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State-of-the-art of Visualization in Post-Mortem Imaging

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Lundström C., Persson A., Ross S., Ljung P., Lindholm S., Gyllensvärd F, Ynnerman A. State-of-the-art of Visualization in Post-Mortem Imaging. APMIS 2011.

Summary: Autopsies constitute a valuable feed-back to the healthcare chain in order to achieve improvements in quality of care and cost effectiveness. This review describes post-mortem imaging, which has emerged as an important part of the pathology toolbox. A broad range of visualization aspects within post-mortem imaging are covered. General state-of-the-art overviews of the components in the visualization pipeline are complemented by in-depth descriptions of methods developed by the authors and our collaborators. The forensic field is represented and related to, as it is spearheading much development in post-mortem imaging. Other topics are workflow, imaging data acquisition, and visualization rendering technology. All in all, this review shows the mature state of visual analysis for a non- or minimal-invasive investigation of the deceased patient.

Keywords: Post-mortem imaging, visualization, computed tomography, magnetic resonance imaging, volume rendering.

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INTRODUCTION

Autopsies have traditionally been a cornerstone for improving the quality of health care. Medical conclusions such as determining cause of death, constitute an important feed-back about the clinical workflow. The increasing demands of quality of care and cost effectiveness can be solved only by continuous improvement process of the entire healthcare chain. In medical imaging this stretches from the acquisition of data until the point at which the clinician receives the diagnostic information, where new methods can be validated. The deceased patient is often an important part of this validation process. It can in some cases be impossible to verify the acquired diagnostic information while the patient is alive. Autopsies can then fulfill the

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role of a real gold standard. This review pertains to post-mortem imaging, which has emerged as an increasingly valuable complement to the pathology toolbox.

Outline of review

This review aims to describe a broad range of visualization aspects within post-mortem imaging. There will be general overviews of different parts of the visualization pipeline, paired with more detailed descriptions of state-of-the-art methods developed by the authors and our collaborators. First, an overview is given of the prerequisites for pathological and forensic autopsies, respectively. Then workflow aspects of virtual autopsies will be described, outlining the steps involved. Next topic being covered is the acquisition of imaging data. An overview of pertinent rendering techniques is then presented, followed by a section dedicated to visualization methods developed specifically toward post-mortem imaging needs. Concluding remarks are presented in the last section.

PREREQUISITES FOR CLINICAL AND FORENSIC RADIOLOGICAL AUTOPSIES

Traditional invasive autopsy is a central procedure in pathological and forensic investigation. State-of-the-art autopsy procedures, however, also include modern cross section imaging techniques that can assist and supplement conventional autopsy providing improvements for the general workflow of post-mortem examinations.

The demands on radiological autopsy are identical with those of traditional autopsy, namely to address and explain the so-called Atrium mortis (i.e., a pathophysiological reconstruction and explanation of the cause of death) with a depiction of relevant patho-morphologic findings in bones, soft tissues and organs. In medicolegal cases, a few more points have to be addressed. 1: Vital reactions. In forensic pathological investigations, the question whether an injury was received before or after death is often an important matter because they give an explanation about the sequence of injuries finally causing the death. The answer to this question lies with findings that only occur with intact circulation (e.g., fatal hemorrhage, air and fat embolism, cutaneous emphysema) and respiration (e.g., aspiration). 2: The reconstruction of injuries with regard to force, biomechanics, and dynamics. 3: Identification of a person. It is very important to identify a deceased rapidly and accurately, both for juridical reasons and for the relatives to be able to mourn. Post-mortem imaging enables this by the possibility to match singular individual findings like the denture, nasal sinuses or metallic implants with ante mortem radiological imaging.

