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Comparison between computed tomography and silicone-casting methods to determine gunshot cavities in ballistic soap

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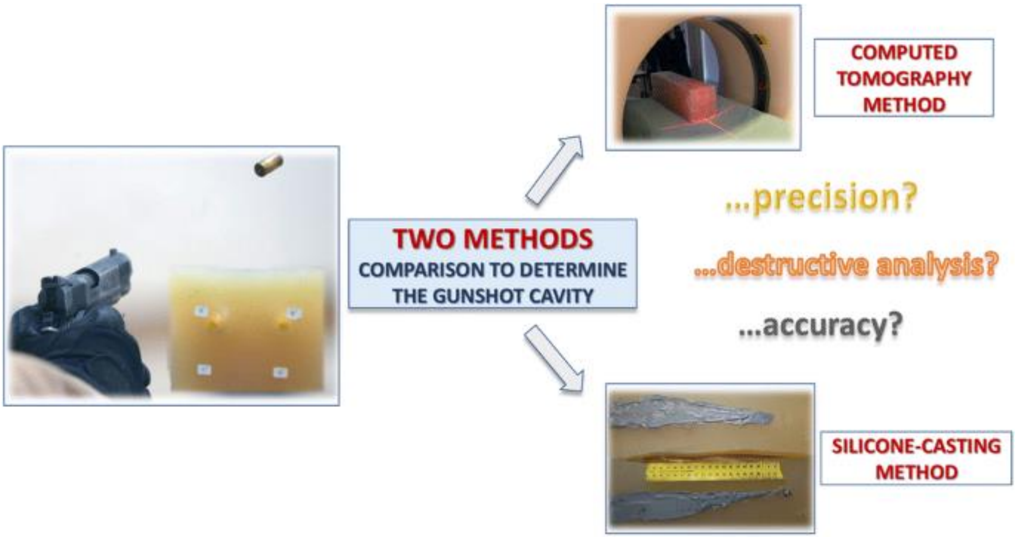
Abstract: Current methods used in terminal ballistics to determine the volume of temporary cavities created by projectiles in soft tissue simulants (such as ballistic soap) usually involve silicone-casting to obtain the cavity moulds. However, these methods have important drawbacks including their little sensitivity and precision, besides the fact that they are destructive. Imaging techniques such as computed tomography (CT) might not only overcome those limitations but also offer useful tools for digitally reporting the scientific results. This work accomplished the 3D digital reconstruction of the cavities created by different projectiles in ballistic soap blocks. This way, the total volume of the cavities, the projectile penetration depths, and other measurements were determined, rendering better capabilities when compared to the current silicone method. All these features were achieved through the CT analysis and 3D Slicer imaging software. In addition, it is worth mentioning that the method can preserve the evidence by digitally obtaining, signing, and storing the infographic videos displaying the 3D-reconstructed cavities.

Keywords: 3D-reconstructed cavity; ballistic soap simulant; computed tomography; temporary cavity; terminal ballistics; wound ballistics.



1. Introduction

Terminal ballistics is the part of forensic ballistics that studies the behaviour and effects that a specific projectile fired with a specific weapon causes on a body [1].

The projectile penetrates the human body to a greater or lesser extent, generating an internal cavity that might be temporary and/or permanent [2]. The temporary cavity is the deformation that the human body undergoes during the motion of the projectile through its interior. The temporary cavity deformation occurs due to the transfer of kinetic energy, but without exceeding the human body's yield point, and thus, the human body returns to its original form [2]. On the contrary, the permanent cavity is the hole that the projectile produces in the human body while passing through it and destroying the tissues. Because the permanent cavity deformation exceeds the human body's yield point, the tissues do not return to their original shape [2].

Wound ballistics studies are carried out using specifically designed targets that behave like a human body against the firing of a projectile. Ballistic laboratories use internationally tested soft tissue simulants, such as ballistic gelatine and glycerine ballistic soap [1, 3]. Ballistic gelatine is a transparent elastic material in which most of the energy transferred by the projectile produces an elastic deformation. Usually, when a projectile passes through the gelatine block, it leaves a path that remains in it, representing the permanent cavity, which is as wide as the projectile diameter [2]. However, given the gelatine transparency, the temporary cavity can also be studied using high-speed cameras. Unlike ballistic gelatine, ballistic soap is opaque and undergoes a plastic deformation when shot. That is, when a projectile passes through it, it does not return to its original shape. The temporary cavity remains permanent, allowing forensic practitioners to study in detail the cavity in the soap [4]. In this study, the temporary cavities of four different shots in ballistic soap were studied using different measurement methodologies.

