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Volume Cutting for Virtual Petrous Bone Surgery

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Abstract

Objectives: A profound knowledge of anatomy and surgical landmarks of the temporal bone is a basic necessity for any otologic surgeon. Since this knowledge, so far, is mostly taught by limited temporal bone drilling courses, our objective was to create a system for virtual petrous bone surgery, which 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.

Methods: The system is based on a volumetric, high-resolution model of the temporal bone, derived from CT. Interactive volume cutting methods using a new multi-volume scheme have been developed. In this scheme, cut regions are modelled 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, for the artifact-free rendering of sharp edges, as formed by intersections of a cut and an object surface, was developed.

Results: The new multi-volume visualization technique allows the high-quality visualization of interactively generated cut surfaces. This is a necessity for a realistic simulation of petrous bone surgery. Therefore, our system facilitates the comprehension of the complex morphology and enables the recognition of surgical landmarks, which is most important to avoid injury of delicate organs (e.g. facial nerve, auditory ossicles).

Conclusion: The system for the 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.

Keywords: surgery simulation, petrous bone surgery, volume visualization, voxelization, sub-voxel resolution, haptic rendering

Introduction

The simulation of surgical procedures using virtual anatomical models is a rapidly growing field in medical imaging. This is, on one hand, due to the availability of *Virtual Reality* techniques, and on the other hand, due to the availability of detailed virtual anatomical models. However, applications in surgery simulation have to overcome conflicting requirements of 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, utilize simplified anatomical models, which are often based on surface representations. Inherently, such models are 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 in a simplified manner, which do not provide the ‘look and feel’ close to 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 respectively) operations must be achieved with high precision. On the other hand, the simulation of soft tissue deformation is not of high importance and therefore, can 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. Since cadaveric bone material which is needed for temporal bone drilling courses has a limited availability, there is a strong demand for alternative training methods. A system for virtual temporal bone surgery which meets the above mentioned requirements could fill this gap.

Therefore, the goal of the work presented is the development of a system for virtual petrous bone surgery which allows the realistic simulation of specific laterobasal surgical approaches. For this, 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 which cannot be visualized directly. We developed new methods for the representation, modelling and high quality rendering of arbitrarily shaped cut regions within the volume model. Although training tactile surgical skills is not intended in the first place, the integration of haptic feedback is used to enhance the realism of the procedure and to ease navigation.

Related Work

3D visualization of medical data has frequently been used for a wide field of applications, spanning from surgical planning, computer assisted intra-operative navigation to surgical simulations. Most often, datasets produced by imaging modalities like Computer Tomography (CT) or Magnetic Resonance Imaging (MRI) build the basis for 3D modelling 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 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 a 2D image have been developed over the past decades, which can mainly be characterized by 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 surgery simulation, where most applications utilize surface based models[14,15] or geometric primitives like tetrahedra.[16–19]

In the past decade, the field of *Volume Graphics*[20] has gained increasing interest. Volume graphics is concerned with modelling and rendering of synthetic scenes out of geometric models. Within the scope of the work presented here, there are two aspects of volume graphics of importance: *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 is not suited for medical applications. The non-binary (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. These methods have in common 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, e.g. 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) respectively.[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. 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.[39,40] Both of them 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 aims mainly on 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 integrating a multi-volume representation and interactive cutting tools together with a high accuracy subvoxel resolution surface rendering method.

Material and Methods

Multi-Volume Representation

We created a 3D volume model of the temporal bone based on CT (156 slices, 512x512 pixels, 1mm slice thickness, 0.33mm * 0.33mm pixelsize). Within the model 30 objects such as the mastoid bone and the semicircular canals were defined using a semi-automatic 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 to 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 multi-volume representation, where cut out regions are not only represented by an additional attribute but 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 easily be reversed.

Volume Cutting

Apparently, attributes at voxel level are 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 gradually 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 since 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 utilize the conversion of the geometric description of the cutting tool (or drill respectively) 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), which 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.

