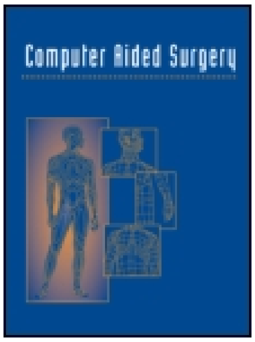

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Volume Cutting for Virtual Petrous Bone Surgery

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ABSTRACT A profound knowledge of anatomy and surgical landmarks of the temporal bone is a basic necessity for any otologic surgeon. Because this knowledge, so far, has been mostly taught by limited temporal bone drilling courses, our objective was to create a system for virtual petrous bone surgery that allows the realistic simulation of specific laterobasal surgical approaches. A major requirement was the development of an interactive drill-like tool, together with a new technique for realistic visualization of simulated cut surfaces. The system is based on a volumetric, high-resolution model of the temporal bone, derived from CT. Interactive volume cutting methods using a new multivolume scheme have been developed. In this scheme, cut regions are modeled independently in additional data volumes using voxelization techniques. The voxelization is adapted to successive cutting operations as needed for the simulation of a drill-like tool. A new visualization technique was developed for artifact-free rendering of sharp edges, as formed by the intersection of a cut and an object surface. The new multivolume visualization technique allows high-quality visualization of interactively generated cut surfaces. This is a necessity for a realistic simulation of petrous bone surgery. Our system therefore facilitates comprehension of the complex morphology, and enables the recognition of surgical landmarks, which is most important if injury to delicate organs (e.g., the facial nerve or auditory ossicles) is to be avoided. The system for virtual petrous bone surgery allows the simulation of specific surgical approaches with high-quality visualization. The user can learn about the complex three-dimensional anatomy of the temporal bone from the viewpoint of a real otosurgical procedure. Comp Aid Surg 7:74–83 (2002). ©2002 Wiley-Liss, Inc.

Key words: **surgery simulation; petrous bone surgery; volume visualization; voxelization; subvoxel resolution; haptic rendering**

INTRODUCTION

The simulation of surgical procedures using virtual anatomical models is a rapidly growing field in medical imaging. This is due on the one hand to the availability of *virtual reality* techniques, and on the other to the availability of detailed virtual anatomical models. However, applications in surgery simulation have to overcome conflicting requirements regarding the complexity and accuracy of the anatomical model and the speed of interaction with the model. Most of these applications concentrate on the simulation of elastic deformation of soft tissue and, for the sake of interactivity, use simplified

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anatomical models which are often based on surface representations. Such models are inherently not capable of representing the interior structure of objects. Moreover, simulation of cutting operations is a far less developed field, and simulation systems either do not include cutting operations at all, or only include them in a simplified manner that does not reproduce the "look and feel" of a real incision.

The simulation of petrous bone surgery has quite different requirements: the model, due to the complex surgical anatomy of the temporal bone, must be of high accuracy, and the simulation and visualization of cutting (or drilling) operations must be achieved with high precision. On the other hand, the simulation of soft-tissue deformation is not of high importance and can, therefore, be neglected. For a profound comprehension of surgical landmarks and approaches to the middle ear, a precise spatial perception during dissection is needed, which so far can only be achieved by temporal bone drilling. Because the availability of the cadaveric bone material needed for temporal bone drilling courses is limited, there is a strong demand for alternative training methods. A system for virtual temporal bone surgery that meets the above-mentioned requirements could fill this gap.

Therefore, the goal of the work presented here is the development of a system for virtual petrous bone surgery that allows realistic simulation of specific laterobasal surgical approaches. To achieve this goal, a major requirement is the development of an interactive drill-like tool with which the user can lay open the access path to the middle ear. The key point here is that the drilling process produces irregular surfaces that cannot be visualized directly. We developed new methods for the representation, modeling, and high-quality rendering of arbitrarily shaped cut regions within the volume model. Although the system is not intended for training in tactile surgical skills, the integration of haptic feedback is used to enhance the realism of the procedure and to ease navigation.

