Year: 2023

Illustrated argument for CT-scanning a whole car for the forensic investigation of projectile holes, defects, fragments and possible trajectories

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DOI: https://doi.org/10.1016/j.fri.2023.200562

Originally published at:
Schweitzer, Wolf; Ebert, Lars C; Thali, Michael J; Bolliger, Stephan A (2023). Illustrated argument for CT-scanning a whole car for the forensic investigation of projectile holes, defects, fragments and possible trajectories. Forensic Imaging, 35:200562.
DOI: https://doi.org/10.1016/j.fri.2023.200562

Forensic Imaging 35 (2023) 200562

Contents lists available at ScienceDirect

Forensic Imaging

journal homepage: www.sciencedirect.com/journal/forensic-imaging

Short communication

Illustrated argument for CT-scanning a whole car for the forensic investigation of projectile holes, defects, fragments and possible trajectories

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ARTICLE INFO

Keywords:
3D scanning
Surface
Forensic pathology
3D reconstruction
Computed tomography
Forensic sciences
Vehicle

ABSTRACT

Contemporary documentation of a car with bullet defects after a shooting incident can secure the usual tracks and gunshot residue, take photographs, and use trajectory rods and probes. Since the advent of the "XXL-CT -Scanner" (Fraunhofer Institute, Germany), we have wondered if the advantages of volume scanning CT, already noted for forensic pathology, could be applied to cars. To this end, we damaged a small 3D-printed car model with an electric drill and added CT -dense material with a soldering iron, simulating linearly configured defect morphologies with metal particles. This model was CT -scanned and the resulting data visualized to illustrate how these visualizations can support reconstructive visualization of trajectories. Performing a real XXL-CT scan of a bullet-riddled car requires extensive preparation, transportation, and other logistical measures that are costly and time-consuming. Nonetheless, we suggest that this is a worthwhile research direction to explore.

Background

Shooting incidents involving vehicles may be complex, dynamic events. Typical subsequent forensic questions may involve the positions of shooters, visibility, and so on and so forth. Before any of these can be addressed, however, a full documentation of the scene, the involved persons and of course the involved vehicles is something one would regard as the essential basis.

Now, one could argue the opposite: that a full 3D examination and 3D documentation of a vehicle can provide little to no evidence compared to examination by eye. We would agree with that view, especially in cases where the vehicle has a skeletal structure that is mainly under or next to the person, the driver, the occupant, such as a typical bicycle or moped: such has only a skeletal structure or frame, and the occupant will actually cover parts of it in normal use, whereas such a vehicle typically has no shell-like features. Indeed, it may seem like a waste of resources to perform extensive 3D documentation of such a vehicle, such as a bicycle, if its rider was shot in the head from a passing car.

Conversely, we would consider such an investigation and documentation quite promising if the vehicle had the general construction of a clamshell, such as a typical car. In such a case, the typical constellation might be that an occupant suffered a gunshot wound, or at least was shot at, while seated inside the vehicle and the weapon was fired at that vehicle from outside that vehicle. It can then be assumed that a projectile hitting the occupant first penetrated the vehicle shell, unless there are special circumstances, such as the vehicle being a convertible or it had open windows or the like.

A typical forensic objective pursued in such cases is to obtain a reasonably good estimate of the position of the shooter when the shots were fired. For this purpose, at the very least, two separate reference points are usually required, for example, an entry and exit hole through the body of a car [1].

Firing angles and distances, as well as the weapons and bullets used, are the first typical technical questions asked. As equipment, cameras, tripods, tape measures and trajectory rods and probes remained a constant for decades [1]. The introduction of various methods of 3D surface documentation, most notably photogrammetry and laser scanning, provided a whole new level of scene capture – particularly also for the documentation cars and in the context of shooting [2,3]. Thereby, a whole scene may be captured in high resolution 3D at the cost of overwhelmingly large amounts of data [3]. With that, surface scanning techniques are explicitly limited to documenting surfaces. Underlying structures and even some overhangs tend to be omitted and not available for reconstruction. While the level of precision of 3D data captured just by surface scanning can be considerable, it is limited to surface defects, deformations or damages [3].