Recent developments in post-mortem imaging have led to an implementation of post-mortem Computed Tomography (pmCT) and post-mortem Magnetic Resonance Imaging (pmMRI) for the benefit of forensic investigations. Several studies published over the past 10 years have demonstrated that a combination of autopsy techniques and cross-sectional imaging can augment the value of postmortem examinations for the jurisdiction (1-9). Contrary to the forensic field, the autopsy numbers of clinical pathological examinations suffer from a continuous decline. Depending on the country, up to more than 90% of the deceased do not undergo a comprehensive postmortem examination. The resulting negative consequences for medical education, quality assurance in medicine, public health and mortality statistics are substantial as discussed by numerous authors (10-17). Ongoing research investigates if and when pmCT and pmMRI can be used as the primary tool to determine the cause of death in non-forensic cases (18).

Post-mortem imaging has, largely due to methods development in the forensic domain, matured into a valuable examination method to acquire patho-anatomic details with a high spatial resolution. An increasing number of forensic institutes have started to install CT and MRI systems to use the imaging techniques for the purpose of quality improvements in the forensic field. The experiences obtained in forensics may provide the scientific background necessary for an increased clinical use of post-mortem imaging to the end of improving the quality of care. This review intends to raise awareness among clinicians about the potential and recent progress of visual analysis for a non- or minimal-invasive investigation of the deceased patient. One usage scenario is as a complement to a traditional autopsy, to enhance the quality of autopsy results. Another scenario is whenever clinical autopsies are unwillingly avoided due to cost or organization limitations, or not agreed to by next of kin. In these situations, post-mortem imaging could become a substitute for clinical pathological examinations that retains a significant part of the medical value. On a larger scale the benefit of post-mortem imaging could be the reestablishment of a reliable base of data of cause of death in our society.

Example of radiological autopsy procedure

In this section we will present key characteristics of a routine, large-scale forensic autopsy procedure running in Linköping, Sweden (19). There are many components that are relevant also for clinical autopsies, and those will be further discussed in the following section. The presented autopsy procedure has been developed through collaboration between the Center for Medical Image Science and Visualization (CMIV) and the Swedish National Board of Forensic Medicine has been applied to over 380 cases so far.

The workflow of the forensic procedure is illustrated in Fig. 1. The post-mortem imaging activities, extending the traditional invasive autopsy, are shown in red. At the crime scene the human cadaver is placed in a sealed body bag before being transported to the forensic department, and put in cold storage. The following morning, a full body CT scan is performed. A radiologist makes a first assessment of the imaging data through a number of visualizations. In preparation for the physical autopsy a collaborative session between the pathologist and the radiologist is conducted. The meeting is either in person or over the phone. The radiologist presents an overview of the entire body and the forensic pathologist can then selectively focus on different types of findings, such as the skeleton to localize fractures, the distribution of gas in the body or foreign objects such as metal fragments or bullets. This can provide essential information in the early part of the police investigation. If feasible, the radiologist responsible should attend the autopsy. First, to further contribute knowledge gained by imaging and second, to obtain a better correlation between the radiological findings and the reality seen at autopsy. Only a direct correlation between radiological imaging and autopsy allows for a proper learning curve for both the radiologist and the pathologist. An important aspect is the high resolution of the data, which allows for extraction of details such as dental information for identification purposes.

An important added value of introducing pot-mortem imaging is that the captured CT data is stored which gives the possibility to iterate the procedure. Often findings during the physical autopsy lead to new questions that an image review can answer. Also, in crime scene investigations new findings may require that other hypotheses need to be scrutinized through the use of the imaging data.

The introduced workflow overhead is minimal as the time needed for the scan and assessment sessions is short in comparison to the clinical autopsy. Furthermore, the total investigation time may, in fact, be reduced since the pathologist has prior knowledge of the case before conducting the clinical autopsy.

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Lessons learned from virtual forensic autopsies

There are significant differences in the prerequisites and demands of clinical autopsies compared to forensic autopsies. Nevertheless, when investigating challenges for post-mortem imaging in a clinical setting, experience gained from forensic procedures can be useful. A first challenge may be infrastructure. In the forensic case there are often two sites, a forensic institute and a radiological institute that have to be connected by sufficient corpse logistics. Furthermore, a sufficient data exchange has to be set up to allow both parties using the imaging data, which can be both a technical and an organizational challenge. An alternative solution would be to fully integrate imaging equipment and radiology expertise into the pathological institute.

