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Integrated computer-aided forensic case analysis, presentation, and documentation based on multimodal 3D data

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ABSTRACT

Three-dimensional (3D) crime scene documentation using 3D scanners and medical imaging modalities like computed tomography (CT) and magnetic resonance imaging (MRI) are increasingly applied in forensic casework. Together with digital photography, these modalities enable comprehensive and non-invasive recording of forensically relevant information regarding injuries/pathologies inside the body and on its surface. Furthermore, it is possible to capture traces and items at crime scenes. Such digitally secured evidence has the potential to similarly increase case understanding by forensic experts and non-experts in court.

Unlike photographs and 3D surface models, images from CT and MRI are not self-explanatory. Their interpretation and understanding requires radiological knowledge. Findings in tomography data must not only be revealed, but should also be jointly studied with all the 2D and 3D data available in order to clarify spatial interrelations and to optimally exploit the data at hand. This is technically challenging due to the heterogeneous data representations including volumetric data, polygonal 3D models, and images.

This paper presents a novel computer-aided forensic toolbox providing tools to support the analysis, documentation, annotation, and illustration of forensic cases using heterogeneous digital data. Conjoint visualization of data from different modalities in their native form and efficient tools to visually extract and emphasize findings help experts to reveal unrecognized correlations and thereby enhance their case understanding. Moreover, the 3D case illustrations created for case analysis represent an efficient means to convey the insights gained from case analysis to forensic non-experts involved in court proceedings like jurists and laymen. The capability of the presented approach in the context of case analysis, its potential to speed up legal procedures and to ultimately enhance legal certainty is demonstrated by introducing a number of representative forensic cases.

1. Introduction

1.1. Forensic case analysis using 3D data

Digital information has proven to be highly useful for the reconstruction of crime or accident scenes as well as for the documentation of forensic findings. Forensic investigations have made use of digital photography for around two decades. Images can be further exploited to reconstruct 3D surface models based on computer-aided photogrammetric methods. 3D scanners are increasingly used to document the three-dimensional geometry of crime scenes, items and humans.

Additionally, recent years have brought an increasing interest in 3D medical imaging modalities like computed tomography (CT) and magnetic resonance imaging (MRI) [1–4]. These modalities are now on the cusp of routine use in legal medicine. The additional benefit of CT and MRI over images and 3D surface reconstruction is

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their ability to record and thereby preserve forensic information from the inside of victims, such as the spatial configuration of findings, which inevitably gets destroyed in autopsies. MRI data are the only non-invasive source of information from inside the body in living victims. In post mortem cases, CT and MRI are both a valuable tool to complement autopsies by preserving spatial interrelations of findings. However, CT and MRI are limited to visually perceptible sensations and therefore will not replace autopsies unless evidence from olfactory and tactile sensations may be neglected.

Generally speaking, 3D imaging modalities help to get a more complete impression of a forensic case. Evidence invisible by sole investigation from the outside becomes readily available for case analysis.

1.2. General requirements

Tomography data has the potential to be extremely helpful in the forensic context, but there are several problems exacerbating its daily use. Unlike photographs, understanding X-ray computed tomography or magnetic resonance tomography data requires radiological knowledge and experience in their interpretation. Radiologists typically read the data by browsing through stacks of 2D slices in orthogonal planes using a radiological workstation and radiology software designed for clinical investigations. Such tools assume that the main problem is the detection and classification of anomalies in the data, as required for clinical diagnosis. Furthermore, it is assumed that users are radiology experts, who are able to build up a mental 3D model of the anatomy. Functionality to generate visually appealing 3D visualizations based on direct volume rendering techniques (DVR) [5] is typically included. However, it is limited, since the focus is laid on clinical questions, which rarely demanded complex 3D visualizations.

Forensic questions differ from the clinical view on tomography data. In the clinical context, radiologists are trained to detect and assess pathological findings with the goal to find or optimize treatment strategies. Forensic case analysis is interested in findings supporting case understanding. This includes everything that can explain the cause of death, injuries and the course of events. Such findings are not limited to clinically relevant ones. In addition, lesions such as haematomas, bruises, air/gas inclusions in atypical regions and other findings, which are mostly irrelevant for medical treatment, demand attention. Another fundamental difference to clinical diagnostics is the fact that the spatial distribution of findings is at least as important as their occurrence. Spatial relationships between findings are valuable clues for forensic event reconstruction, to e.g. determine direction of a force application. Therefore, visualization tools depicting all the structures of interest and aiding the understanding of 3D properties, such as the spatial locations, distances, and shapes of individual findings are of utmost importance. In some cases lesions need to be explicitly extracted from the data to obtain quantitative indices. This requires image analysis functionality to perform image segmentation, i.e. the separation of semantically meaningful structures from the rest of the dataset. These operations are not optimally supported by standard radiology software.

Forensic case analysis should include as many pieces of evidence as possible. They must be jointly studied to maximize the probability to recognize complex connections between findings. Therefore, a computer-aided case analysis tool should ideally support data from all sources of digital information available. Integrated visualization techniques offering conjoint display of multiple spatially overlapping 3D datasets and seamless inclusion of 2D images and 3D surface models are a key requirement. Joint visualization can greatly help forensic experts to study spatial interrelations, draw conclusions, and thereby help to reconstruct the course of events. However, this type of visualization is not possible with current radiology software. Therefore, tools which support forensic case analysis based on interactive processing and joint visualization of heterogeneous 3D datasets are highly desirable.

After successful case analysis, the information gained needs to be conveyed to the court scenario, where persons without medical background need to understand the findings and the course of events. Illustrations composed of all the data used in the analysis stage are a good starting point. However, for the target audience further explanation might be required. Ideally, images and videos presented in court should be self-explanatory to great extent. Therefore, a forensic software toolkit should also include functionality to point out and highlight particular case relevant findings and features to illustrate their interpretation by the expert. In case this is still not sufficient, animations and text or image annotations may be needed.

1.3. Data characteristics

CT has established itself as the most frequently used 3D imaging modality in post mortem forensic imaging. Reasons include high resolution and volume coverage, low scan costs, comprehensive availability of scanners, and very importantly, the fact that radiation exposure is irrelevant for post mortem examinations. CT is especially well suited for cases involving bone injuries or gas inclusions. On the downside, soft tissue contrast is limited, and artefacts due to metal objects may occur. MRI excels in soft tissue related questions. Since MRI is free of ionizing radiation, it is also the ideal 3D modality for clinical-forensic examinations of the living. Forensic questions often benefit from MRI protocols tailored to the task at hand or the modification of existing ones to better depict forensically relevant information, like haematoma [6]. MRI images share the property of good contrast for tissues in question, but they suffer from signal inhomogeneities and geometric distortions. These issues complicate 3D visualization. Scanning time restrictions and image quality requirements often lead to small scan regions around injuries in question. While this is acceptable for case analysis by forensic experts with anatomical knowledge, jurists and laymen in court might fail to understand or even misunderstand the case, if not provided with illustrations showing sufficient anatomical context. Therefore, computer-aided tools to visually relate spatially restricted scan data to their anatomical context are needed.

1.4. Tool overview

In this work, we present a novel software tool for forensic case analysis and illustration based on almost any type of 3D data and other sources of digital information available. The tool supports the whole case work-flow from analysis to presentation in court by providing three-dimensional visualizations and illustrations of the data at hand at any time. This is facilitated based on co-joint three-dimensional display of data from different sources, including but not limited to volumetric 3D CT or MRI datasets, 3D surface models, and 2D images. Furthermore, the data can be interactively conditioned and processed to reveal and visualize forensically relevant details and to obtain quantitative indices. Joint visualization of multiple datasets allows to study spatial interrelations of findings. Case presentation is further aided by annotation functionality based on text labels, images and animations to explain individual findings in more detail and to illustrate the experts' interpretation. Results can be exported as largely self-explanatory illustrations and video clips suitable for presentation of the forensic findings in court.