In addition to 3D surface scanning, a new examination method has

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https://doi.org/10.1016/j.fri.2023.200562
Received 2 February 2023; Received in revised form 13 August 2023; Accepted 25 August 2023

recently been developed that could be of the highest interest for the forensic examination of cars in gunshot wound cases: a very large computed tomography [4]. A first application has been described for the examination of the battery of electric vehicles after an accident, but we believe that another relevant application could be the reconstruction of shootings.

Qualitatively, a full 3D volumetric dataset can provide the basis for a more sophisticated and accurate reconstruction than probes to visualize a trajectory, especially for complex trajectories [3]. Such data may also become important later when unexpected developments or statements in the case require a more detailed investigation of an angle that was previously neglected or considered less relevant.

As it tends to be hard to foresee whether a particular car with shot defects containing potential trajectories ends up being a simple or complex case, 3D data capture may be decided to be the default method for documentation *before* even going further in examining any such case. More importantly, one might claim that it will be difficult or impossible to adequately predict the number and constellations of any projectile perforations, embedments or ricochets inside a particular vehicle, without a prior, initially captured 3D data quite in analogy of the examination of (human) victims [5,6]; that claim also may be founded upon the consideration of the many theoretical morphological options suggested by a "phase diagram" (as in Fig. 6 in [7]) that correlates obliquity or angle of incidence, projectile speed and approximated aspects of resulting post-impact projectile morphologies.

As a research team that pushed the benefits of post mortem CT scanning in forensic medicine [5,8], also with regard to traffic related victims and objects [9–13], we are interested in proposing and discussing other CT scanning applications in forensics, and with this, cars. This article thus is meant to provide arguments for the use of a "CT-XXL" scanner in any given car that is forensically investigated after a shooting. Ultimately, the ability to produce timely, clear and accurate, understandable presentations or written documentation for interested parties can be greatly accelerated by the competent use of volumetric 3D data [3].

How, then, might a volume scan of a car aid in gunshot reconstruction?

To structure the considerations of the suggested documentation approach, one could first look at the hull of the vehicle and then at the interior of the vehicle.

Vehicle hull

In terms of technical focus, a first aspect to be considered for examination may be any perforations or other possibly projectile related damages or defects in the vehicle's hull.

In the case of a car, the hull typically may be comprised of sheet metal, plastic and security glass. There, one may focus on *defect locations, shapes, dimensions* and *constellations of findings*. Conversely, the most common form of sheet metal encountered in forensic shooting reconstruction cases is that found in motor vehicles [3].

Not only the car body defect locations and dimensions, and possibly associated damages of the target, such as attached or lose fragments, but particularly the 3D shapes of material perforations and associated deformations, in context of specifics related to the shots that were fired, tend to represent relevant determinants for a reconstructive understanding. On top, two interrelated phenomena (bullet deformation and sheet metal deformation) have reconstructive implications [3]. This has been studied particularly for sheet metal [7,14–16].

One relevant shot related feature that may be seen on motor vehicle sheet metal is termed "pinch point". That term denotes a small circular area of surviving paint at one end of a projectile entry hole or ricochet mark. It represents the first point of contact of the projectile and provides directionality to the impact mark [1]. Another morphological feature that can indicate the direction of the projectile is the so-called "bow effect," which marks break lines in painted sheet metal [1]. A further aspect to look for are signs for shallow impact angles described as "double headed impact" mark, as well as edges bent both inwards and outwards [16]. Occasionally the characteristic outline of the margins of a hollow-point cavity in a pistol bullet can be seen in the concave side of a plug, and the reverse shape of a knurled cannelure[1] may be seen in a tab produced by such a cannelured bullet (specifically, see [3]), so any groove or ridge like shape deformations are of relevance. Last, but not the least, the full lengths of projectile defects, including the lead-in mark, were found to correlate with the angles of incidence [16], so their dimensions also matter. With advanced exploitation of perforation or damage morphology, a direction may be reconstructed even from just one (instead of at least two) projectile perforation shape [16].

Shotgun pellets, sling shot balls or stones may cause damages that have a different shapes than single firearm projectiles [1], so also there, morphology will be of essence.