RELATED WORK

Three-dimensional (3D) visualization of medical data has frequently been used for a wide variety of applications, ranging from surgical planning through computer-assisted intraoperative navigation to surgical simulations. Most often, datasets produced by imaging modalities like Computer Tomography (CT) or Magnetic Resonance Imaging (MRI) form the basis for 3D modeling of anatomical structures. These volumes are represented as 3D rectilinear grids of volume elements (voxels), where each voxel is associated with a density value. For more sophisticated applications like 3D anatomical atlases,[1,2] this representation scheme has been extended in such a way that each voxel specifies a set of scalar properties and/or attributes (classification, color, material properties, etc.).[3–5]

In the field of volume visualization, many methods for the rendering of 3D objects into 2D images have been developed over the past decades, and can mainly be characterized in three different classes: surface extraction,[6] direct volume rendering,[7–9] and direct surface rendering.[10, 11] The latter category is also known as volume-based surface rendering.

Volume interaction or interactive manipulation of volumetric objects is a far less developed field.[12,13] This is especially true for applications in surgical simulation, where most applications use surface-based models[14,15] or geometric primitives like tetrahedra.[16–19]

In the past decade, the field of *volume graphics*[20] has attracted increasing interest. Volume graphics is concerned with modeling and rendering of synthetic scenes out of geometric models. Within the scope of the work presented here, there are two important aspects of volume graphics: *voxelization*, the generation of volumetric representations for geometric models, and *volume sculpting*, the interactive manipulation of volumetric objects. Some voxelization techniques are based on binary volume data,[21–23] which are not suited for medical applications. The nonbinary (or alias-free) voxelization of geometric objects is a well-studied subject.[24–26] More recently, voxelization methods for the conversion of polygonal meshes,[27–29] parametric surfaces,[30] or implicit surfaces[11] have been developed. A common feature of these methods is that they are not capable of representing arbitrarily formed surfaces.

Volume sculpting techniques are based on the notion of sculpting complex volume objects from solid material, for example, voxel-based tools can be used to interactively remove or add material.[5,31,32] These methods often utilize techniques from the field of *constructive solid geometry* (CSG) or its extension to volume data, *constructive volume geometry* (CVG).[33–35] All of these techniques are based on (mostly boolean) operations between voxel values. This is not sufficient for a precise simulation of cutting or drilling tools.

Virtual 3D models of the temporal bone have been developed for surgical planning[36] and educational[37,38] purposes, but these applications do not provide manipulative tools for drilling simulations.

Systems for the simulation of temporal bone surgery in a virtual reality environment have been proposed by Wiet et al.[39] and John et al.[40] Both are based on hardware-accelerated volume rendering, and the dissection of bone is simulated by the elimination of voxels. This approach does not provide high-quality visualization.

Our work is aimed mainly at the accurate visualization of both the anatomical model and the interactively generated cut surfaces. Therefore, existing volume interaction methods cannot be applied directly, and we propose a new approach that integrates a multivolume representation and interactive cutting tools, together with a high-accuracy, subvoxel-resolution surface rendering method.

MATERIALS AND METHODS

Multivolume Representation

We created a 3D volume model of the temporal bone based on CT (156 slices, 512 × 512 pixels, 1 mm slice thickness, 0.33 × 0.33 mm pixel size). Within the model, 30 objects such as the mastoid bone and the semicircular canals were defined using a semiautomatic threshold-based segmentation approach.[41,42] Structures like the auditory ossicles or the facial nerve have been segmented using a volume editor, with which the user can manually separate objects.

These anatomical objects are represented in a 3D rectilinear grid of volume elements, where each voxel is associated with a value (density) and a set of attributes, such as its membership of anatomical regions or color. This level is equivalent to the previously described *generalized voxel model*.[3] Additionally, this basic representation scheme can be linked to a knowledge base consisting of object descriptions and their relations.[43]

For achieving the new functionality of interactive specification and representation of cut-out regions, we extended the scheme to a multivolume representation, where cut-out regions are not only represented by an additional attribute, but also have their spatial representation in a different data volume. As the representation of cut-out regions is not static, but subject to changes during the interactive specification process, it is important to have this independence from the original volume model. This way, the original object information is available at any point of a cut-out region, and all operations can be easily reversed.