The methodology used in forensic science institutes to study the ballistic effects in a soap usually consists of measuring the generated cavity volume, the projectile penetration depth, the maximum projectiles diameter embedded in the soap after the firing, and the kinetic energy transferred by the projectile.

The cavity volume is usually measured by cutting the big soap blocks into smaller pieces in order to extract, if possible, one soap block per cavity, avoiding as much as possible affecting/damaging the cavities. Once the small one-cavity-soap blocks have been separated, they are longitudinally cut in half practicing a section along the firing path. This procedure tries to make each half symmetrical. After obtaining the two halves of the cavity, the projectile penetration depth is usually measured using a measuring tape (millimetres) from the entry hole to the farthest point reached by the projectile. The projectile is then removed from the soap, and its maximum diameter is measured with the help of a calliper. The maximum diameter of the projectile is the largest dimension measured. Finally, in order to measure the cavity volume, both halves are filled with forensic silicone using a gun dispenser. However, because such silicone has a high drying rate, the casting process must be quick yet accurate. When the two silicone moulds are dry, they are introduced into an adequately sized test tube filled with water. The moulds volume is then calculated using the Archimedes principle, which involves measuring the difference in volume of the displaced water. Therefore, the measured volume is the difference between this new level and the one initially set by the water before introducing the mould. However, this methodology has some drawbacks such us:

The method is invasive since cutting the big soap block into separate small one-cavity blocks might damage the cavity by mistake, which is possible due to the soap's opacity.

- The method is destructive since cutting each cavity into two halves can also destroy the small visually undetectable cavities/ramifications, which may have been generated by a projectile fragment. Hence, those small cavities may remain unmeasured, therefore, giving in a poor damage estimation compared to the real damage generated by the projectile.
- When silicone-casting the cavities, small spaces may remain unfilled or even overfilled in such a way that the measured volume of the cavity results sub-/over-estimated.
- The measurement of the volume by means of the Archimedes principle is normally too vague, imprecise, and not sensitive enough because of the wide uncertainty interval of the test tubes typically used.
- It is a painstaking and time-consuming procedure.

Due to all these drawbacks, this work assessed the suitability of using computed tomography (CT) as an imaging non-invasive technique to measure the temporary cavity in soap blocks. CT is a versatile imaging technique for obtaining three-dimensional images of any anatomical area. Particularly, CT is widely used in forensic medicine to determine the real damage a projectile caused in a corpse [5,6,7,8,9]. Thus, CT instrumentation is usually available in forensic medicine laboratories. Therefore, it is potentially relevant to evaluate whether CT might be also applied to ballistic assays in soap and if it provides better results than the current methods.

To date, few but promising pioneering researches have explored CT for the study of wound ballistics in soft tissue simulants. Particularly, Korac et al. [10, 11], Bolliger et al. [4], and Schyma et al. [12] used CT for the non-invasive analysis of the permanent cavity in ballistic gelatine blocks. On the contrary, to the best of our knowledge, the use of CT for the analysis of the temporary cavity in glycerine ballistic soap has been reported by Rutty et al. [13], Gremse et al. [14], and Tsiatis et al. [15]. Besides performing perimeter/area measurements of the cavity in various sections of the soap, a 3D reconstruction of the cavity was accomplished by Rutty et al. [13]. In brief, a cavity comparison was done regarding shots fired from a distance of 15 cm with four different firearms (revolver, shotgun, and two rifles). However, only the cavity generated by the revolver shot was complete within the small soap blocks that were used. This was because the projectile penetration depths when shooting with either the shotgun or the rifles exceeded the 26-cm length of the soap. Gremse et al. [14] applied CT scanning and digital 3D reconstruction for the analysis and comparison of cavities generated by different lead and lead-free hunting ammunitions in glycerine ballistic soaps. The calibre of the four ammunitions was 7.62 mm, but they differed in their composition (brass/copper/lead) and type (stable/fragmenting/deforming). Despite all being shot from a distance of 10 m, they tested up to four different impact speeds (from 500 to 900 m/s) using each ammunition. An air gun was used to control the impact speed. Finally, Tsiatis et al. [15] evidenced the capability of CT scanning to determine the temporary cavities (volume, depth, and kinetic energy) generated in ballistic soap by four types of projectiles (all in calibre 9-mm Parabellum). Two of them were full metal-jacketed projectiles of 124 and 115 grains, whereas the other two were hollow-point projectiles of 147 and 115 grains.

