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VIRTOPSY—Scientific Documentation, Reconstruction and Animation in Forensic: Individual and Real 3D Data Based Geo-Metric Approach Including Optical Body/Object Surface and Radiological CT/MRI Scanning

ABSTRACT: Until today, most of the documentation of forensic relevant medical findings is limited to traditional 2D photography, 2D conventional radiographs, sketches and verbal description. There are still some limitations of the classic documentation in forensic science especially if a 3D documentation is necessary. The goal of this paper is to demonstrate new 3D real data based geo-metric technology approaches. This paper present approaches to a 3D geo-metric documentation of injuries on the body surface and internal injuries in the living and deceased cases. Using modern imaging methods such as photogrammetry, optical surface and radiological CT/MRI scanning in combination it could be demonstrated that a real, full 3D data based individual documentation of the body surface and internal structures is possible in a non-invasive and non-destructive manner. Using the data merging/fusing and animation possibilities, it is possible to answer reconstructive questions of the dynamic development of patterned injuries (morphologic imprints) and to evaluate the possibility, that they are matchable or linkable to suspected injury-causing instruments. For the first time, to our knowledge, the method of optical and radiological 3D scanning was used to document the forensic relevant injuries of human body in combination with vehicle damages. By this complementary documentation approach, individual forensic real data based analysis and animation were possible linking body injuries to vehicle deformations or damages. These data allow conclusions to be drawn for automobile accident research, optimization of vehicle safety (pedestrian and passenger) and for further development of crash dummies. Real 3D data based documentation opens a new horizon for scientific reconstruction and animation by bringing added value and a real quality improvement in forensic science.

KEYWORDS: forensic science, metric wound documentation, photogrammetry, 3-D/CAD, 3D optical scanning, computed tomography, magnetic resonance imaging, forensic radiology, image fusion, image merging, animation, virtual autopsy, virtopsy, accident research, motor vehicle accident, shoe imprint.

The reconstruction of forensic relevant events is based on morphological findings (on and in human bodies, e.g., patterned injuries) as well on physical evidence (on bodies, crime scene, vehicle damages, injury-causing instruments). Until today, most of the documentation of forensic relevant medical findings was limited to traditional 2D photography, 2D conventional radiographs, sketches and verbal description. Recently, several studies have been presented using 3D imaging techniques and computer based approaches to document forensic injuries or crime scenes (1–17). In addition to the existing knowledge, this paper has the goal to demonstrate some new 3D real data based geo-metric technology approaches (Figs. 1–20).

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Methods

Body/Object Surface Documentation

Classic Forensic 3D Photogrammetry Using Classical Conventional or Digital Reflex Cameras—Using photogrammetry, the position of points in 3D space can be determined by triangulating multiple bundles of observation rays. Therefore multiple images of the object are taken from different angles using a handheld camera. Knowing the projection equations of the used optical elements, 3D coordinates can be calculated from as many object points as needed. That means if the spatial orientation of each bundle is known in the object coordinate system, the intersection of the rays delivers the desired 3D object coordinate of the object.

Forensic, 3-D/CAD-supported Photogrammetry is the science of the wound measurement and 3-D reconstruction of patterned injuries, and their possible injury-causing instruments. Forensic 3D Photogrammetry is an easy to do 3D approach to access 3D data of a small, located injury or defects. For the documentation process there is no requirement for special equipment, only the analysis has to be carried out by an operator with computer and photogrammetric experience. Several papers using this technology have been published during the last years and the method is already established in the court system in Switzerland (11,12,14). An update

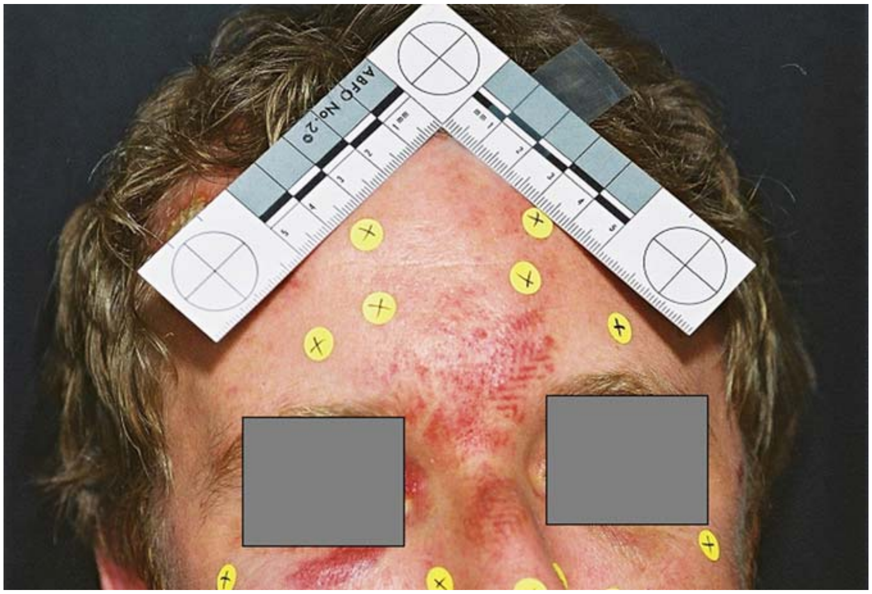


FIG. 1—*Case 1: Patterned injury or morphologic imprint on the face from a shoe sole in a living person.*

FIG. 2—*Case 1: Scanning of the suspected injury causing instruments (upper left) or the soles of different shoes using the optical 3D scanner. The upper right picture shows the fringe projections on the shoe during the scanning process. The lower row of pictures demonstrates the results of the 3D scanning: the 3D individual data models of the shoe soles of the suspected perpetrators.*

of the procedure has been published in the form of a step-by-step protocol (4).

Photogrammetry Based 3D Optical Scanning Using the GOM TRITOP/ATOS II System

3D optical scanning is a method, which is normally used for 3D photogrammetry documentation and measurements in prototyping and design technology, where a very high precision is required. We are using the TRITOP/ATOS II (Fa. GOM, Braunschweig, Germany, see http:// www.gom.com) system which has the advantage that it can be used for the color true 3D surface documentation of small and large view areas (13).

Using this technology, documentation ranging from fine detailed structures (skin lesion or fine instrument structure) to overview documentation (whole body or entire vehicle) is possible. This could not previously be efficiently performed (time and quality) by using the classic forensic, 3-D/CAD-supported photogrammetry approach.

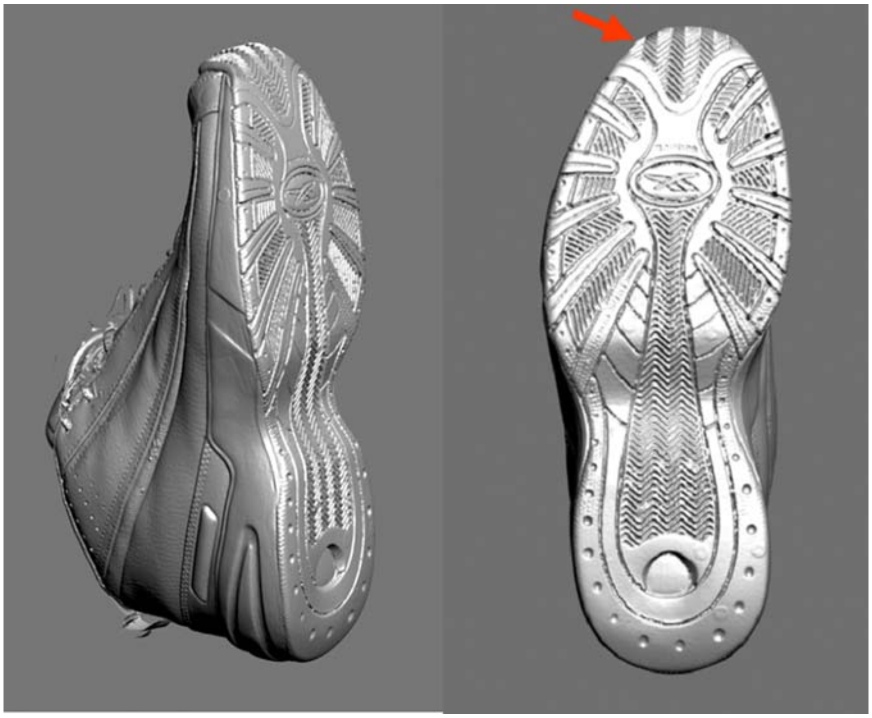


FIG. 3—*Case 1: Detailed 3D individual data model of the specific shoe, linked to the injury pattern. Red arrow: injury-causing shoe sole area.*