2. Related work

Seminal work by March et al. aims at the visualization of forensic pathology data using standard 3D modelling software and freely available 3D anatomical models, which were adapted to represent the case appropriately. Since no case specific 3D data is used, relevant information has to be manually modelled for case analysis and presentation [7].

The utility of CT data in the forensic context has been extensively studied. The *Virtopsy* project started by a Swiss group around *Dirnhofer* and *Thali* resulted in numerous publications covering the use of CT scans for forensic questions and reconstruction [8]. Villa et al. extract 3D surfaces of bones from CT data, and manually rearrange and animate them to better illustrate spatial relationships in forensic scenarios [9]. In [10] they also include 3D surface models from photogrammetric reconstruction, which provide colour information from the body surface. The radiation exposure in CT and the widespread availability of high resolution MRI devices paved the way for forensic use of MRI, especially for clinical-forensic questions. The work by Ruder et al. gives an overview on this topic [11]. As an example, the study in [12] discusses the utility of full body MRI scans for post mortem situations.

The applicability of CT and MRI in the forensic context is indisputable and has been studied in many publications, while software connected to their use in the forensic context has hardly been investigated. One exception are visualization techniques and hardware setups for virtual autopsies, which require interactive rendering techniques for the visual exploration of full body CT and MRI scans. Due to the massive amounts of data this is computationally more challenging than the visualization of typical clinical datasets [2]. Besides computational complexity, 3D visualization of CT data in the forensic context requires functionality to visually depict forensically relevant information. So called *transfer functions* are used to map dataset values to visual properties like colour and transparency. Due to the global influence of such a classification, transfer functions are conceptually suboptimal to emphasize local details in the datasets [5]. Work presented in [13] presents one possible solution to overcome the problem. An overview of visualization techniques in post mortem imaging can be found in [14], which also includes work towards a hardware setup for virtual autopsies using a large scale touch display. Multi-touch interaction suggests a more intuitive way of how to interact with the 3D data based on gestures rather than a regular PC/mouse setup [15]. More recently, augmented reality CT and MRI data have been superimposed with corpses during autopsies [16].

Numerous publications report on the use of 3D scanners like hand scanners, laser scanners, and photogrammetry methods to obtain 3D surface models of victims [17], items and the overall crime scene. Surface data are especially useful for reconstructing the course of events based on, e.g. the trace geometry and spatial interrelations between traces, which such scanners may capture. 3D surface models also have the potential to prove or disapprove subjects' statements or hypotheses by matching quantitative measures with, e.g. actions possible or plausible in the physical world [18–20]. Surface models can be used to match injuries with real world items to identify weapons or tools involved. Unfortunately, 3D scanning using common scanners requires a significant amount of time and/or preprocessing. Together with high costs, this still impairs 3D surface documentation in forensic routine. Recent advances in 3D scan sensor technology driven by the entertainment industry leading to very cheap sensors and new 3D reconstruction algorithm [21,22] are about to ease 3D model acquisition, and will inevitably lead to increased availability of 3D surface models. Consequently, this will raise the need for software tools supporting their joint analysis with radiological and other data.

3. Computer-aided forensic case analysis – status quo

Combining tomography data, 3D surface scans and 2D images to jointly study the findings present in the respective modalities can lead to new insights. After careful registration [23], conjoint visualization of interior findings from tomography data and exterior ones visible in 3D scans or images allows to study their spatial interrelations. Items like weapons and the location of traces can be studied in their context. Joint analysis also serves result dissemination. Integrated case visualizations can support written expert opinions in court, which ideally requires comprehensive illustration of the injuries, and a coherent presentation and description of the assumed sequence of events leading to them. Altogether such a work flow can improve the quality of court proceedings and is intended to lead to a higher degree of legal certainty.

In [18] 3D modelling and radiology software are used to analyse and illustrate forensic cases using both CT and surface scan data. As stated in their paper, case analysis is a time-consuming procedure using such tools, by far exceeding the time needed for CT and surface scan acquisition. This is due to the lack of tailor-made software tools supporting common tasks in case analysis. In [14] the need to combine the different views radiologists and forensic experts have on the data is emphasized. Forensic aspects must be actively supported by the visualization tools used, which is currently infeasible for data from different modalities.

At the moment software tools used for forensic case analysis, preparation and documentation include software on radiological workstations to inspect tomography data, digital content creation software to reconstruct scenes and generate illustrations based on 3D surface data, and special software tools offered by e.g. vendors of laser scanners to inspect and post-process surface scan data. These tools are designed for their originally intended tasks and target user groups. Functionality and the user interfaces match the intended application domains – modifications for forensic case analysis are limited or not present at all. As a consequence, the overall work flow is suboptimal. Missing functionality must be substituted using additional software tools for data conversion and registration. Data conversion often degrades the original data. Florid user interfaces may require additional trained personnel.

There are a few software tools supporting conjoint visualization of volume and surface data like *VG Studio Max*,[1] which is mainly used in material science, and *Voxler*,[2] which is often used in geosciences. Again, target domain specific properties and the lack of tailor made functionality required for complex forensic questions limit their utility for forensic case analysis.

The ultimate goal – intuitive and flexible joint analysis of all data sources in their native form – remains impossible, which further emphasizes the need for a dedicated integrated case analysis tool. At the moment there is no software available, which features integrated data analysis, documentation and illustration in the forensic context.

4. Methods

In this work, we present a novel software framework for forensic case analysis including tools with the following properties:

- Support for all necessary steps from raw data analysis over visual analysis and documentation to in-court presentations.

[1] https://www.volumegraphics.com/en/products/vgstudio-max.html.
[2] http://www.goldensoftware.com/products/voxler.

- Integrated visualization of volumetric and surface data.
- Efficient tools to visually depict relevant findings.
- Support for case documentation based on images, text labels and geometrical markup.
- Tools to quantify structures and distances in 3D datasets.
- Intuitive multi-touch interaction with 3D data for scene navigation and editing.
- Focus on target users: forensic experts and radiologists.

The proposed approach conceptually follows the idea to provide a software tool for 3D data viewing and processing, which offers analogical functionality to software for image editing and graphics based on 2D digital images and drawings. The additional order of magnitude in terms of computational complexity, storage requirements, and degrees of freedom in navigation added by the third dimension is hidden from the user by using a combination of efficient algorithms, powerful hardware, and intuitive interaction design, leading to unprecedented possibilities to analyse and illustrate forensic data.

4.1. Forensic software toolkit overview

4.1.1. Data representation

The case analysis software toolkit was designed with common tasks in forensic case analysis and the different sources of 3D data in mind. In general there are two types of 3D data: surface data and volume data.

Surface data is often available in the form of polyhedral 3D models, so called *meshes*. This form of data representation is used in computer aided design (CAD), digital content creation (DCC) and computer games. Meshes are also the final result of 3D model reconstruction based on raw 3D data from 3D scanners or photogrammetry, so called *point clouds*. Such meshes are primarily surface geometry representations, but they often also include colour information. The presented software supports most common mesh file formats like OBJ, 3DS, and WRL.

3D volume data stores measurements from small portions (*voxels*) within the overall scan volume and is generally available from any tomography device, like CT and MRI. The software supports volume data based on the DICOM standard and all volume data file formats supported by the *ITK* library.[3] Data can either be read from files, or directly from a PACS archive, which ensures good integration with the existing IT infrastructure in most institutions.

Furthermore digital images, which are typically taken at crime- and accident scenes as well as during autopsies, are supported, mainly for documentation in the absence of 3D data. Integration of medical 2D images such as digital radiographs is supported as well.

4.1.2. Scene representation and editing

The datasets to study a particular case are managed using a *data repository*. Datasets of any supported type can be loaded into or removed from this repository at any time.

For case analysis, individual datasets from the repository are used to define *objects*. The reconstruction of a case typically involves multiple objects forming a *scene*.

