Accelerating Virtual Surgery Simulation for Congenital Aural Atresia

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ABSTRACT

In this paper, we proposed a new efficient implementation for simulation of surgery planning for congenital aural atresia. We first applied a 2-level image segmentation schema to classify the inner ear structures. Based on it, several 3D texture volumes were generated and sent to graphical pipeline on a PC platform. By exploiting the texturing-mapping capability on the PC graphics/video board, a 3D image was created with high quality showing the accurate spatial relationships of the complex surgical anatomy of congenitally atretic ears. Furthermore, we exploited the graphics hardware-supported per-fragment function to perform the geometric clipping on 3D volume data to interactively simulate the procedure of surgical operation. The result was very encouraging.

Keywords: Virtual surgery planning, congenital aural atresia, segmentation, 3D reconstruction, texture-based rendering, graphics board.

1. INTRODUCTION

Surgical repair of congenital aural atresia is challenging and complex. Preoperative computerized tomography (CT) is essential in surgical planning. Conventional two-dimensional (2D) CT demonstrates the key anatomic structures, including the stapes, middle ear space, inner ear, and facial nerve. 2D CT is limited, however, in its ability to represent the spatial relationships between these important structures. Computer-enhanced 3D CT is a major advance over conventional CT for demonstrating the complex spatial relationships in congenitally atretic ears[1].

Surgery for congenital aural atresia is challenging in part because of the complex anatomy of the structures within the temporal bone. The internal structures within the temporal bone, such as facial nerve and stapes, are even more critical to the success of this type of surgery. Three dimensional reconstructions have previously allowed us to display the surface contour anatomy of the temporal bone[3,4], and this has occasionally been helpful for judging the feasibility of surgical reconstruction. A more complete computer aided virtual surgery planning might advance it by visually present the procedure of a surgery and show different reconstructions, which made it more predictable and comparable, therefore more feasible[2].

In recently years, texture-based volume rendering with direct support from graphics hardware becomes an overwhelming tendency[6,7], with which not only the image quality and performance could be significantly improved, but also some special effect, such as geometric clipping, could be achieved[8]. The high performance can be realized by currently available PC platform with an inexpensive graphics/video card. We applied this advanced graphics technique to the virtual surgery planning for congenital aural atresia.

In this paper, we proposed a new implementation that exploits texture-mapping hardware for graphical rendering to present surgery simulation reconstructions on a PC platform. In next section, we will outline our technique for surgery planning, and briefly describe our 2-level image segmentation schema to classify the inner ear structures. We will also give the implementation detail to render congenital atresia ear structure exploiting the multi-texturing capability on the PC graphics/video board, and how we exploit the graphic hardware supported per-fragment operation function to perform the geometric clipping on 3D volume to simulate the procedure of surgical operation. In last two sections, we will show the results and draw our conclusions.

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Medical Imaging 2004: Visualization, Image-Guided Procedures, and Display, edited by Robert L. Galloway, Jr., Proceedings of SPIE Vol. 5367
(SPIE, Bellingham, WA, 2004) · 1605-7422/04/$15 · doi: 10.1117/12.535689

2. VIRTUAL SURGERY PLANNING

Our previous work[1,2] advanced a technique for the virtual surgery planning for congenital aural atresia. With this technique, the congenital ear first underwent the CT scan through a high-resolution helical scanner. Then a two-level image segmentation schema was applied on the CT dataset to distinguish structures in the temporal bone. An interactive tool was used to mark the facial nerves. After that, the segmented dataset was sent to the graphical pipeline to extract the contour of anatomy structures and interactively displayed on screen to show the spatial relationships of inner ear structures as well as their surrounding transparent temporal bone. A virtual surgery was performed to subtract a cylindrical volume bone lateral to the atresia plate, and show possible results, which made the surgery planning more predictable and comparable and, therefore, more feasible. We provided all these functions through a prototype visualization system[2].

One kernel function of this project was to display the contour of anatomy structure with surrounding transparent object. Our previous 3D reconstruction was surface-based which applied classical Marching Cubes method to segmented dataset to extract isosurfaces of anatomy structures and used two-pass rendering to create desired 3D images. In recently years, texture-based volume rendering exploiting texture-mapping hardware becomes an overwhelming tendency that might bring higher image quality and improved rendering performance. Further, some extra effects, such as geometry operation, may easily be performed through intensive texturing unit programming. We aimed to apply this advanced graphical technique to virtual surgery planning project. We utilized NVidia's GeForce GPU to support texture-mapping operation and implemented required functions through its register combiner programming[10].

