Computer-Aided Virtual Surgery for Congenital Aural Atresia

*Eric E. Smouha, †Dongqing Chen, †Bin Li, and †Zhengrong Liang

Department of Surgery, Division of Otolaryngology and Head and Neck Surgery, and †Department of Radiology, State University of New York at Stony Brook, Stony Brook, New York, U.S.A.

Hypothesis: Computer-enhanced three-dimensional (3D) computed tomography (CT) provides accurate spatial representation of the complex surgical anatomy of congenitally atretic ears, and is superior to conventional CT for surgical planning.
Background: The surgical repair of congenital aural atresia is challenging. Conventional CT, routinely used for surgical planning, is limited in its ability to represent spatial relationships between important structures. Because of the lack of density differences between bony structures in the ear, 3D CT has thus far been useful for representing surface contour but not internal anatomy.
Methods: A two-level segmentation scheme was developed to distinguish structures in the temporal bone. 3D CT reconstructions of congenital ears were produced with a high-resolution helical scanner. An interactive tool was used to mark the ossicles and facial nerve. The segmentation scheme was used to color-enhance the ossicles and otic capsule, and render the surrounding bone translucent. "Virtual surgery" was then performed by subtracting a cylindrical volume of bone lateral to the atresia plate. The enhanced 3D CT reconstructions were correlated with intraoperative video recordings.
Results: In four congenital ears, computer-enhanced 3D CT was highly predictive of the actual anatomy. Surgery was avoided in two anatomically unfavorable cases.
Conclusion: Computer-enhanced 3D CT is a major advance over conventional CT for demonstrating the complex spatial relationships in congenitally atretic ears. **Key Words:** Computed tomography—Congenital aural atresia—Image segmentation—Radiology.
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The surgical repair of congenital aural atresia is challenging and complex. Preoperative computed tomography (CT) is an essential tool for surgical planning. Conventional two-dimensional (2D) CT demonstrates the key anatomic structures, including the stapes, middle ear space, inner ear, and facial nerve. Jahrsdoerfer and colleagues' 10-point scale of CT elements (1) has been helpful for determining the feasibility of surgical reconstruction. In their schema, the number of structures present (stapes, middle ear space, pneumatized mastoid, normal facial nerve, unobstructed oval and round windows, ossicular complex, incudostapedial joint, and ear canal) predicts the likelihood of success.

Conventional 2D CT is limited, however, in its ability to represent the spatial relationships between these important structures. For example, an aberrant facial nerve, a posteriorly displaced temporomandibular joint, or a low-lying tegmen tympani might make surgical reconstruction difficult or impossible. The facial nerve is of

particular concern during surgery, and its position may be camouflaged on 2D CT (2). An accurate method of preoperative depiction of three-dimensional (3D) anatomy of the facial nerve would be of great benefit. On 2D CT, the tympanic segment of the facial nerve is seen on axial images and the mastoid segment is seen on coronal images, but no image shows the entire nerve. Anomalies of the nerve, such as upward rotation through the middle ear or lateral exit point from the mastoid, might not be readily evident on conventional 2D CT scans, and might place the nerve at risk during surgery.

Successful surgical repair depends on proper alignment of the meatus with the middle ear cleft. In some congenital ears, oblique or downward orientation of the reconstructed canal can make it difficult to maintain patency after surgery. Surface contour 3D reconstructions, which are now widely available, provide some help in this regard. Jahrsdoerfer et al. (3) found that surface contour reconstructions of the mastoid showed the mandibular condyle, and, when present, the bony cleft transmitting the vertical facial nerve, duplications of bony structures, and anomalies of the zygomatic arch. Although surface images are useful, they offer limited information about the anatomic structures contained in the bone. Andrews et al. (4) proposed constructing a 3D cast from CT scan images as a means of rehearsing the sur-

gical procedure; this method is valuable, but is difficult to perform.

Our goal in the current study was to develop a new method of producing 3D CT images of the temporal bone that would be useful for the surgical reconstruction of congenital aural atresia. An interactive image segmentation/graphics tool was designed and tested for this purpose. The use of 3D CT scanning for surgical planning and anatomic display is not new. Andrews et al. (5) introduced the use of 3D CT in congenital ear surgery in 1992. In their study, 3D reconstructions were created using a commercial software program, and the facial nerve and ossicles were mapped out manually. They were successful in visualizing surface landmarks and the position of the atretic plate and facial nerve, but reported limited resolution due to volume averaging.

