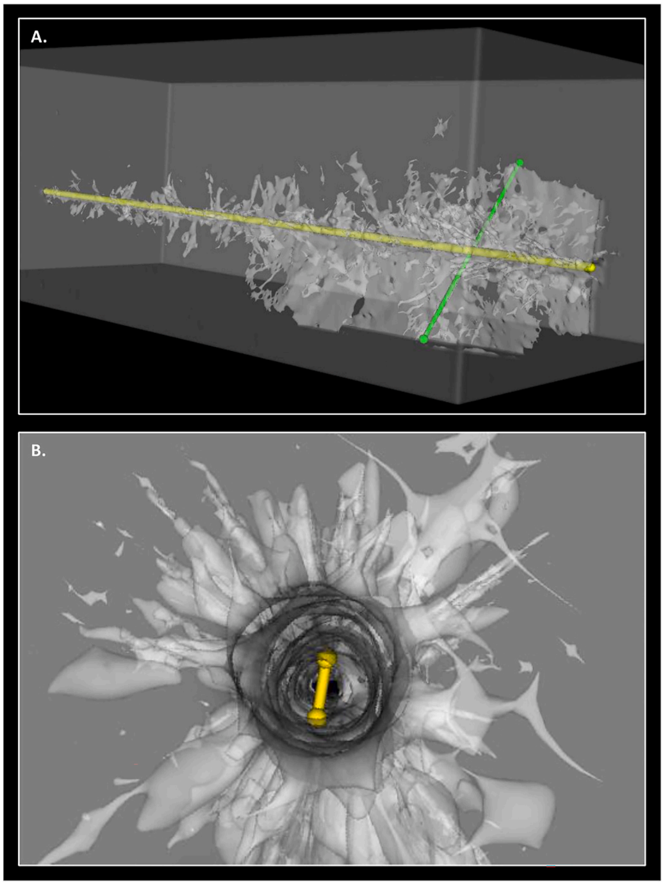

Fig. 7. Reconstruction of the Oryx gelatine block demonstrating sample measurements that can be easily obtained using the digital data. A, Length of bullet channel (yellow) and widest diameter of cavity (green); B, Diameter of bullet channel (yellow) with high magnification. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.4. 3D reconstruction

The CT scans were evaluated and processed using the open-source 3D Slicer image computing platform version 5.4.0 (https://www.slicer.org/)[19] by the first author (PO). The initial scans were first uploaded to the software in DICOM format and visually inspected in three perpendicular planes corresponding to axial, sagittal, and coronal orientations. In 3D Slicer, the Segment Editor module and Local Threshold tool were then used to segment the gelatine block ("gelatine segmentation") and gunshot cavities ("air segmentation") from the imaging data. For the purposes of this study, the threshold ranges for intact gelatine and gunshot cavities were set at −30 to 200 HU and −10 000 to −100 HU, respectively. The segmentation procedure was performed with the GrowCut algorithm with minimum diameter 0.500 mm. 3D views were constructed with surface smoothing factor 0.50. Opacity level 0.30 was added for gelatine segmentation. Finally, the Scissor tool was used to trim the edges of the scans. Various standard (oblique, lateral, perpendicular) and custom views of the segmented gelatine and air components were captured, and sample measurements were obtained to demonstrate the potential uses and benefit of the method. The 3D reconstruction procedure took approximately 5 min per gelatine block on a standard office laptop.

3. Results

Figs. 1–3 illustrate the reconstructed gelatine blocks with gunshot cavities (gelatine segmentation) from oblique, lateral, and perpendicular views, respectively. Figs. 4–6 illustrate the corresponding reconstructed gunshot cavities (air segmentation).

The Jaktmatch bullet started rotating along its longitudinal axis and fragmented inside the gelatine block at a depth of approximately 25 cm. The direction of the bullet shifted towards the top-right corner of the block, causing extensive cavitation in this area (maximum diameter 15–20 cm).

The expanding Ecostrike and Oryx bullets perforated through the gelatine blocks in a more stable manner. The Ecostrike produced a cavity that expanded from the entrance to a depth of approximately 12 cm, where it had the maximum diameter of 10 cm, and narrowed down neatly thereafter. The Oryx cavity was most prominent from the entrance to a depth of approximately 25 cm (maximum diameter 10 cm), narrowing down into a spikey cavity 5 cm wide thereafter. Although small cavities and cracks appeared to stand out better in the gelatine segmentation approach, the differences between bullet types were evident in both gelatine and air segmentation.

