Forensic-Case Analysis: From 3D Imaging to Interactive Visualization

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An interactive framework prepares raw computed tomography and magnetic resonance imaging scans for courtroom presentations. The framework makes use of combined computer graphics and computer vision techniques to enable a forensic case analysis workflow.

Forensic-case analysis relies heavily on digital information for documentation, especially to reconstruct accident and crime scenes and to present forensic findings in court.[1] Although forensic investigations have used photography for decades, interest has been recently increasing in 3D medical-imaging modalities such as computed tomography (CT) and magnetic resonance imaging (MRI).[2,3] The obvious benefit of these modalities is the possibility of imaging a whole 3D anatomy from the inside of the subject. This lets investigators retrieve additional forensic information that's often not visible from the outside.

Although forensically analyzing and presenting 2D photographs is an established courtroom method (despite potential difficulties in interpretation), working with 3D data (rather than photographs) requires more sophisticated tools. Directly presenting 3D data in the form of stacks of 2D images (that is, *slices*) isn't feasible in court because the number of slices is usually large and, even more important, requires a trained radiologist to interpret. For 3D volumetric data to be useful for courtroom presentations, we must reduce its complexity and have a forensic expert highlight the findings.

3D volume rendering addresses the need for appealing visualizations of CT and MRI scans.[4] However, in clinical forensics, the scans are usually restricted to relatively small regions of the body to limit the victim's exposure to harmful radiation (in CT) or to limit the scanning time (in MRI). Moreover, the need for high spatial resolution argues against full-body scans because injuries of forensic interest are often locally restricted. Nonetheless, injuries can be distributed over several body regions, and investigators can end up with a number of locally restricted scans. A full-body reference model must accompany these partial scans for them to be useful in courtroom presentations.

We've developed a software framework for analyzing and presenting forensic cases involving 3D volumetric data from medical-imaging modalities. This integrated, interactive framework supports all the necessary steps to process raw CT and MRI scans into courtroom-suitable presentations. All the components must work such that the elevated storage requirements and computational complexity are hidden from the user. Forensic experts should be able to use the tool freely to explore and manipulate the data with immediate feedback and without incurring frustrating waiting times, as if they were just processing 2D images from their digital camera. We address this high-performance requirement by leveraging recent improvements in parallel processing on the

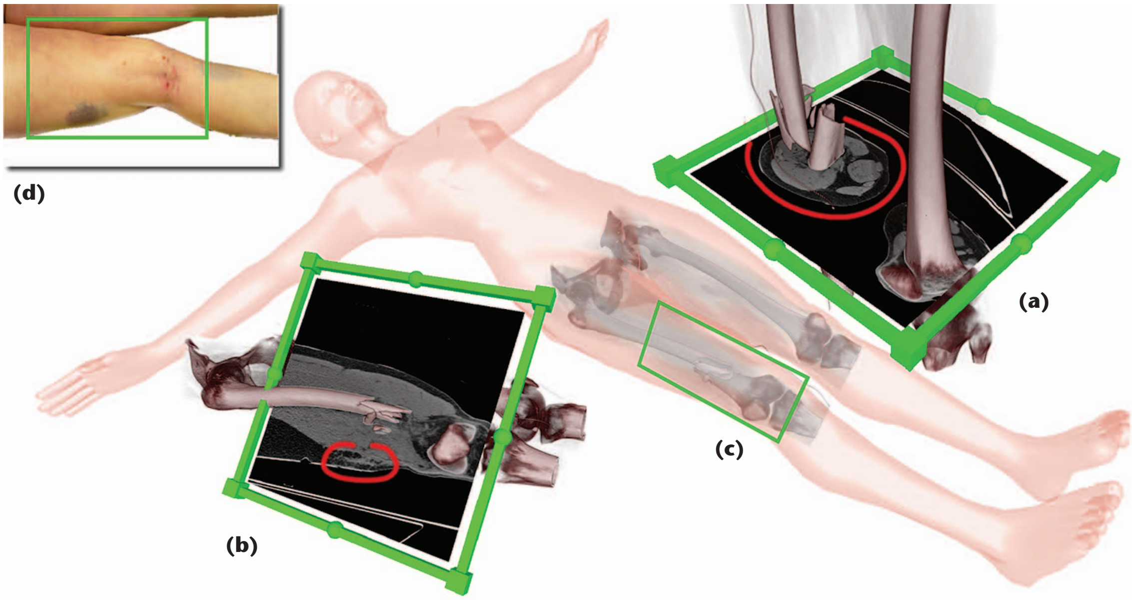

Figure 1. A forensic-case analysis and courtroom presentation—a CT scan of a motor vehicle accident victim. Volume rendering depicts bone structures and presents 2D slices showing the original gray values, with the red-circled regions highlighting (a) the fractured bone and (b) a hematoma. (c) A reference body model provides context for the data. (d) The presentation also employs a photograph from an external examination.