Based on previous studies, CT arises as a suitable technique for the analysis of temporary cavities in glycerine ballistic soaps. However, no direct comparison of the results obtained by using CT scanning with respect to the silicone-casting method has been published yet. Hence, the present study compares CT with the mould-silicone method currently used in many ballistic laboratories. In addition, the present study used a simple and user-friendly software to process the CT data for performing the depth measurements, 3D image reconstruction, and infographic videos of the temporary cavity.

In this respect, judges and courts need the expertise of forensic practitioners to understand the ballistic effects of different weapons. The reconstruction of 3D images seems a very useful tool for forensic experts to explain their reports to the judge in court, and thus the judge could easily understand them. Specifically, this study pursues to obtain ballistic information about the gunshot cavity in ballistic soap generated by two different kinds of 9-mm Luger hollow point ammunitions, both fired with the same gun. The 9-mm Luger calibre was chosen because it is currently the most common among the Spanish police units. In addition, expansive ammunition was selected because of economic reasons. The use of expansive ammunition is cheaper because it only penetrates one block of ballistic soap, unlike armoured ammunition that needs at least two blocks to stop the projectile.

2. Material and methods

2.1. Samples

A commercially purchased ballistic soap of dimensions 25 × 25 × 40 cm was used (Higasar Seguridad, Madrid, Spain, http://www.higasarseguridad.com). The soap was 1 month old right before being shot.

Ammunition (9-mm Luger—9 × 19 mm): Golden Saber Bonded (124 grains, 8.03 g) (Remington, Madison, NC, USA) and Silver Tip (115 grains, 7.45 g) (Winchester, Herstal, Belgium). These ammunitions were purchased few months before being fired.

The whole study was carried out in the same week. To minimize the degradation of the soap, it was kept wrapped in plastic inside a closed cardboard box.

2.2. Shooting procedure

The shooting was carried out by the Guardia Civil ballistics personnel inside a shooting range (Criminalistics Service, Guardia Civil HQ, Madrid, Spain). Two shots were performed with the Golden Saber ammunition (labelled as GS1 and GS2), and another two shots were fired with the Silver Tip ammunition (labelled as ST1 and ST2). The shots were made in the following order: GS1, ST1, ST2, and GS2. The shooting was carried out using a short semi-automatic 9-mm Parabellum gun (HP 35, FN BROWNING) held with a Random-Rest jaw located 3 m from the soap block. Specifically, these 3 m are measured from the muzzle of the gun to the 25 cm × 25 cm face of the soap. This distance allowed placing the speed metre between the gun and the soap. The jaw was used to ensure that each shot impacted at the designated aim points on the soap near corners, in such a way that the shots were distanced from each other (Fig. 1). The aim points were established 5 cm from the edges of the soap. This distance (5 cm) was chosen because of two reasons: (i) to prevent the soap from breaking when the cavity was generated and (ii) to prevent the cavities from affecting each other. A DRELLO BALL 4030 P speed metre was used to measure the projectiles' speed. The speed metre was placed 1 m away from the weapon's barrel muzzle in order to prevent the firing gases cloud from affecting the speed measurement. The speed metre was not placed so close (approximately 50 cm) to the face of the soap to avoid the speed metre being affected by projections of the soap when being impacted by the projectile.