Perforation of safety glass can be documented using 3D scanning methods if the panes are not completely shattered. Tempered glass (rear and side windows of cars) can become very fragile or even immediately shatter ("dice") into small pieces instead of maintaining its overall integrity upon projectile impact [3]. Laminated glass ("windshield") can have uncanny effects on projectiles; deflection of otherwise penetrating projectiles or separation of projectile jackets from their lead cores can occur [3]. In some cases, the defects can be considerably larger than the projectiles. [1]. A sequence of multiple shots may or may not be derived from earlier radiating fault lines terminating later fault lines [1,3].

With regard to tires, rubber and elastic materials behave a bit like skin: around the edge of a bullet hole, there is often some sort of abrasion edge that roughly corresponds to the caliber of the bullet. The actual bullet hole is usually smaller (in some cases much smaller) than the bullet that caused it. Car tires are the most common example of rubber being struck by bullets. Hollow-point pistol bullets, such as those commonly used by U.S. law enforcement, can create a more easily detectable bullet hole due to the "cookie-cutter" effect [3].

Comparison of shapes and dimensions of deformations or defects between actual vehicle findings and the result of any ancillary experimental ballistic tests [7] may be better on basis of actual 3D data than by using just 2D photographs. Research and systematic investigation into how the morphology of such projectile defects particularly on sheet metal can best be used for trajectory determination efforts during scene reconstructions is considered a contemporary imperative [16].

Vehicle inside

As second step, one then may approach examination of the inside of the car.

There, one may particularly search for *projectiles, projectile fragments, ammunition parts, gunshot residue or bullet wipe*: depending on firearm and projectile specifics, the penetrability of materials will vary [7]; the physical interaction between projectile and materials may then result in gunshot residue (which may be detected using CT [17,18]) being transferred to materials, or projectile fragmentation, ricochet or embedment.

In the context of initial and intermediary targets, one might consider sheet metal (car chassis) and metal tubes (seat frames). The term "plastics" encompasses a variety of materials, from relatively hard and brittle Plexiglas and polycarbonate windows and patio covers to polyvinyl shower curtains, bright orange hunting vests, and polypropylene flatbed liners for pickup trucks. The former respond to gunfire much like glass, bone, and ceramic materials. This behavior includes cone fracturing, propagation of radial fractures, and adherence to the crack rule regarding shot sequence [3]. One could also consider mobile objects

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[1] A cannelure describes a circumferential groove or channel of a bullet or cartridge. Generally, knurling is a process that creates ridges in straight or diagonal patterns, or diamond shaped. For further reading see referenced literature.