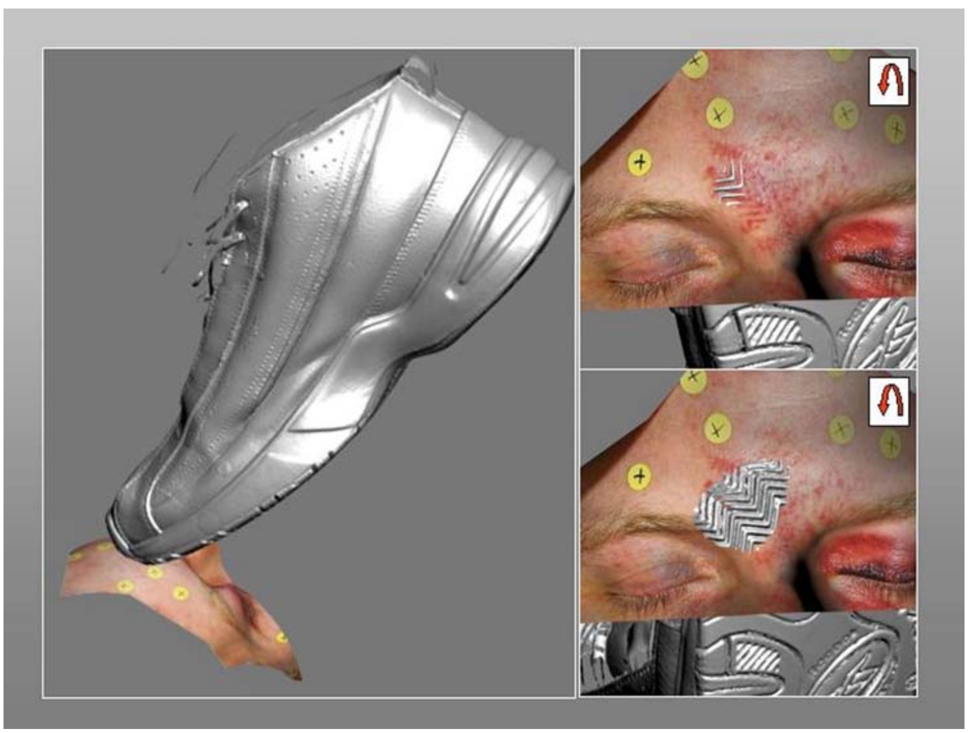


FIG. 4—*Case 1: 3D match analysis of patterned injury and suspected injury-causing shoe. Pictures on the right side show the sole structure and the corresponding area of patterned injury in an "inside out view," which is indicated by the "red boomerang arrow box." This visualization means that the observer's view is from inside the 3D-head model of the victim towards the skin. This allows side-by-side analysis of the matching areas of the shoe sole pattern and the skin lesion; using the classic approach (picture on the left side), it may be difficult to visualize the match of patterns.*

The advantage of the GOM TRITOP/ATOS II system is that it is easy to use, has a high stability, accuracy and the different 3D optical data are automatically composed.

For better understanding, the photogrammetry-based two-step 3D optical scanning documentation process is explained in the following:

Optical Coordinate Measuring System TRITOP—The photogrammetric measuring device TRITOP is based upon the principle of photogrammetry and determines 3D coordinates. For this, multiple photos taken freehanded and sequentially by a high-resolution digital camera from different views/directions are required, with a partially overlapping image area. Furthermore it is necessary that

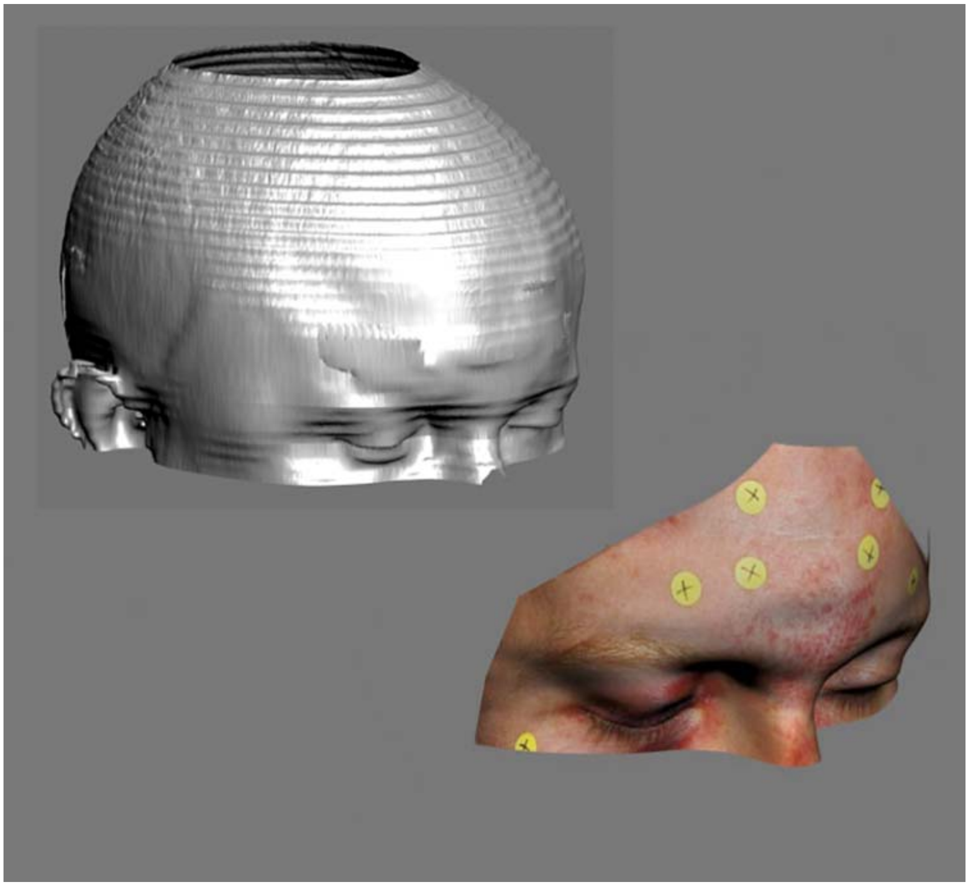


FIG. 5—*Case 1: Left upper picture: 3D visualization of the clinically acquired CT scan. Due to a limited radiation exposure of living persons, scans in the clinical environment are normally not of such a high resolution. 3D reconstruction artefacts are visible in clinical scans. Right lower picture: 3D surface data model of the victim with the patterned injury on the bridge of the nose.*

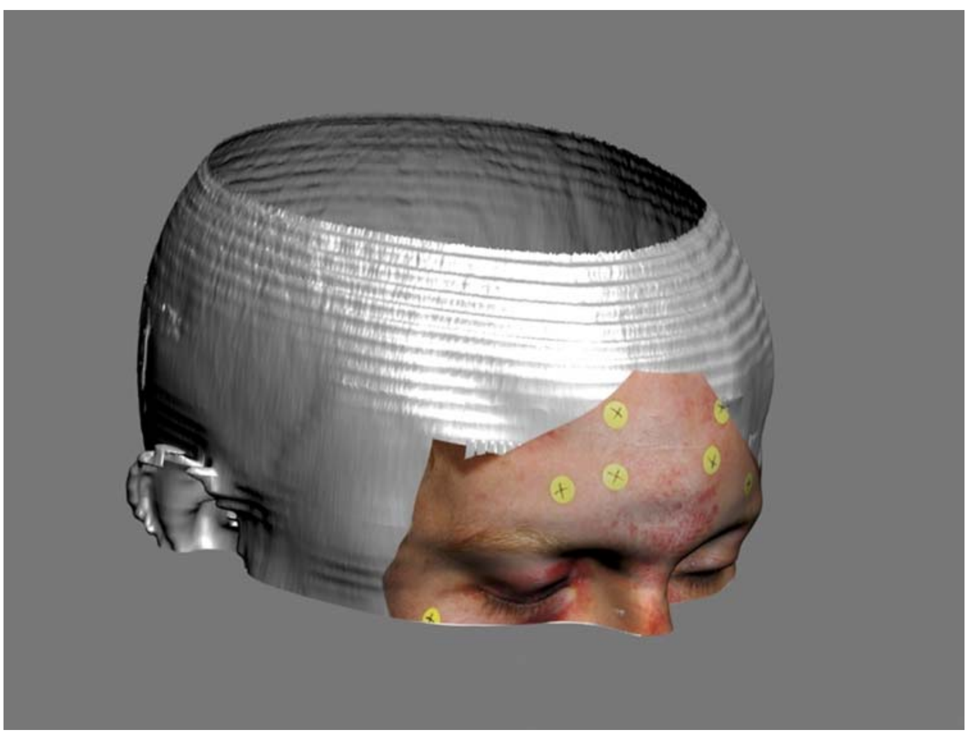


FIG. 6—*Case 1: Merging the color 3D data set of the face with the 3D CT skin reconstruction using "anatomical landmarks." In this case no radiological multi-modality markers were used, because the radiological examination was done for medical reasons prior to the forensic 3D documentation of the patterned injury.*