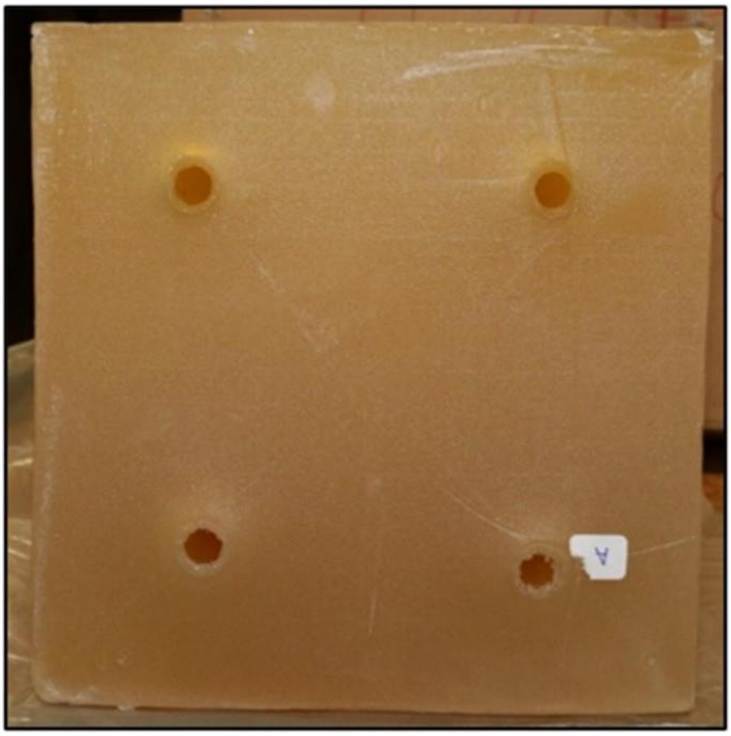


Figure 1. Frontal view of the studied soap block after the shooting.

The kinetic energy of the projectile, before its impact, was calculated as Eo = 1/2 mV^2, where (m) is the projectiles' mass in kilogrammes, (V) is projectiles' impact velocity in $m \cdot s^{-1}$, and (Eo) is the kinetic energy of the projectiles in Joule ($kg \cdot m^2 \cdot s^{-2}$). Since the kinetic energy calculations are based on the projectile's velocity, which can vary depending on where it is measured, it should be indicated that the impact speed measured for the projectiles in this study is the speed provided by the speed metre. This device calculates the time it takes for the projectile to travel the calibrated distance, i.e. 1 m before impacting the soap.

After the shooting, the soap block was cut lengthwise in half. Each half was again cut lengthwise in half, in such a way that four soap pieces 12.5 × 12.5 × 40 cm were obtained, each containing only one shot cavity. This was done in order to facilitate the soap transport from the shooting range to the CT laboratory.

2.3. Computed tomography instrumentation

The four ballistic soap blocks were scanned at the Defence Veterinary Centre using a Philips MX4000 Dual CT system (Amsterdam, The Netherlands) (Fig. 2). The selected exam protocol for performing the helical scans was “fine abdomen”. The optimized mode for the image reconstructions, which consists of adjusting the filter to obtain the sharpest images, was “body standard (metal)” with “bone 1” display modes. These two modes were included by default in the MX 4000 Dual software. Hence, the reconstruction is the method that best eliminated the streak artefacts and blooming produced by the metallic projectile. The soaps scanning consisted of the sequential capture of cross-sectional images of the soap throughout its length. All the scanned images were saved as DICOM files for further processing.

Figure 2. Ballistic soap with the GS1 shot scanned using CT.

2.4. Image processing

The CT DICOM files were processed with the 3D Slicer v4.10 program (MA, USA). This software allowed reconstructing the cavity in 3D, whilst easing the calculation of both the cavity volume and the projectile's penetration depth.

A fast simple way to select in the software the pixels corresponding to the cavity was using the airway filter (specially designed in medicine for lung analysis and included by default in 3D Slicer software). This way, the software can automatically calculate and provide the volume of the cavity, which theoretically contains air. Additionally, any hard material, harder than soap, was set in the program as foreign object. This way, it was easy to locate and visualize the projectile and then determine its penetration depth from the entry hole to where the projectile was located. It is a straight line from the impact hole on the face of the soap block to the furthest point reached by the projectile (Fig. 6). Whenever the projectile's path is curved, the penetration depth is calculated in sections. In addition, 3D Slicer enabled taking pictures and videos of the reconstructed cavity. Hence, it was easy to create infographic videos that visually explained the most representative features regarding the shot cavity.

2.5 Current methodology of silicone

For comparative purposes after the CT analysis, the silicone destructive method was performed on the soap blocks as is currently done by most forensic science institutes. Thus, the four soaps were cut lengthwise in half to expose the half cavities generated by each projectile. This was done with a nylon cutting wire and a large knife. A lamp helped maximize the soap transparency and contrast, to better visualize the cavities and avoid damaging each cavity more than necessary.

The projectile penetration depth was determined with a measuring tape for measuring the distance between the entry hole and the projectile (including the projectile's length) along the cavity's path. This procedure was done just before the silicone-casting of the cavities. If the projectile's path is curved, the penetration depth would be calculated in sections with the same method explained above.