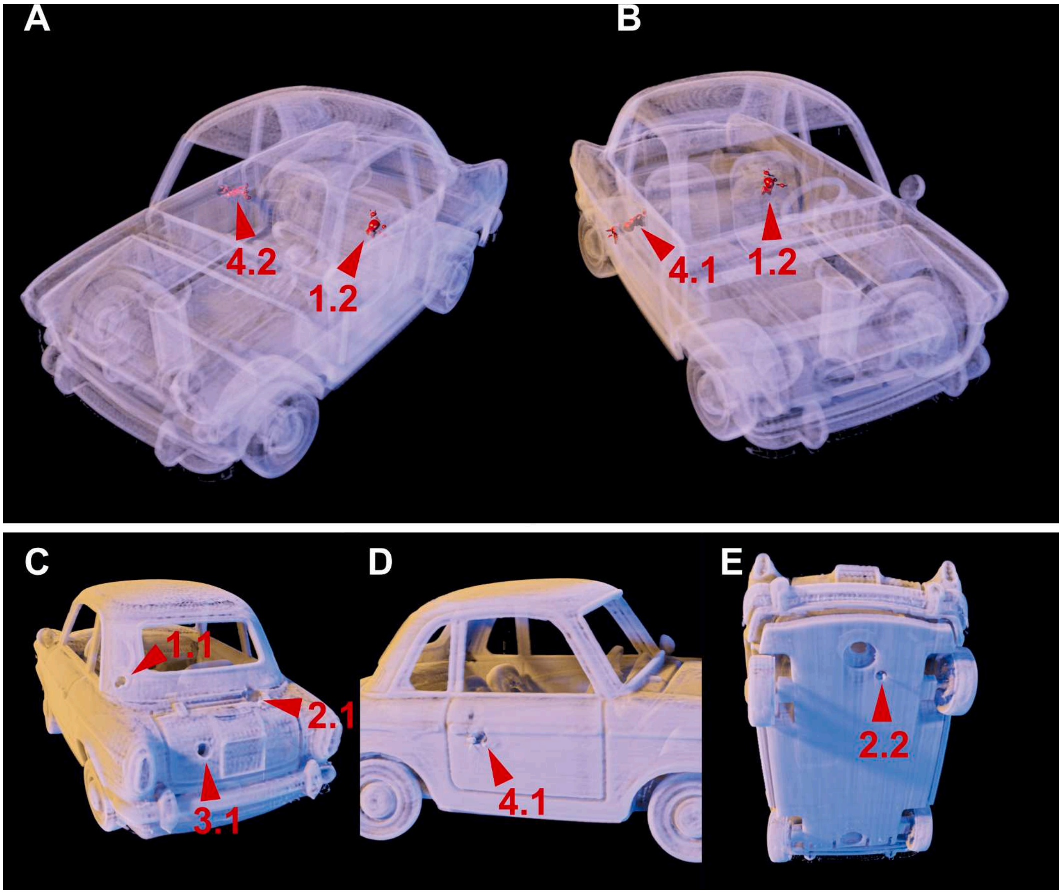

Fig. 1. **A, B**: Transparent volume rendering of car frame combined with red opaque representation of metal density in this case of a plastic car model with metal that had been added to the perforating defects. **C–E**: opaque volume rendering of car model exhibiting perforating defects. The numbering of the defects relates to Figs. 2 and 3. – The typical first encounter with a bullet riddled car may look as shown in **C–E**. A typical large X-ray may at best show potential projectiles or projectile fragments (as shown in **A–B**). Then there still is the question which of the outer shell perforations is related to which inner defects, and in what precise way they might be relevant for occupant injury or death.

such as luggage as well as passengers or other people such as bystanders, where essentially 3D surface or 3D volume documentation may also be relevant.

Methods

A model of a car (left-side steering wheel, hardtop, four-seat sedan, 3 doors; similar to Trabant model 601) was 3D printed at $\sim 1:20$ scale [19], modified with a commercial electric drill and soldering iron to simulate material defect tracks and bullets. Thereby, the drill was used to impart tubular defects onto the plastic car, and the soldering iron was used to add small metal particles to simulate the appearance bullet fragments. However, it is important to note that this model was *not* designed to replicate *all aspects* of a real car that had been subjected to *actual* gunfire; it also does not, for example, simulate the deformation and penetration patterns that occur in real metal when impacted by bullets or the difficulty that is encountered when scanning different metal structures. This is a very crude simulation of only a few selected aspects.

The car model was then CT-scanned (120 kV, 35 mAs); reconstructions (Figs. 1, 2, and 3) were made using standard software for both surface model and volume data visualization [20].

Results

Our model car exhibits drill holes and bits of soldering iron that were applied to illustrate just some aspects of visual firearm defect reconstructions. The results of CT-scanning the whole model car are exhibited in Figs. 1, 2 and 3.

The defects and bullet fragments may be identified and labeled first. All aspects of the data can be cut, sliced, and rendered separately in order to expose defect and structural detail. Defects with a distinct and directional morphology can be visualized and evaluated, on basis of CT data. It is possible, for example, on basis of that data, to explain how certain external and internal defects account for a correct or incorrect match. In this way, the forensic reconstruction value of CT - scanning an entire vehicle with bullet holes - is visually explained.