Volume Cutting

Attributes at the voxel level are apparently limited to the resolution of the underlying data volume, and do not provide means for a proper visualization of cut surfaces. Therefore, the irregular cut surface resulting from gradual cutting or drilling operations has to be represented in a way that allows the exact determination of location and inclination at any point on the surface. Theoretically, this could be achieved by using the geometrical description of the cutting tool directly, but because a cut surface is formed by hundreds of small cutting operations, the determination of this complex surface would be computationally too expensive for interactive purposes. Therefore, we use the conversion of the geometric description of the cutting tool (or drill) into a volumetric representation (voxelization).

A number of methods have been developed for the voxelization of geometric objects (geometric primitives, polygonal meshes, parametric or implicit surfaces) .that allow the generation of alias-free 2D renderings. The voxelization process resembles the partial-volume effect as it would be generated by an imaging device. This effect is a prerequisite for a high-quality estimation of surface normals, as needed for shading purposes. For rendering surfaces in tomographic volume data, the *gray-level gradient* method[10,44] has proven to be accurate, and by using a voxelization technique, this method can be applied for visualization of arbitrarily shaped cut surfaces.

For specification of cuts, we implemented interactive tools that can be moved arbitrarily in 3D space. The tip of such a tool can be parameterized in many ways, such as by shape, size, and "sensibility," which means if and how objects can be affected by a virtual instrument. This allows the flexible imitation of different instruments, such as a scalpel, drill, or laser beam. Once the shape and position of a tool have been specified, the volume to be cut out is voxelized. Voxelization is done using a weighted filtering technique, with which the tool tip (represented geometrically or as a polygonal mesh) is sampled at subvoxel resolution (Fig. 1).

Whenever this process results in a gray value that satisfies the threshold definition of the cut region, the voxel has to be labeled.

Progressive Cutting

In contrast to other voxelization techniques, which aim at the conversion of one object into its volumetric counterpart, we use voxelization for the simulation of progressive cutting with a "scalpel-like" tool. Here, it is important to preserve existing cut surfaces, and it is not sufficient to voxelize the tool tip alone. Additionally, the amount of an ex-

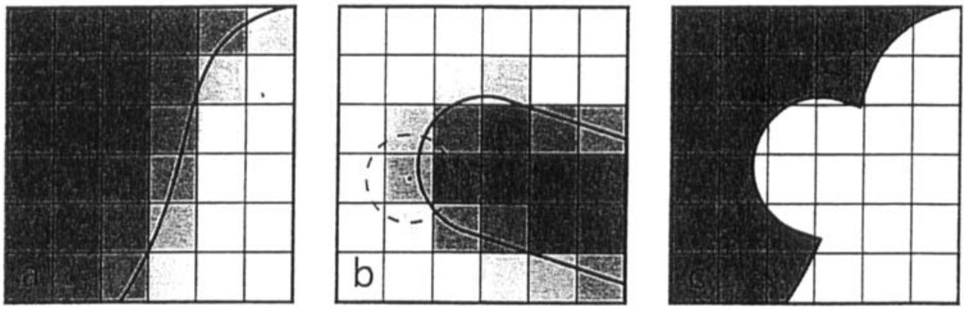

Fig. 1. Volume cutting: (a) Representation of an object surface in a 2D grid of pixels. The different shades of gray are due to the partial volume effect introduced by the imaging device. (b) Voxelization of the cutting tool. A filtering technique is used to simulate the partial volume effect. The dashed circle shows the filter support. (c) The resulting cut surface.

isting cut region that is unaffected by the new cutting has to be determined.