GPU through languages such as CUDA (Compute Unified Device Architecture) and by using relatively inexpensive multi-GPU workstations.

By using a flexible scene abstraction, our framework can also help prepare appealing courtroom-suitable visualizations in the form of images, videos, or interactive demonstrations. Figure 1 illustrates a case prepared with our framework: a car ran over a person, causing a fractured femur and hematoma. Our workflow visualizes all the data sources involved.

Requirements and System Overview

To support complex medical-imaging applications, computer vision and computer graphics must converge so that experts can command solutions from these two disciplines without unnatural or unproductive restrictions. So, when designing our framework, we analyzed forensic experts' goals and derived requirements from their workflow. We intend for the framework to help forensic experts visualize different information sources, segment and highlight forensically relevant information, and prepare intuitive courtroom presentations.

Visualization

The core visualization component must be able to work with different data sources (for example, 3D volumes, 3D geometry, and 2D photographs). Furthermore, users must be able to work with multiple datasets concurrently. So, we used Bernhard Kainz and his colleagues' rendering engine, which integrates volume rendering with surface geometry rendering in a way that's transparent to users; it's based on GPU-accelerated ray casting.[5] This engine allows the concurrent visualization of multiple volume or geometry datasets at interactive frame rates; thus, it's suitable for combining different sources of forensic information. See the "Multivolume Rendering" sidebar for more information.

Segmentation

To enhance presentations, findings of forensic relevance must be extracted and distinguished from other volumetric data. In computer vision, this process is called *segmentation*. Forensic-case analysis requires a generic, interactive 3D segmentation framework. Such a framework isn't designed for specific application cases (as is common in medical image segmentation) but allows flexibility in choosing the structures to extract. Structures of forensic interest might include bones, muscle tissue, hematomas, vascular structures, or injured organs.

We use an extensible segmentation mechanism that adapts to the difficulty of the given segmentation task. Adding increased amounts of prior knowledge into the segmentation models increases their complexity. So, as with the visualization component, the segmentation component relies on a highly parallel GPU implementation. See the "Two-Label Volume Segmentation" sidebar for more information.

Presentation

Courtroom presentations should present forensic

Multivolume Rendering

Direct volume rendering (DVR) has recently achieved interactive performance using GPU programming. Our research builds on that of Bernhard Kainz and his colleagues,[1] which allows real-time rendering of multiple volumes with arbitrary polyhedral boundaries. Such polyhedral DVR supports many simultaneous volumes, complex translucent and concave polyhedral objects, and Boolean operations of volumes and geometry in any combination.

Polyhedral DVR scales with only the volumetric dataset's memory footprint. Its performance doesn't depend strongly on the number of volumetric intersections in the scene. It's based on a software rendering pipeline written entirely for CUDA (Compute Unified Device Architecture), which lets us circumvent the limitations of the GPU's conventional fixed-function graphics pipeline. Low-latency local memory on the GPU accelerates the two computationally intensive stages of ray casting. First, hierarchical tiling with coverage masks rasterizes all polyhedral boundaries. Second, this method sorts by depth all fragments produced in the rasterization that cover a single pixel. It then forwards the results to the sampler, which steps along the ray and can adjust its sampling strategy at each depth segment's boundaries.

Unlike depth-peeling strategies,[2] which are conventionally used for directly rendering multiple volumes, polyhedral DVR traverses the scene only once. It's also fully flexible in interpreting current rays. Moreover, it can define the whole scene as a tree of Boolean operations with arbitrary depth.

This behavior is crucial for rendering multivariate or multivolume datasets. It also makes it easy to mix volume rendering and polygonal surface geometry. For example, a segmentation obtained by our framework can be used in both polygonal and voxelized form to constrain or alter the rendering of a larger enclosing volume.