To calculate the volume, the two soap halves were filled with forensic silicone (Loco Forensics B. V, Nieuw-Vennep, The Netherlands) by means of a gun dispenser (Fig. 3). After drying, the possible remaining surpluses (fringes) in each silicone mould were cut with scissors. This way, a handmade reproduction of the cavity was obtained. Finally, the volume of the cavity was measured by introducing the silicone moulds into a test tube, filled with a known amount of water.

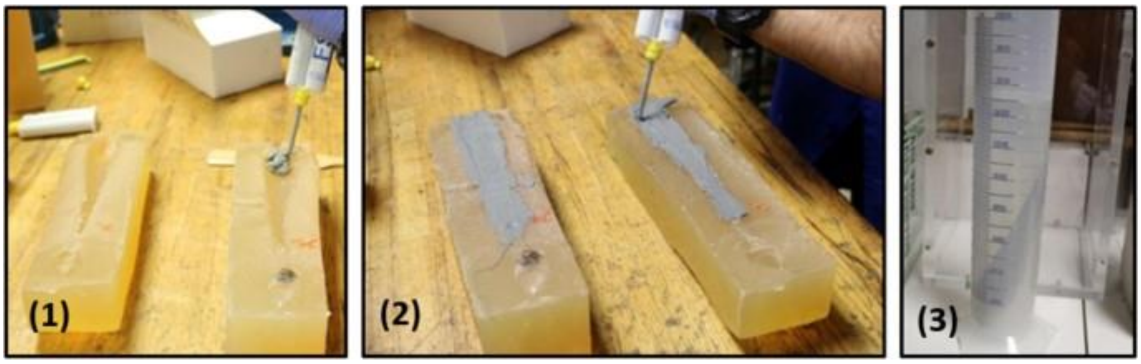


Figure 3. Silicone methodology for determining the cavity volume of GS1: 1. Silicone-casting of the cavities. 2. Drying of the silicone. 3. Measurement of the cavity volume by measuring the increase in the water volume in a test tube when the mould was submerged.

All these manual measurements (penetration depth and volume) using the silicone method were determined right after the CT scans and before the digital analysis using the 3D Slicer program from the CT scans. This was done in that order because the soap dries up rather quickly; thus, the experimental manual handling took place before the digital data treatment. In other words, the CT scanning and silicone-casting were performed as close in time as possible.

3. Results

As previously explained, the ballistic soap was shot four times (2 different ammunitions, 2 shots per ammunition) and cut into the respective only-one-cavity parts. Figure 4 shows the cavities generated in the soap against the source light. The average projectiles' speed was 282.5 m·s^{-1} for the Golden Saber and 309.7 m·s^{-1} for the Silver Tip ammunitions.