A second challenge is to accomplish an effective collaboration between radiologist and pathologist. A large part of the added value stems from the combined radiology/pathology expertise when interpreting the image data. Whereas the radiologist is used to assess the images in order to establish the diagnoses that can guide a future therapeutic strategy it is the pathologist who searches the past within the images. These different views have to be combined to fulfill the potential of post-mortem imaging. The need for unhindered collaboration entails a strong need for tailored visualization tools.

Apart from use during the investigation, visualizations for presentation purposes are very important in the forensic case. This is particularly important when many medical laymen are involved and need to understand the findings. The result of a clinical autopsy does not typically require the same type of elaborate guiding through the imaging finding. There is, however, reason to believe that easily graspable visualizations such as 3D renderings can enrich the feedback to clinicians from the autopsy.

A final challenge is the data set sizes. The imaging corresponds to whole body data sets with slice stacks up to 30000 images. Post-mortem imaging, not being limited by any radiation dose restrictions or scanning time limits, can make use of the maximal possible spatial resolution which boosts the data volume to be handled. The technical challenge to create volumetric renderings of such data sets is substantial.

IMAGE ACQUISITION

The first part of the visualization pipeline in post-mortem imaging is the image acquisition. In this section the most relevant types of acquisition methods will be described.

Post-Mortem Computed Tomography

To be able to acquire sufficient Post-Mortem Computed Tomography (pmCT) image quality it is an advantage to have a scanner that can conduct a full body scan with sub millimeter slices in extended field of view. Furthermore, a data set reconstructed in an extended CT scale is useful when foreign objects such as projectiles or fragments of knife blades are present. Intra venous or arterial admission of contrast can visualize the vessel lumina and can in certain cases help to determine the cause of death. Postmortem gas in the vascular system can in certain cases also be used as a “negative” contrast agent. The scan time is not crucial since it is a negligible part of the total workflow even with a slow scanner.

Dual energy CT (DECT) distinctively improves soft tissue discrimination and visualization (3), which can be of great benefit in post-mortem imaging. DECT with two X-ray sources running simultaneously at different energies can acquire two datasets showing different attenuation levels. Since X-ray absorption is energy-dependent, scanning an object with 80 kV results in a slightly different attenuation than scanning it with 140 kV. This physics phenomenon can help to discriminate between materials that have the same attenuation at a certain energy level. In the visualization, colors can then be mapped to the difference between the two measurements, effectively discriminating materials that cannot be differentiated in a traditional CT scan. This technique can be used to visualize post-mortem blood clots in vessels, and possibly bleeding in soft tissue (Fig. 2). Soft tissue discrimination is much improved, for instance between blood, soft tissue, tendons, and cartilage (Fig. 3). The absence of any motion related artifacts in combination with unlimited radiation exposure possibilities allows the acquisition of highly detailed data, sufficient for high-quality 3D renderings.

PmCT has been proven to be especially valuable in cases of skeletal alterations (20; 21), foreign materials, gaseous findings (Fig. 4) (6; 22; 23) and angiography (24), making it a fast triaging tool for conventional autopsy in traumatic cases. Post mortem CT-angiography provides substantial added value when it comes to the depiction of vascular pathologies both in natural and traumatic causes of death.

Post-Mortem Magnetic Resonance Imaging

In selected cases, a post-mortem MRI (pmMRI) examination can be of great value. Whole body scans can be acquired for example with T1 and T2 sequences. Used for subsequent soft tissue visualizations the clinical information is a substantial complement to CT data. Compared to pmCT, pmMRI offers superior visualization of brain, thorax, gastro regions and other soft tissues. For instance the exact localization of hematomas in the subcutaneous fat is highly appreciated when comes to the forensic reconstruction of the sequence of traumatic events.