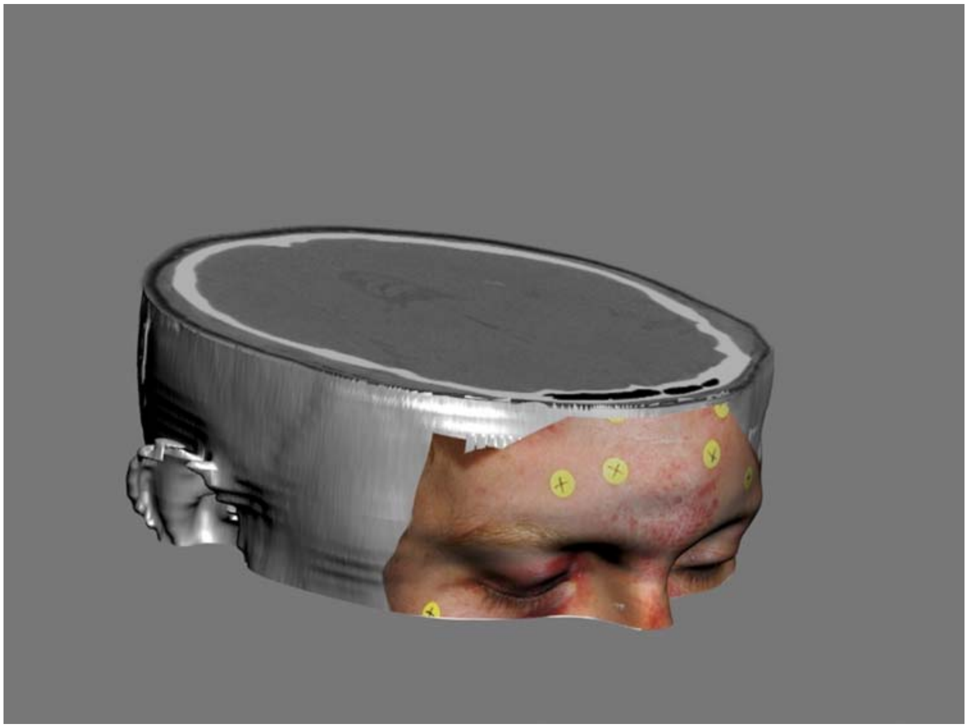


FIG. 7—*Case 1: Using a "virtual knife" it is possible to look at the internal 3D structures of the body, in this case for example the scalp, skull and brain.*

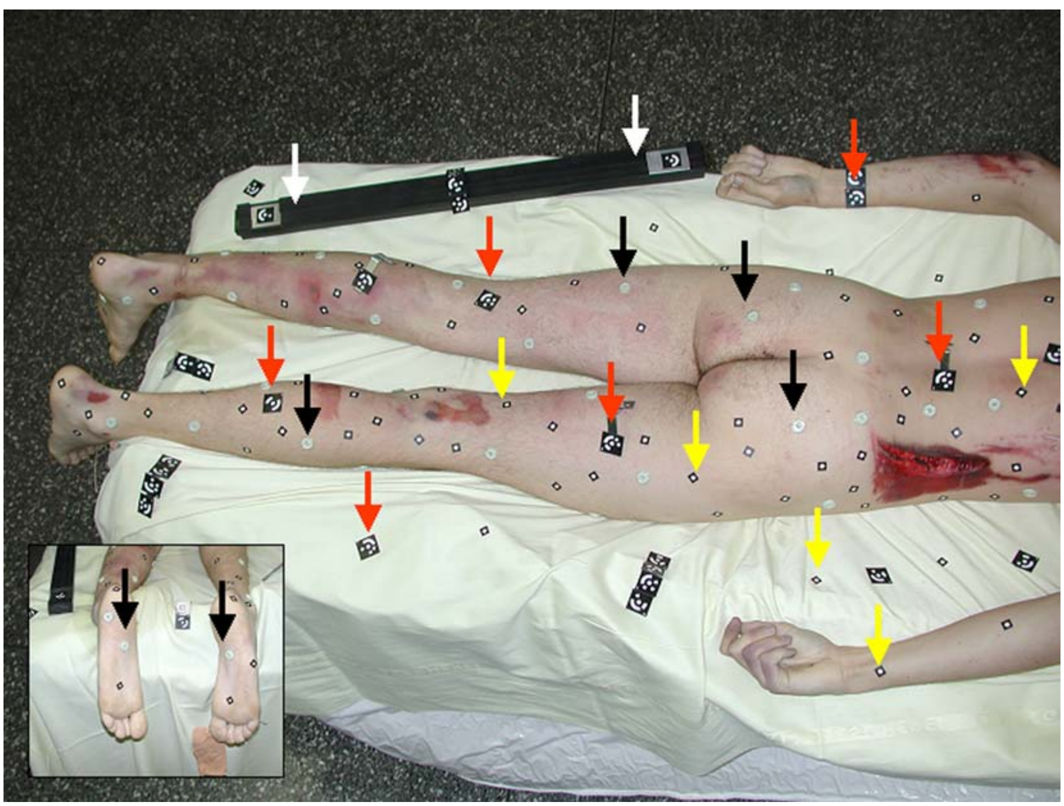


FIG. 8—*Case 2: Traffic accident victim with tools and markers used for the 3D documentation using the GOM TRITOP/ATOS II system:*

a) Reference scale (white arrows),
b) Coded reference circular markers (red arrows),
c) Non-coded markers (yellow arrows), and
d) Multimodality radiological markers (black arrows) for the merging process of surface and internal body data.

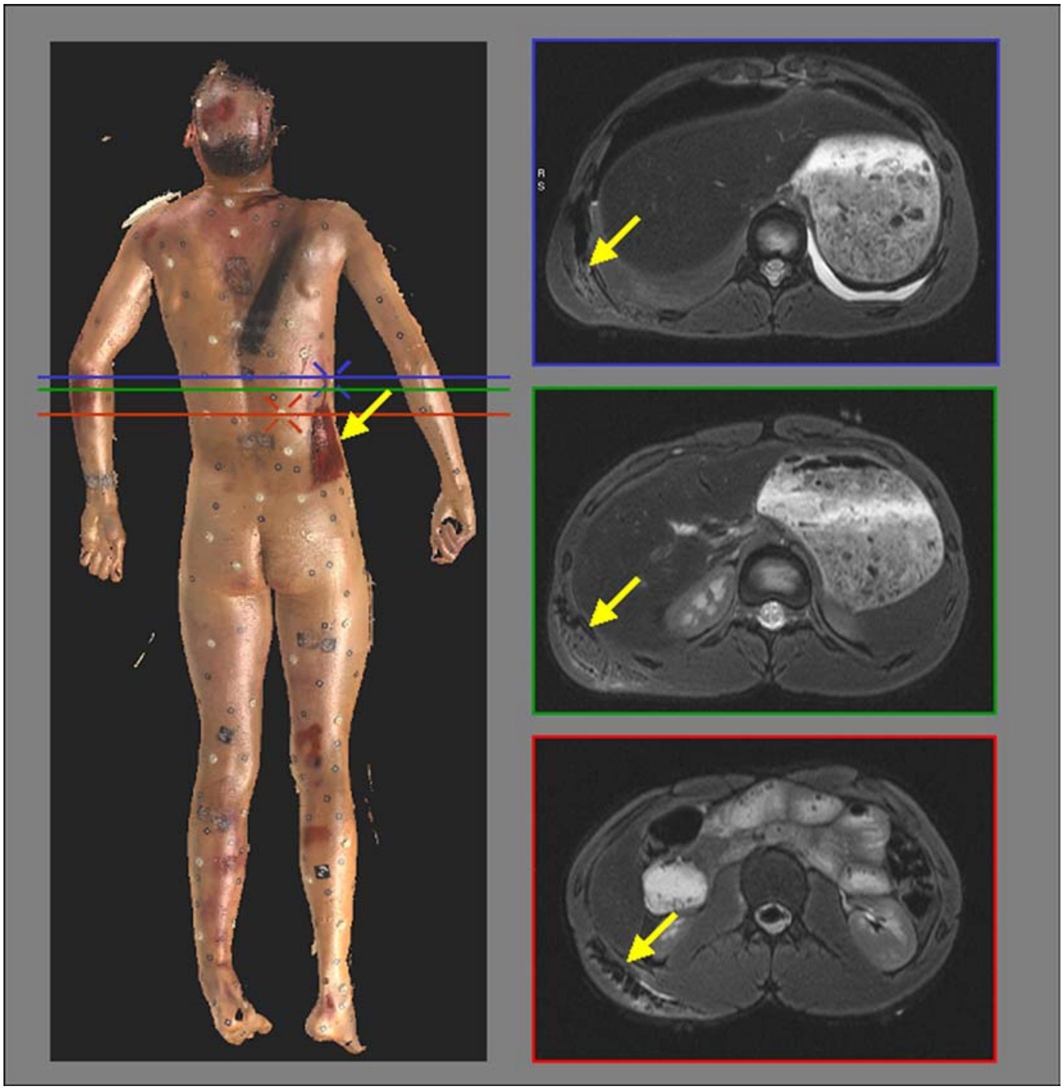


FIG. 9—*Case 2: Result of 3D body surface documentation of the forensic relevant injuries using the 3D optical scanner (left side). Corresponding MRI cross sections at different levels, demonstrating the soft injury lesion of the body wall beneath the patterned skin injury on the right body side (arrows).*

some key reference object points (see below) exist in three views. A minimum of three observations of some object points are required to create enough equations for the derivation of their position. For reference purposes a measurement unit has to be on some images.