Accordingly, it is important to note that it is not sufficient to voxelize the tool and combine the resulting voxel value with the value of the voxel representing the existing cut surface. This approach is commonly used by volume sculpting techniques or in the field of constructive solid geometry (CSG). The correct amount of an unaffected cut region can only be calculated by performing voxelization of the tool and resampling of the existing surface simultaneously, and combining the results at subvoxel resolution (Fig. 2). This way, every surface point (location and inclination) of a irregularly formed cut surface can be determined within subvoxel resolution.

The key point here is that sharp edges are formed by the intersection of a cut surface and a surface of an object. These edges cannot be represented properly in a standard voxel model, thus leading to rendering artifacts. Some approaches use smoothing filters to reduce rendering artifacts,[35,45] but this technique also smooths out the edges. Hence, these techniques are not applicable in the field of surgical simulations, because the edges of a cut should be modeled as precisely as possible. Therefore, our approach combines the independent multivolume representation of both the anatomical model and the cut-out regions together with a new visualization technique that allows artifact-free rendering of surface intersections.

Multivolume Visualization

Multivolume visualization is the rendering of volumetric scenes incorporating multiple volume represented objects from, for example, different imaging modalities or simulated volume data. The generation of a volumetric scene from multiple volumetric objects requires the combination of these objects in a true volumetric fashion.

This combination can be achieved by merging the different volumes into a single volume prior to visualization[46–48] or by combining the data from different volumes during the ray-casting process.[4,49] These techniques have been used for many different applications, such as radiotherapy treatment planning[50,51] or anatomical atlases.[52,53] All these applications are based on voxel-by-voxel op-

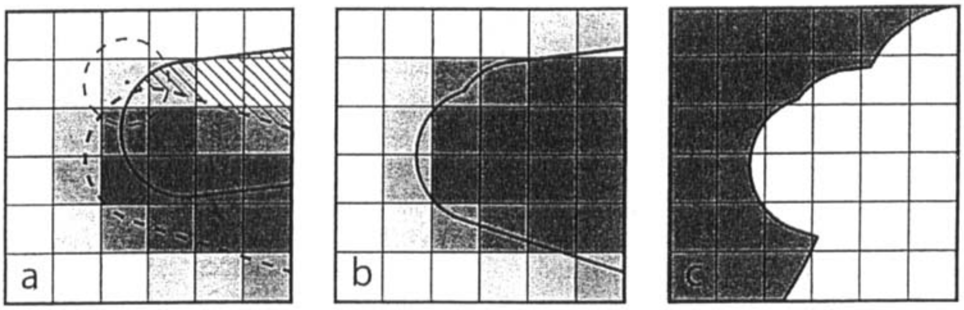

Fig. 2. Progressive cutting: (a) For a successive cutting operation, only the hatched area has to be considered. Thus, the existing cut (dashed contour) has to be resampled during voxelization (dashed circle shows the filter support). (b) Representation of the new cut surface with partial volume effect. (c) The resulting cut surface.

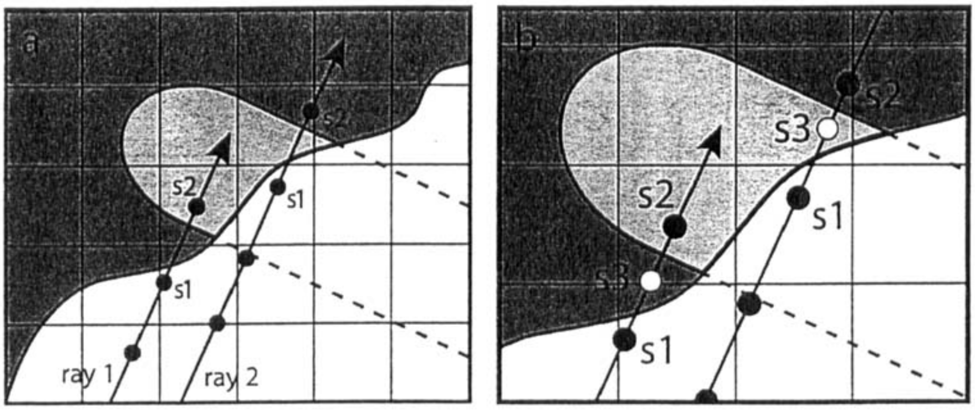

Fig. 3. Adaptive sampling. (a) Two situations with two surfaces between successive sample points (S1 and S2). Ray 1: a part of the object is missed; Ray 2: a removed part is visualized. (b) Additional sample points S3 are generated, and the object at this position is determined. Thus, the correct surfaces are used for visualization.