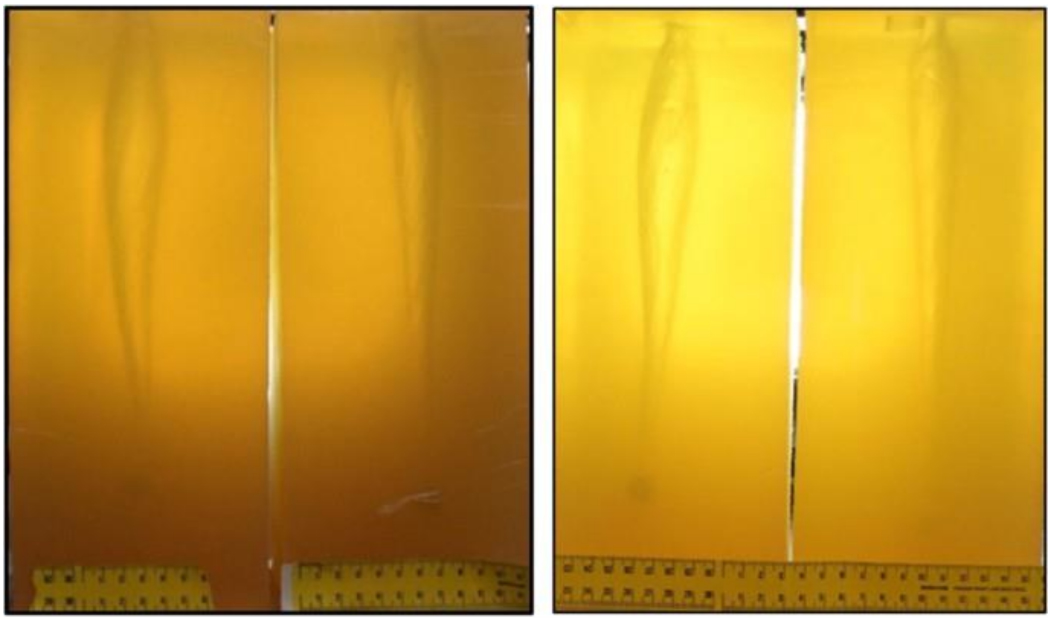


Figure 4. Coronal views of the cavities generated in ballistic soaps after the shooting. From left to right, the cavities correspond to the ST1, GS1, GS2, and ST2.

The ballistic soaps were scanned, and the obtained DICOM files were processed with the 3D Slicer program. After recreating the 3D cavities, the measurements of the cavity volumes and projectile penetration depths were digitally accomplished. The 3D Slicer program provided a 3D image of the soap together with three different soap perspective views (front, top, and side) (Fig. 5).

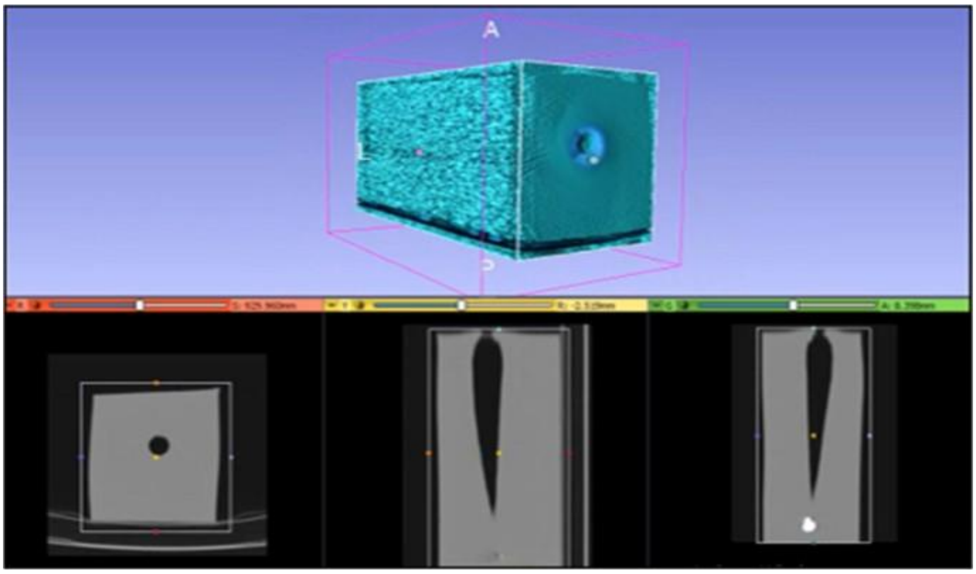


Figure 5. Views of the soap GS1 in the three coordinate planes, provided by the 3D Slicer program. From left to right, the views are the axial, sagittal, and coronal.

It should be noted that Fig. 5 is a static image, where each shown perspective view is actually a soap cross-section frame. Different frames for each perspective view can be sequentially displayed and studied in more detail. This way, many useful features can be measured, such as the entry hole diameter, the cavity shape, the maximum diameter of the projectiles, length and shape of the small air branches, etc. The 3D Slicer program, besides enabling the 3D visualization of the cavities and providing distance (millimetres), area, and volume measurements (millilitres) (Fig. 6), also enabled the soap to be visualized from different views frame by frame.