To characterize the object points in the camera image, so called "reference targets" are used, which are applied onto the object's surface and/or the surrounding area. In photogrammetry, typically "circular markers/targets" are used, as they meet these criteria.

For the coordinate determination of the "reference targets" using the bundle adjustment, the commonly used "circular markers" have to be identified uniquely in the different images, to ensure that they can be related to each other. The reason for this, is to allow an automated identification and to eliminate a time consuming and erroneous manual procedure.

For the unique identification of the "circular markers" a special ring coding was developed for the TRITOP system: A rotation invariant identification of the reference targets is realized.

The disadvantage of these "coded circular marker" is the large area, which they cover in comparison to the additionally used "non-coded circular markers." It is therefore necessary to use less "coded reference circular markers" and to identify the remaining "non-coded markers" based upon their relationship to the coded ones for matching the scans.

After the markers are placed on the object of measurement, a digital metric camera is used to record images of the object from different directions, which are then transferred to the computer. The automatic calculation of the object coordinates is enabled by modern image processing algorithms and mathematical adjustment methods. Based on photogrammetric principles the 3D-coordinates of the reference markers and therefore the object, are determined automatically and with high accuracy by the TRITOP software.

Again in review, the steps of a photogrammetric measurement using the TRITOP system are:

- Calibration of the system and positioning of scale length as reference
- Applying some 'coded reference markers'
- Applying the 'non-coded markers'
- Taking images from different directions/angles/views
- Automatic processing of all images and automated calculation of the 3D coordinates of all markers using the TRITOP software.

FIG. 10—*Case 2: 3D optical body surface visualization of the patterned injury to the loin in a closer right oblique lateral view.*

- Transformation of the results into a distinct coordinate position.

Optical 3D Digitizing System ATOS (Advanced Topometric Sensor)—Traditionally, objects are scanned on coordinate measurement machines with tactile probes or laser scanning devices producing sections (4). This strategy is time-consuming and has great demands on the hardware but it provides measurement values with sufficient accuracy. A problem for all further post-processing steps is the low resolution of these data. Problems arise out of the immobility of such systems: Therefore, the requirements on an efficient digitizing system are high speed of the measurement, flexibility, mobility and ease of use.

The fringe projection sensor ATOS, a portable and easy to use system, is based on the triangulation principle: different fringe patterns are projected onto the object of measurement and are observed with two cameras. If the optical transformation equations are known, the 3D coordinates can be determined automatically and with a very high precision.

A projection unit and two CCD-cameras are integrated in the ATOS-sensor heads. The following versions are at this time available: The sensor can cover measurement volumes/objects from $35 \times 28 \times 28\,mm^3$ up to $1\,200 \times 960 \times 960\,mm^3$ for single views.

For the measurement of complex and large objects, reference markers are attached to the object prior to the documentation process. Their coordinates are determined by photogrammetry (see TRITOP system above). These markers define the object coordinate system in the particular object ranges.

During the ATOS measurement, fringes are projected on the object surface and recorded by the two CCD cameras. The single views are recorded with the sensors and are then transformed automatically, using the non-coded reference markers, into the TRITOP object coordinate system. When recording the views it is important that at least three reference "non-coded markers" are visible in each view for both cameras simultaneously (the bigger coded markers, which can cover a bigger area than the non coded ones, can be removed before the ATOS scanning). The 3D coordinates are determined in the sensor coordinate system and then transformed into

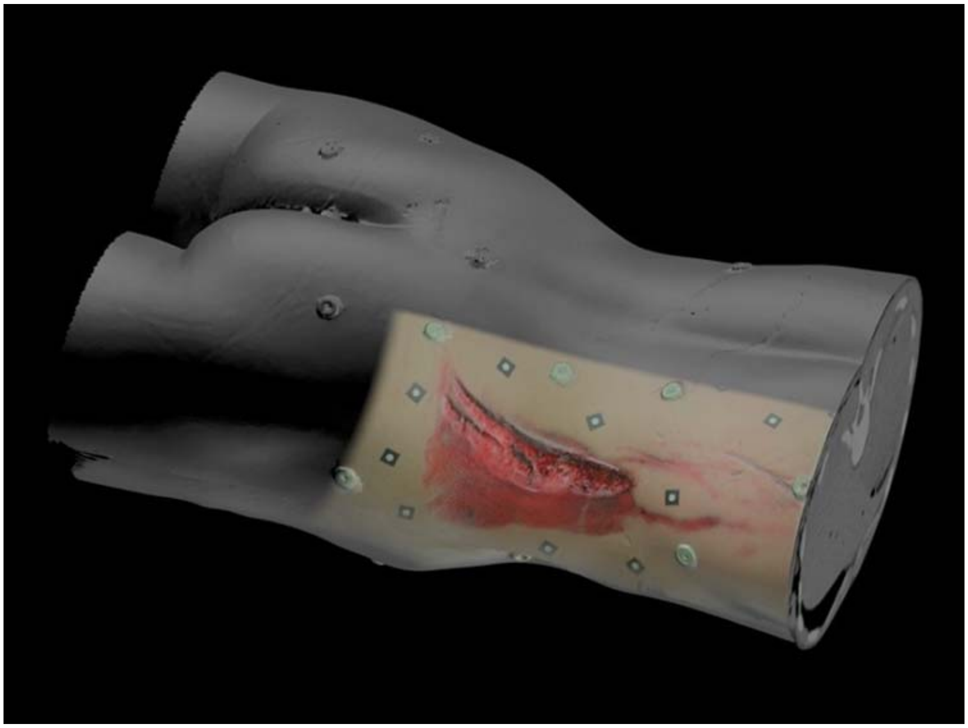


FIG. 11—*Case 2: Merging the data sets of surface scanning and of radiological scanning based on the radiological landmarks (Multi-Modality Markers). Note that it is possible to generate a 3D structure combining the optical surface with the radiological internal data (grey area). In contrast to the grey-scale information of CT and MRI, the surface information of optical scanning shows a higher precision and color information.*

the global coordinate system. The system checks for disturbances like ambient vibrations and automatically repeats the measurement if necessary. The ATOS II sensor head mounted on a tripod can be easily positioned around the object or the object can be placed on a rotation platform. For a body documentation of a deceased the scanner can also be installed in a framework over the autopsy table.

Finally, all the data of the TRITOP (including the color photos taken with the high resolution camera) and ATOS software are merged in a single data set, the result is a colored 3D data set.

The automatically fused and colored 3D TRITOP/ATOS data can then be exported as point clouds, sections or STL-data in 3D animation, modeling and rendering programs for further (3D) analysis.

Radiological Body Volume Documentation—Multi-Detector or Multi Slice Computed Tomography (MDCT/MSCT) and Magnetic Resonance Imaging (MRI) techniques are used to document the internal body morphology and/or trauma. This approach in the postmortem whole body examination has been evaluated up-to-date by our VIRTOPSY research group on more than 100 forensic cases (10,16).

Image Fusion/Merging the Data Sets—For the purpose of surface and radiological volume dataset fusion, additional “radiological landmarks” (Multi-Modality Markers for CT and/or MRI, IZI Medical Products, Baltimore, MD) were placed on the human bodies. These markers help to correlate the surface injuries with the underlying injuries which are visible in CT/MRI scanning. For measurement reasons we put at least one marker as reference point on the foot sole of a human body.

The above-mentioned markers are ideal, but in cases where these markers cannot be used, the surface and radiological data can be merged by using “anatomical landmarks,” such as a prominent skin or bone area for merging the surface and body internal data. The merging or fusion process is actually made by specific 3D software programs.

Until today the following methods have been validated by our research group to fully merge surface and radiological body internal data sets in 3D:

- The photogrammetric data set of a *smaller* injury can be merged with the radiological 3D skin/soft tissue reconstruction. It is useful to use visible radiological landmarks to connect the datasets together. If the wound location is in an anatomical stable region, a fusion process based on a geometric anatomical fusion is even possible without using radiological markers (Figs. 5–7).
- The 3D optical surface scan, acquired with the TRITOP/ATOS II system can be matched/merged with the radiological data set (Figs. 9–13). This approach is new and shows promise for the analysis of *large*, *wide spread or complex* injuries on the body surface or when whole body documentation is necessary.

Matching Analysis—Morphologic Imprint and Injury Causing Instrument—By the use of the 3D body surface documentation so-called patterned “morphologic fingerprints” can be documented and analyzed (11). Surface scanning creates morphologic data models of the injury *and* of the suspected injury-causing object (13). This allows the evaluation of a match between the injury and the object.

Animation—Purchasable software programs can animate the documented real data-based geo-metric findings on and within the body or object step by step or even by a movie clip. The skeletal system, documented radiologically, serves to animate the movements of the scanned person in a case-specific, biomechanically correct manner, because the exact location of the articulation point of all the joints is known (Fig. 16).

