Journal of Digital Imaging

Use of Computed Tomography Scans for Cochlear Implants

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While 3-dimensional (3D) imaging by computed tomography has long been desirable for research and treatment of cochlear-implant patients, technical challenges have limited its wide application. Recent developments in scanner hardware and image processing techniques now allow image quality improvements that make clinical applications feasible. Validation experiments were performed to characterize a new methodology and its imaging performance.

KEY WORDS: Computed tomography, image registration, cochlear implants

INTRODUCTION

Cochlear implants have been one of the great success stories of modern biomedical engineering, enabling many with profound deafness to achieve highly functional hearing after treatment. However, there is still a wide variation of recovered hearing capability among individuals,[1] motivating continued effort to improve the performance of hardware design and signal processing algorithms, as well as refining surgical methodology. An essential component of these research efforts is the ability to visualize cochlear anatomy and the 3-dimensional (3D) location of implanted electrodes relative to landmarks in the ear. While various imaging modalities have been used, computed tomography (CT) is particularly attractive because it provides 3D positional information, offers excellent contrast for different tissue types, and can be utilized even with the implant device in place.[2]

In point of fact, cochlear implants are the stress case for CT imaging, demanding submillimeter spatial resolution and the avoidance of artifacts generated by radio-opaque metal and dense-bone structure within the scan field. When our group first applied CT imaging to cochlear implants a decade ago,[3] resolving electrode arrays was problematic and artifacts severely limited visualization of anatomical features. In the interim, much effort has been applied to improving CT scanner hardware, scanning protocols, and reconstruction algorithms. Additionally, image processing algorithms have matured with the capability to manipulate large 3D data sets and accurately compare different volumes and reference atlases. As a result, CT imaging has recently become a very capable tool in the research and development for improvement of cochlear implants.

Clinically, CT patient scans are used in several treatment steps. Before surgery, scans are commonly preformed to identify abnormal anatomical structures and assist in surgery planning. After surgery, in our clinic, the patient is imaged to determine the position of the implanted array relative to ear anatomy, as a guide to selection of electrodes for stimulation programming and as an aid in interpreting the reports of the percepts that

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Online publication 16 June 2007

doi: 10.1007/s10278-007-9045-4

patients experience. In these applications, the ability of the CT images to resolve submillimeter anatomical features and array electrodes is crucial. A limiting factor is the presence of image reconstruction distortions and artifacts in the vicinity of the electrode array, which in turn limits visualization of the fine anatomical detail near the electrode. To overcome this limitation, we have developed an approach in which image volumes are acquired before surgery and later registered to postoperative volumes. The electrode array is segmented in the postoperative volume and superimposed onto the undistorted preoperative scans. Important questions about these processing steps are the spatial resolution of the images and the accuracy of the image volume registration process. This communication summarizes this application of CT for characterizing in vivo the electrode location within the cochlea of implanted patients.

METHODS AND MATERIALS

To avoid patient radiation risk, several cadaver head specimens were prepared for testing under approval of the Washington University Human Studies Committee. To test spatial resolution, a cadaver head was scanned on the clinical scanners. Both ears were then implanted with electrode arrays (AB), manufactured by Advanced Bionics HiFocus I™, Valencia, CA, USA, and rescanned. A single array consists of 16 pure platinum rectangular plates (0.3×0.4 mm) mounted colinearly along the surface of a conically shaped silicone carrier whose diameter varies between ~0.4 and ~0.7 mm over a distance of ~17.6 mm. The electrode plates are spaced with a ~1.1-mm center-to-center distance. The electrode lead wires lie along the center of the carrier and consist of 80% platinum and 20% iridium, with diameters ~0.025 mm. The electrode arrays were fixed in position with dental cement and the temporal bone regions were next removed for scanning in a high-resolution micro-CT device.

To determine the resolution for soft-tissue structures and the accuracy of registration with reference images, a fresh cadaver from a donor was scanned on a clinical scanner within 7 h of death, and the temporal bones were removed and fixed in formalin within 9 h of death. These samples were then scanned on clinical and micro-CT devices. The samples were then processed (decalcified) for orthogonal-plane fluorescence optical sectioning (OPFOS)[4] scanning.

Images in this report were acquired from multirow CT scanners (Siemens Volume Zoom, Siemens Medical Solutions, Forchheim, Germany) that have been used for patient scans. (Other multirow scanners have been evaluated, e.g., Siemens Sensation 64 and Toshiba Aquilion 16, and produced similar results.) The standard protocol is 120 peak kilovoltage (kVp), 350 mAs, 2×0.5 mm collimation, and pitch=0.9. Image volumes were reconstructed with isotropic 0.1-mm voxels using an ultrahigh resolution (U70u) reconstruction kernel, employing an extended Hounsfield scale (10× expansion) to accommodate the high absorber array elements (>10,000 HU) for postoperative images. Additionally, the samples were scanned on a micro-CT device (Scanco Micro CT 40, Bassersdorf, Switzerland) using a standard protocol (70 kVp, 114 μA, 200 ms integration time, 36 μm isotropic voxel). The OPFOS scans were performed by Voie, with parameters giving in-plane voxel resolution of 6.12 μm and 6-μm interplane dimension.