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findings intuitively and present anatomical context in a way that people without radiological backgrounds can easily understand. This can be done with a reference body model. Presenting different information sources requires tools that align the different coordinate systems of 3D volumes, 2D photographs, and reference-model geometry into a common coordinate frame through registration algorithms. Presentations can also benefit from focus-plus-context visualization, in which presenters can highlight specific details while showing them in the context of the remaining dataset and reference model.[6] Focus-plus-context visualization is possible due to our flexible, multivolume visualization component. Animations to highlight relevant structures create an improved cue for forensic-case interpretation. Our framework can present them in the form of videos or interactive demonstrations.

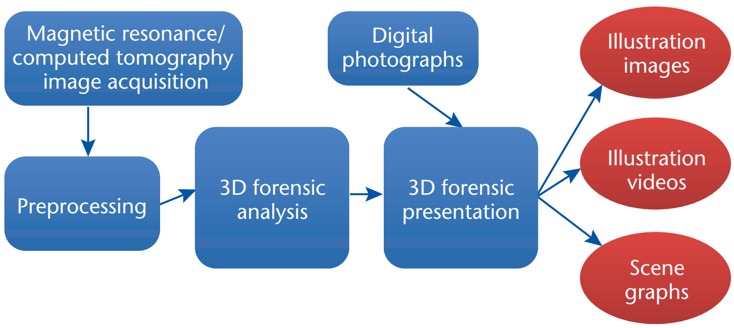

Figure 2. Our forensic analysis and presentation workflow. After image acquisition, preprocessing enhances the 3D volumes if necessary. Next, the analysis stage extracts forensically relevant structures from the 3D volumes. Finally, the presentation stage combines all available data, places it into a reference coordinate system, and allows the output of images, videos, or scene graphs describing the combined scene.

Workflow

We map forensic experts' requirements for analysis and courtroom presentations into a four-stage workflow (see Figure 2).

The image acquisition stage captures medical-imaging data (or it can also use photographs). The preprocessing stage simplifies the data representation and improves the image quality if necessary. The 3D-forensic-analysis stage extracts additional information from the given data. Finally, the 3D-forensic-presentation stage embeds all the data sources into a visualization, using reference models if necessary. This presentation tool then creates videos, still images, or interactive demonstrations. (For more information on the software components' implementation, see the "Implementation Details" sidebar.)

Image Acquisition

Our research doesn't focus on forensic investigations of virtual autopsies,[3] but rather on those of living subjects—an area where other technology had been inadequate. CT has very high resolution and

Two-Label Volume Segmentation

Extracting forensically relevant details requires flexible segmentation. Our core segmentation tool is an interactive foreground-background segmentation formulated as an energy minimization.

The underlying mathematical formulation describes a geodesic active contour (GAC) model that separates the foreground and background—that is, the hypersurface at the border between the foreground label and background label.[1] The GAC model can include prior knowledge of the gray-value distribution, the texture characteristics, and shape-constraint information of the foreground and background regions. We use a continuous formulation of GAC energy minimization in a variational framework.[2] The minimization of the GAC energy is equivalent to solving the weighted total variation (TV) model, with the benefit of the energy formulation being convex and converging to a global optimum representing the desired segmentation result.[3] Traditional segmentation approaches such as level-set methods are prone to get stuck in local minima.

The weighting g is related to edges in the input image $I(x)$; g is close to 0 for edge locations and 1 for homogeneous regions; λ is a weighting variable that determines the balance between the first term (regularization) and the second term (data fidelity). The GAC energy formulated as a weighted TV minimization is

$$\min_{u}\left\{\int_{\Omega} g(I(x))\left|\nabla u(x)\right| dx + \lambda \int_{\Omega} u(x) f(x)\, dx\right\}.$$

Given input image $I(x)$ in the domain $\Omega \subset \mathbb{R}^3$, we seek u, a binary labeling of the image into foreground ($u = 1$) and background ($u = 0$). The first term is the weighted TV regularization term, penalizing discontinuities in the segmentation via the gradient of u. The second term is a pointwise data term in which a positive $f(x)$ forces $u(x)$ to be background and a negative $f(x)$ forces $u(x)$ to be foreground. We call f our seed image.

The minimization of our convex energy formulation relaxes the nonconvex binary labeling $u \in \{0,1\}$ to the convex set $u \in [0,1]$. We can solve the convex minimization by deriving and solving the associated Euler-Lagrange equations. The solution is globally optimal for the user-specified foreground and background seeds in f.