FIG. 12

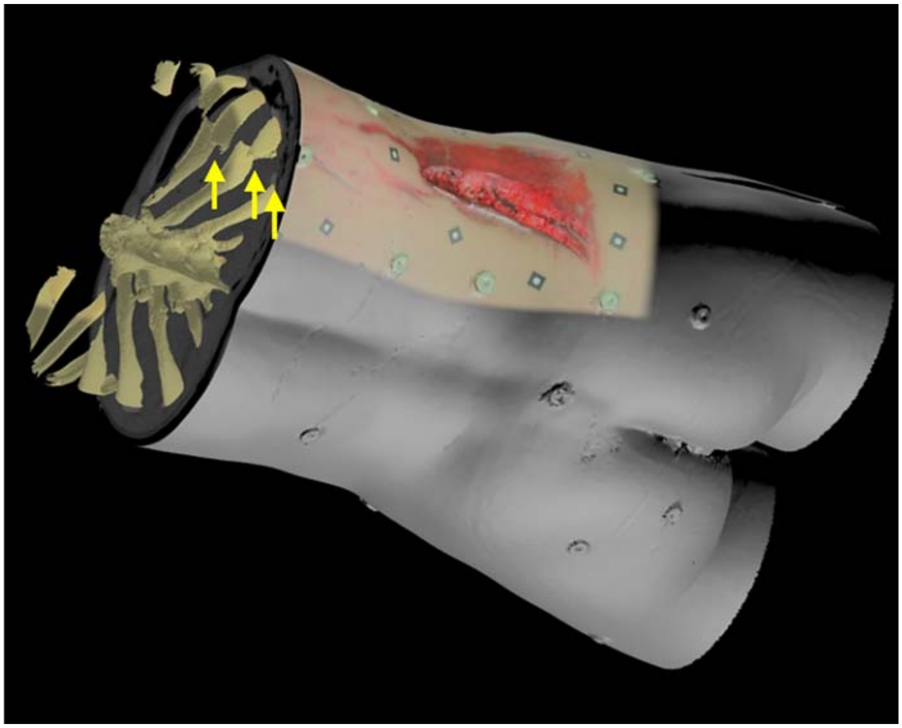
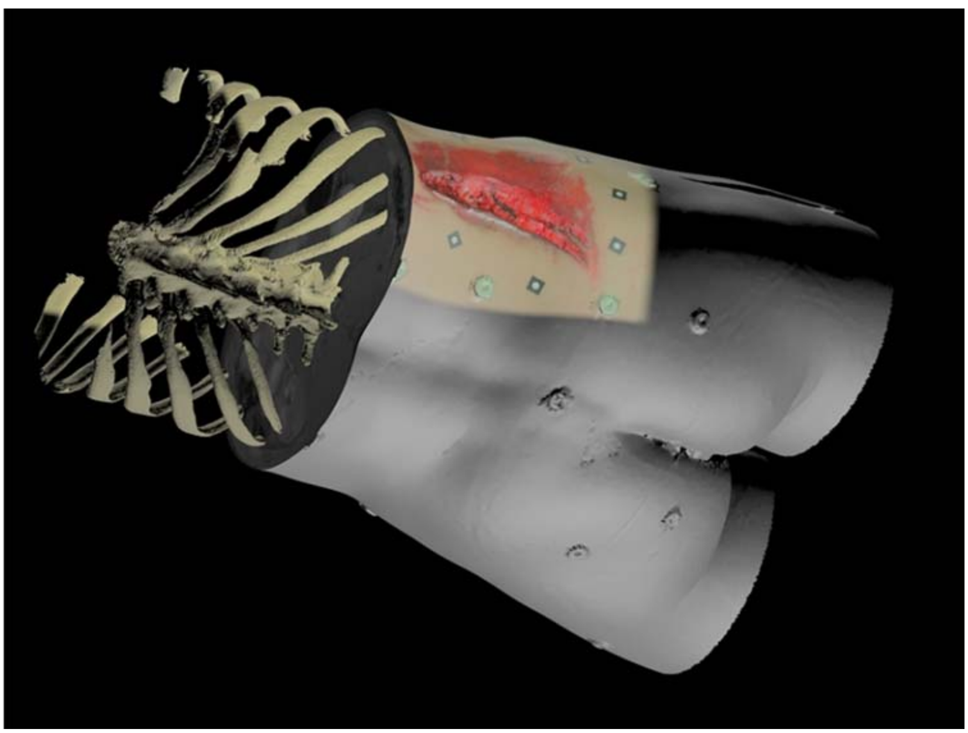


FIG. 13



FIGS. 12 and 13—*Case 2: Virtual knife: 3D virtual autopsy dataset showing not only the surface injury of Fig. 11 but progressively also underlying injuries, in this case fractures of the 8th and 9th ribs and soft tissue injury (arrows).*

Therefore, based on the acquired body surface and radiological body internal data (including the above mentioned skeletal system) a real 3D data based animation of the movement of persons is possible.

The above-mentioned techniques of subsequent data acquisition, fusion, reconstruction and animation are used to produce results of significant forensic impact.

Material

Two demonstrative forensic cases illustrate the documentation and the practical use of the new techniques:

- Case 1 (Figs. 1–7): Several persons had beaten a man. A shoe sole pattern in the face of the victim (Fig. 1) had to be linked

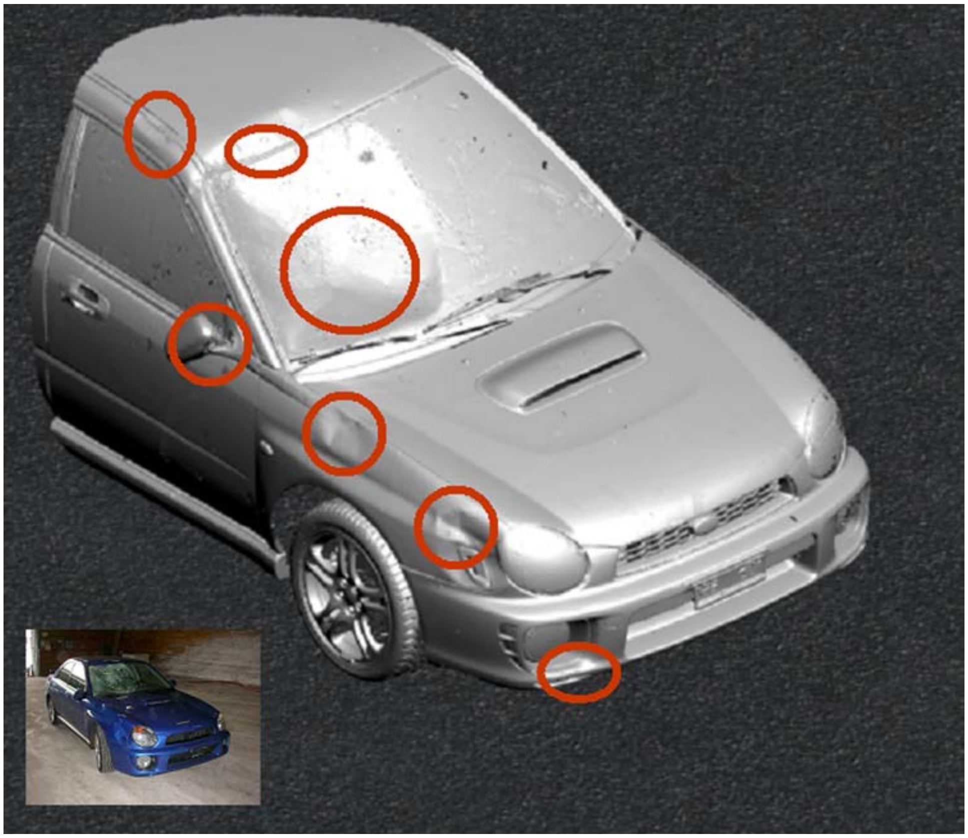


FIG. 14—*Case 2: Scanned 3D surface of the car involved in this accident. Note the classical damages in the front parts, the front window and the right rear view mirror.*