In our clinical and research studies, image registration is an important operation for comparing pre- and postoperation image volumes, or to compare an individual's anatomy to a standard reference atlas. The image registration operation is performed in the ANALYZE software package (Mayo Clinic, Rochester, MN, USA), using the "volume registration" module.[5] The algorithm maximizes the normalized mutual information (NMI) between the two target volumes.[6] It was developed for registering images from different modalities, being robust even when the voxel representations are different (e.g., Hounsfield units vs. magnetic resonance relaxation times). Successful operation requires that an operator must place the two volumes in reasonably close alignment, with the central (modiolar) axis of the cochlea in each volume to within several millimeters. After this initial alignment procedure, two matched subvolummes are extracted and a transformation matrix is generated that describes the translation/rotation operations required to map one volume onto another.

The spatial resolution of the scans was established by examination of the edge profiles in the cadaver

scans. Individual electrodes, composed of submillimeter-sized attenuation objects (e.g., 0.4×0.5 mm platinum electrodes for the AB device), served as impulse functions. Bone–fluid boundaries represented normal contrast responses. Also, comparisons were made of clinical scan edges with the corresponding locations in micro-CT scans.

To study the accuracy of registration, a second cadaver head, prior to being implanted with the electrode array, was scanned three times in different positions, corresponding to a preoperative orientation, a postoperative orientation where the head is rotated approximately 45° in the sagittal plane relative to the preoperative position, and a position of sagittal rotation halfway between the two. The resulting volumes were registered to each other with the ANALYZE software. The NMI for the registered image pairs was calculated using MATLAB software (Mathworks, Natick, MA, USA). To gauge the sensitivity of NMI to misregistration, the NMI was calculated for a single image relative to itself, having undergone a known amount of translation or rotation. By equating values of the NMI, the amount of displacement required to diminish the NMI to that of two separate scans was taken as an indication of accuracy.

A second method for estimating registration accuracy was also applied to the above data scans. For each registered image volume, a binary object of the cochlear channel wall was created by the following morphological operations. The channel volume was segmented by applying a threshold of 800 HU (midway between fluid and bone). A copy of the segmented volume was dilated by two voxels and a logical "and" operation performed with the original segmented volume, creating a two-voxel-thick "shell" of the cochlear boundary. This procedure was repeated for each registered image volume, thus providing two shells, each describing a common anatomical feature (cochlear canal wall) of their respective original volumes. For the two shells, the minimum ("chamfer") distance from each point on one surface to the closest point on the other surface was calculated. The average minimum distance of all surface points is then a measure of the goodness of registration directly of the two shells and indirectly of the original volumes based on a common significant anatomical feature.

RESULTS

Typical images from scans of the cadaver specimen are shown in Figure 1. Individual electrodes are well resolved by the clinical scanners, although distortions in the surrounding tissue are apparent. In Figure 2, the corresponding micro-CT scan has much sharper detail, even resolving lead wires between electrodes. Plots of profiles through electrodes indicate an edge spread distance of 0.55 mm for the clinical scanner and about 0.1 mm for the micro-CT scanner. Typical body donor scans are presented

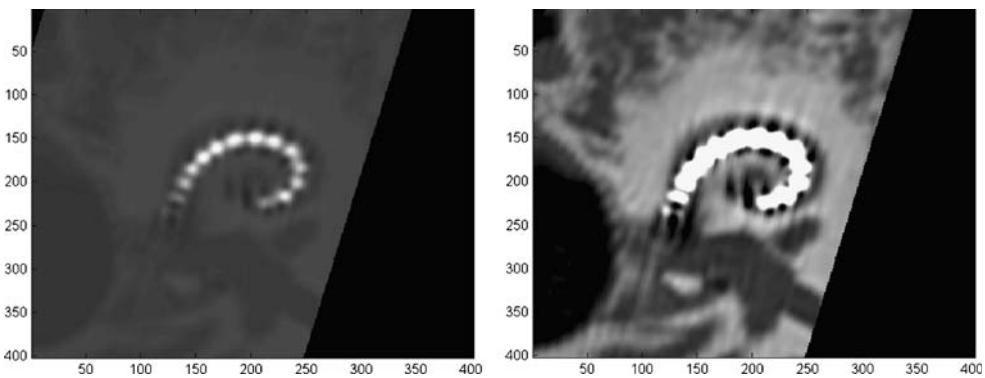

Fig. 1. Images from a clinical scanner of an electrode array inserted into a cochlear canal within an excised temporal bone specimen. *Left panel* is with a low-contrast window, demonstrating resolution of 11 individual electrodes along the array that lie in the plane of this section. *Right panel* has a higher-contrast window appropriate for bone/soft-tissue viewing, showing distortions in the canal wall in the vicinity of the electrode array.