We distinguish two types of seeds. *Hard segmentation seeds* are specified with $f = -\infty$ (foreground) and $f = \infty$ (background). We can use them for interactive segmentation refinement by removing or adding structures to the foreground. *Weak foreground seeds* use $f < 0$ to model a tendency to develop the foreground label both in the corresponding regions and regions similar to the seed region's gray values. At these regions, the data term tries to make $u = 1$. However, depending on λ, the regularization can still work toward $u = 0$. A weak background seed $f > 0$ works equivalently for the background region.

Our partial differential equations' numerical solver uses a primal-dual algorithm, in which a dual representation rewrites the weighted TV energy. A gradient descent on the primal unknown u combined with a gradient ascent on the dual variable solves the associated saddle point problem.[4] We can efficiently parallelize this algorithm in CUDA (Compute Unified Device Architecture).

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is often used to examine bone injuries; however, it emits harmful ionizing x-ray radiation. MRI doesn't involve harmful radiation and has a range of applications in soft-tissue imaging, owing to many possible scanning protocols; however, this flexibility requires an experienced physicist to help design protocols for different cases (for example, to depict hematomas).

Preprocessing

Depending on the acquired volumetric datasets' quality, some preprocessing might be necessary. We perform denoising using the Rudin-Osher-Fatemi model,[7] which implements a robust, edge-preserving reconstruction based on a total-variation energy minimization. (Although this model is suited for fast GPU implementation, it denoises offline for convenience.) After denoising, an optional resampling using tricubic interpolation reduces the input images' size to increase efficiency and compensate for the acquisition's anisotropic resolution. (Typically, the in-plane resolution is higher than the slice thickness.)

3D Forensic Analysis

Volumetric-data visualization requires a transfer function that maps intensity ranges from the medical-imaging source (typically 12-bit data) to color and opacity values. This mapping of intensities and intensity gradients (for lighting calculations) enables high-quality 3D volume renderings that are much better suited to courtroom presentation than the original stack of 2D grayscale images. Unfortunately, applying a transfer function alone makes it impossible to discriminate anatomical structures lying in the same intensity range. It also makes it impossible to emphasize structures of interest (for example, hematomas, bones, or injured organs) while retaining sufficient contextual structures for the visualized data.

To extract such structures, we need segmentation followed by multiobject visualization. The visualization displays the original volume data, segmentation results, and additional user-provided information (for example, arrows indicating an impact's direction). Segmentation also lets us derive quantitative indices such as a structure's mass or volume. The segmentation uses either a standard 3D-region-growing approach or an energy-minimization algorithm based on geodesic active contours (see the "Two-Label Volume Segmentation" sidebar).

Unlike most medical-analysis software, our framework lets users perform both segmentation and visualization concurrently and directly in the 3D view. This integrated approach (see Figure 3) avoids manual switching between separate segmentation and visualization tools, thereby accelerating the workflow by providing immediate feedback on the segmentation. So, interactively changing parameter choices for the segmentation algorithm becomes feasible.

The GUI provides users with a 3D view and optional 2D views (axial, coronal, or sagittal). Painting tools let users interact with the visualization (for example, by specifying seed regions), select regions of interest, and refine the segmentation. To define the structure to segment, the segmentation tool lets experts paint foreground and background seed regions directly on the volumetric structure or on an embedded cutting plane.

To quickly specify regions of interest, a space-carving tool lets users prune space by defining a screen space region from which the system constructs a geometric extrusion. It then voxelizes the extruded volume and uses it to restrict segmentation operations to a volumetric region of interest. We can combine results from several space-carving steps with Boolean operations to support more complex region-of-interest geometries.

3D Forensic Presentation

This stage uses the same core visualization module (described in the "Multivolume Rendering" sidebar) as the analysis stage. However, its objective isn't to identify and highlight relevant forensic findings but to combine and arrange different information sources into still, animated, or interactive illustrations. It arranges all the elements—volume data, segmentations, and supplementary geometry (such as reference manikins and photos)—into a scene graph that users can manipulate as needed with 3D direct-manipulation widgets.

Elements embedded in the scene graph can be instanced multiple times with different parameters such as a geometric transformation or a transfer function. Moreover, volume rendering can support a full set of Boolean operations on volumes. So, users can easily create in-place focus-plus-context techniques, such as a magic lens that makes the skin transparent above a region of interest to reveal the interior.