Current advances in CT technology have allowed us to improve on these early results. The problem with 3D CT of the temporal bone is that important structures in the middle ear have similar intensity values to the bone that surrounds them. Our basic idea was to display all the relevant organs in a single 3D view while retaining spatial information. A two-level segmentation scheme was developed to solve this problem. The capabilities that we sought included displaying the surface anatomy with and without the overlying soft tissue; showing the relationships of structures in the ear (stapes, ossicles, facial nerve); rendering the surrounding bone transparent while displaying the ossicles, facial nerve, and inner ear in a contrasting opaque color; permitting the end-user to navigate spatially in the temporal bone in three dimensions; and positioning and creating an image of the postoperative external auditory canal ("virtual surgery").

METHODS

Data acquisition

Raw CT data were collected on a GE CTI High Speed (General Electric, Milwaukee, WI) helical scanner at 1-mm collimation, 2:1 pitch in the axial plane. The image set was reconstructed to 0.2-mm images, axial and coronal. The raw data were transferred to a Silicon Graphics (Mountain View, CA, U.S.A.) workstation. Image processing was performed on a Unix-based system, using software developed by the authors.

Image processing

Segmentation is basic to most medical applications of 3D CT. The problem unique to the temporal bone is that the relevant anatomic structures (stapes, facial nerve, inner ear) are difficult to separate from the bone that surrounds them. Because of this, a two-level segmentation scheme was devised.

During low-level processing, the ear was roughly extracted from the surrounding soft tissues by removing the outside background using a region-growing technique. The voxels in the ear region were then segmented into several classes by classifying voxels based on their local intensity value vector. Then the principle of components analysis was used to extract a feature vector series from the series of local vectors. A vector quantization algorithm was used to cluster the feature vectors (6). Finally, the voxels were classified according to their feature vectors. A stack of slice images was created to represent the segmentation result, where voxels in the same class were assigned unique integer values.

During high-level processing, seeds for the regions of soft tissue, bone, and pneumatized spaces of the ear were first determined manually. Then the associated volumes were obtained from the previous segmentation. The bony labyrinth has an intensity value on CT similar to that of soft tissue, and was manually delineated by tracing its edge contour in each slice image. The stapes could be similarly delineated because it is surrounded by the pneumatized space. These steps were relatively non-labor intensive because the volume of the labyrinth and the stapes is small.

The image of the facial nerve was manually extracted from each CT slice by the otologist, using a mouse-based graphics tool. The facial nerve travels in a complex course and only a small segment of it appears on each CT image. At present, it is time-consuming to delineate the facial nerve in each patient.

Surface-based rendering was used to construct the solid 3D images and to allow for 3D navigation. Polygons that fit the surfaces of structures were extracted using the traditional Marching Cubes approach (7). To avoid generating millions of polygons, the polygons were organized in a binary space-partitioning tree (8). An intersection test was done on its leaf nodes, and on this data structure, a voxel-based constructive solid geometry subtraction was applied. The total number of polygons in a given area in 3D space was calculated by first coding each voxel in the area, then indexing them into a look-up table, and finally summing all the polygons in each voxel.

For construction of a virtual external canal, a voxel-based method was developed in which the solid volume of the temporal bone and the solid canal, represented by a cylinder, were first voxelized, then a volume constructive solid geometry operation was applied on these objects, in the leaf nodes of the binary space-partitioning tree. The Marching Cubes algorithm was then applied on each node if the subtraction operation occurred in it. The sequence of steps permitted testing and revising the position of the cylinder, and included a warning if any of the color-coded internal structures were included in the cylinder before the subtraction operation was performed.

Patients

We obtained raw CT data and created 3D images on five patients with congenital aural atresia—three had unilateral atresia, two bilateral, for a total of seven atretic ears. Four of these patients were male. Ages ranged between 5 and 28 years. Four ears underwent reconstructive surgery. One was previously operated at another institution and had revision meatoplasty and ossiculoplasty at our medical center. Three of the four ears have had a good result with regard to meatal patency; two had hearing improved to a speech reception threshold of ≤30 dB; one has had persistent external otitis; and one has had meatal stenosis awaiting revision. Of the three unoperated ears, one is awaiting surgery (pending microtia repair as a first stage) and two were considered unfavorable for surgery.

RESULTS

Five patients (seven ears) with congenital aural atresia underwent 3D CT scanning; surgery was performed on four of these ears. After segmentation of the 2D images, the bony cortex was rendered transparent and the facial nerve and labyrinth were color-coded to contrast them from the surrounding bony structures. "Virtual surgery" was then performed by removing a core of bone corresponding to the external auditory canal. The 3D CT im-

ages proved to be highly correlated to the actual surgical anatomy. The virtual representation of the surgical reconstruction demonstrated the clinical potential of this imaging technique.