Objects are defined by four main properties:

- **Geometry:** Arbitrary 3D surface model with modifiable colour, texture and transparency information.
- **Volume:** Volumetric dataset such as a CT or an MRI scan.
- **Transfer function:** The transfer function maps the scalar dataset values to colour and opacity values defining the visual appearance of the data.
- **Location:** The location attribute defines the position and orientation of an object in the scene coordinate system.

Fig. 1 gives an overview of the scene object model including an example. The location is the only mandatory attribute, while geometry and volume/transfer function are mutually optional. If just a volume and a transfer function are specified, an object is visualized using DVR algorithms. Pure geometry objects are visualized using surface rendering techniques as used in 3D computer games. In the presence of both, the geometry defines the portion of volume to be visualized. Volumes, geometries and transfer functions can be reused in arbitrary combinations and multiple scene objects. This functionality constitutes the basis of the flexible visualization engine used in the presented forensic case analysis tool. By changing the location properties of individual objects the rendering algorithm can generate conjoint views of multiple CT and MRI datasets. It is also possible to show multiple copies of a single dataset rendered next to each other using different transfer functions. Moreover, conjoint visualization of transparent surface data and volume datasets is possible. Clipping using geometry data can be exploited to, e.g. locally emphasize findings in a very flexible way (see Section 4.2.1). This concept and its implementation using modern graphics hardware is the key to achieve the advanced visualization functionality needed for forensic case analysis tasks.

The scenes needed to analyse and illustrate forensic cases are prepared using a scene object editor, which allows to pull in geometry data, volumes and transfer functions from the repository in a drag and drop fashion. Predefined transfer functions can be customized using an editor, in order to perfectly depict the structures of interest. Once the object description is complete, objects are automatically displayed.

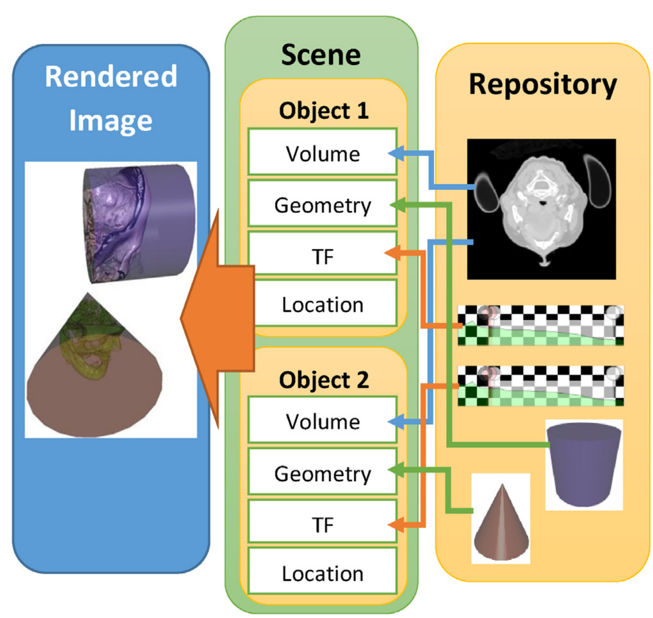


Fig. 1. A scene may consists of multiple objects. Individual scene objects are described by one or more out of four main attributes: a volume, the transfer function needed for visualization, a polyhedral model used as clipping geometry, and a location. Data attributes may be picked from the repository. The rendering engine implicitly performs an intersection of the dataset and the polyhedral object leading to the visualization result on the left.

[3] https://itk.org.

4.2. Visual data inspection

3D visual inspection can be performed by navigating through the scene using intuitive multi-touch interaction techniques or the mouse. A supplementary 2D view based on cross-sectional slices is available for high precision tasks like the detailed delineations of forensically relevant structures. Spatial relationships between scene objects can be altered using similar techniques. Changes are automatically stored in the location attribute of the affected objects. Objects can be freely and independently moved around in 3D space. Furthermore, independent movement of geometry and volume of a single object is possible. This can for example be used to search for bone injuries corresponding to surface lesions as shown in Fig. 3.

Cutting objects such as planes through volumetric data visualizing the cut data in analogy to 2D views on radiology workstations can be automatically generated at any location in space using the scene editor. This is particularly useful to depict small details and to verify the results of e.g. segmentation algorithms (see Section 4.2.2). Cutting planes can be synchronized with 2D views for convenience.

4.2.1. Visual processing

Efficient techniques to visually depict forensically relevant portions of the data are a key feature for efficient computer aided forensic case analysis. Their realization requires tools to intuitively select the desired regions and visualization techniques, e.g. to restrict volume rendering to the selected region of the dataset, or *focus and context* visualization techniques to emphasize the selected data region(s).

The selection tools provided by the proposed system are three-dimensional analogues of selection tools in 2D image processing software, where e.g. rectangular regions are used to crop or cut out portions of the image or to specify regions for enhancement filters. Their 3D counterparts are geometric primitives, like cuboids or spheres, which can be interactively placed in 3D space or on opaque surfaces of the visualized dataset. Cutting functionality is achieved by assigning such primitives to the geometry property of scene objects (see Fig. 3).

Space carving is a more flexible way to specify such 3D regions. It is based on 2D contours drawn on the screen, which are extruded along the viewing direction to define 3D polyhedra (see Fig. 2).

Multiple geometric primitives and space carving stages can be combined using Boolean operations [24], which allows to further refine selection region geometry to better depict structures of interest or to cut away portions of the dataset obstructing the view on important findings. Selection geometry can be inverted resulting in surface models representing the dataset region outside the selection geometry. This allows to create focus and context illustrations by creating scene objects based on the same volume dataset, complementary geometry, and different transfer functions for the respective dataset portions. Fig. 3 shows an example of focus and context visualization functionality illustrating its value for computer-aided forensic case analysis.

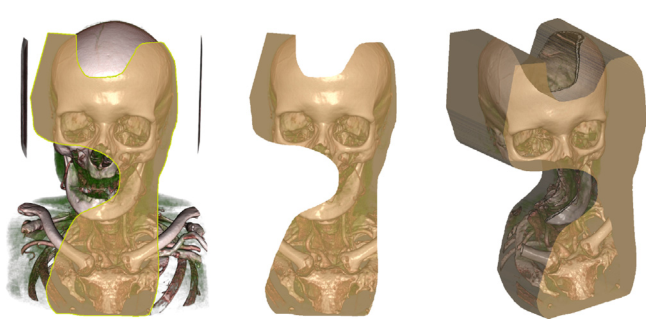


Fig. 2. Space carving example showing the polyhedron generated by extruding the area (orange) enclosed by a contour (yellow) drawn on the screen along the viewing direction (left). Intersection with the CT dataset allows to restrict rendering to regions inside (or outside) the geometric primitive (middle). Changing the view direction reveals its 3D nature and the resulting clipped dataset (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

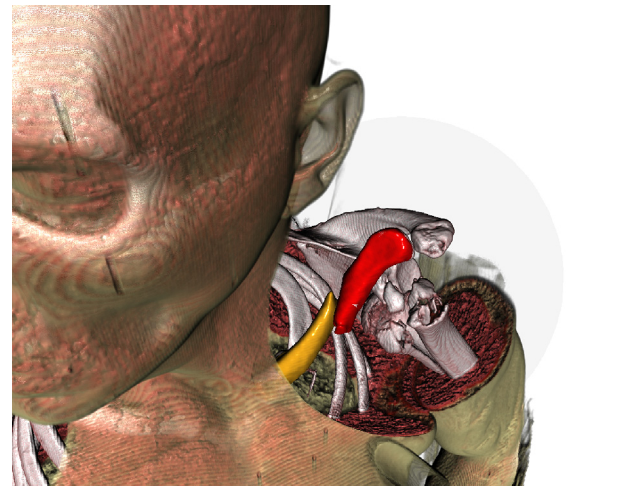


Fig. 3. Focus and context visualization example: correspondences between superficial lesion and inner injuries can be studied using multiple scene objects and different transfer functions. Here the broken clavicle was separated from the rest of the dataset using a locally applied transfer function. A spherical shape defines the application domain for a transfer function hiding soft tissue dataset portions. For identification of correspondences between superficial and inner lesions it can be interactively moved through the data. It this example, the two clavicle fragments were segmented using techniques described in Section 4.2.2. This optional step further emphasizes the relevant dataset regions.