- The configuration of defect **1.1**, featuring torn off material at **1.1.1**, aids in identifying the shot direction as moving towards defect **1.2**, where the metal simulates a lodged projectile (Fig. 2 **B**–**E**).
- By considering the exact 3D shape and position of the defects, an inspector can correctly associate defects **2.1** and **2.2**, while dismissing a connection between **2.1** and **3.2**. For instance, the cylindrical shape of **2.1** makes any internal defect other than **2.2** an implausible match (Fig. 2 **G**–**I**).
- The unique form of defect **3.1**, coupled with the internally adjacent material flake **3.1.1**, guides the examiner to the relatively subtle defect **3.2** (Fig. 2 **K-M**).
- Defect **4.1** can be linked to defect **4.2** by way of a tubular defect (Fig. 2 **O**–**R**).

An overview of the whole car may then be labeled using the respective defect labels, as in Fig. 1. At this stage, the model can be rendered as

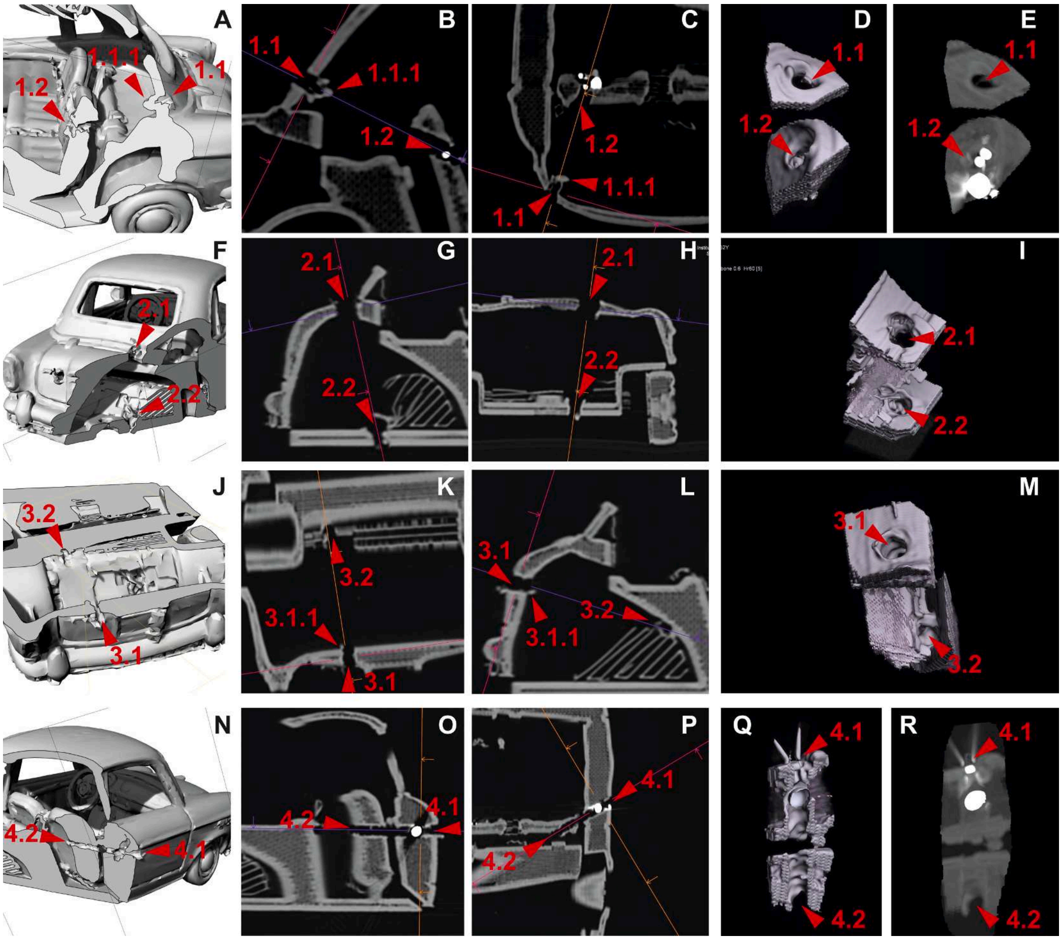

Fig. 2. Left [A, F, J, N]: 3D rendering with clip plane exhibiting the modeled projectile trajectory with aligned defects. **Middle [B,C,G,H,K,L,O,P]**: related to the 3D rendering on the left of each image row, there are the matching multiplanar reformation images to exhibit defect morphology, in constellation of the trajectory reconstruction. **Right [D, E, I, M, Q, R]**: Shape visualisation in 3D (volume renderings, and, where applicable, maximum intensity projection) – **1.1**: cylindrical perforating defect of left C-pillar; **1.1.1**: fragments adherent to inside of defect **1.1.**; **1.2**: cylindrical perforating defect in driver's seat back rest, metal dense particles there; **2.1**: cylindrical perforating defect in trunk on the right side; **2.2**: cylindrical perforating defect in floor of trunk / car underbody; **3.1**: cylindrical perforating defect in the trunk on the left side; **3.1.1**: small material fragment adhering to inside of **3.1**; **3.2**: cylindrical non-perforating defect in the back of the left rear passenger seat; **4.1**: cylindrical perforating defect of left front passenger seat sided car door, containing metal dense particles; **4.2**: cylindrical perforating defect of the front passenger seat backrest.

either transparent (Fig. 1 **A-B**) or opaque (Fig. 1 **C-E**).

Finally, *trajectories can be visualized* based on this data structure. This visualization offers a unique opportunity for examiners to visually communicate the results, further highlighting the capabilities of CT scanning in this context (Fig. 3).

