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Research Paper

Reconstruction and exploration of virtual middle-ear models derived from micro-CT datasets

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ABSTRACT

Background: Middle-ear anatomy is integrally linked to both its normal function and its response to disease processes. Micro-CT imaging provides an opportunity to capture high-resolution anatomical data in a relatively quick and non-destructive manner. However, to optimally extract functionally relevant details, an intuitive means of reconstructing and interacting with these data is needed.

Materials and methods: A micro-CT scanner was used to obtain high-resolution scans of freshly explanted human temporal bones. An advanced volume renderer was adapted to enable real-time reconstruction, display, and manipulation of these volumetric datasets. A custom-designed user interface provided for semi-automated threshold segmentation. A 6-degrees-of-freedom navigation device was designed and fabricated to enable exploration of the 3D space in a manner intuitive to those comfortable with the use of a surgical microscope. Standard haptic devices were also incorporated to assist in navigation and exploration.

Results: Our visualization workstation could be adapted to allow for the effective exploration of middle-ear micro-CT datasets. Functionally significant anatomical details could be recognized and objective data could be extracted.

Conclusions: We have developed an intuitive, rapid, and effective means of exploring otological micro-CT datasets. This system may provide a foundation for additional work based on middle-ear anatomical data.

1. Introduction

The middle-ear anatomy is integrally linked to both its normal function and its response to disease processes. To improve our understanding of middle-ear anatomy, we require an intuitive and effective method to examine its morphology in a non-destructive manner. The advent of volumetric CT has made it possible to image features of interest relatively quickly and without the need for physical sectioning. While images acquired using standard clinical CT scanners lack the spatial resolution needed to fully capture the intricacy of middle-ear anatomy, micro-computed tomography (micro-CT) imaging provides high-resolution anatomical data that accurately represent finely detailed structures such as the ossicles.

The traditional method of evaluating volumetric middle-ear datasets has been through the examination of sequential two-dimensional images. This approach presents a challenge to accurately identify critical anatomical structures and to locate their relative positions in three-dimensional space (Seemann et al., 1999; Rodt et al., 2002). Unless structures of interest happen to be aligned with the image-acquisition plane, accurate measurements of locations, distances, and angles can be particularly difficult to obtain.

A number of approaches have been presented for reconstructing and visualizing 3D models of the middle ear for education (Jun et al., 2005; Wang et al., 2007), construction of biomechanical models (Decraemer et al., 2003; Sim et al., 2007), and pre-operative assessment (Handzel et al., 2009). Most methods employ a computer-assisted manual segmentation (Rodt et al., 2002), an automatic threshold-based segmentation (Neri et al., 2001), or some combination thereof (Seemann et al., 1999; Jun et al., 2005; Sim et al., 2007; Sim and Puria, 2008; Handzel et al., 2009) to delineate the anatomical structures of interest. Specialized software can then be used to generate 3D polygonal surface geometry from the segmented data. The resulting hollow surface "shells" can then be interactively rendered for visualization and analysis.

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A significant limitation of this method of surface extraction is the difficult and laborious preparation of the data, particularly in the segmentation step. Preparation times of up to several hours are common (Seemann et al., 1999; Jun et al., 2005; Rodt et al., 2002) before any interactive visualization and analysis can take place. Additionally, volume data located inside these surfaces are obscured from the user unless they are explicitly retained and rendered by other means.

An alternative is the use of volumetric rendering (Seemann et al., 1999), which preserves and displays the entire 3D dataset, rather than solely extracting and displaying surfaces. It does not require dataset preparation and image segmentation techniques, reducing the learning curve and time investment for the user. Volumetric rendering has the capability to display geometry in real time, and has been employed for use in "virtual endoscopy". However, the majority of these programs run exclusively on proprietary clinical scanners and has not been optimized to run on the commodity hardware currently available on desktop workstations. Similarly, available software cannot easily manage the large size of the high-resolution datasets from micro-CT scanning.

Most of the rendering tools available today also lack the capability to rapidly and intuitively navigate, explore, and analyze a dataset once it is rendered. The user should be able to move through the virtual space in a familiar, comfortable way, and be able to "reach into" the virtual anatomy to identify specific features of interest. Our sense of touch, which is critical in our interactions with real 3D objects, can now be applied to the exploration of virtual environments through haptic interfaces. Enabling such a fundamental sense promises to provide the user with insight that is currently unavailable in most visualization software. In addition, the ability to rapidly and intuitively perform quantitative measurements is an easy and logical extension of such a tactile user interface.