If a volumetric dataset encompasses a limited portion of the body, we can further register this dataset to a generic, anonymous reference manikin (provided by the Makehuman project; www.makehuman.org). This also lets users focus on

Implementation Details

All components must be integrated into a common software framework. We used the Qt library (http://qt.nokia.com) to create the GUI. We implemented both the volume ray casting and the segmentation subsystems in CUDA (Compute Unified Device Architecture), which significantly improves these tasks' performance compared to conventional GPU shading languages. So, the system greatly benefits from the processing power of recent GPU technology. We wrapped the rendering components in nodes of the scene graph Coin3D (www.coin3d.org), which makes creating, manipulating, and storing complex visual scenes easy.

The software intelligently distributes processing tasks to different GPUs if more than one is available. The test configuration for our case studies consisted of a workstation with a quad-core Intel i7 (6 Gbytes of RAM) and three Nvidia GTX 285 graphics cards (2 Gbytes of RAM each). After the initial uploading of the dataset to the GPU memory, all user interactions, such as specification of foreground and background seed regions or segmentation refinement, execute directly on the GPU for rapid feedback. In our implementation of the forensic analysis and presentation tools, we use one available GPU solely for analysis tasks running on its own thread and distribute the remaining GPUs to the core volume rendering in a parallelized fashion. Each GPU renders a part of the final frame. Scheduling prioritizes rendering over segmentation processing for the sake of interactivity.

We also provide a way to perform demanding computations transparently over the network on a dedicated GPU server (an Nvidia Tesla S1070, in our environment), using the Ice software library (www.zeroc.com) for remote-object communication.

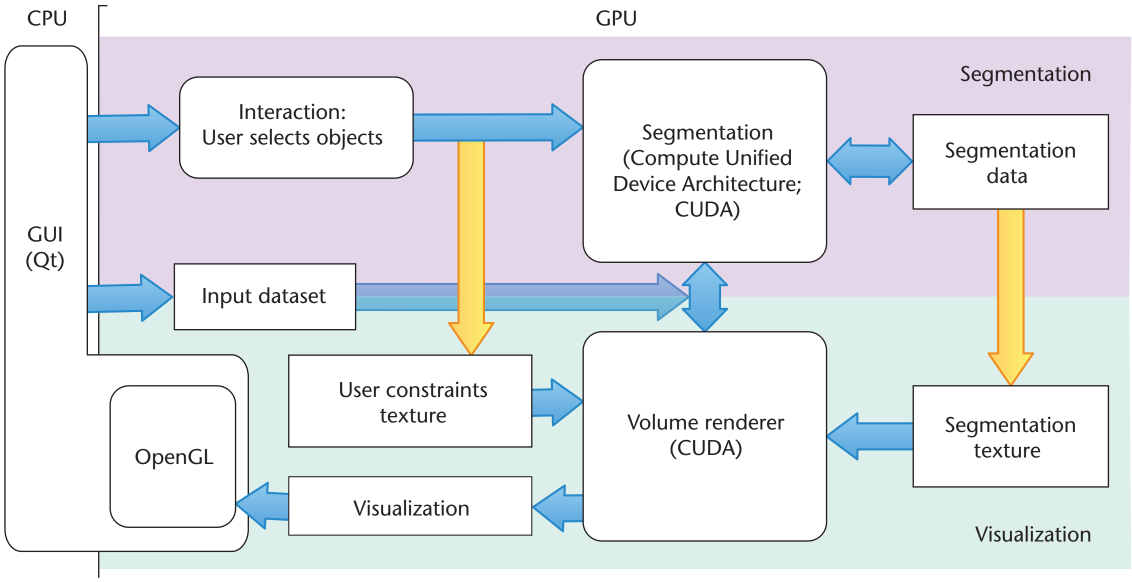

Figure 3. Conventional approaches separate segmentation and visualization into sequential tools. In contrast, our integrated segmentation and visualization system provides immediate feedback on intermediate or final segmentation results and enables more efficient interaction.

forensic data in the context of the whole body—a crucial issue for intuitive presentation.

The registration employs deliberately placed or anatomically derived markers that are available on both the reference model and dataset. This provides a rough, rigid registration, which the system refines using a surface-based, iterative closest-point algorithm. After registration, the system aligns the surfaces from the reference model and the outer surface of the 3D volumetric scan and places the structures of forensic interest into the reference coordinate system.