Discussion

It is essential to note that our CT-scanning of a plastic car model was not designed to fully encapsulate the complexity of a real vehicle and all of its scanning aspects. What we try to illustrate however is how visualization of *some reconstructive aspects* may be helpful in a real case.

Penetrating a real car with X-rays poses a challenge due to the variety of metallic X-ray dense materials. However, researchers at the Fraunhofer Institute in Fürth, Germany, utilizing the "XXL-CT" scanner built around a Siemens SILAC[2], have devised strategies to mitigate these issues.

Their approach involves the use of X-ray energies up to 7.9 MeV and minimizing X-ray penetration paths to reduce artifacts to improve data quality. They found that this is best achieved by scanning a vehicle in a vertical position. This presents significant logistical challenges. To place the vehicle in a vertical position, the developers have provided a vehicle mount that can scan vehicles weighing up to 3.2 tons ("VERTICAGE") [4]. The cage itself provides a rigid frame structure that is optimized for low X-ray absorption. Further preparation contains draining vehicle fluids (e.g., windshield washer fluid, coolant, engine oil, transmission oil) and disconnecting all batteries to avoid leakage and electrical hazards. Then, the vehicle must be allowed time to settle in its new position to prevent motion artifacts during the scan. Loose objects can also shift when a vehicle is rotated to a vertical position, contributing to the phenomenon known as evidence dynamics [21]. Preparation time alone is estimated to take 24 h.

The image acquisition phase is lengthy, with a typical scan lasting around 48 h. The raw data may be as large as 130 GB, and each reconstruction produces a final data volume of approximately 30 GB. Data volume may cover a volume of Ø2.2 × 2.8 m^3, with a voxel size of 0.4 × 0.4 × 0.6 mm^3. Despite these challenges, the end results can be invaluable, offering potential to identify different materials, including various types of sheet metal, electrical and plastic assemblies, and even seat leather covers [4].

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[2] Siemens Industrial Linear Accelerator 'SILAC' model "SILAC p 9 MeV": rotatable X-ray head 1210 × 900 × 1700 mm; weight <2 tons; interlaced dual energy: optional; source: website https://www.oem-products.siemens-healthineers.com/linear-accelerator