erations, in which a new value is calculated according to a merging rule or a CSG operation. This way, the information about the exact location of the different surfaces is lost and, in the case of object intersections, the combined resulting surface can only be an approximation. In particular, sharp edges cannot be represented and rendered using these techniques.

The new quality of the presented visualization technique originates from the combination of data from multiple volumes at subvoxel resolution during ray-casting. A prerequisite for this combination is the technique for subvoxel classification of multi-attributed volume data presented in ref. 54. With this technique, the existence of an object boundary (iso-surface) between successive sample points is detected during the ray-casting process. Such a boundary is indicated by a change of the classification result for a given object from one sample point to the successive one. Once a boundary has been detected, its exact location is calculated using a bisection technique.

In multivolume visualization, however, it often occurs that more than one surface is located between sample points. This is the case for intersections, where objects penetrate each other, and in situations where a part of an object has been cut out. In both cases, a decision has to be made as to which surface is to be visualized. For applications that do not incorporate cutting simulations, the surface nearest to the image plane, or viewer, can be chosen. Unfortunately, the situation is more complicated for applications that involve removal of object parts, and usage of such a simple rule would lead to severe artifacts in the rendered image: (a) visualization of cut surfaces without an object; (b) visualization of removed object parts; and c) missing an object part. Hence, a method for the exact determination of the topology of a constructed volumetric scene had to be developed. Theoretically, this could be achieved by straightforward subsampling, but in practice it would be computationally far too expensive.

We therefore developed the method of *adaptive sampling* (Fig. 3), which allows distinction between an object surface and a cut surface at subvoxel resolution, and hence allows rendering of intersections without artifacts.

This distinction has to be made whenever multiple surfaces between successive sample points have been detected, because this indicates object intersections. For each surface, it must be determined which part of which object forms this surface, and if this part is visible or has been cut out. Therefore, additional sample points between successive surfaces are generated. Because the location of each surface has been calculated using the above-described method, the additional sample points can be positioned exactly between successive surfaces. At each of these points, the object, which is bounded by these surfaces, is determined using multivolume classification. If this object is not to be visualized (e.g., if it has been removed), the next additional sample point will be classified or the ray-casting process will be continued. This way, the decision as to which object is to be visualized can be made correctly, and the above-mentioned artifacts are avoided. In summary, the main steps of the *adaptive sampling* method are:

1. Classification at new sample point

2. Subvoxel localization of all borders between successive sample points
3. Classification of objects between successive borders
4. If a visible object has been found: calculation of surface normal and shading; otherwise: continue with step 1.

Haptic Rendering

We integrated both haptic rendering and 3D specification into our system for virtual petrous bone surgery. For this purpose, we use a 3-degree-of-freedom haptic device (PHANTOM 1.0A, SensAble Technologies, Inc., Woburn, MA). The main challenge here was to achieve a haptic rendering of the anatomical model with the same resolution as the visual rendering. Most techniques for haptic rendering are based either on surface representations or volumetric representations with a limited spatial resolution,[5,55] and thus could not be used directly for this purpose. We therefore developed an extended technique for haptic rendering of complex anatomical models with interactive manipulation capabilities. Because this technique is based on exactly the same ray-casting algorithm as described in the previous section, a congruent visual and haptic display is achieved. A detailed description of this technique can be found in ref. 56.

RESULTS

The described multivolume visualization scheme introduces new capabilities for applications like surgical simulation or interactive 3D atlases. Volume cutting can be simulated in a flexible and interactive fashion. The independent modeling of cut-out regions using an adapted voxelization technique, together with a novel ray-casting method for visualization of cut surfaces and object intersections, makes it possible to render even sharp edges, as formed by cutting operations, without artifacts.