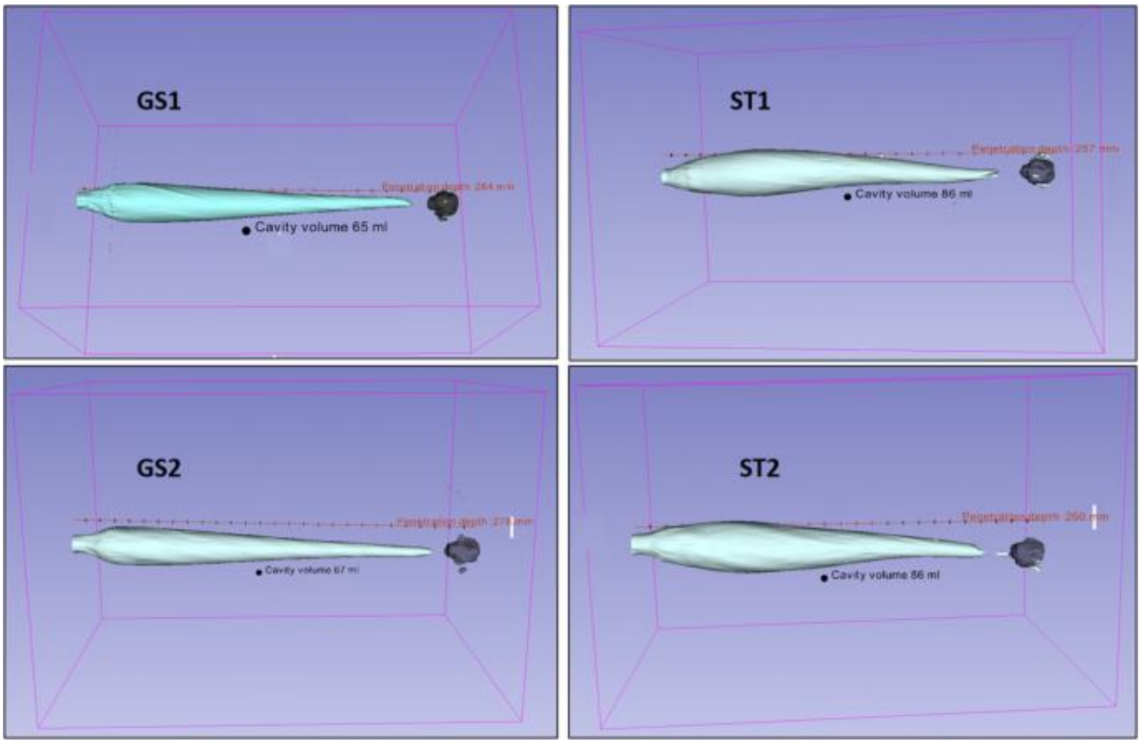


Figure 6. Sagittal view of the 3D cavity reconstructions (3D slicer) of the GS1, GS2, ST1, and ST2 shots.

Table 1 shows the gunshot cavity volumes and the projectile penetration depths obtained by both the CT and silicone methods and for the different shots. The uncertainty of the CT results was calculated by performing five measurements (of the same volume and projectile penetration depth) using the 3D Slicer software. The uncertainty of the silicone results was already delimited by the inherent uncertainty of the test tube and measuring tape.

Table 1. GS Golden Saber ammunition, ST Silver Tip ammunition.

Computed tomography

Shooting	Projectile's speed (m·s−1)	Projectile's kinetic energy (J)	Cavity volume (mL)	Projectile penetration depth (cm)
GS1	282.087	319.5	65 ± 2	26.4 ± 0.1
GS2	282.925	321.4	67 ± 2	27.8 ± 0.1
ST1	311.527	361.5	86 ± 2	25.7 ± 0.1
ST2	307.834	353.0	86 ± 2	26.0 ± 0.1

Silicone

Cavity volume (mL)	Projectile penetration depth (cm)
80 ± 20	26.4 ± 0.1
80 ± 20	27.8 ± 0.1
100 ± 20	25.1 ± 0.1
100 ± 20	27.2 ± 0.1

Firstly, it should be highlighted that there is a high reproducibility in the cavity volume and projectile penetration depth obtained for the two different shots fired with the same ammunition. This is evidenced by the negligible differences between GS1 and GS2, or ST1 and ST2, for both the CT and silicone-casting methods.

The cavity volumes generated by the Silver Tip ammunition were about 20 mL larger than the cavity volumes from the Golden Saber ammunition. In this case, in the knowledge that both ammunitions were expansive, with similar shape, the highest volumes were generated by the ammunition with higher projectile's kinetic energy.

The volumes obtained by CT were quite in agreement with those obtained with the current silicone method. In fact, the CT volumes were also within the large estimated volume range obtained using the silicone method. A smaller volume range was obtained when using CT. This has great relevance because the volume range obtained using the silicone method (± 20 mL) is too big and provides imprecise results, unlike CT method which provides a volume range of ± 2 mL. In other words, this imprecision implies that the ammunition damage is not correctly determined when using the silicone-mould method.

In the case of the projectile penetration depth measurements, both methods have the same uncertainty (± 0.1 cm) and provided similar distances. In addition, the projectiles penetration depths are similar for the two types of ammunitions, GS and ST.