In addition to the standard oblique, lateral, and perpendicular orientations, digital 3D reconstructions could be freely tilted, rotated, and zoomed. Fig. 7 shows customized views and sample measurements obtained from the Oryx block reconstruction. Fig. 8 demonstrates the Ecostrike block reconstruction in relation to a photograph of the actual block.

4. Discussion

This forensic ballistics case study aimed to explore the potential of CT and 3D reconstruction in digital analysis of gunshot cavities in ballistic gelatine. Three bullet types (two types of expanding bullets and a full metal-jacketed bullet) were used in the experiment. In our preliminary data, the differences between bullet types were present in both gelatine and air segmentation, although small details appeared to stand out better in the gelatine segmentation approach. This preliminary study suggests that CT-based 3D reconstruction would potentially make a promising means of digitally visualizing and examining projectile performance in ballistic gelatine. Future studies are needed to validate and fine-tune the method, and to confirm whether the method proposed here will surpass the conventional method of destructive slicing.

Ballistic soap and gelatine are widely used as media for human soft tissue simulation.[3,7–10] Traditionally, practitioners are required to manually slice open the blocks in order to analyze the findings after test firing. It is not surprising that slicing decreases the accuracy of the method. However, to date there are only a few previous studies addressing CT and 3D reconstruction of simulant blocks, most based on ballistic soap instead of gelatine. The studies of Burgos-Díez et al.,[13] Gremse et al.,[14] and Rutty et al.[3] report firing projectiles of various calibers, speeds, and distances into ballistic soap, demonstrating the utility of 3D reconstruction in the assessment of cavity volume, projectile penetration depth, depth of maximum damage, and deflection angle, among other variables. Independent studies on ballistic gelatine are crucial as it is fundamentally different from ballistic soap in mechanical properties such as tensile strength and plasticity.[10,15] Previous CT reconstruction studies on ballistic gelatine have been scarce and they have mainly focused on total crack length analysis[12] and use of radiocontrast material in the visualization of temporary cavity.[17] The studies of Korac et al.[16] and Moraitis et al.[10] reported attributes such as cross-sectional dimensions of the projectile channel, projectile directions, gelatine destruction area, and gelatine density, but did not focus on the visual 3D reconstruction aspect. We believe that similar attributes to those referred to here may be digitally obtained from ballistic gelatine based on the method proposed in the present study. Future studies are encouraged to evaluate the forensic value and interpretation of these variables in larger datasets.

Explicit visualization of findings may play a pivotal role in medicolegal and judicial settings. The present case study introduced a

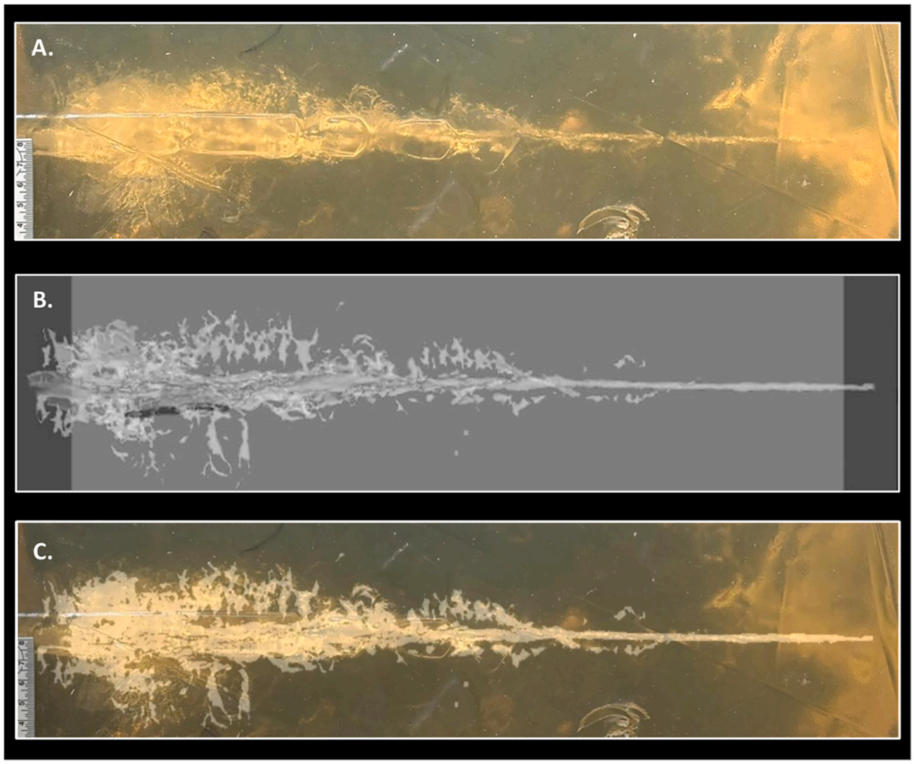

Fig. 8. Photograph of the Ecostrike gelatine block (A), the corresponding computed tomography reconstruction (B), and a fusion image combining the two (C). Bullet direction was from left to right.