This technique of image processing allowed the images to be displayed and manipulated in a variety of ways. A "pseudo-3D" view proved to be a useful means of representation (Fig. 1), wherein 2D images are displayed simultaneously in three planes of space, intersecting at a single point. By moving the cursor, the surgeon could quickly run through the temporal bone images in any direction in serial 2D CT views, using a familiar visual paradigm. This view allows serial images to be accessed and visualized quickly, and spatial anatomic relationships can be integrated in the mind's eye.

Three-dimensional CT reconstructions were used to display both the surface and internal anatomy of the temporal bone. In the surface anatomy display, the bone and overlying soft tissues were rendered in contrasting opaque colors. The eventual position of the meatus could be estimated by first displaying and then subtracting the skin and cartilage. The surface contour views of the temporal bone were valuable for studying the relationships of the mandibular condyle, mastoid tip, and zygomatic arch to the final position of the canal (Fig. 2), as previously described (3).

The anatomic structures contained in the temporal bone were displayed by rendering the bone transparent and coloring the labyrinth, stapes, ossicular mass, and facial nerve in different opaque colors (Fig. 3). The degree of transparency of the bone could be adjusted—less transparency allowed for better visualization of the bony anatomy and for estimating a route to be used at surgery; more transparency permitted assessment of the spatial
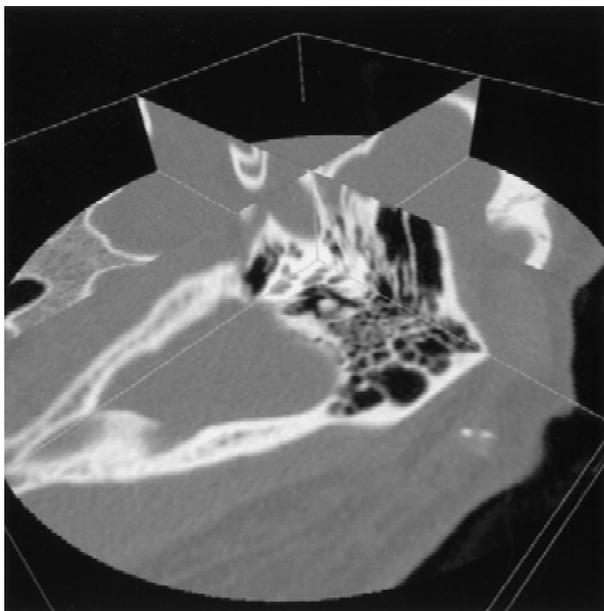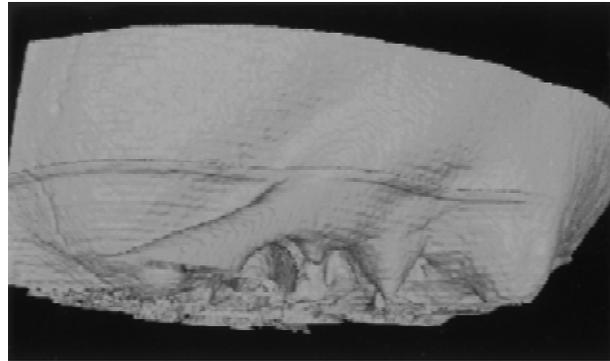

FIG. 2. Surface contour views of the temporal bone, demonstrating the relationships of the mandibular condyle, mastoid tip, and zygomatic arch.

relationships between the ossicles and the anatomic course of the facial nerve. Images were produced and saved in axial, coronal, sagittal, and oblique views.

Virtual surgery provided a view of the predicted surgical result. This technique was performed interactively. A cylinder was created first, with a diameter corresponding to that of the final ear canal (approximately 1 cm). The axis and length of the cylinder were then manipulated to conform to the position of the final ear canal, with the inner end over the ossicular mass and the outer end at the cribriform area of the mastoid cortex (Fig. 4). The computer program provided feedback warning if the virtual canal traversed any of the important structures in the ear, and then "constructed" the virtual canal in a way that simulated the actual view at surgery.

DISCUSSION

Three-dimensional imaging of the temporal bone has been an elusive goal because of the complexity of the

FIG. 1. Pseudo–three-dimensional display of two-dimensional computed tomography images of congenital aural atresia.
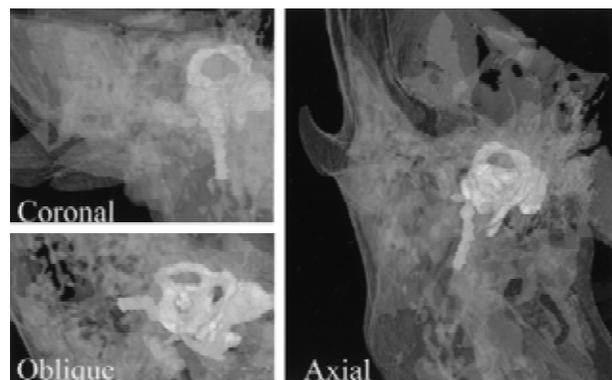