In this paper, we present a software and hardware suite with the objective of overcoming some of the limitations of existing methods. We have developed a system with interactivity and ease of use in mind that allows clinicians and scientists to explore and analyze micro-CT scans of the middle ear. By combining state-of-the-art software and hardware technologies such as direct volume rendering, haptic feedback, virtual surgical microscope navigation, and a user-friendly interface, we seek to create an interactive morphometric workstation that allows the user to quickly and intuitively explore micro-CT data and perform quantitative measurements directly on the anatomical structures of interest. This software represents an effective method to reconstruct and explore otological micro-CT datasets for education and research, and to yield greater understanding of relevant middle-ear functional anatomy.

2. Materials and methods

2.1. Micro-CT scans

Human temporal bones from three cadavers were harvested within 2 days of death and frozen immediately upon extraction. The surrounding tissues were removed to allow the specimen to fit within the micro-CT scanner and to minimize the potential beam-hardening artifacts caused by adjacent dense bone (Sim et al., 2007; Baek and Puria, 2008).

High-resolution micro-CT scans were obtained of these specimens using a Scanco VivaCT 40 micro-CT system (Scanco Medical, Basserdorf, Switzerland). The scans were obtained with the default medium resolution setting, an energy level of 45 keV, an X-ray intensity setting of 145 μA, and an integration time of 2000 ms. This produced an isotropic volume dataset with a resolution of 19.5 μm per voxel side-length, with 2048 by 2048 pixels per slice. The total number of slices ranged from 508 to 868. The scanned region included at least the tympanic annulus, middle-ear cavity, and inner ear.

We designed and coded custom software utilizing the Insight Segmentation and Registration Toolkit (ITK) (http://www.itk.org/) to prepare the datasets for loading into our visualization software suite. The original dataset resolution exceeded the maximum memory capacity supported by our highest-end video graphics card, which was 768 MB on the GeForce GTX 260. Therefore, the datasets were cropped and/or down-sampled to yield a final size of 512 by 512 by 512 voxels. The resulting final resolution ranged from 19.5 to 76.0 μm per voxel side-length. When possible, cropping was used preferentially to optimize the resolution in areas of interest.

2.2. Three-dimensional visualization

Our visualization software suite supports two distinct volumetric rendering techniques: isosurface and direct volume rendering. Isosurface rendering generates contiguous surfaces along regions of the dataset that share the same radiodensity value (Hadwiger et al., 2005). These isosurfaces are displayed by shading them with a single color and opacity. This is effective for demonstrating boundaries between tissues with distinctly different Hounsfield units. In contrast, direct volume rendering maps a color and opacity to each voxel based on its radiodensity (Kniss et al., 2002). By utilizing a combination of both techniques, our software can render both solid homogeneous and inhomogeneous tissues.

2.3. Virtual microscope

Our virtual microscope interface is an input device custom-designed to resemble the pistol grip of a surgical microscope. The interface consists of two SpaceNavigator (3Dconnexion, Fremont, CA) three-dimensional navigation devices, connected to the ends of a grip bar, housed within a particle-board enclosure. In order to move through the virtual three-dimensional environment, the user grips the bar and applies translational or rotational force. These forces result in displacement of the bar from its neutral position, which is interpreted by our software as instructions to move the point of view of the user while keeping the rendered volume dataset stationary, just as is the case with a real surgical microscope. Our initial experience has suggested that this approach yields an intuitive means of navigating even complex 3D geometry, with a reasonable learning curve even for those not familiar with the use of a surgical microscope.

2.4. Haptic interface

Measurements of 3D structures can be performed interactively using a Phantom Omni (SensAble Technologies, Woburn, MA) haptic interface device. The device resembles a pen or surgical instrument mounted on a robotic arm, which is capable of sensing position and orientation in three-dimensional space. More importantly, it can apply directional force feedback to simulate the sense of touch or deliver haptic feedback. We use this haptic device to control the position of a virtual measuring tool, represented by colored spheres within our 3D environment as seen in Fig. 2. As the virtual tool is moved through the 3D environment, a haptic rendering software algorithm (Salisbury and Tarr, 1997) is employed to command resistive forces through the haptic device whenever the virtual tool touches structures that are visually rendered. As a result, anatomical surfaces and contours in the data can be physically touched and felt.