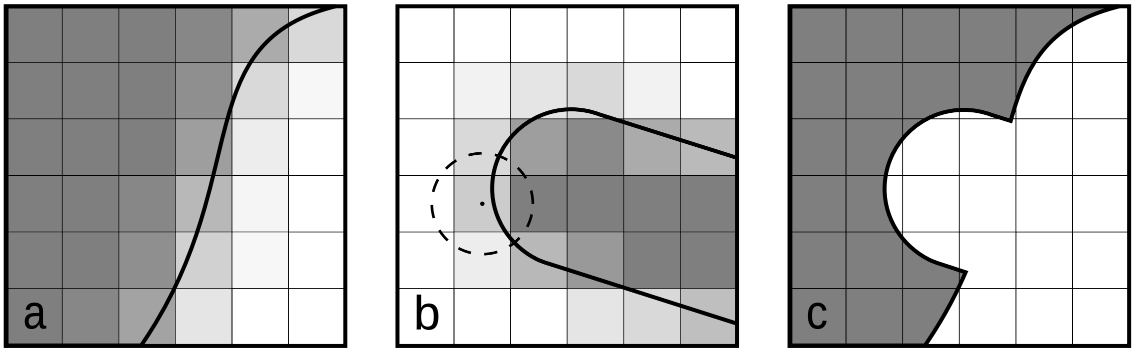

Figure 1: Volume Cutting: **a:** Representation of an object surface in a 2D grid of pixels. Different shades of gray are due to the partial volume effect, introduced by the imaging device. **b:** Voxelization of the cutting tool. A filtering technique is used to simulate the partial volume effect. The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

For specification of cuts we implemented interactive tools which can be moved arbitrarily in 3D-space. The tip of such a tool can be parameterized in many ways , e.g. 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 like a scalpel, a drill, or a laser beam. Once 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, which is represented geometrically or as a polygonal mesh, is sampled at sub-voxel resolution (Fig. 1). Whenever this process results in a gray value which 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 utilize the 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 only. Additionally, the amount of an existing cut region which is unaffected by the new cutting has to be determined.

Hereby, it is important 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 voxelization of the tool and resampling of the existing surface simultaneously and combining the results at sub-voxel resolution (Fig. 2). This way, every surface point (location and inclination) of a irregularly formed cut surface can be determined within sub-voxel resolution.

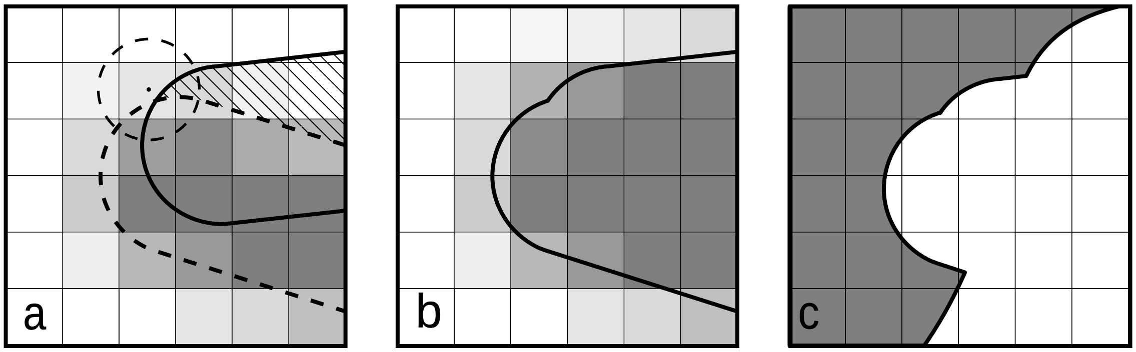

Figure 2: Progressive Cutting: **a:** For a successive cutting operation, only the hatched area has to be considered. Thus, the existing cut (dashed contour) has to be resampled during voxelization (dashed circle shows the filter support). **b:** Representation of the new cut surface with partial volume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

The key point here is, that sharp edges are formed by the intersection of a cut surfaces 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 in order to reduce rendering artifacts,[35, 45] but this technique at the same time smoothes out the edges. Hence, these techniques are not applicable in the field of surgery simulations, since the edges of a cut should be modelled as precisely as possible. Therefore, our approach combines the independent multi-volume representation of both the anatomical model and the cut out regions together with a new visualization technique, which allows the artefact-free rendering of surface intersections.

Multi-Volume Visualization

Multi-volume visualization is the rendering of volumetric scenes incorporating multiple volume represented objects, e.g. from 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, like radiotherapy treatment planning[50,51] or anatomical atlases.[52,53] All these applications are based on voxel-by-voxel operations, with 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. Especially 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 sub-voxel resolution during ray-casting. A prerequisite for this combination is the technique for sub-voxel classification of multi-attributed volume data presented in.[54] With this technique, the existence of an object boundary (iso-surface) between successive sample points is detected during the ray casting process. Hereby, 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.

However, in multi-volume visualization 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 which surface is to be visualized. For applications, which do not incorporate cutting simulations, the surface nearest to the image plane, or viewer respectively, can be chosen. Unfortunately, the situation is more complicated for applications which 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 straight forward sub-sampling, but practically it would be computationally far too expensive.