A recently developed approach known as Isotropic Quantified Post-Mortem Magnetic Resonance (IQpmMR) (25) shows great potential. One typical problem with pmMRI is the temperature dependence when scanning cold bodies (26). IQpmMR works equally well for low temperatures due to its quantitative approach. Furthermore, IQpmMR provides high detail, which enables high-quality reformatting and volume rendering. Each point in the data set has three quantified values (T1 relaxation time, T2 relaxation time and proton density) and this rich information can be used for distinctive soft tissue discrimination.

Decomposition considerations

Decomposition of cadavers is less pertinent in clinical autopsies than in forensic ones. As it may, however, occur also when investigating natural deaths, a brief discussion is provided.

With the post-mortem passage of time in a non-chilled environment, the investigation of a corpse becomes more and more complicated. Putrefaction processes beginning 2–3 days after death can destroy findings obtained at autopsy as well as at post-mortem imaging. Putrefaction can be recognized in post-mortem imaging as massive gas accumulation within the vascular system, body cavities, and soft tissues (27-29). At detailed scale putrefaction gases need to be considered when reviewing the imaging data, since they are omnipresent as gas micro bubbles assembled around fatty cells and muscle fibers. This gas requires special assessment of the pmCT findings and for pmMRI the signal intensity can be decreased due to changes in the chemical properties of the soft tissue.

In advanced putrefaction, the texture of an organ can be completely dissolved, leading to a liquefaction of entire organs. If preexisting anatomical boundaries such as collagenous are intact, liquefied organs may be assessed to a certain extent. A traditional autopsy will destroy these boundaries whereas pmCT and pmMRI will leave the organ boundaries intact.

Furthermore, the analysis of the distribution pattern of gas in a corpse makes it possible to do discrimination between the above mentioned signs of decomposition and potentially lethal pathologies like traumatic

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soft tissue emphysema or gas embolism into the vascular system (6).

VISUALIZATION OF VOLUMETRIC DATA

Once the imaging data has been acquired the next step in the visualization pipeline is to transform the measured data into a visual appearance. In this section an introduction is given to the basic types of visualization relevant for pmCT and pmMRI data. Since both acquisition methods are volumetric, the description will be restricted to volumetric data. For a thorough overview of medical visualization methods, please refer to (30).

Slice visualization

The most straight-forward visualization method is to explore the volumetric data by browsing 2D slices in one of the major orientations (axial, sagittal, coronal). The slices are viewed using a grayscale mapping from scanned value to screen pixel value. More interaction is provided by Multiplanar Reconstruction (MPR), where a slice through the volume of arbitrary orientation is displayed. The slicing plane can also be curved. MPR is the dominating and most important visualization method for post-mortem imaging today. The risk of missing important findings using only the major orientations is substantial. MPR views of the three main planes are often used as reference views as a complement to other volume visualizations.

Volumetric visualization

There are several techniques that visualize the full volume rather than a slice of it. A commonly used method is Maximum Intensity Projection (MIP). In MIP renderings are constructed from the entire volume or a slab. The volume is projected onto the image plane and the maximum intensity of all data points projected onto it is retrieved. This maximum value is then, as for the slice visualization, transformed to a screen pixel value through a grayscale mapping. The viewpoint can be changed freely. MIP is particularly useful for narrow, high-contrast objects which in post-mortem imaging could be metal fragments and calcifications.

Surface rendering (also known as Shaded Surface Display, SSD) is a method where a surface is extracted from the data and rendered using a mosaic of connected polygons. Surface rendering is fast, but it is not suitable as a general data exploration tool in clinical use (31). A special niche-application for SSD in forensic radiology is the generation of polygon mesh models of skeleton and body surface, enabling the integration of radiological data into a so-called virtual incident/crime scene reconstruction including the matching of a potentially injury causing instrument with skeletal findings of the victim (32).

Direct Volume Rendering (DVR) (33; 34) is a visualization technique that aims to convey an entire 3D data set in a 2D image. The key to making this work is to assign semi-transparent colors to the data samples. In this way, objects at all depths in the volume can be seen at once, without obscuring each other. The term “Direct” in DVR stems from the fact that the rendered image is constructed directly from the data, as opposed to techniques that create an intermediate representation, for instance an extracted surface model. DVR is a common scientific tool, where visualization of medical data sets is one of the main areas. A central component of the exploration is that DVR allows the user to navigate between highly differing alternative depictions of every single data set.