In the rest of this section, we would give the details of the new implementations of some kernel techniques with the project, which included two-level segmentation schema, texture-mapping based 3D reconstruction and virtual surgery simulation.

2.1 Two-Level Segmentation

Segmentation is the basis to almost all medical applications. The problem with 3D imaging of the temporal bone is that the relevant anatomic structures (stapes, facial nerve) are difficult to separate from the bone which surrounds them. Different structures within the temporal bone have similar intensity values and are difficult to separate because of the complex anatomy of the ear and the low tissue contrast of the CT image. A two-level segmentation scheme was developed to solve this problem.

At the low-level, the region of ear was roughly extracted by removing the background with the help of region-growing technique since the background was of very low intensity value on CT image. The voxels in the ear region were then segmented into several classes using segmentation methods described in [5]. One method classified voxels based on their local intensity value vector. In this study, all intensity values of the second-order neighbor for a given voxel consisted of its local vector, and local vectors associated with all voxels in the ear region formed a series of vectors. After that, the well-known principle of components analysis was employed to extract feature vector series from the series of local vector. The feature vectors were clustered by a modified self-adaptive on-line vector quantization algorithm. Finally, the voxels were classified according to the classification of their feature vectors. The segmentation result was represented by a stack of slice images where voxels in the same class were assigned with unique integer value.

At the high-level processing, seeds for regions of the soft tissue, bone, and pneumatized spaces of the ear were first determined manually. Then the associated volumes were obtained from the previous segmentation results using the three-dimensional region-growing technique. The canal and the cochlea possess a similar intensity value to the soft tissue in CT image. They were labeled the same value as soft tissue in the segmentation result. Since they were surrounded by bone, which was in a different segmentation class, they could be delineated manually by tracing the edge contour between the two classes in each slice image. The stapes could similarly be delineated since it is surrounded by the pneumatized space. These steps were relatively non-labor intensive because the volume of the labyrinth and the stapes was small.

The facial nerve travels in a complex course and only a small segment of it can be seen from on each CT image. The 3D image of the facial nerve must be extracted manually by an otologist using a special graphical tool.

2.2 3D Reconstruction

In a desired 3D reconstruction of temporal bone, all relevant structures were represented in a single view with the surrounding bone rendered transparent and the important internal structures (the inner ear, stapes, and facial nerve) rendered in contrasting opaque colors. We employed NVidia's GeForce FX to perform the texture-based 3D reconstruction, and exploited the multi-texturing hardware to implement texture-based volume rendering. The GeForce FX GPU has up to 16 texture units, and support multi-texturing and multi-stage rasterization through its programmable register combiner. The construction was as follows:

Followed by segmentation, a 3D texture volume was set based on the segmentation result: each voxel was a 4-component element with the first 3 components representing the gradient, and the 4th representing transparency: set it to *zero* if it belong to background, or *one* if it belong to the opaque tissue, or α ($0<\alpha<1$ and was adjustable) if it belong to temporary bone. Voxel gradient was calculated on original intensity dataset but based on segmentation result to ensure smoothness. This texture volume was named *Norma volume* in Figure 1.

Next, another 3D texture volume was set for shading, which was named *Label volume* in Figure 1. We applied the local illumination model to render the shaded contour surfaces of tissues in contrasting colors. The following equation evaluated the local shading effect:

$$I = I_a + I_d \cdot (\vec{n} \bullet \vec{l}) \qquad (1)$$

where $\vec{l}$ was the direction of light and $\vec{n}$ was the normal of the contour surface which coincided with the volume gradient.

In order to display objects in contrasting colors with this model, a solution might through assigning different ambient coefficient I_a in equation (1). In our implementation, the cochlea was rendered in red, the mellus in green, the stape in blue, the facenerve in yellow and the temporal bone was rendered in white gray. We set the coefficient I_a in *Label volume* on a per-voxel scale based on the segmentation:

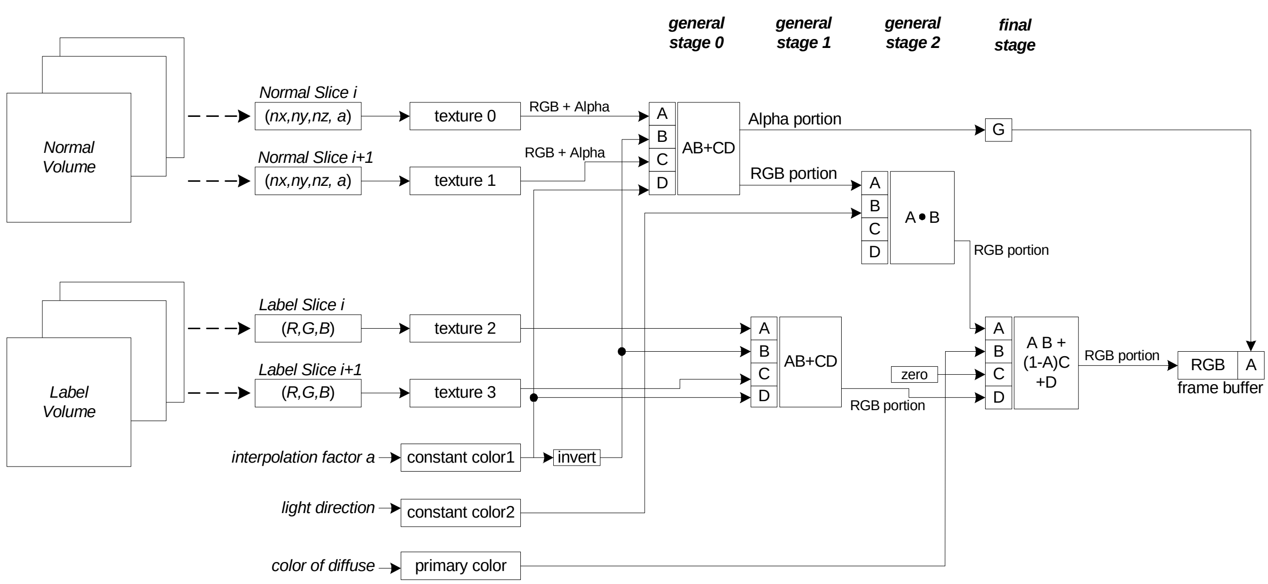

Figure 1: Register combiner setting for 3D reconstruction.

With this setting, multi-texturing was exploited to first interpolate the adjacent slices at general stage 0 (*normal*) and general stage 1 (*label*) respectively to ensure image quality. Then the diffuse color was calculated at general stage 3. The evaluation of (1) was fulfilled at final stage. Figure 2 was the 3D reconstruction of inner ear structure: the snapshot image on the left showed the inner ear structures, and the image on the right showed the transparent temporal bone around inner ear.

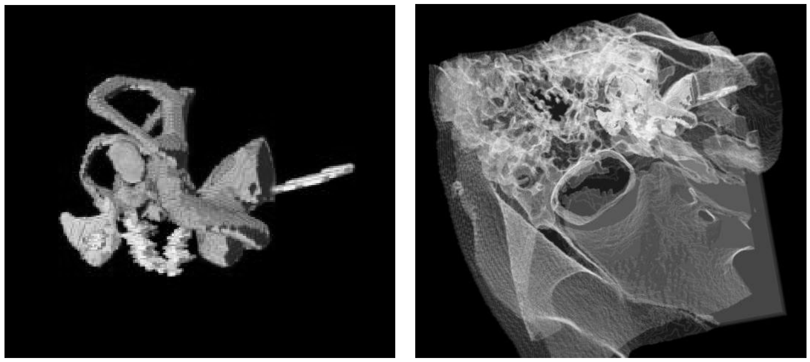

Figure 2: Shaded anatomy contour of ear structures
Left: inner ear structures
Right: ear structures with transparent temporal bone

2.3 Surgery Simulation

The surgical repair of congenital aural atresia consist of several steps: drilling a new external auditory canal in the temporal bone, creating a new meatus in the concha, forming a new eardrum using temporalis fascia, and re-lining the bony canal with a skin graft. An essential aspect of surgical planning was to define a path from outer cortex to the inner ear, and to visualize the important internal structures and their spatial relationships. We advanced a computer simulation through a cylinder as well as its interactive geometric operation on temporal bone to rehearse the surgery in our previous work. The simulation was is a three-step process: First the cylinder was interactively positioned and adjusted to form clear path within the temporal bone toward the inner ear. Next the area of temporal bone within the volume of the cylinder was colored contrasting to its original. Followed, the cylindrical volume, those colored differently in last step, was removed from temporal bone to form the external auditory canal. The first step was an interactive procedure to plan surgery virtually and visually. If a possible path existed, a warning display in next step would show the surgeon which parts of temporal bone would be removed and if this removal would violate important surrounding structures. As a further check, removing those marked areas represented the possible result after virtual surgery. These steps (positioning, warning, and drilling) were repeatable. The evaluation was given based on visual presentation at each stage of surgical planning. The entire procedure was depicted in Figure 3.