Explosion diagrams are another variety of focus and context techniques. In the proposed forensic case analysis software framework, such illustrations can be produced by splitting a volume dataset into multiple complementary but individually displaced parts, as shown in Fig. 5.

Visual processing and focus and context visualization techniques contribute to computer aided case analysis in two ways:

1. **Case understanding by experts:** They allow forensic experts to jointly study dataset features, which cannot be visually separated or depicted by transfer functions at the same time. Common examples are osseous findings inside and outside the skull or correspondences between skin lesions and inner findings like fractures. A forensically important application field for focus and context techniques are occurrences of entrapped gas. Such findings greatly aid the reconstruction of, e.g. stabbing channels. However, it is not possible to visually separate them from air in the lung, the colon or outside the body using globally applied transfer functions.
2. **Case understanding by non-experts:** Focus and context techniques contribute to the understanding of forensic findings and comprehension of their interpretation by forensic experts. Complex anatomical circumstances can be illustrated in a way that is comprehensible by an audience lacking fundamental anatomical knowledge.

4.2.2. Image processing

Visual processing tools are efficient means for delineation tasks involving geometrically simple regions, or if an approximate separation of structures is sufficient. Complex anatomical shapes or measurement tasks require a more accurate delineation.

Consequently, the proposed software framework includes several semi-automatic state-of-the-art segmentation methods, which act in the sense of intelligent selection tools [25]. They can be regarded as the 3D equivalent of advanced 2D selection tools in common 2D image processing software. Such segmentation algorithms require seed regions defined by the user or interactive marking of object and non-object regions in the dataset, leading to additional mask-volume datasets accurately describing the respective dataset portions. Segmentation is indispensable for quantitative measurements of forensically relevant structures, e.g. volumes or surface areas. The generated mask-volumes are automatically added to the data repository and can readily be used as new scene objects.

Same as focus and context techniques, explicit segmentation allows to visualize structures in datasets, which cannot be sufficiently delineated using transfer functions. Segmentation is for example useful to highlight individual bones or bone fragments in CT datasets like the clavicle fracture in Fig. 3. Due to the spatial proximity of other bones and fragments, a delineation based on space carving requires more user input. MRI datasets often expose a high degree of inhomogeneity. Dataset values for the same tissue vary within the scan volume, prohibiting 3D visualizations depicting particular anatomical structures without explicit segmentation (see Fig. 6: the two lesions were segmented for better visibility).

4.2.3. Case analysis and documentation

Once all case relevant structures have been revealed, the case can be analysed from a course of events perspective, by putting individual findings into spatial relation. In case only local data evidence is available, datasets are placed into the context of generic 3D models, surface scans, or whole body volumetric scans. Additional objects, like 3D models of vehicles, tools, weapons etc., can be included and interactively placed according to findings. The toolbox includes functionality to locally register surface geometry and volumetric datasets, and to efficiently align e.g. weapon CAD models or 3D scans to shot or stabbing directions. Mark-up geometry like arrows can be added to draw the observers' attention to particular regions or to illustrate the direction of impact.

In order to clarify facts still not self-explanatory in the illustrations and to include expert interpretations, text and image labels can be added to the scenes. This only has to be done once by specifying anchor points in 3D space, entering text and eventually adding images from the data repository. The corresponding labels are automatically placed on the screen for arbitrary views. An automated algorithm ensures high quality label layouts. Long distances between labels and anchors, occlusion of important dataset details, and other unfavourable constellations are avoided [26]. The annotation process during case analysis is independent from the preparation of particular illustrations for presentation in court. Once a scene is annotated, the information entered is readily available to be included in arbitrary illustrations. An additional animation component allows to simulate the movement of, e.g. projectiles or vehicles.

4.2.4. Export and presentation

For presentation in court, arbitrary views on the scene can be defined and recalled at any time. It is possible to export the corresponding images to be enclosed with the written expert opinion. Alternatively, it is possible to present a case based on video clips from interactive scene visualization navigation or user defined fly-through paths, which can be shown in court trials. Technically it is also possible to interactively show reconstruction results in court. The presentation mode of the software tool allows forensic experts to fall back to the digital case reconstruction when answering spontaneous questions from the jury.

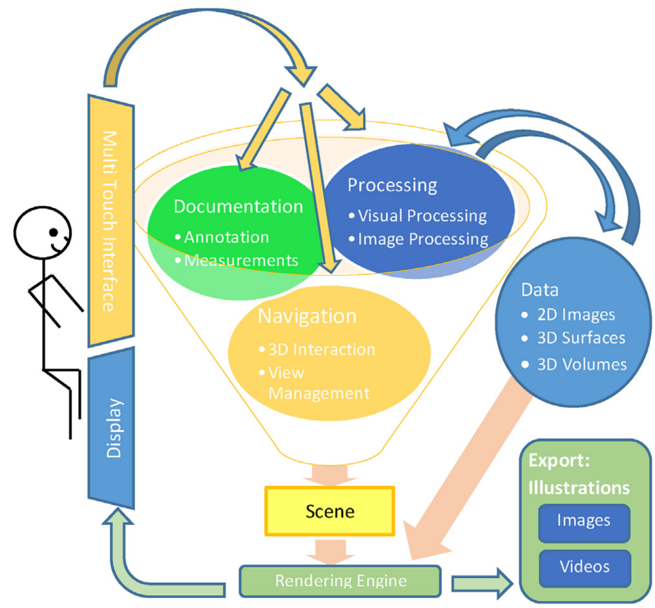


Fig. 4. System overview: the three central components are used to prepare scene descriptions based on the data available and user input for processing tasks, documentation, the spatial configuration of scene objects and views for illustration. A multi-touch capable screen is used for both, interaction and display of the illustrations computed by the rendering engine PC based on the scene description and the involved datasets. Rendering and all processing tasks can be performed in real time, which allows to interactively explore the data and to iteratively refine the illustrations. Final results can be exported.

4.3. System architecture and technical details

The proposed case analysis tool consists of three main components, which provide all the functionality needed to interact with the data, to visually depict findings, and to document them. The components are used to iteratively elaborate a scene description, which is the semantic basis for how the rendering engine computes a particular illustration based on the data provided. Fig. 4 gives an overview of the system, its work flow and the data involved.

4.3.1. Rendering engine

The rendering engine is the backbone of the system. It is the key component for integrated visualization of heterogeneous and thereby computer-aided forensic case analysis utilizing any type of 2D and 3D data available. The rendering engine of the system is capable of seamlessly fusing these data types in the rendering process. The engine combines rendering of 3D surface models using techniques similar to computer games, with a solution for order-independent transparency, and direct volume rendering based on ray casting [27]. Time-consuming and inaccurate data conversion to a common representation (iso-surface mesh extraction or voxelization) is not necessary. Furthermore, multiple overlapping datasets are supported. In order to facilitate this, the developed system is nurturing from ideas published in Kainz et al. [28], but it removes its limitations regarding dataset size, complexity and fidelity.