Case Studies

The following two case studies illustrate the use of our framework.

A Broken Clavicle

In this case, the 20-year-old male subject was involved in a motor vehicle accident (as the driver in a frontal car crash) and had a fastened seatbelt. The heavy impact broke his right clavicle.

The victim's thorax CT was available; it contained the fractured right clavicle. To demonstrate the injury, we decided to visualize both clavicles—the fractured and the unharmed one—in the context provided by the volumetric CT data. (We didn't have to place the CT scan into a reference body model for courtroom presentation because the bodily context was clearly visible.)

We denoised the CT input volume and cropped a portion of the dataset so that the body surface of the CT scan still gave a good indication of the injury's overall location (see Figure 4a). We had to downsample the dataset from its original resolution to 256 × 256 × 256 voxels for further processing.

First, we loaded the CT data into the 3D-forensic-analysis tool (see Figure 4a) to interactively segment the clavicles. To segment the right clavicle, we quickly specified a region of interest around it, using space carving (see Figure 4b). This set up the rough location for the following detail segmentation, which distinguished the bone from a nearby tubular structure with similar density.

We painted foreground and background seed regions to specify which structure we wanted to segment (see Figure 4c). By removing unwanted structures, we refined the segmentation results (see Figure 4d). Finally, we stored the refined segmentation (see Figure 4e) for later use. We repeated this procedure for the unharmed left clavicle. After producing the segmentations, we combined all our information sources (the volumetric dataset and segmentation datasets) into one scene.

Using the 3D-forensic-presentation tool, we further arranged the scene. Using a different transfer function, we placed a spherical-geometry object in the main volume. Although that volume showed the skin as context, the spherical focus used a low-opacity transfer function and revealed the fractured clavicle (see Figure 4f). We animated the sphere so that motion cues further improved the presentation (see the video at http://biomedrix.icg.tugraz.at/videos/ieee_cg_a/ieee_cg_a_video.avi).

We could also freely arrange the segmented clavicles (see Figure 4g). This technique could aid further investigations, such as estimating the likely direction of the force that broke the bone and, in turn, the chain of events leading to the accident.