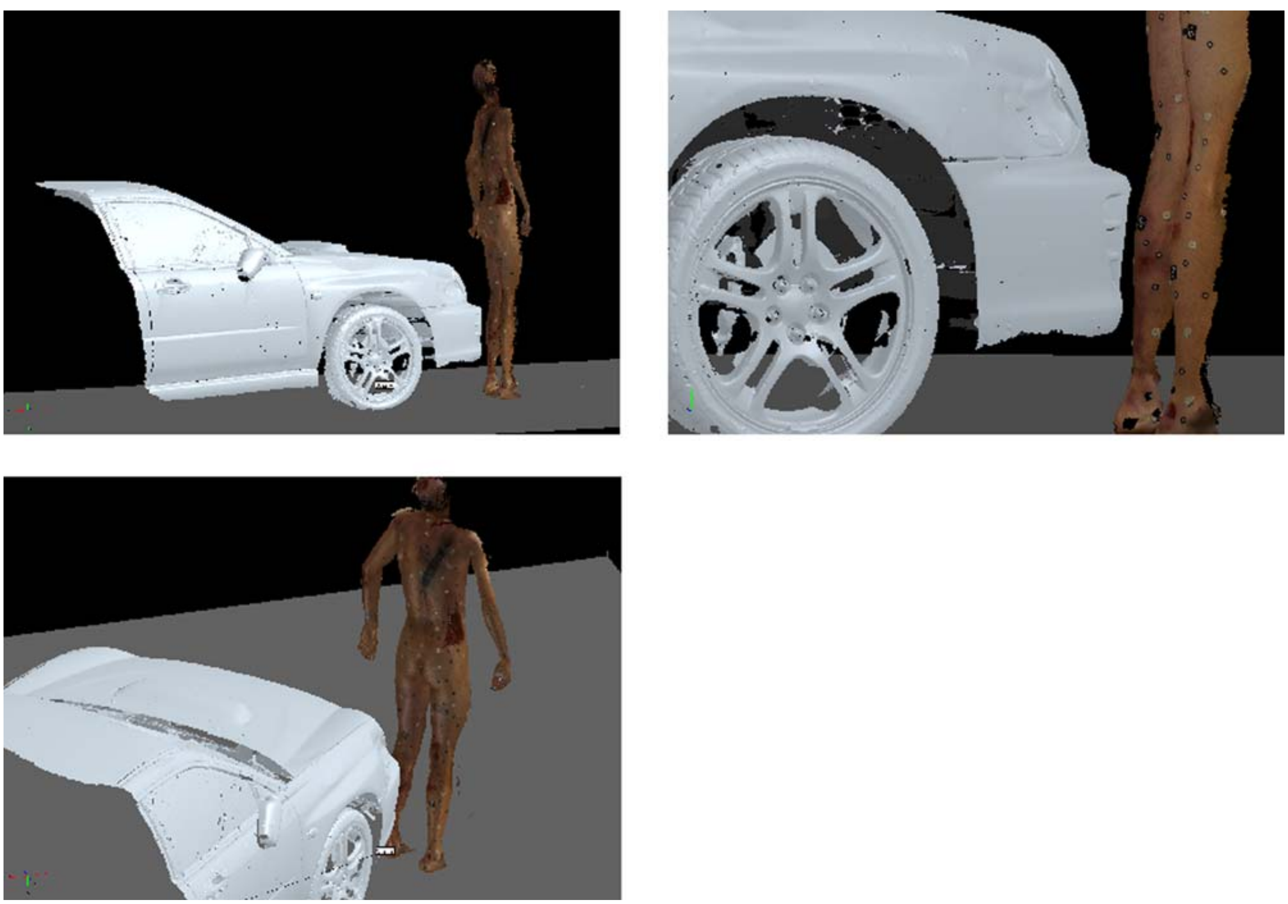


FIG. 15—*Case 2: Combined geo-metric 3D surface data sets of the vehicle and the body back in different views.*

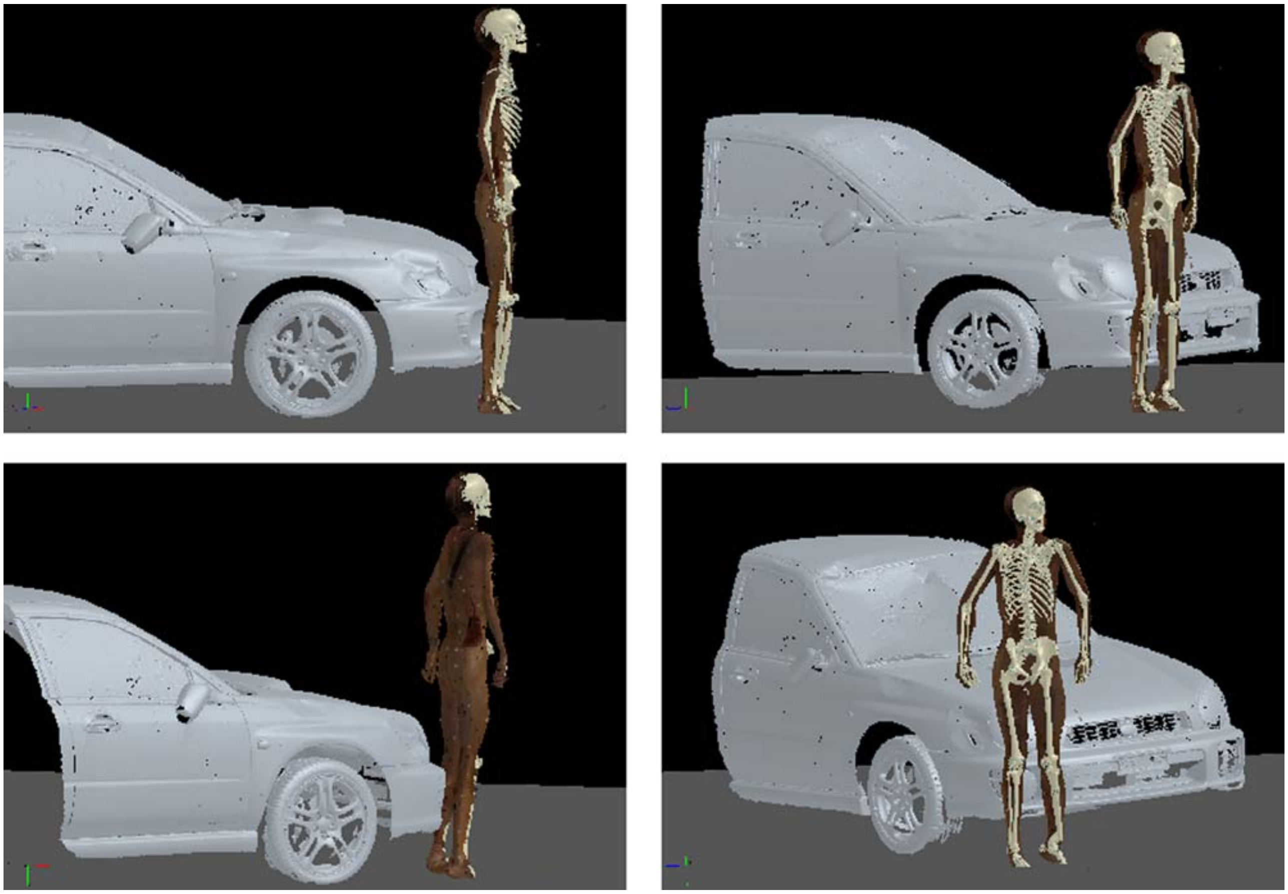


FIG. 16—*Case 2: In contrast to Fig. 15 implementation of the skeletal and joint information into the data set of the car allows for individual and correct (real data based) simulation of movements of the body.*

to the injury-causing shoe—one out of seven shoes belonging to seven suspected persons (Fig. 2). No DNA based evidence linking was possible. All the suspected shoes were 3D documented using the GOM system (Fig. 2). All skin injuries of forensic relevance were documented using the mentioned 3D technology. The beaten, living person underwent a CT scan in a hospital.

- Case 2 (Figs. 8–19): A pedestrian, who was fatally struck from the back by a car, had several abrasions on the backside of the body (Fig. 8). In the loin there was a deeper patterned laceration (Figs. 9–10). The car had several points of impression damage on the front and the roof (Fig. 14). The front glass was broken and the rear view mirror damaged. The vehicle was documented as well as the forensically relevant lesions on the back of the deceased, using the 3D optical scanner system. Because there was no relevant injury at the front part of the body, no anterior 3D surface data were acquired. Figure 8 shows a complete measurement setting with coded and non-coded markers, adapters and a scale bar.

A postmortem CT/MRI examination following the Virtopsy protocol was carried out on the deceased pedestrian (1,16).

Results

Based on the fusion of surface and radiological data the patterned injury structures could be linked to the injury causing instruments:

- Figures 4–7 are showing the 3D documentation and match analysis of patterned injury and suspected injury-causing shoe in Case 1.
- The documentation of Case 2 with merged 3D datasets, matching the patterned injury of the pedestrian with the injury-causing instrument, is demonstrated in Figs. 9–19.

Further detail description and information are mentioned in the legend of each figure.

Discussion

There are still some limitations of the classic documentation in forensic medicine especially if a 3D documentation is necessary. The medicolegal value of a forensic postmortem report is limited in terms of creating dimensionally accurate, individualized models of human topomorphology. In contrast to this fact, the imaging technology made enormous technological progress. Our goal was to implement and use this newer technology in forensic medicine to improve the plausibility and understandability of medical findings for the medical laymen in the court system.