4.3.2. Visual processing and segmentation

Visual processing is technically based on so-called constructive solid geometry (CSG) operations applied to volume and surface data [29]. CSG techniques allow dataset regions enclosed by a geometric primitive or 3D surface model to be cut out or to locally use a different transfer function to emphasize particular findings or

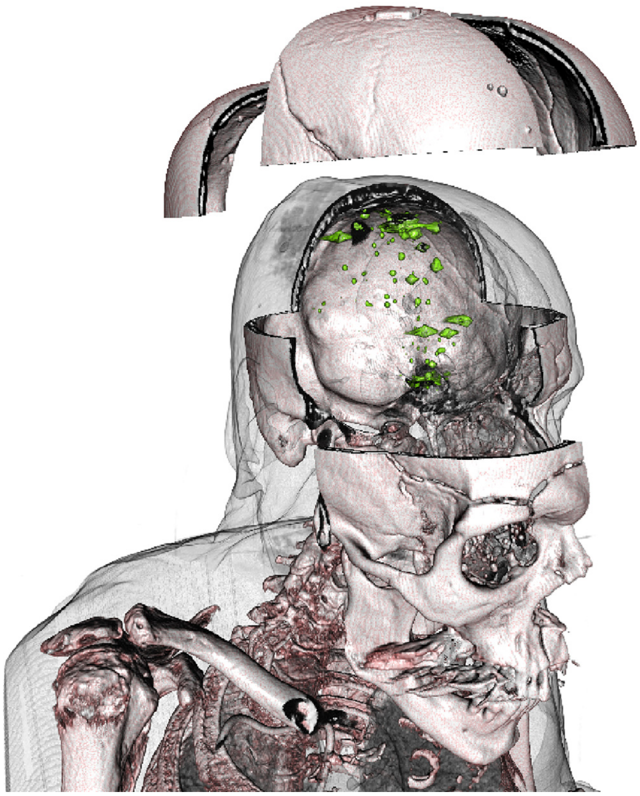


Fig. 5. Explosion diagram example. Spatial displacement of dataset portions occluding other important details such as bullet fragments and bone particles inside in this example allows to preserve the full dataset information. The particles inside the skull can be shown along with the fracture at the end of the bullet path.

to aid context perception as already shown in Fig. 3. Interactive and independent displacement of selected dataset regions is the key to explosion diagrams and cut-off views which help to obtain an unobstructed view on important details occluded by other dataset parts. Explosion diagrams preserve all dataset portions at the price of changing their relative positions in space. In practice, they are especially useful for injury overviews. Fig. 5 shows an example in the context of a gun shot in the head.

Image processing is facilitated based on state of the art algorithms of differing complexities. Dataset denoising based on edge-preserving smoothing methods ensures better visualization results with noisy data while preserving the important image information [30]. The tool includes various automatic and semi-automatic segmentation algorithms, which range from simple region growing to complex energy minimization methods using non-convex and convex partial differential equations [31–33]. All of the mentioned methods are implemented to utilize the computing power of modern graphics processing units (GPUs), which ensures interactive processing even for full-body CT and MRI datasets.

4.3.3. Dynamic label placement

Dynamic label placement functionality is based on an algorithm computing an approximate solution for the label placement problem formulated as an optimization problem using a cost function. This function penalizes solutions, where labels are placed far away from their anchors, or in regions where they are occluded by other scene objects or labels. Our approach is a generalization of work in [34] for volumetric scenes with semi transparent content. Technical details can be found in [26].

4.3.4. User interface

The user interface of the developed tool consists of a main area, which displays 3D views of the whole scene. An editor window allows to logically control scene objects and their parameters. Datasets can be pulled in from a data repository. 3D navigation and direct interaction with the data are performed directly in 3D. This is either done using a mouse or using a multi-touch capable display. In the latter case, it is for example possible to perform camera zoom, pan,[4] and tilt[5] at the same time based on the motion of two fingers.

5. Results – case examples

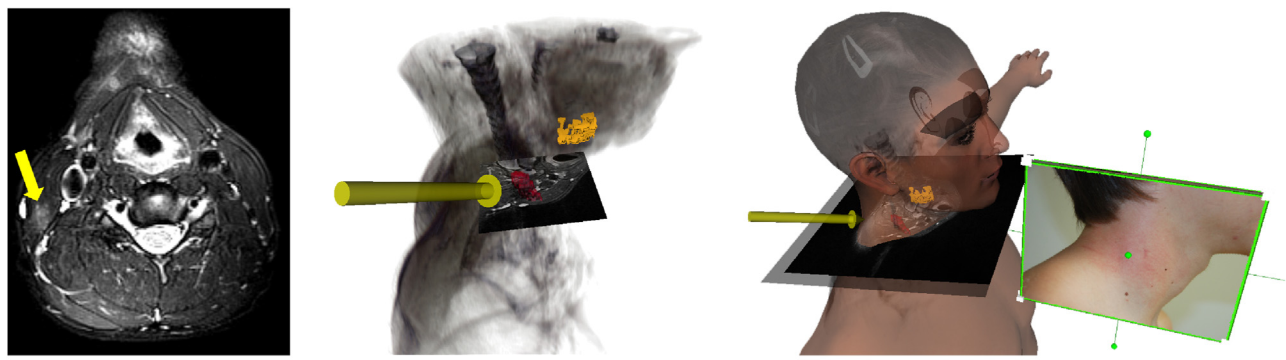
We applied our forensic software tool to more than 20 real world cases over the years. Most of these cases were reconstructed retrospectively, some have been presented in court trials. For the following section we picked out 4 example cases with the goal to give an extensive overview of the technical possibilities using the tool for a wide variety of forensic questions. We analysed, documented, and illustrated them using the developed software framework. An elaborate evaluation of the methods presented is subject to future work.

5.1. Strangling case

The first example (Fig. 6) is a clinical forensic case, where the victim reported that he was manually choked. An external examination revealed neck bruises, which were documented using a digital camera. In addition, an MRI scan was acquired for a documentation of internal soft tissue injuries of the neck. The following reading performed by a radiologist with advanced forensic skills revealed two haematomas (see Fig. 6(a)). The existence of such lesions can be an indicator that a relevant force had been applied to the neck. This allows to differentiate between a short grip to the neck and a manual and potentially life-threatening strangulation. Only a 3D view on the MRI data from the bruise-showing photograph perspective allows to decide if the two internally documented haematomas correspond to the externally visible bruises or if they are additional injuries.

Volume rendering gives a good overview and allows to put the photograph and the MRI dataset into relation. Still, it is not possible to visually depict the lesions using transfer functions, which would be necessary to determine whether the lesions in the MRI image correspond to the bruise on the photograph. Therefore, interactive segmentation was performed to explicitly extract the lesions, which were visualized in the context of the original dataset. The haematoma in yellow confirmed the victim's statement of the course of events, an initial stranglehold near the mandibular, for which no corresponding exterior findings exist. Now the correspondence between the bruise visible on the photograph and the segmented bleeding is obvious. The supposed pressure force direction is indicated by a markup arrow added to the scene (see Fig. 6(b)). In this example the use of a generic human reference model further improves context perception and leads to the final scene in Fig. 6(c), which is now suitable for presentation in court. Alternatively, 3D surface models from a 3D scanner or photogrammetry could be used. Due to the flexibility of generic models, which can more easily be adapted to match the body proportions and posture needed, we only use person specific 3D scans, if they are absolutely necessary for case understanding. Apart from that, photorealistic surface models can raise legal issues related to the identifiability of the victim. Altogether, such illustrations help the

[4] Movement perpendicular to view direction.
[5] Rotation around the view direction.



(a) (b) (c)

Fig. 6. Computer aided case preparation of a strangling case based on an MR scan: the haematoma indicated by the yellow arrow in (a) is hardly visible in the raw data – the exact location inside the human body is hard to imagine by none experts. It is not possible to draw a link to the bruise visible in the photograph in (c). For (b) the lesion from (a) has been interactively segmented together with a second lesion of the glandula submandibularis. Both lesions are visualized in the context the whole MRI dataset (DVR) together with an arbitrarily oriented slice showing original data. The resulting visualization provides all spatial interrelations needed for comparison to the photograph, which is done in (c), where photograph and MRI data are visualized side by side. The correspondence between the red haematoma and the bruise is obvious now. In (c) context perception is further improved by using a generic reference model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

authorized expert to explain the injuries, the mechanisms leading to them, and the assumed course of events to jurists and laymen. Since the case relevant parts of the illustrations are based on the visualization of real data rather than abstractions like drawn sketches or computer animated manikins, they do not interfere with the goal of objectivity.