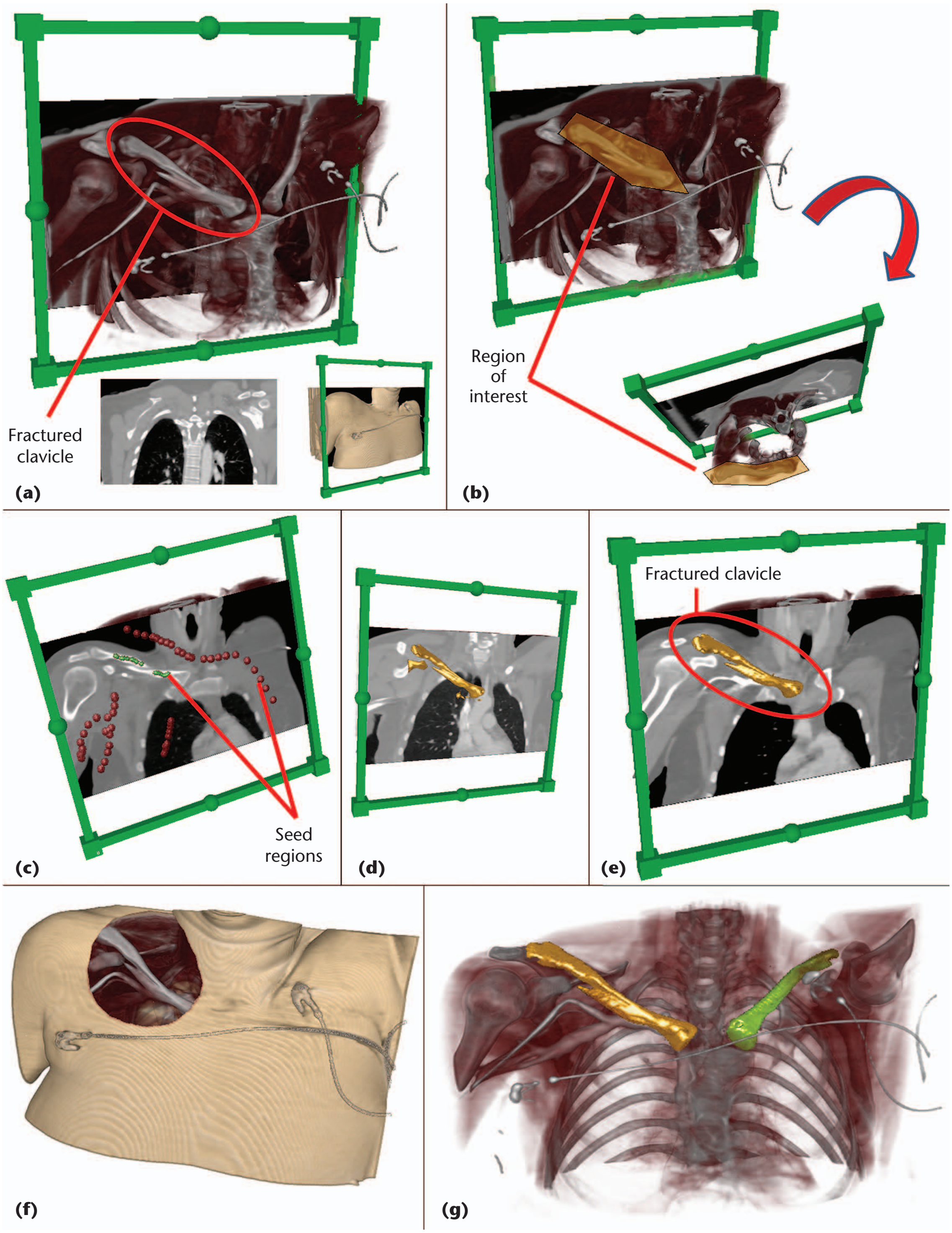

Figure 4. The workflow of the fractured-clavicle case. (a) A volume rendering shows the clavicle; the smaller visualizations depict the context of the body surface and the slice through the volume (the green rectangle). (b) The space-carving approach specifies a region of interest, restricting the segmentation. (c) Seed regions mark background (red) and foreground (green) objects. (d) The initial segmentation result is cluttered. (e) We refine the previous image to produce a new image of the fractured clavicle. (f) A separate image presents the data in a focus-plus-context fashion. (g) The two segmented bone structures are visualized together with the volume rendering.

A Hematoma

This case consisted of two MRI volumes showing a rough localization and detailed depiction of a hematoma in the left gluteus after a sports accident. A T1 weighting in a spin-echo sequence[8] acquired the first volume, which provided an overview of the left hip and upper thigh (see Figure 5a). However, this image doesn't show much contrast