This paper presents new approaches to a 3D geo-metric documentation of injuries on the body surface and internal injuries in living and deceased cases. Using modern imaging methods such as photogrammetry, optical surface and radiological CT/MRI scanning in combination a real 3D data-based individual documentation of the body surface and internal structures is achieved in a non-invasive and non-destructive manner (Fig. 20). Using the mentioned data

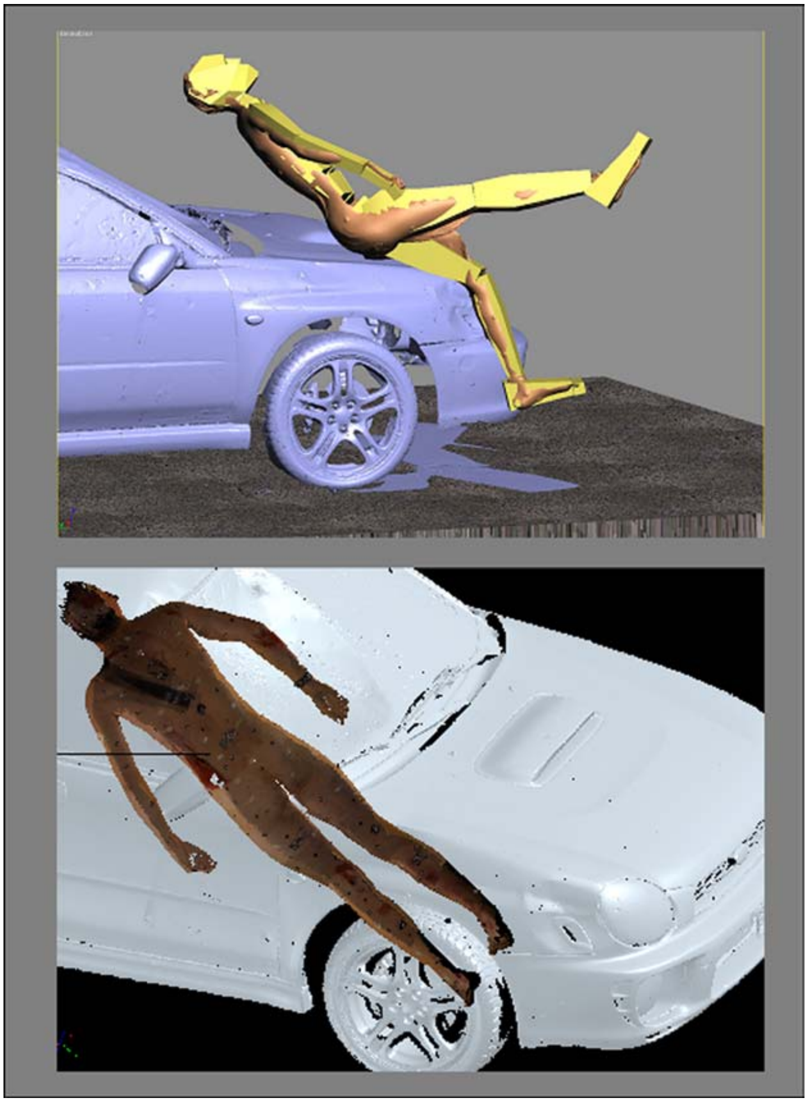


FIG. 17—*Case 2: Based on these geometric 3D data forensic analysis and reconstructive animation are possible. Investigative opinions can be analyzed, helping to develop an expert opinion.*

fusion and animation possibilities, it is possible to answer reconstructive questions of the dynamic development of patterned injuries (morphologic imprints) and to evaluate their matchability or linkability to suspected injury-causing instruments. These methods can be used in forensic medicine in living and deceased persons.

Real 3D data based documentation opens a new horizon for scientific reconstruction and for dynamic animation. It improves the quality of forensic science, as related to accuracy, precision, variability, and objectivity. In contrast to computer generated animations of computer games and the film industry, which are not real 3D based data, the added value of the Virtopsy approach may qualify this tool as visualization method of choice for the courtroom.

In contrast to recent published papers, this paper is the first study where 3D body surface information acquired by optical scanning is merged with the radiological data. Using these data including the specific rotation axes or points of all body joints, the real 3D data-based digital models can be moved to create dynamic forensic reconstructions. This allows the link of the surface information with real internal body structures, including joint geometry and defined motion.

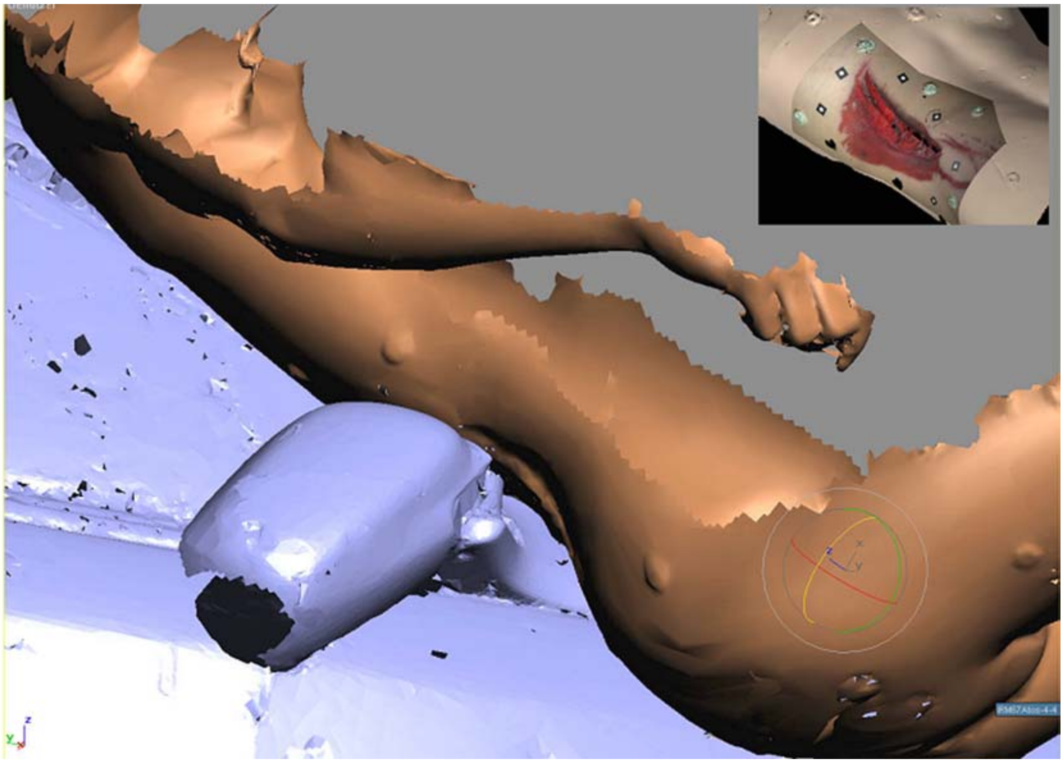
To our knowledge, the method of combined optical and radiological 3D scanning was used for the first time to document relevant forensic injuries of the human body in vehicle accidents. By this comprehensive documentation approach, individual real databased forensic analysis and animation were possible, linking pedestrian injury to vehicle deformation or damage.

Up to date animations were normally based on virtual dummies out of visualization programs and virtual car models. In contrast to this computer visualization approach, our approach is based on the real geo-metric surface and radiological internal data of the body of the victim.

In addition, these data allow conclusions to be drawn for automobile accident research, such as optimization of vehicle safety for pedestrians and passengers, or further development of crash dummies.

Detailed measurement and analysis of the deformation of the vehicle and comparison to an undamaged vehicle allows not only the determination of the impact points and areas but also enables the calculation of involved physical factors, such as the forces of impact and therefore the vehicle speed. Similar real 3D data based