Therefore, we developed the method of *adaptive sampling* (Fig. 3), which allows the distinction between an object surface and a cut surface at sub-voxel res-

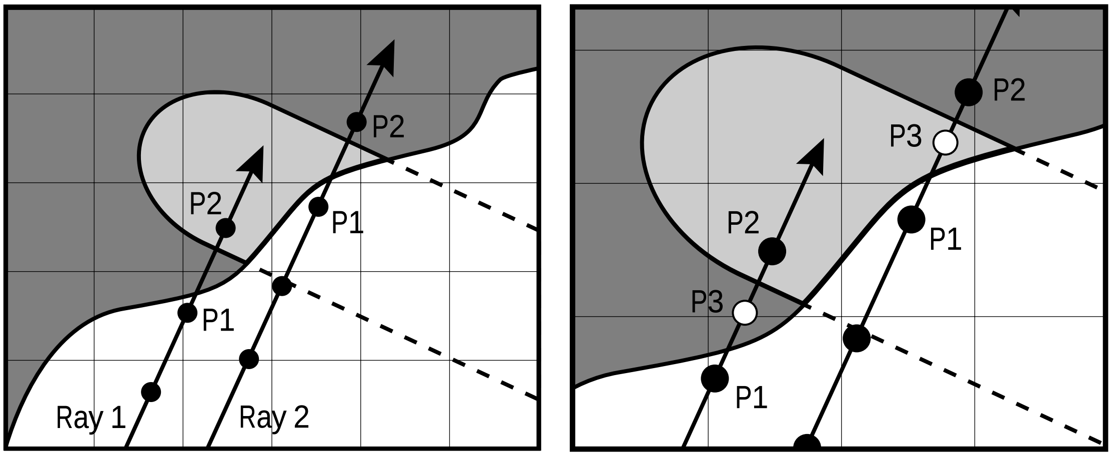

Figure 3: Adaptive Sampling. **a:** Two situations with two surfaces between successive sample points (P1 and P2). Ray 1: A part of the object is missed. Ray 2: A removed part is visualized. **b:** Additional sample points P3 are generated and the object at this position is determined. Thus, the correct surfaces are used for visualization.

olution and hence allows rendering of intersections without artifacts. This distinction has to be made whenever multiple surfaces between successive sample points have been detected, since this indicates object intersections. For each surface, it has to 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. Since 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 multi-volume classification. If this object is not to be visualized (e.g. it has been removed), the next additional sample point will be classified or the ray casting process will be continued. This way, the decision, 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. sub-voxel localization of all borders between successive sample points
3. classification of objects between successive borders

4. if a visible objects 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 is computed. 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 directly be used for this purpose. Therefore, we developed an extended technique for haptic rendering of complex anatomical models with interactive manipulation capabilities. Since 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 is found in Petersik, et al.[56] .

Results

The described multi-volume 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 modelling 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 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, 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 the object surfaces are visualized without artifacts.

As a major application we developed a system for the 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 region is to avoid the injury of these organs, as this could lead to se-

Figure 4: Application of volume cutting in osteotomy: **a:** Parts of 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.

vere 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, so far, is mostly taught by temporal bone drilling using cadaveric material. Since temporal bone drilling courses are limited in numbers, a virtual model of the petrous bone surgery, which enables the student or training surgeon to simulate different laterobasal surgical approaches, would be of high value. This simulation can only be achieved with a model, which represents the complex anatomy of the temporal bone in an adequate manner together with the simulation of an otologic drill, which allows to enter the temporal bone in a realistic way. Hereby, at each stage of the procedure, the simulated cut surfaces have to be visualized with high accuracy, in order 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 multi-volume 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, like the labyrinth and the 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 arbitrarily be positioned and oriented within in the model using the force feedback device, thus allowing a realistic handling. Since only these parts of the model, which 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. The comprehension of the complex spatial topology is easily accessible and can be further improved by using a stereoscopic mode for display. Since the model of the temporal bone is volumetric, cut planes can be used to check the success of the drilling operation (Fig. 5d).

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 multi-volume scheme for representation and visualization which allows the interactive simulation of cutting or drilling operations using complex anatomical models. Here, the multi-volume representation together with the developed ray-casting method (*adaptive sampling*), leads to a high quality