4. Discussion

The high image resolution provided by the non-destructive CT method allowed the generation of a detailed projectile cavity model. The measurements obtained by both the CT and current silicone methodologies provided comparable results. Gremse et al. [14] had previously noted a systematic overestimation of the silicone cutting-based volume compared to the CT-based volume, though they did not provide further details regarding the silicone method to compare both methodologies. In the present study, this issue is also glimpsed considering that the calculated mean value in the CT-based volume was lower. In fact, our results verify that the cavity volumes provided by CT were more precise than those given by the silicone method. This is because the uncertainty using CT is much lower than using a test tube big enough to contain the moulds of each cavity. This was confirmed for both ammunitions, Golden Saber and Silver Tip. Thus, the lack of precision and resolution of the silicone method can be clearly improved using the higher fidelity of the CT method.

Regarding the projectile penetration depth measurements, this study showed that both techniques provided very similar results in terms of both accuracy and precision. In this respect, the uncertainty of using either CT or a measuring tape (for determining the projectile penetration depth) is the same (± 0.1 cm).

The damage caused by a projectile depends on its type, shape, and kinetic energy as well as on the elasticity of the material where it impacts [16]. As evidenced in Table 1, Golden Saber ammunition produces higher volumes than the Silver Tip ammunition. The penetration into the ballistic soap is quite similar in both ammunitions. In this study in which two projectiles of the same type and shape impacted the same material (soap), the different damage is mainly due to their different kinetic energy. The more kinetic energy the projectile had, the more damage was created in the soap.

In addition, an important advantage of using CT is that the volume given by its images gave a permanent record of the shooting cavity. Besides, once the images are recorded and stored, the further measurements (volume, diameter, projectile path, etc.) on the resulting 3D body do not get affected by the storage, mechanical, or ageing effects (squeezing, shrinking, drying, etc.) on the soap material itself. Previous CT studies also visualized the shooting cavity, the dispersion pattern of the projectile, and the projectile penetration depth in the ballistic soap [13, 15]. However, they did not compare the tomography results against the silicone method used in forensic science institutes, which is a necessary step in order to transfer the new methodology to the judicial system.

The advantages of the CT method compared to the silicone-casting procedure are quite many:

- CT is a non-invasive and therefore non-destructive method, guaranteeing an intact cavity for further analysis.
- CT has less uncertainty and provides more precise cavity volumes than the silicone method. Consequently, the sensitivity of the CT method is much larger than that of the silicone one.
- The silicone method requires more time, that is, an average of 20 min per soap, considering the cutting, silicone-casting, drying, and test tube analysis. In contrast, it takes less than 10 min to perform the CT imaging, the image processing, and the digital reconstruction of the cavity.

- CT renders a 3D digitally reconstructed cavity, which can be copied, distributed, and 3D printed by any forensic expert or law representative that requires it. On the other hand, the silicone method gives a unique physical mould per cavity, which would need further scanning or mechanical procedures to be copied or distributed.
- Silicone method requires additional consumable material such as silicone cartridges, corresponding cartridge nozzles, and silicone dispensable guns. On the contrary, CT does not require the purchase of additional consumable material. However, CT scanner method requires access to a CT scanner.

In addition, the possibility of creating infographics of the 3D-reconstructed cavities from the CT files is an excellent way to visually support the understanding of the ballistic reports. This can even assist the ballistic experts when they are explaining the forensic scientific results to the judge or jury.

5. Conclusions

Considering the above-mentioned results, we can conclude that CT method is faster, more precise, and more sensitive than the method currently used in the forensic laboratories based on the use of silicone moulds. Furthermore, CT is a non-invasive and therefore non-destructive method, guaranteeing that the original soap cavity will remain intact for further analysis. Thus, the methodology reported in this work, using CT and the 3D Slicer software, proved to be really useful in terminal wound ballistics in soap. This overcomes the limitations of the current methods based on silicon-casting, whilst offering new promising infographics-based possibilities for the forensic experts in court. Therefore, the ballistic laboratories can take advantage of using CT for their ballistic analysis provided they have access to such technology, perhaps available in a neighbour department for forensic medicine purposes. As future trends, further research might study whether the reconstructed cavity could combine additional information regarding the body’s wounds, affected organs, and maximum damage. This could be a great step towards a better understanding of the forensic results in courts.

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