Figure 4 demonstrates the capabilities of the described method for applications in osteotomy. Parts of the soft tissue have been removed using a "virtual scalpel," and two parts of the skull have been resected and repositioned. The movement of objects in the volume model is simulated using an extended ray-casting algorithm, as described earlier.[57] It can be seen that the surfaces generated by sectioning can be visualized with high accuracy, even when the scene is zoomed (Fig. 4b). The sharp edges of the intersections of the cut surfaces and object surfaces are visualized without artifacts.

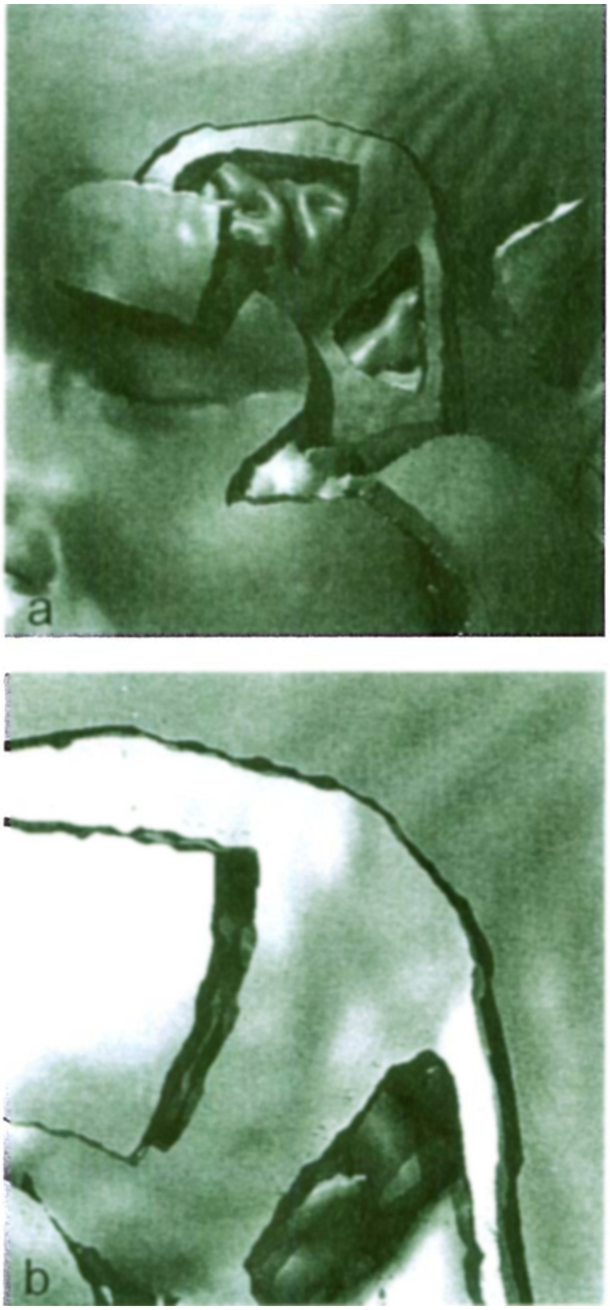

Fig. 4. Application of volume cutting in osteotomy: (a) Parts of the soft tissue have been removed using a "virtual scalpel," and two parts of the skull have been resected and repositioned. (b) A detailed view. It can be seen that the surfaces generated by sectioning can be visualized with high accuracy, and that sharp edges, formed by the intersections of the cut surfaces and the object surfaces, are visualized without artifacts.