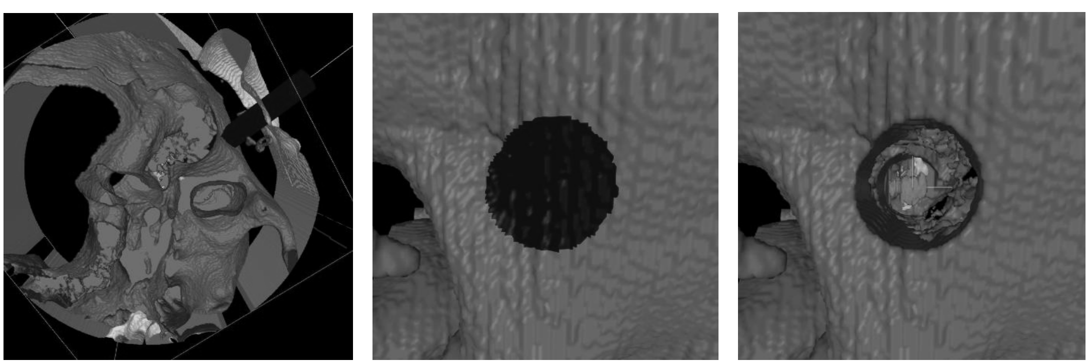

Figure 3: Virtual surgery planning: positioning (*left*), warning (*middle*), and drilling (*right*)

A graphical implementation would perform geometric operation that subtracted cylindrical volume from temporal bone volume, which was resource consuming with traditional graphics. With texture-mapping and per-fragment operation supported from graphics board, a new implementation was given below:

Besides texture volumes of *Normal* and *Label*, a third binary texture volume, named *Cylinder* volume, was set by voxelizing the cylinder into it: the voxel was set to *zero* if it was within the cylindrical volume, or *one*, otherwise. Passed all these three texture volumes to register combiner, and the setting of it was shown in Figure 4:

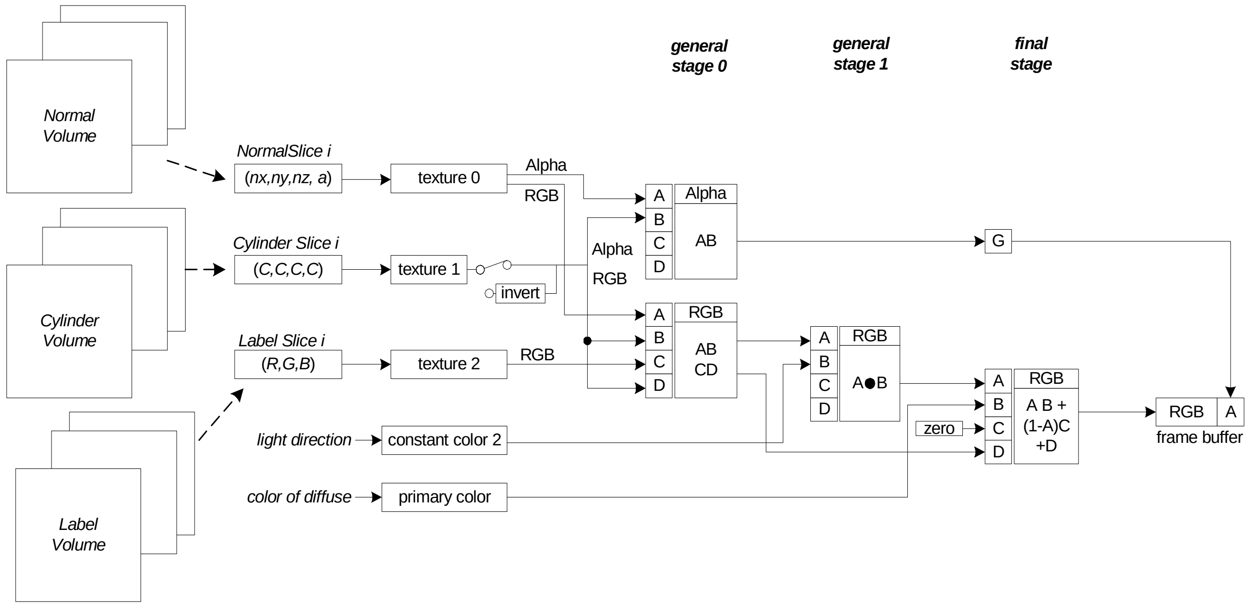

Figure 4: Register combiner setting for virtual surgery simulation.