preliminary method for rapid 3D reconstruction of gunshot cavities in ballistic gelatine. The digital reconstruction method introduced here is rather easily employed as it is based on an open-source software. Future users of the method are encouraged to explore the gelatine and air segmentation approaches, and adjust parameters such as HU thresholds in order to best meet the requirements of their own material (e.g., composition of gelatine; size and shape of the block; CT equipment; firearm, caliber, and ammunition used). Validity and reliability of the final reconstructs will naturally have to be tested before implementation. In our preliminary data, the gelatine segmentation approach produced higher resolution of small details such as small cavities and cracks, even though the differences between bullet types were clear in both gelatine segmentation and air segmentation.

In addition to the standard oblique, lateral, and perpendicular orientations, the digital reconstructs can be freely tilted, rotated, and zoomed. This provides obvious benefits in the accuracy of the examination, and may aid in cases where there is an actual injured organ or CT scan of a gunshot victim available for comparison. For example, the shape and size of gunshot cavitation in simulant material has been successfully matched with the actual damage observed the liver.[15] Moreover, two-dimensional projections and cross-sections can be explored, and measurements such as penetration depths, maximal damage diameters, crack lengths, and projectile angles can be obtained from any plane. Area and volume approximations can be obtained as required. Alongside gunshot cavities, projectile fragments may prove valuable in the forensic assessment of gunshot cases.[1,4–6] An interesting possibility is the opportunity to combine projectile fragment dispersion and gunshot cavitation into one visual reconstruct; there are some previous reports based on ballistic soap[3,14] but none based on gelatine. The potential forensic value should be confirmed in future studies.

The strengths of this case study include clinical CT equipment, open-source image processing software, and use of three distinct bullet types in the experiment. This study is among the first to propose a digital 3D visualization method for ballistic gelatine. The main limitation of this preliminary study is lack of validation against the conventional method, i.e., physical slicing of a gelatine block. Correspondingly, intra- or inter-observer reliability was not assessed, as the aim was merely to introduce a new visualization method instead of reporting findings that would have been subject to intra- or inter-observer error. Future users are likely required to modify the method to best suit their own material; validity and reliability should be confirmed at that stage. Moreover, as with most imaging studies, the radiographic result may be influenced by the fact that the amount of air in the gelatine cavities decreases with time. Finally, even though there are an increasing number of imaging modalities available for forensic purposes, CT was selected for this study as it is widely implemented in forensic institutions.[1]

We hope that our case study will serve as a starting point for further analyses. Speculatively, in the future, our digital reconstruction method may be combined with conventional methods to study ballistic gelatine. For example, there is potential to utilize the total crack length method[20] provided that further validation is completed. This would allow assessment of energy transfer profiles as demonstrated by Bolliger et al.[12] Potentially, there will also be novel ways to utilize the 3D data, and the assessment of parameters such as temporary cavity volume could be rather easily developed and validated. Moreover, inspired by the work of Schyma et al.,[17] gelatine blocks could also be examined after injecting contrast agent in the projectile channel prior to CT ("ballistic fistulography") to find out if there is improvement in the air/gelatine reconstruction.

5. Conclusion

This forensic ballistics case study aimed to examine the potential of CT-based 3D reconstruction to digitally visualize gunshot cavities in blocks of ballistic gelatine. We introduced a preliminary method to be fine-tuned and implemented by researchers and practitioners in forensic institutions. Our study is expected to advance the field in several potential ways. Forensic pathologists and clinical trauma centers may benefit from enhanced digital 3D reconstruction methods when evaluating and/or treating gunshot injuries. Forensic scientists and ballistic experts may benefit from digital methods for documenting gunshot cavitation in gelatine. The judicial system may benefit from comprehensible, yet accurate visualization of findings in gunshot victims. The method introduced in this study might also have applications in wildlife forensics. We hope that our case study will serve as a starting point, providing a methodological basis for further analyses in larger datasets.

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Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

The data are available from the corresponding author on reasonable request.

Code availability

Not applicable.

Author's contributions: CRediT authorship contribution statement

Petteri Oura: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Juho-Antti Junno: Writing – review & editing, Supervision, Methodology, Conceptualization.

Mikael Brix, Eveliina Lammentausta, Timo Liimatainen, Juha Kiljunen, Alina Junno, Jaakko Niinimäki: Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

None.

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