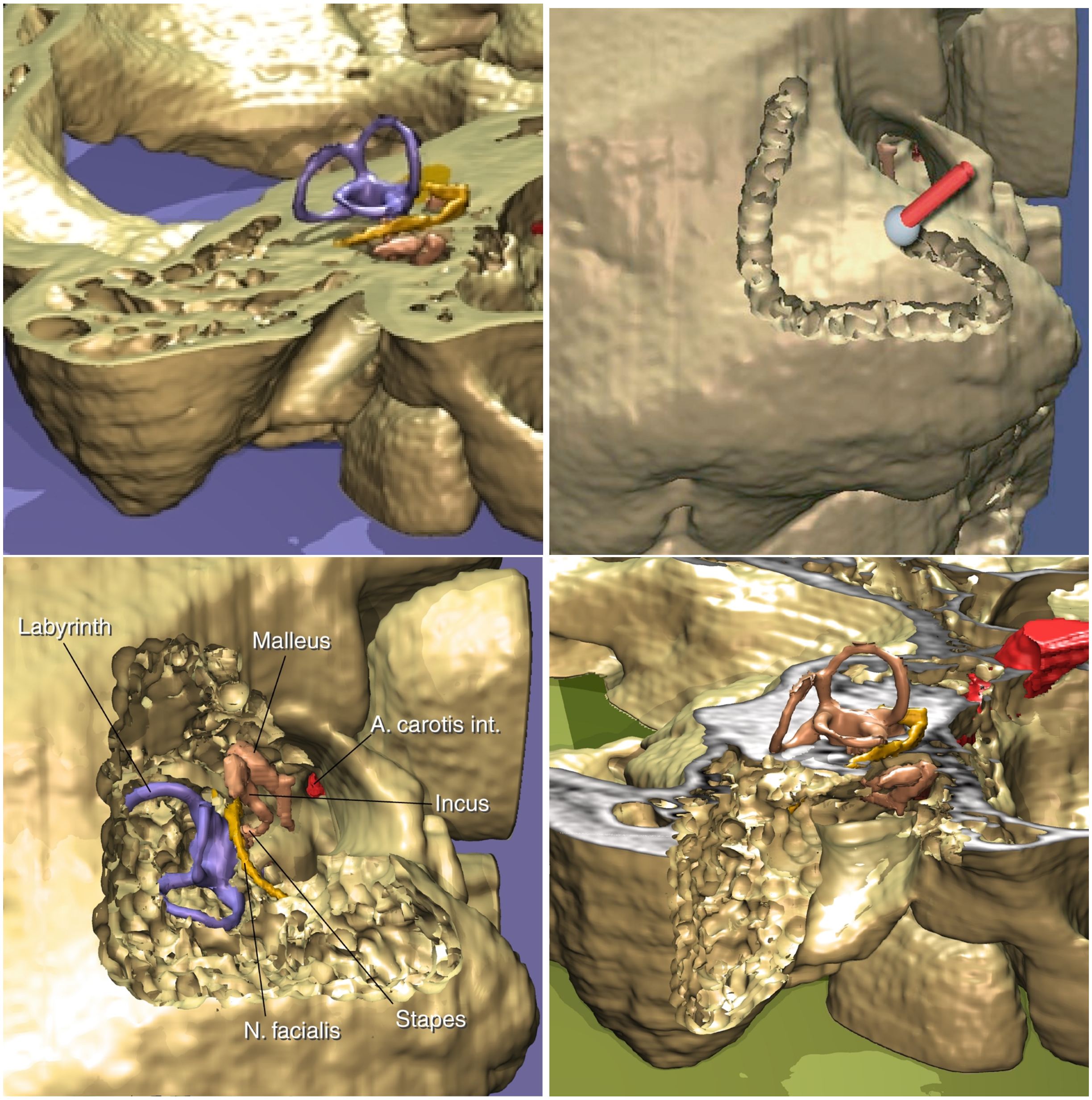

Figure 5: Virtual petrous bone surgery: **a:** model of the temporal bone showing the structures of the inner ear (e.g. auditory ossicles, semicircular canals). **b:** the view of the surgeon during the procedure. Parts of the mastoid bone have been opened using the virtual otologic drill. **c:** The 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 during surgery. This way, the user can check his performance.

rendering of cut surfaces and even sharp edges, formed by intersections of a cut and the surface of an object, can be visualized without artifacts, which could not be achieved with previous volume based approaches.

We demonstrated the capabilities of this novel approach 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. facial nerve, auditory ossicles). The precise simulation of drilling is achieved by using a force feedback device and the 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 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 hours) necessary for the preparation of a single model, it is only applicable for special cases.

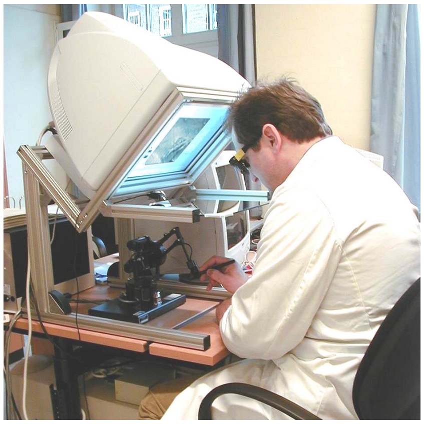

Figure 6: Configuration of the simulator for virtual petrous bone surgery: the position of the surgeon's hands, patient orientation and viewing direction similar to the real procedure and spatial perception is enhanced by stereoscopic viewing.

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