In an interactive exploration setting, the success of any visualization application is dependent on performance. The rendering must promptly respond to the user’s actions, otherwise the understanding of the visualization will be hampered. Rotation of the volume is a typical operation that needs a perceived real-time performance of 20-30

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frames per second (fps). Below 5 fps the response times are usually experienced as very disturbing. Since DVR is a technique essentially utilizing all data in the post-mortem imaging volumes, the performance challenge is highly pertinent even with the rapid progress of computer hardware (19).

Sample classification

A central component of most visualization methods is the visual mapping of a data value. This mapping is known as a Transfer Function (TF). In essence, this corresponds to a classification, where different tissues should preferably be given different visual appearance. In DVR, the TF controls not only the color but also the transparency of a sample, which highly affects the resulting image presented.

The most common situation is that a single data value is input to the TF. Multi-dimensional TFs are however needed when there is more than one value in each data point, such as for DECT or IQpmMR. The additional values can also be attributes derived from the original data, such as statistical properties of a local neighborhood (35-38).

VISUALIZATION TECHNIQUES TAILORED FOR POST-MORTEM IMAGING

In this section a number of visualization advances with particular bearing on post-mortem imaging will be presented.

Feature enhancement

A limitation of traditional TFs is that no information about spatial relations between data points can be encoded. This type of knowledge includes, however, very useful information that could be exploited for effective and informative visualizations. One approach to exploit such knowledge is spatial conditioning of the TF (39). In this method, the user names a number of tissues and materials and identifies their typical data range. The user then uses the labels to express semantic conditions on the rendering, for instance "Only render air when close to blood". The result of the method is a reduction of clinically redundant data which leads to increased image clarity and relevance (Fig. 5)

In some cases, detection of foreign objects such as metal fragments can be essential in post-mortem imaging. For instance gunshot cases, the foreign body may be a projectile, which may not only lead to the identification of the ammunition used, but often even the individual weapon. Furthermore, fragments of intermediate targets such as a window pane may be found in the corpse, thus permitting a reconstruction of the shooting and perhaps even the crime scene. A problem is that minor metal fragments can be overlooked since their location may be unexpected. A method to highlight minor features is to identify not only those samples themselves, but also samples in their vicinity (40). As illustrated in Fig. 6, the visual localization and therefore also the retrieval during classical autopsy becomes easier.

A general challenge for volumetric visualization is that important findings can be obscured. In post-mortem imaging, this can be highly relevant for minor findings of, for instance, foreign objects or gas. A visualization method to remedy this problem is to have a dual TF, where the second TF only picks up a prioritized material and makes sure it is visible when blending the two renderings (19). The benefit of this approach is illustrated for metal objects in Fig. 7.

Illumination

The effectiveness of a rendered image is highly dependent on whether it agrees with human intuition. Representing volumetric data on a 2D screen is challenging and visual cues to improve the perception of shapes and depth are important. Techniques for virtual illumination are known to significantly enhance the ability

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of humans to distinguish objects and their properties (41).

A commonly used lighting approximation in volume rendering applications is the Phong (42) and Blinn-Phong (43) shading models. This approach is fast but cannot well model lighting for noisy data or homogeneous regions. Global illumination is a type of more advanced lighting model. It is, however, often overly computationally expensive. Moreover, in the context of medical visualization, regions can be shadowed by dense objects occluding the light. The skull, for example, can occlude the light such that a tumor or other feature may not be illuminated and so cannot be identified.

Local Ambient Occlusion (LAO) (44; 45) is a shading model targeting some post-mortem imaging challenges. LAO considers shadowing by structures in the vicinity of each voxel. The method computes the incident light for each voxel by sampling a spherical neighborhood around each voxel, capturing shadows and light emissions locally, as seen in Fig. 8. The method is less sensitive to noise and homogeneous regions with poorly defined gradients. As an integrated part of the LAO approach, data points can be turned into virtual light sources, which can add further valuable discrimination effects.