As a major application, we developed a system for virtual petrous bone surgery. The temporal bone has a very complex anatomy, with several delicate organs of minute size embedded in dense bone. One of the main difficulties of surgery in this

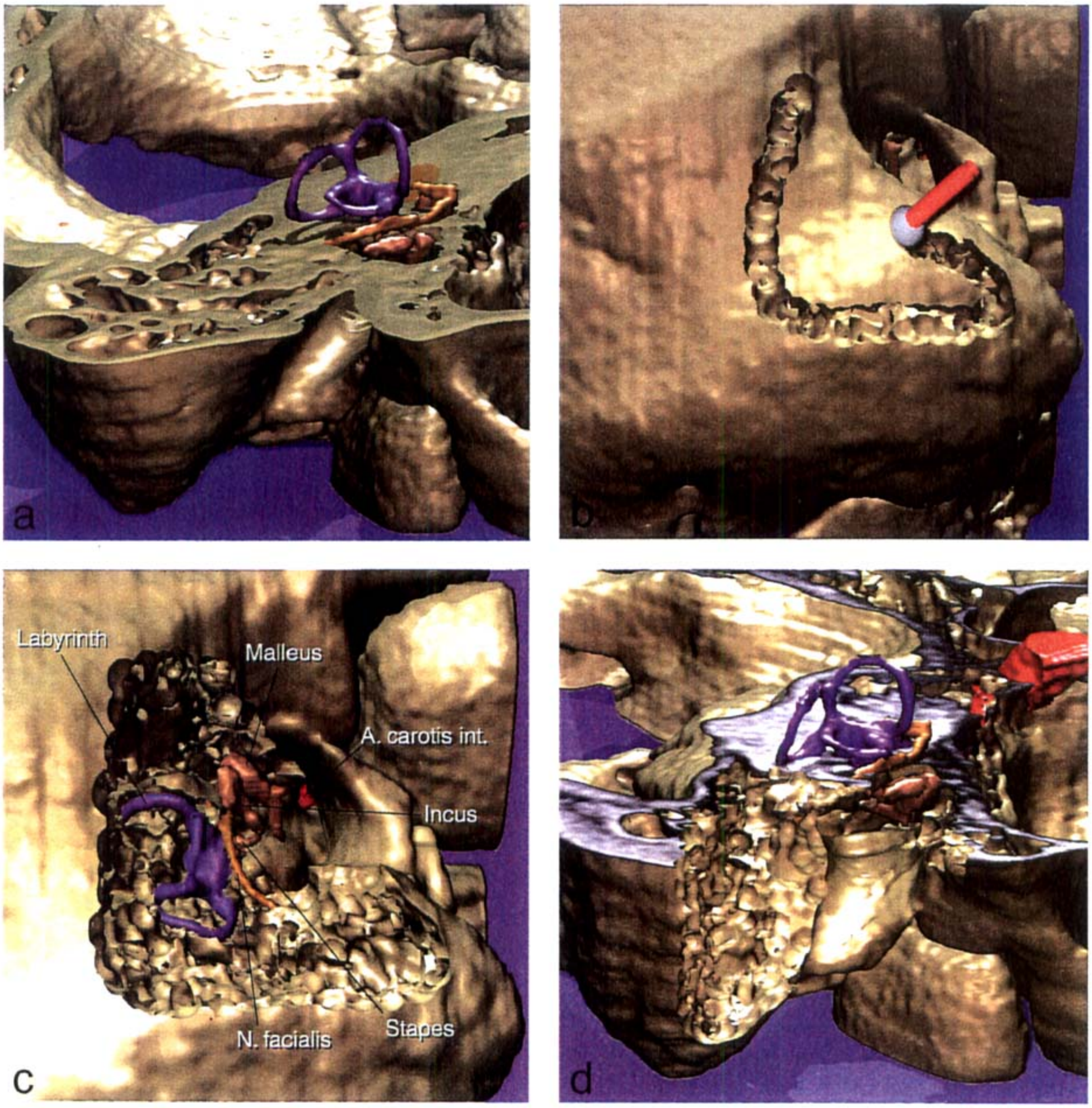

Fig. 5. Virtual petrous bone surgery: (a) Model of the temporal bone showing the structures of the inner ear (e.g., auditory ossicles, semicircular canals). (b) The view of the surgeon during the procedure. Parts of the mastoid bone have been opened using the virtual otologic drill. (c) The result of the simulation of a radical mastoidectomy. Additionally, parts of the labyrinth and the facial nerve have been revealed. (d) Cut planes can be used for inspection of the region "in depth" at every stage of the surgery. This enables the user to check his performance.

region is avoiding injury to these organs, as this could lead to severe pathologies like deafness or facial paralysis.