With this setting, clipping occurred at general stage 0 where the voxels from *Normal* volume and *Label* volume respectively would multiple with corresponding voxel from *Cylinder* volume on a per-component base. Unset voxel, which was within the cylinder, from *Cylinder* would filter out corresponding voxels from *Normal* and *Label*, which made them have no contribution to diffuse and ambient component respectively. The entire clipping was fulfilled through per voxel filtering.

A complement image would be easy to get by simply revise the setting of register combiner parameter (in Figure 4, switcher right after texture unit 1). This complement image showed those parts of temporal bone to be removed to form the aural canal. Simultaneously displayed these two complement views on screen would provide a better prediction for the surgery planning. Figure 5, 6 showed these images.

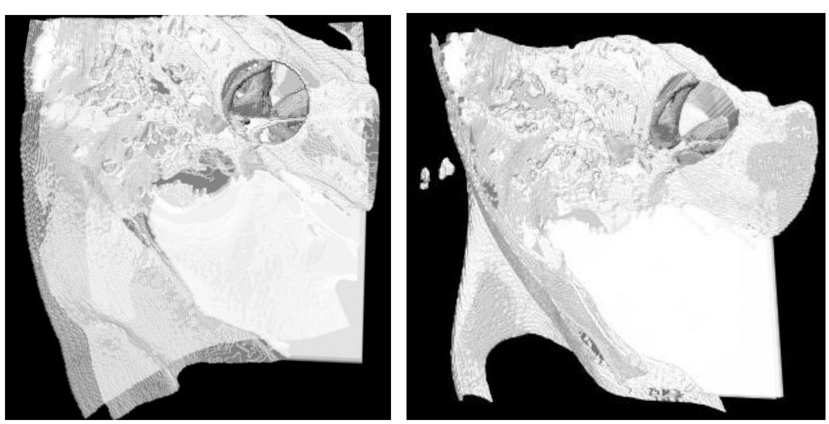

Figure 5: Virtual surgery simulation: left - BEV, right – REV

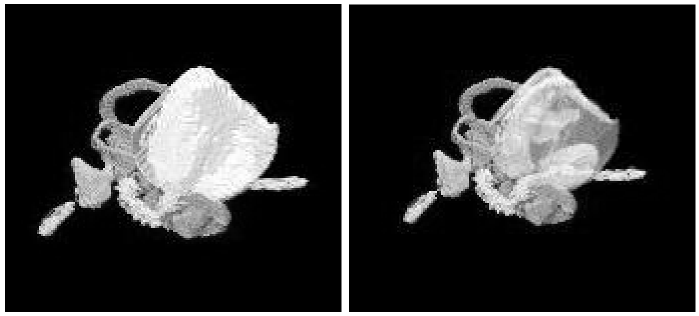

Figure 6: Virtual surgery simulation: complement views to image in Figure 5
(In *left*, temporal bone was rendered opaque, in *right*, transparent)

3. RESULTS

Our technique was applied to six patients with congenital aural atresia. The 3D image had proven to be highly correlated to the actual surgical anatomy, and virtual representation of the surgical reconstruction demonstrated the clinical potential of this imaging technique. Four patients underwent really surgery and had good results. Two patient surgeries were avoided because of some anatomically unfavorable causes.

We compared our new implementation on PC graphics board with the previous version on SGI/UNIX platform. The new implementation had noticeable improvement in image quality on smoothness, and significant improvement in rendering performance, especially on interactive operation for virtual surgery simulation. The new implementation was integrated into our prototype system for virtual surgery planning of congenital aural atresia.

4. CONCLUSION

Direct volume rendering has proven to be an effective method for the visualization of three-dimensional scalar field. Recent development of volume rendering technique exploiting texture-mapping hardware has significantly improved its performance and interactivity. We applied texture-base volume rendering to the project of virtual surgery planning for congenital aural atresia and presented some technique details to implement the key functions of the project. Methods included 2-level image segmentation schema, multi-texture mapping for 3D reconstruction of inner ear structure and surrounding transparent temporal bone, and texture-mapping based geometric operation for surgery simulation. With these methods, we created high quality 3D images that show accurate inner ear anatomy structures, and ensure the performance and interactivity simulation for virtual surgery planning.

Because high quality 3D images can provide accurate spatial anatomic relationships encountered at surgery, we exploited texture-mapping hardware and applied texture-based volume rendering technique to virtual surgery planning for congenital aural atresia. The technique can also be applied to medical applications that involve geometric operation, such as clipping. Significant improvement of rendering efficiency is expected.

ACKNOWLEDGEMENT

This work was supported in part by the NIH National Heart, Lung and Blood Institute under Grant No. HL54166 and the NIH National Cancer Institute under Grant No. CA82402.

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