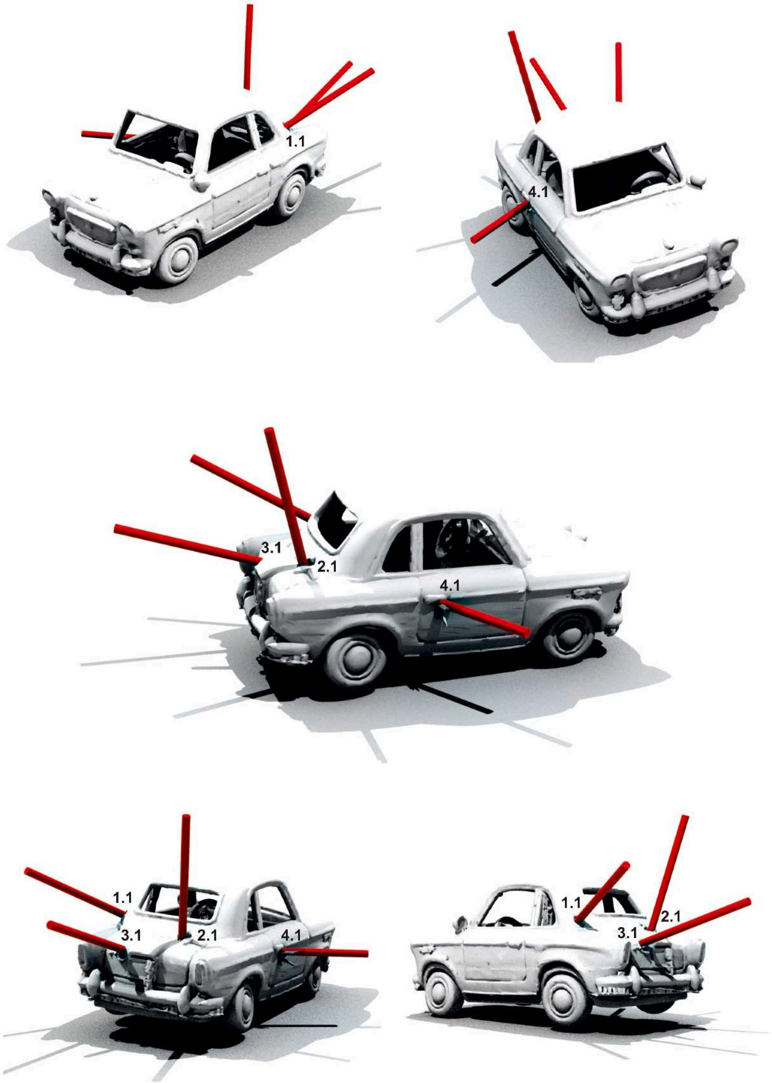

Fig. 3. Real-3D data-based visualization of trajectories after careful manual placement of trajectory lines in full view of defects. This means that the intersection of each trajectory line with each identified defect (see Fig. 2) was visually verified and ensured. From then on, the trajectories can be used for further reconstructive considerations. The numbering of the defects refers to Fig. 2.

Before trajectories can be considered, the CT data has to be analyzed for defects and bullet fragments. The difficulty of identifying a bullet may also depend on whether it fragmented or not. Identifying sheet metal defects may be relatively easy, but matching these to a trajectory may be a challenge, depending on the specifics of these defects. Even if the resulting CT data cannot serve to reliably differentiate all relevant aspects, it can be used as 3D blueprint to manually mark forensic evidence findings during subsequent conventional forensic examination. Then, further reconstructions may be performed on such a data model.

The overall results of any 3D scans, regardless of whether they are based on surface or volume scans, may then be used for virtual scene reconstructions [10,22].

Reconstruction of a dynamic event involving people and objects can be limited when only relying on rigid 3D models [23–25]. While determining or estimating perforation angles for vehicles seems difficult enough, reconstructing an entire gunfight, including a good estimate of the shooter's position, can be far more challenging [10,22]. Numerous dynamic aspects – e.g., how people ran around, how people reacted and acted in the moment, how a vehicle swerved – that can be of great importance to reconstructive understanding are usually not documented. One might then conclude that even with a conventional approach that does not use CT or 3D scans, not much is lost depending on the specific circumstances of a given case. However, in other cases, the result of extensive 3D surface and volume scans can provide very useful results for forensic investigation.

Ultimately, one will have to weigh cost, effort, risk and drawbacks against benefits, advantages and improved documentation when considering an XXL-CT of a vehicle after a shooting incident.

Declaration of Competing Interest

The authors declare that they have no competing interests.

Acknowledgments

The authors express their gratitude to Emma Louise Kessler, MD for her generous donation to the Zurich Institute of Forensic Medicine, University of Zurich, Switzerland.

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