Visualization table

An area with high importance for the effectiveness of the total visualization pipeline is the display and interaction devices that are the front-end for the user. Recently, a touch-controlled visualization table was developed for the virtual autopsy scenario (46) (even though its application domain has subsequently been extended to also include pre-operative planning and teaching). A major design objective was to target an experience of virtually having the body on a table. Therefore, a large (46’’) display was chosen where DVR images in natural size cover a large part of the body, see Fig. 9.

Another fundamental design objective was to have a very low learning threshold and therefore the touch–controlled user interface was opted for. The table has a multi-touch technology based on infrared sensors placed on top of a regular screen. The touch gestures used are based on the popular rotate-scale-translate (RST) design (47), but extended to control 3D interaction. A key characteristic, known as “sticky fingers”, is that interacting fingers always remain with the original virtual contact point in the data set.

Another design decision targeting a low learning threshold was let the medical image heavily dominate the screen area. There are no menus or toolbars visible and very few other GUI elements. On demand, the user can launch a set of browsable Multiplanar Reconstruction (MPR) views showing the three main orientations.

CONCLUSIONS

Visualization of post-mortem images has matured significantly in recent years. The state-of-the-art in autopsy workflow, image acquisition and image rendering provide a solid platform for employing virtual autopsies. Thus, there are no significant technological obstacles for introducing virtual autopsies on a larger scale. Future evaluations of the cost/benefit of autopsies need to consider that post-mortem imaging as a complement or alternative to traditional clinical autopsies.

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FIGURES

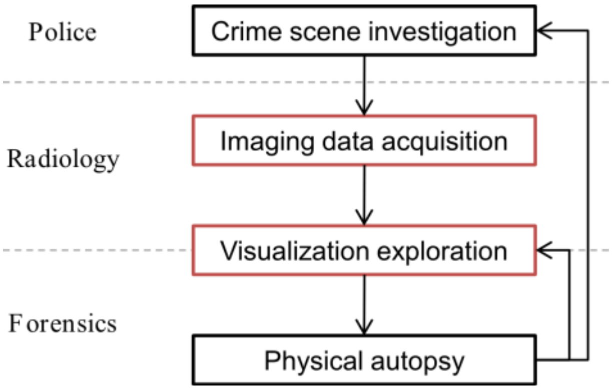

Figure 1: Example of virtual autopsy procedure from the forensic domain. Virtual autopsy activities, shown in red, are added to the traditional workflow and enable an iterative approach. The procedure is based on a continuous interaction between the forensic pathologist, the radiologist, and the police.

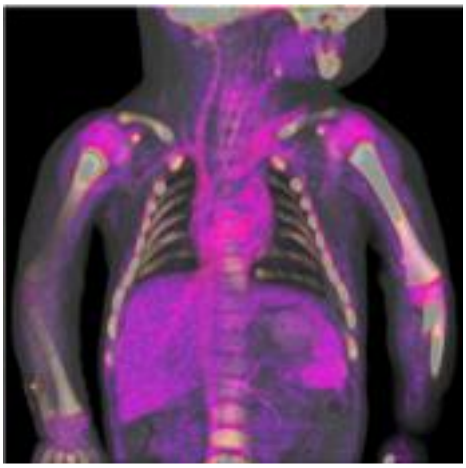

Figure 2: Post-mortem dual energy CT examination of a child. Visualization of hemosiderin (purple color). Great vessels and organ containing blood can be seen without any iodine contrast.

Figure 3: Post-mortem dual energy CT examinations can facilitate classifications of different tissue types, such as blood, soft tissue, tendons, and cartilage.