The time taken to produce this illustration excluding the radiological inspection is around 10 min.

5.2. Stabbing case

Sharp force injuries are frequently seen in homicide victims. Determination of the cause of death and reconstruction of the incident, including identification of the weapon(s) used are the main goals of the forensic autopsy. Forensic imaging can significantly contribute to the reconstruction and documentation of stabbing path(s) or the detection of air embolism. Fig. 7 illustrates this case with Fig. 7(a) giving an overview of the findings.

5.2.1. Short case report and gross autopsy findings

We used the software tools to process and illustrate the case of a 23-year-old man who was fatally stabbed with a knife during a fight in a tavern. A double-edged hunting knife with an overall length of 30.5 cm, a blade length of 18 cm and a blade width of up to 4 cm was identified as the murder weapon (Fig. 7(c)). The forensic autopsy revealed a total of 11 sharp force injuries on the head, the neck, the thorax, and the extremities. The fatal stab wound was located on the left side of the thorax, where the knife severed the 3rd rib completely and the 4th rib partially, passed through the upper lobe of the left lung, opened the pericardium, the pulmonary arteries, the aorta, and ended in the middle lobe of the right lung. The thoracic cavities contained a total of 600 ml of blood. Sparse livores and anaemic inner organs were found as a sign of a fatal blood loss. Both lungs showed blood aspiration foci. The deceased showed no relevant pre-existing diseases.

The cause of death was an exsanguination; the manner of death was classified as a homicide.

5.2.2. Case illustration

Computer-aided case processing served multiple purposes.

First, an illustration giving an overview of all the external findings was generated by documenting the location of the injuries on a generic surface model. This was done due to the large number of injuries found and their presumed importance concerning the course of events (see Fig. 7(a)). The same was done based on post mortem CT data of the victim. Focus and context visualization techniques were applied to show exterior and interior lesions at the same time (Fig. 7(b)). Using these techniques it was possible to depict unnatural gas inclusions in the brain artery system (Fig. 7(f)), which can often be found in fatal stabbing cases. Individual findings were documented by adding text and image labels showing photographs taken during autopsy.

Second, the cause of death was analysed and illustrated based on CT findings and a 3D model of the knife, which was carefully placed in the dataset in order to match the lesions found. In this case this could easily be done based on the lesion faces of the 3rd rib (Fig. 7(c)), the severed pulmonary arteries, and unnatural occurrences of entrapped air in the stab channel (Fig. 7(d)) The small offset between rib lesion and gas-filled stab channel is due to the different arm posture in the CT scanner. It can provide an indication on the posture when the stab was inflicted, in this case actions in self-defense, which is supported by the injuries shown in Fig. 7(e).

5.3. Case: gunshot injury

In gunshot injuries, the routine work of the forensic pathologist includes the reconstruction of the bullet path. However, gross morphological methods alone may not always suffice in demonstrating the path of the projectile. In the case shown here, the toolbox is used for the reconstruction of the primary direction of the bullet as well as the eventual path using post mortem CT data acquired prior to autopsy (see Fig. 8).

5.3.1. Short case report and gross autopsy findings

The deceased, a 63 years old man, was found lying on the ground at a cemetery with a shotgun entry wound located submentally. A pistol (Ithaca, model 1911, calibre.45) was discovered next to the body. Even though a suicide was suspected, a post mortem CT and a subsequent forensic autopsy were performed to exclude a third party fault and to clarify the missing exit wound.

The bullet was located in the right temporal lobe of the brain in the CT scan. Furthermore, there were subtle changes in the brain tissue as an indication of the effective bullet path. The forensic autopsy confirmed the diagnosis of a fatal gunshot injury with a submental entry wound (Fig. 8(d)) and a retained projectile

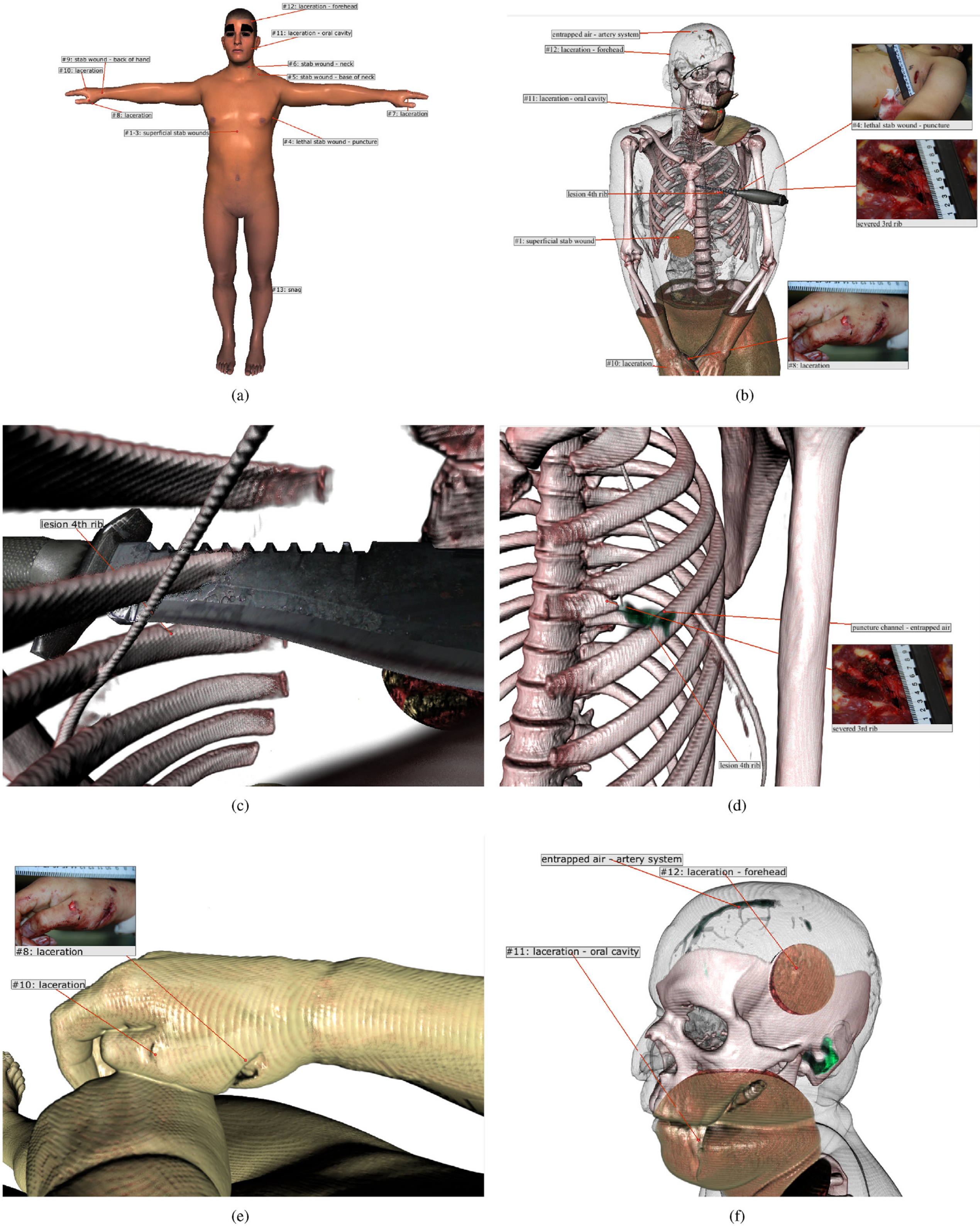


Fig. 7. Stabbing case reconstruction and presentation example: injury overview using a generic reference model and automated placement of text labels, to emphasize lesion distribution rather than morphology/colour (a). Alternative injury overview based on full body CT dataset and visual processing showing interior and exterior findings at the same time. Text and image labels provide additional detail information (b). Visualization of the 3D model of the weapon used for the crime (knife) inside the post mortal CT dataset (c). It was carefully placed according to findings like severed ribs and entrapped air in the stab channel (d). Cut injury contracted in self defense visualized based on post mortem CT data and an image taken during autopsy (e). Visualization of exterior head injuries and entrapped air in the brain artery system indicating exsanguination using focus and context techniques (f).