Therefore, a profound knowledge of the anatomy and surgical landmarks of the temporal bone is a basic necessity for any otologic surgeon. This knowledge is still mostly taught by temporal bone drilling using cadaveric material. Because temporal bone drilling courses are limited in number, a virtual model of the petrous bone surgery that enables the student or trainee surgeon to simulate different laterobasal surgical approaches would be of high value. This simulation can only be achieved with a model that represents the complex anatomy of the temporal bone in an adequate manner, together with a simulation of an otologic drill that allows entry into the temporal bone in a realistic way. Accordingly, at each stage of the procedure, the simulated cut surfaces have to be visualized with high accuracy to enable the user to recognize surgical landmarks and to understand the complex 3D arrangement of the structures within the temporal bone.

We developed a system for virtual petrous bone surgery based on the described multivolume representation and visualization scheme. The model of the temporal bone is shown in Figure 5a. A cut plane has been used to reveal the inner structures, such as the labyrinth and auditory ossicles. In Figure 5b, the view of the surgeon during the procedure is shown, and parts of the mastoid bone have been opened using the virtual otologic drill. The virtual tool can be positioned arbitrarily and oriented within the model using the force-feedback device, thus allowing realistic handling. Because only those parts of the model that have been modified are re-rendered during the procedure, the simulation of drilling is achieved at interactive speed. With this system, specific laterobasal surgical approaches can be simulated, and the user can learn about the complex 3D anatomy of the temporal bone from the viewpoint of a real otosurgical procedure. Figure 5c shows the result of a simulated radical mastoidectomy. Additionally, parts of the labyrinth and the facial nerve have been revealed. Comprehension of the complex spatial topology is easily accessible, and can be further improved by using a stereoscopic mode for display. Because the model of the temporal bone is volumetric, cut planes can be used to check the success of the drilling operation (Fig. 5d).

Fig. 6. Configuration of the simulator for virtual petrous bone surgery. The position of the surgeon's hands, patient orientation, and viewing direction are similar to those in the real procedure, and spatial perception is enhanced by stereoscopic viewing.

DISCUSSION

We have presented a new method for volume cutting which provides a basis for a wide field of applications in the field of planning and rehearsal of surgical interventions. It is based on a new multivolume scheme for representation and visualization that allows the interactive simulation of cutting or drilling operations using complex anatomical models. Here, the multivolume representation, together with the developed ray-casting method (*adaptive sampling*), leads to a high-quality rendering of cut surfaces, and even sharp edges, formed by intersection of a cut and the surface of an object, can be visualized without artifacts, which could not be achieved with previous volume-based approaches.

The capabilities of this novel approach were demonstrated with the application for virtual petrous bone surgery. We developed a virtual otologic drill of adjustable size and shape, with which the user can enter the temporal bone, thus simulating specific laterobasal surgical approaches. High-quality visualization of both the model and the cut surfaces facilitates the comprehension of the complex morphology in this region and enables the recognition of surgical landmarks, which is most important to avoid injury of delicate organs (e.g., the facial nerve or auditory ossicles).

Precise simulation of drilling is achieved by using a force-feedback device, and spatial perception is further enhanced by stereoscopic viewing. Furthermore, the configuration of the simulator provides a position of the surgeon's hands, patient orientation, and viewing direction similar to those in the real procedure (Fig. 6). Due to the limited availability of alternative teaching methods (cadaveric bone drilling), the presented system for virtual petrous bone surgery is of high value for educational purposes. For the planning of patient-specific operations in clinical routine, the system has to be extended by a robust and fast segmentation method. So far, due to the amount of time (2–3 h) necessary for the preparation of a single model, it is only applicable for special cases.

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