FIG. 3. Three-dimensional computed tomography reconstructions of congenital aural atresia. The temporal bone is rendered transparent and the membranous labyrinth is shown in orange, the stapes in blue, the ossicular mass in violet, and the facial nerve in green. The image can be rotated in any position in space. Images are reproduced here in the coronal, oblique, and axial planes.
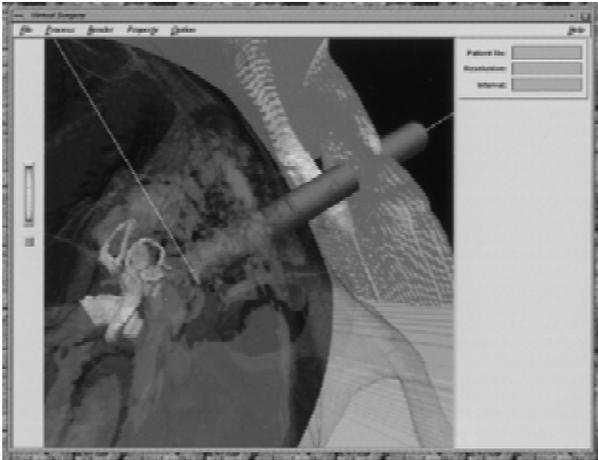
FIG. 4. "Virtual surgery" provides a reconstructed view of the predicted surgical. A cylinder is created and interactively manipulated to conform to the position of the final ear canal, as shown here.

anatomy and the lack of contrast differences between tissues. The current methodology advances our ability visually to represent this anatomic region in a way that is useful for surgical planning. We chose to study a series of patients with congenital aural atresia because the need for an accurate "road map" is particularly acute in the presence of this developmental abnormality. This technology could easily be applied to other forms of temporal bone disease.

The static images generated using this technique are visually compelling and rich in detail. For students and inexperienced observers, these images could be very useful for demonstrating spatial relationships between structures contained in the ear. For experienced surgeons, 3D CT reconstructions help to verify the distances and relationships between the important landmarks that will be encountered at surgery, and represent an improvement over conventional 2D CT images.

No single, static view, however, can give a complete picture of the important anatomic relationships. The navigational capability of the program—which allows the end-user interactively to rotate the image, move the visual perspective, and "walk" through the 3D image—was most valuable, and provides a visual road map that simulates the anatomy encountered at surgery. By traveling beside, around, and through an object, one can formulate a coherent spatial image that cannot be obtained on any 2D image.

The current technique was valuable for displaying the facial nerve. Predicting the position of the facial nerve and its relationship to the atretic plate and ossicles is useful, particularly if an anomaly is present. The technique of marking the nerve on sequential 2D CT scans is still time consuming and requires a foreknowledge of facial nerve anatomy. An automated method for extracting the nerve would be helpful, and is in development. The ossicles and stapes were more easily extracted than

the facial nerve. Our technique displayed these structures with only moderate resolution; although this was adequate for the purpose of our study, a refinement in the image quality would be desirable.

Virtual surgery allowed the surgeon to simulate the operation and create an image of the postoperative result. The technique was interactive, and allowed the surgeon to rehearse the procedure, mentally adjust the approach, and visualize the final result. With some refinement, this technique could find broader application in planning and teaching otologic surgery.

There are several limitations of the current program that prevent its use in clinical applications. At present, the software is Unix based, and is not available for use on a desktop PC system. Image files are large and require large bandwidth and drive capacity. Segmentation of the facial nerve is labor intensive, and the technique for virtual surgery is not automated. Goals for the future include automating the method of image processing, developing an interactive tool that is user friendly, and reducing costs and technical requirements.

We believe that these goals can and will be achieved with currently available technology. The system we have developed is useful in its current form for the surgical planning of congenital aural atresia, and represents a major advance in our imaging capabilities for the treatment of this complex disorder. The system interface is user friendly for displaying and navigating through the anatomic structures contained in the temporal bone. We believe this methodology is versatile for a variety of otologic applications. With a few refinements, the system holds great promise for widespread clinical use.

CONCLUSION

The 3D CT model we have developed provides a realistic model of the spatial anatomic relationships encountered at surgery. Our two-level segmentation scheme is novel and is both adaptive and interactive. The combination of transparently rendered bone volumes and color-coded surface landmarks is a promising technique that allows clear visualization of the anatomy before surgery. The system also allows the surgeon to perform virtual surgical reconstruction of the external auditory canal in congenital ears. The accurate spatial rendering provided by 3D CT is a significant improvement over conventional 2D CT in the planning of this complex and difficult surgical procedure.

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