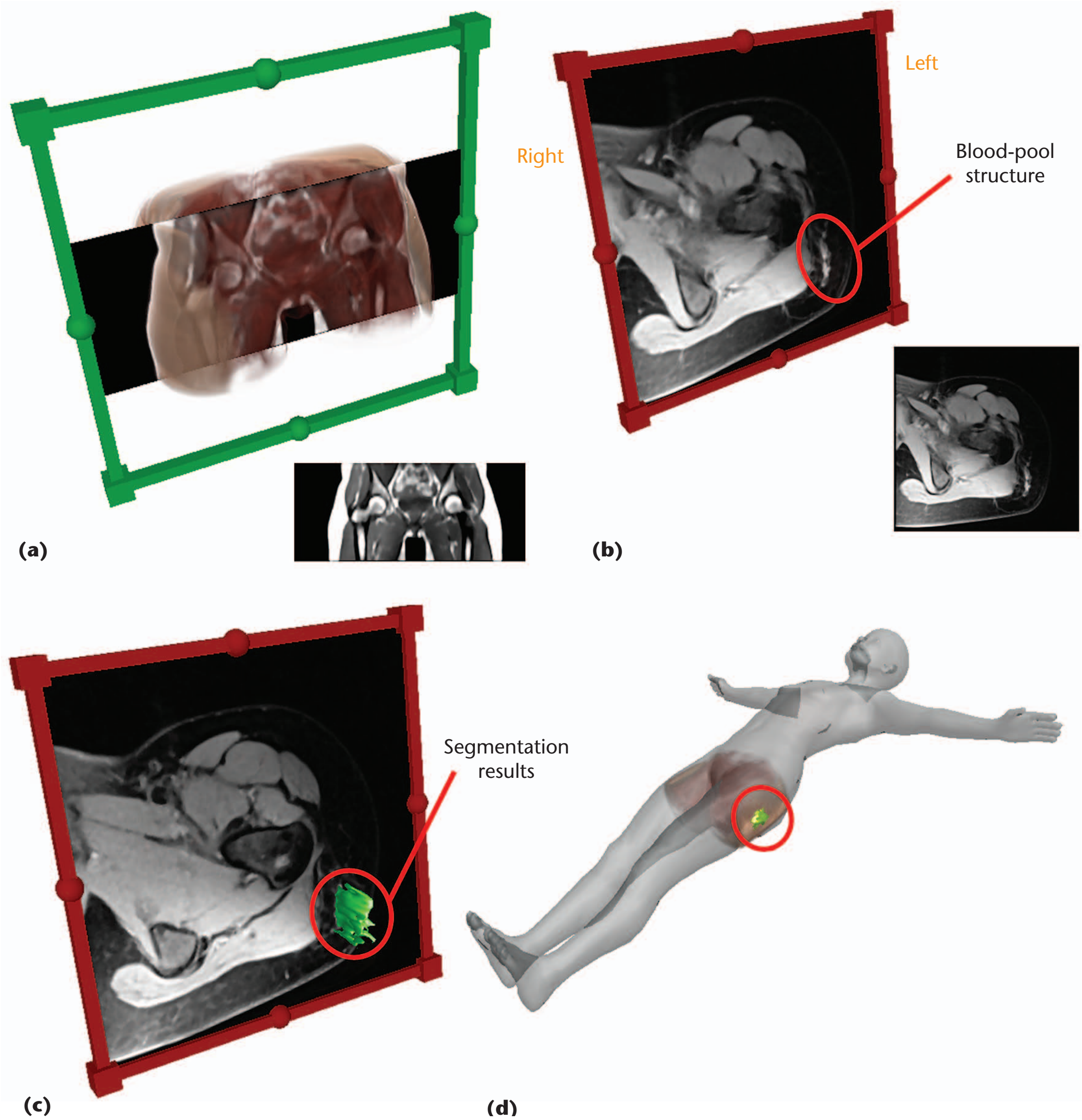

Figure 5. The workflow of the hematoma case. (a) The volume rendering shows the T1-weighted scan and a coronal slice through the volume. (b) The proton-density scan shows a good contrast in the hematoma. However, anyone but a radiologist would have difficulty interpreting the depicted slice. (c) The segmentation of the blood pool is visualized together with the volume-rendered T1 scan. (d) The virtual reference body model includes the hematoma visualization.

in the blood pool, so diagnosing the hematoma from it would be difficult.

The second volume was a proton-density scan, again with a spin-echo sequence and fat saturation enabled to suppress the MR signal in the fatty tissue. This contrast made localizing the blood-pool structure easier because the blood pool remained unchanged by the fat saturation. The second scan (see Figure 5b) shows the left gluteus in higher resolution.

The forensic interest in this case is in visualizing the blood pool indicating a hematoma, which might not be visible from the outside. Unfortunately, this blood pool is a very local structure with a fuzzy appearance, which makes defining it difficult. Radiologists have little experience with imaging subcutaneous tissue lesions because these lesions usually have no clinical relevance. However, such lesions can give forensic experts important clues for analyzing and forensically reconstructing a case. If we only have slices from the MRI detail, nonradiologists will have difficulty interpreting the anatomy. A further motivation for volumetric analysis and presentation of the hematoma is the need for privacy, which could restrict showing photographs of injuries in courtrooms in the future.

In preparing this case, we first segmented the blood-pool structure (see Figure 5b) from the MRI scan detail. Because the blood pool showed good contrast with the surrounding tissue, we used the region-growing segmentation algorithm for this task. The green structure in Figure 5c shows the segmentation results.

For the presentation, we created a scene containing the segmentation result, the T1-weighted MR scan of the hip and upper thigh, and our reference body model. We performed surface-based iterative closest-point registration on the reference body model and the MR datasets. Because the datasets didn't contain markers, we manually initialized the registration. This visualization could be the basis for determining the force directions that led to the hematoma or investigating dependencies between internal and external injuries. Furthermore, you could derive quantitative indices from this representation. (For example, in this case, the blood-pool volume was 4.13 milliliters.)

We're extending our framework to provide a more generic analysis tool and investigating segmentation models involving stronger prior knowledge. In this way, we intend to deal with forensic-analysis tasks in which our framework currently has limitations, such as investigating tubular structures and structures with strong shape constraints.

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