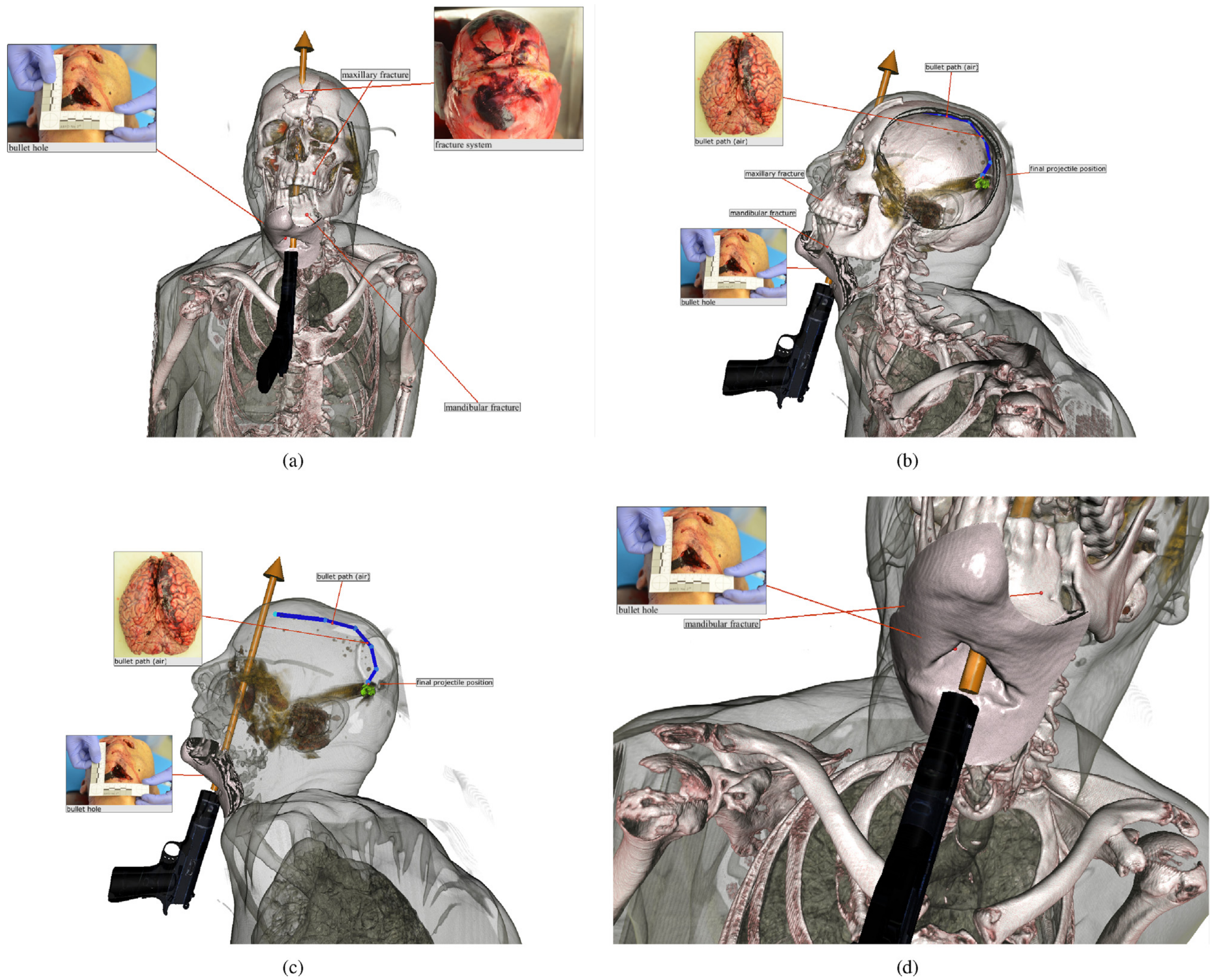


Fig. 8. Gunshot injury case: injury overview (a). Intended and actual bullet path illustrated using geometric objects and annotations. Bones were partially removed using focus and context techniques (b) or entirely using a different transfer function (c). In (b) and (c) the bullet itself was emphasized in green. Close-up view of the entry wound – focus and context visualization techniques allow to show both, the entry wound surface and the nearby mandibular fracture (d).

(Fig. 8(b) and (c)). The mandibular and maxillary bones as well as the ethmoid and frontal bones of the skull were fractured (Fig. 8(a)). The brain showed extensive tissue damage and swelling (brain weight 1.455 g). Gunpowder residue was found on the dorsal sides of both hands.

The cause of death was a gunshot wound to the head, and the manner of death was classified as a suicide.

5.3.2. Case illustration

Autopsy and reading CT data successfully clarified the cause of death, while the actual bullet path remained unclear – at least for people lacking in depth anatomical knowledge.

To illustrate the bullet path together with all relevant findings, a 3D visualization of the CT dataset was complemented by a surface model of the gun placed in accordance with the entry wound and the intended shot direction, which was illustrated by placing a 3D arrow model pointing in the direction of the skull fracture system. For path reconstruction and illustration, portions of the skull occluding the view were removed using focus and context visualization techniques. In fact the projectile entered submentally, intruded the cranial cavity through the cribriform plate, ricocheted from the frontal bone, and finally came to rest in the right temporal brain lobe, which is a rather special scenario. The path was reconstructed based on findings in CT data (tissue changes and final projectile position). Due to the low contrast between traumatized and healthy brain tissue the bullet path could not be visualized directly. Instead, it was depicted using geometric primitives, which were interactively placed along the path in accordance with dataset findings and with the help of a cutting plane moved through the data. Furthermore, important findings were annotated using text labels and photographs from autopsy. Fig. 8 shows different views of the scene used to explain the findings and the bullet path in court.

5.4. Case: blunt force

In forensic routine work, injuries due to blunt force are frequently seen. Especially in cases in which tools or other objects are used as striking tools, the reconstruction of the case may help to either identify the tool of crime or to match the instrument in question with the detected injuries.

5.4.1. Short case report and gross autopsy findings

A 93 years old woman was found lying in her bed with severe head injuries after having been beaten with a scabbling pick. In spite of immediate medical attention by an emergency physician including resuscitation measures, the woman died at the scene. The forensic autopsy revealed severe craniocerebral injury with