FIG. 18



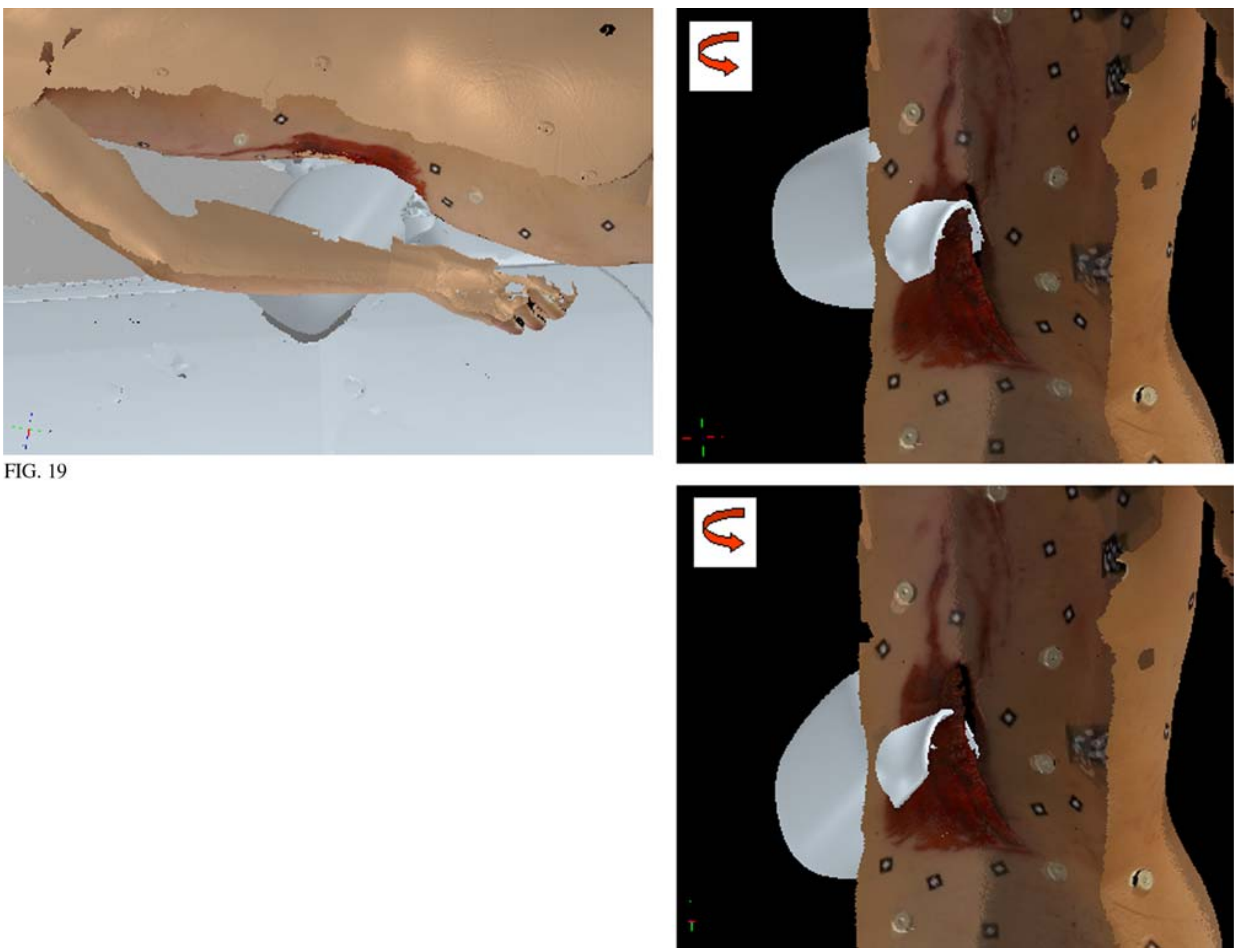


FIG. 19

FIGS. 18 and 19—*Case 2: Merged 3D data sets, matching the patterned injury with the injury causing instrument, in this case the side view mirror. Figure 19 is visualizing the matching in the so-called "inside-out look view."*

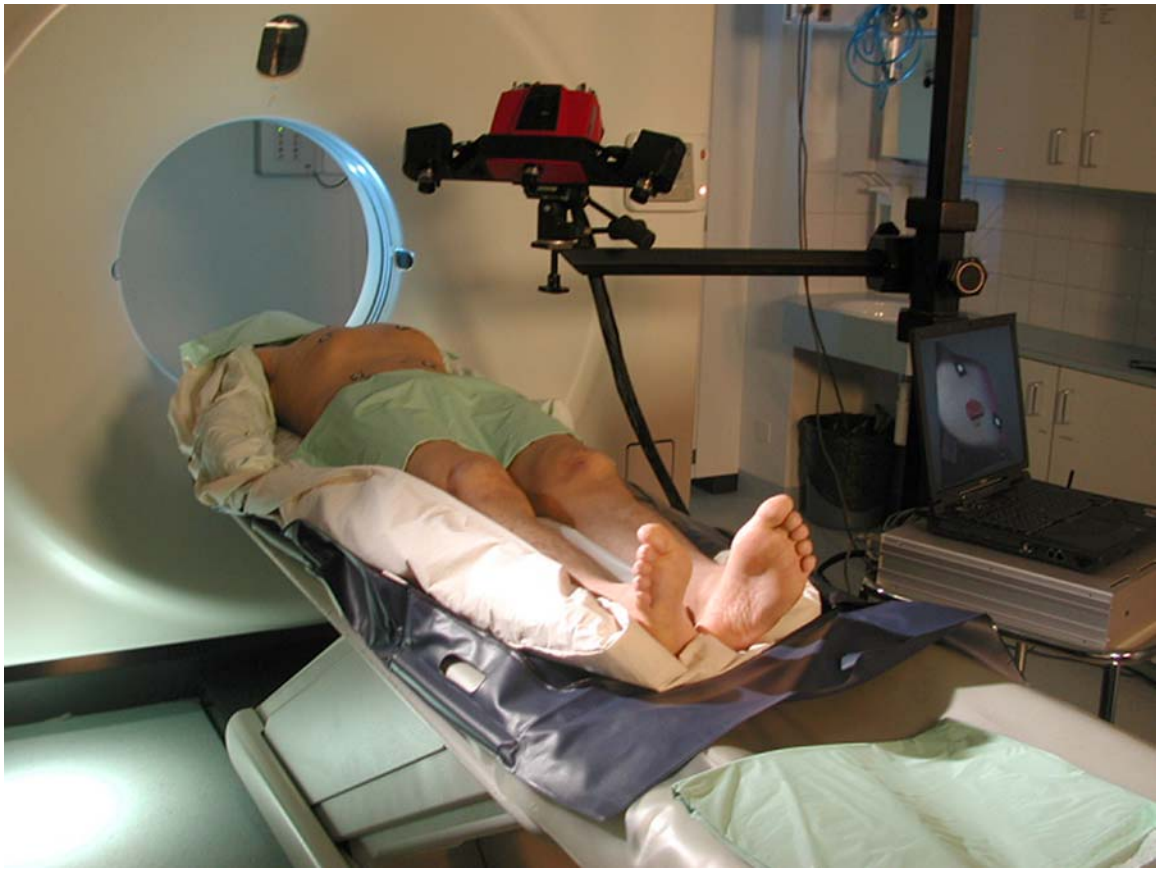


FIG. 20—*Modern virtual autopsy table: Set-up of the combined tools of 3D surface and radiology scanner.*

documentation and analysis can be made for passenger injuries and corresponding internal vehicle damage.

Surface Documentation

For body surface 3D documentation of living persons, it is necessary that the examined persons do not move during the scanning period. To document a body area, such as the face, the two-step photogrammetric 3D optical documentation approach takes some minutes. To scan bigger body or object areas, depending of the scan resolution, it takes more time. It is also possible to scan the body with clothes on, for example to demonstrate some defects of or blood on the clothes.

In addition, this study showed that a classic photogrammetric documentation is still useful for the documentation of smaller injuries, such as the case with a face injury due to a shoe. For larger and complex injuries and damages, such as the back of the victim involved in a vehicle accident, the use of a 3D optical scanner of high quality is becoming the state of the art. It is only a question of time until 3D optical or laser scanners are used to document even complex traffic as well as airplane accidents and crime scenes.

Radiological Documentation

The radiological datasets of living persons are normally acquired based on a medical indication. This is necessary because a CT examination is linked with some radiation exposure. This clinically acquired radiological data set can be used for further forensic analysis.

Postmortem radiological examination is not limited by radiation exposure and has the advantage, that the examination can be performed without movement artifacts and at a higher resolution than in a clinical diagnostic environment.

As shown in this study, for forensic purposes, a body surface documentation in color is useful because a radiological documentation, including 3D reconstruction, does not visualize discrete findings on the skin, such as detailed abrasions and other patterned injuries, in a high resolution. Therefore, acquiring 3D photogrammetric surface data based on optical scanning and merging them with 3D radiologic internal data is necessary.

Forensic animations gain more acceptance in courts as a valid form of demonstrative or illustrative evidence. Therefore, the limitation of an animation should be recognized: In contrast to the geo-metric 3D documentation, which is a real physical or substantive evidence, reconstructive scientific animation as a visualization tool presents a qualified investigative opinion and should not mislead the jury. An animation, thus, presents an interpretation of how an action may have happened and not the action itself. Our approach has the goal to use the 3D real databased documentation to add some relevant forensic value. Our opinion is that scientific animation has only evidence character or quality if the data are geo-metrically documented. To hold and improve forensic quality and standards, poor data documentation has to be eliminated, and evidence-based guidelines have to be defined.

The costs are currently higher using this technology, but over the time technology cost tends to steadily go down while the quality is improving, similar to the developments in computer or DNA technology. The information achieved through exhaustive 3D real data documentation and presented by well-used scientific animation is well worth the involved costs. High profile cases where the basic documentation was carried out improperly result in long court trials with increased costs, much higher than a good initial documentation.

The method of determining 3D coordinates for (accident) reconstruction delivers an accuracy in measurement that can hardly be achieved by the tools in general use nowadays. It is time-consuming and costly, but the added value is a real databased 3D documentation that can be easily stored and recovered for further analysis, even when the injury of a living person has healed or when the body of a deceased person has been destroyed by autopsy or putrefaction. In addition, it is cheaper to store the 3D data of a vehicle on a CD than to store the whole vehicle for a period of time. Based on these data an "investigative opinion" can be created. The final "expert opinion" can be drawn at some later time after having made conclusions based on all the circumstances and, when necessary, involving second opinions. Evaluation of the raw data can be carried out by a third party at any location, since the information is electronically stored and easily transferred.

Therefore, only high-level research based on geo-metric real data collected under validated guidelines, in combination with expert knowledge and experience can gain and hold evidential value in forensic sciences.

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