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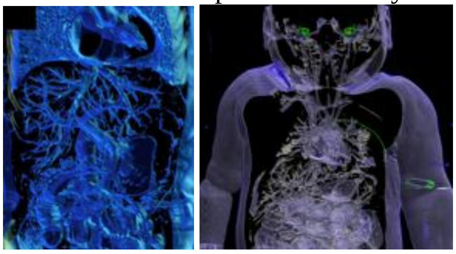

Figure 4: CT examinations were post-mortem gas in vessels can be used as a "negative" contrast agent. The stomach, intestines and the heart are filled with gas.

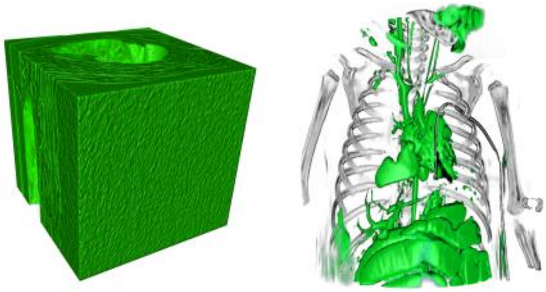

Figure 5: Visualization of air with spatial conditioning. Left: The result of applying a traditional Transfer Function displaying air, where air outside the body is highly obscuring. Right: Applying the spatial condition "Only render air when close to blood" for the same data set, revealing the autopsy-relevant parts.

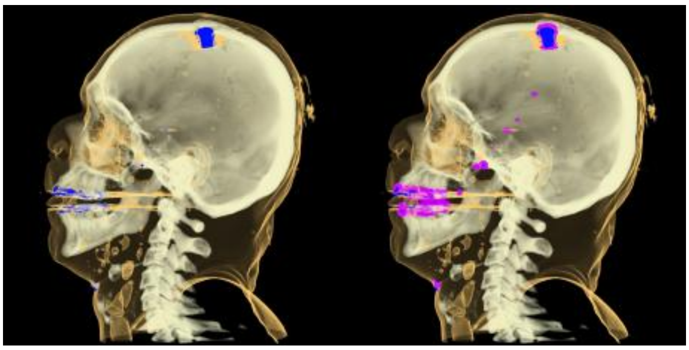

Figure 6: Left: Minor metal fragments (blue) may be difficult to locate. Right: Metal fragments are highlighted by extending the Transfer Function to render neighborhoods of metal fragments (purple).

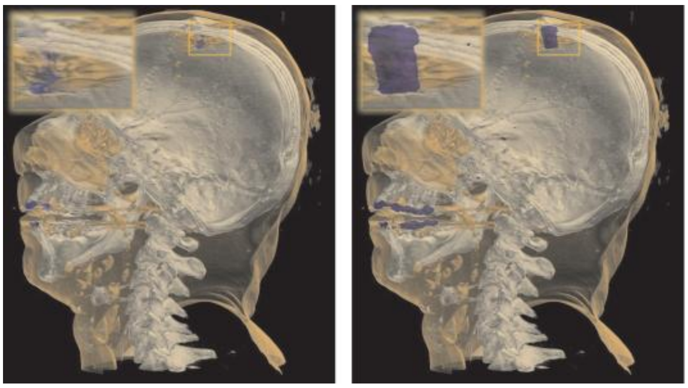

Figure 7: Left: Even though objects can have distinctive data values, they may be hard to detect in 3D, as the bullet in this case. Right: The dual TF rendering feature significantly improves localization of such objects.

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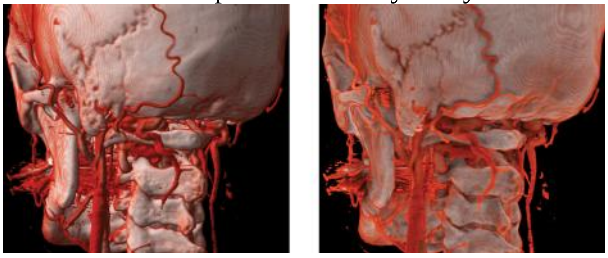

Figure 8: Left: Traditional shading. Right: Enhanced depth cues achieved through the Local Ambient Occlusion lighting model for virtual illumination.

Figure 9: The Visualization table, having post-mortem imaging as one of its targeted application domains.