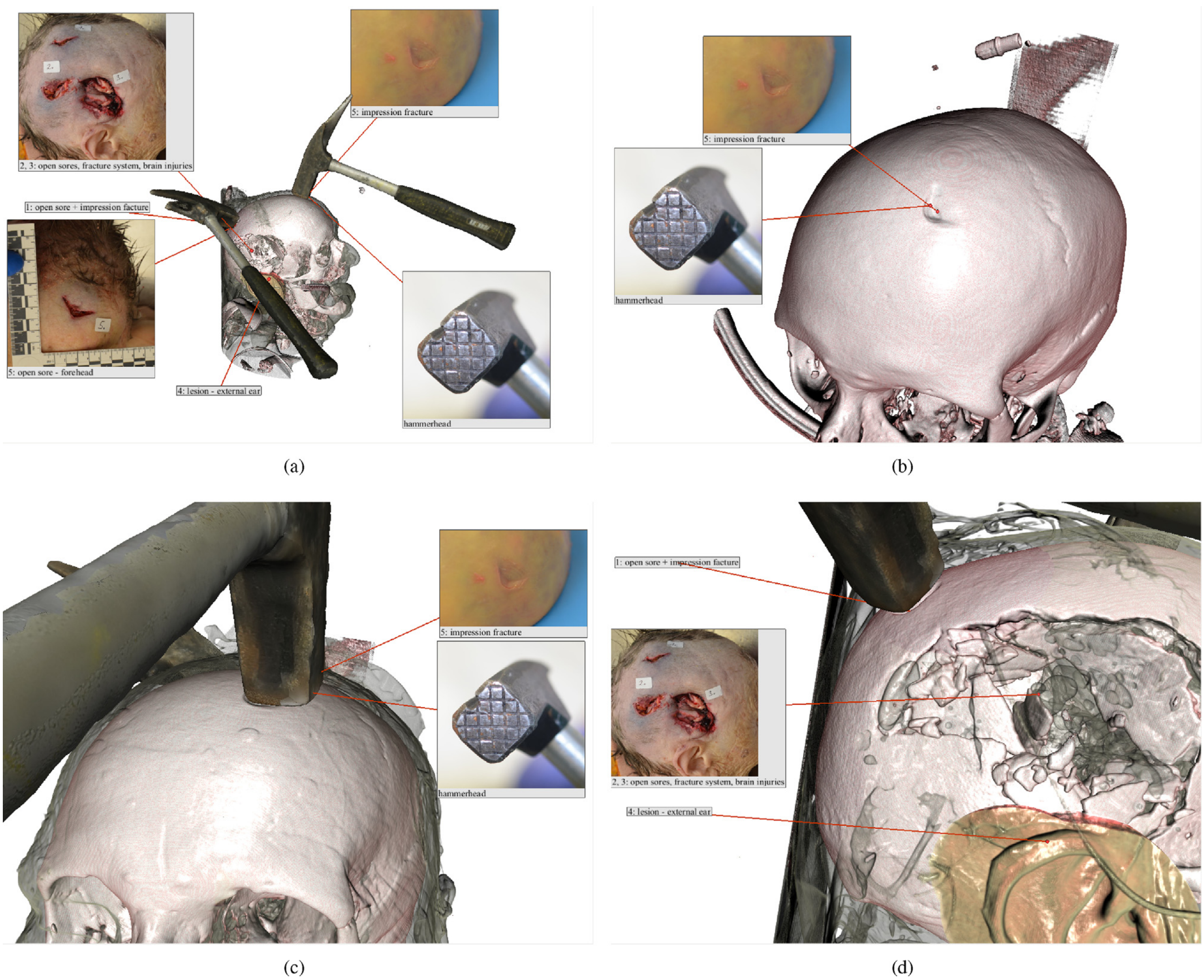


Fig. 9. Blunt force injury case: injury overview including text and image labels describing individual lesions (a). Close-up views showing one out of two impression fractures to identify the tool of crime and its orientation at the time of infliction (b and c). Illustration showing the second impression fracture, used for tool identification as well as the massive fracture system on the right temporal and parietal region due to multiple strokes (d).

impression fractures of the frontal and right parietal bones, a comminuted fracture of the right temporal bone, an open brain injury with extensive tissue damage of the right temporal and parietal lobes, and a bleeding in the basal ganglia. The scalp showed a total of five lacerations caused by blunt force. Microscopic examination revealed a mild fat embolism. The cause of death was severe craniocerebral trauma in combination with massive blood loss, the manner of death was classified as homicide.

5.4.2. Case illustration

For case analysis the post-mortem CT dataset was 3D visualized as shown in Fig. 9. Findings were interactively annotated and completed with photographs of the injuries taken before and during autopsy. A 3D model of the scabbling pick was reconstructed using photogrammetry software and added to the scene for fitting and comparison with the lesions, which resulted in a perfect match with two impression fractures. The hammer orientation at the time of infliction could be determined by comparing tool geometry and wound morphology. Besides constituting largely self-explanatory means explaining the location and the infliction of the injuries, the illustrations can be used to discuss, e.g. the chronology and number of strokes and considerations concerning the overall course of events.

6. Results

The presented software tool turned out to be very useful to aid forensic case analysis, documentation and illustration. This is mainly due to its key concept, which allows to visually combine all available data sources and types for joint analysis, which is a unique characteristic among software used in this area. Visual processing functionality turned out to be both helpful and effective to depict interior and exterior findings at the same time and to study their spatial interrelations. Moreover, it supports a direct and intuitive approach to analyse the data. The set of tools to select particular dataset regions was extended, whenever new cases demanded it. These changes lead to incremental growth of the software and new functionality like the creation of explosion diagrams requiring only a few mouse clicks. By now the set of tools has stabilized. The core concept of the software never had to be changed.

Multi-touch interaction turned out be efficient to navigate and edit 3D scenes, as it allows for more intuitive interaction metaphors for 3D tasks than, e.g. a mouse. Although the tool was generally operated by a technician in the presence of a forensic expert and/or a forensically skilled radiologist, the physicians were encouraged to perform individual navigation and 3D editing tasks themselves. They found the interaction to be intuitive and stated that they could imagine to use the tool themselves in the future. The possibility to document a case in the analysis phase – i.e. decoupled from the generation of images for illustration – was well perceived.

Forensic experts asked to comment on images and videos produced using the software generally liked the idea to be able to have these additional means at hand to explain their written expert opinion to people lacking profound anatomical knowledge in court. Jurists found the illustrations useful to better understand case details without the need to look at original photographs of injuries with potential impact on objectivity. A previous study among prosecutors in Austria confirmed this impression [35].

7. Discussion and conclusion

3D surface data and tomography data are valuable pieces of evidence in forensic procedures, but like every new technology they come with the risk of misuse and abuse. The persuasive power of images and illustrations can easily lead to misunderstanding and influence, especially, if they present fragmentary information rather than the “big picture”. Integrated computer aided forensic case reconstruction is the perfect way to combine information, reveal and show connections and thereby to ultimately increase legal certainty, by reducing the dependence on abstract summaries and fragmentary evidence. Jurists can be provided with more complete, comprehensive, and reproducible material to understand forensic data and their expert interpretations. Data can be presented in a detailed but still factual fashion. Unnecessary details like scandalizing images can be excluded.

Integrated case analysis and illustration implicitly complicate the manipulation of the underlying data, since this would have to be done in a coherent fashion. Computer aided case reconstruction is reproducible and can be verified at any time in contrast to a manipulation of a written expert report or an image.

One important aspect in computer-aided case analysis is data registration accuracy. An illustration presenting an overview of injuries can meet its goal based on approximate lesion locations. A generic reference model like in Fig. 7(a) might even be better suited for this task than an annotated CT scan like in Fig. 7(b). Quantitative questions clearly require a high level of registration accuracy. Multimodal data, e.g. surface data from the crime scenes and tomography data, inevitably exhibit different postures. A general technical solution for fusion of surface models and tomography data leads to a complex registration problem. A solution taking boundary conditions such as physical tissue properties into account is far ahead of the current state of research. In practice, a perfect combination of tomography data and surface scans is only possible if the subject does not move, which can only be achieved using integrated scan setups limited to post mortem examinations [36]. Local rigid alignment approaches or local non-rigid registration, while partially solving the problem, come with the risk of inwardly introducing misleading facts.

Even single datasets may exhibit ambiguities caused by tissue movement and deformation. This leads to artefacts like curved stab channels and offsets between osseous and soft tissue findings like in Fig. 7(c) and (d) making it hard to accurately reconstruct stab directions and to place weapon models accordingly. In return, such ambiguities can be used to qualitatively infer, e.g. the posture of the victim at the time of infliction.

The practical integration of computer-aided case analysis in the court proceedings is still unclear. Ideally, forensic experts could present their export opinion on the basis of an interactive presentation of the case reconstruction results. However, the infrastructure required to do so is currently not always available in courtrooms. Therefore, only static images and videos can be added to the expert reports. Once digitally reconstructed case scenarios can be interactively shown, computer-aided case analysis could be extended to include more crime scene (3D) data and thereby increasingly supplement legal analysis and forensic expertise in courtrooms.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.forsciint.2018.03.031.

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