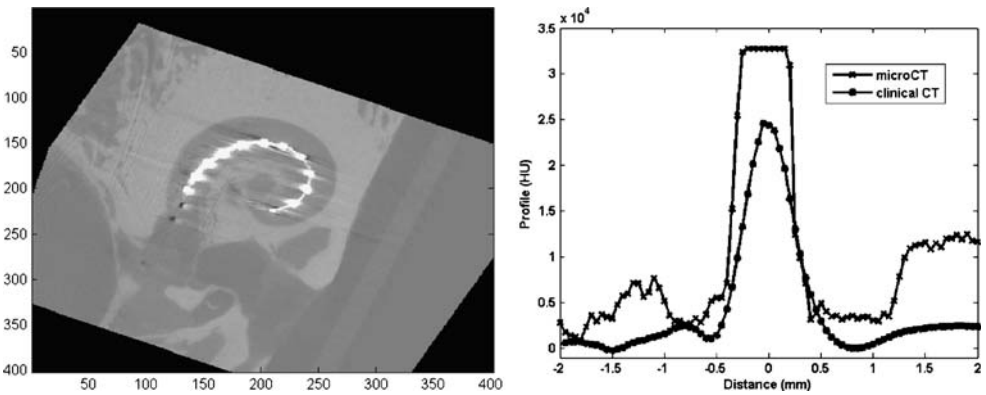

Fig. 2. *Left*: micro-CT scan of specimen from Figure 1. Note higher spatial resolution, including the resolution of lead wires between individual electrodes. *Right*: Hounsfield scale profile of an electrode (approximate coordinates 240,200) in Figure 1, from clinical scanner and micro-CT device. The spatial resolution is related to the "rise time" of the edges, here being about 100 μm for the micro-CT and about 500 μm for the clinical CT.

in Figure 3 for clinical CT, micro-CT, and OPFOS scans, each with increasing detail and contrast. The clinical scanner provides adequate resolution (100 μm) to identify anatomy and electrode array features, whereas the micro-CT (36 μm) and OPFOS (6 μm) techniques reveal additional details about underlying bony and soft tissue structures.

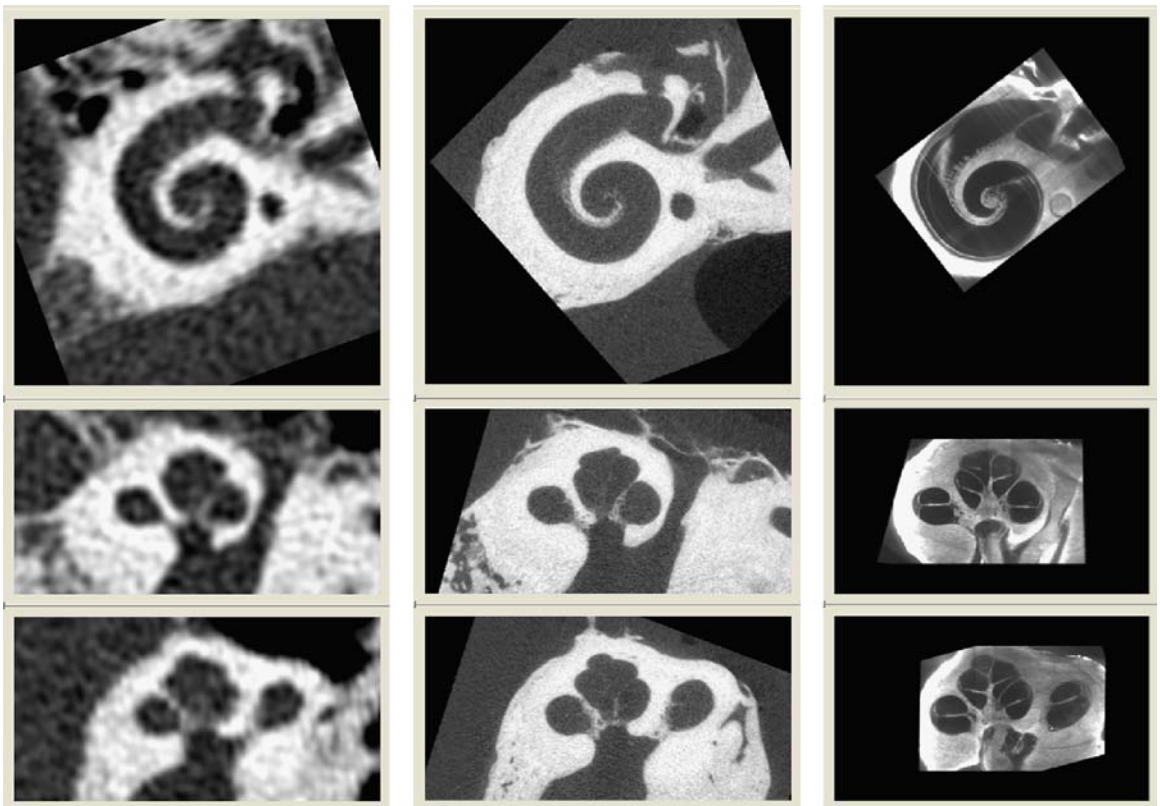

Fig. 3. Images from clinical CT (*left*), micro-CT (*middle*), and OPFOS (*right*) for the same three orthogonal sections cut through a common donor cochlea. Soft tissue features are clearly rendered in OPFOS and well correlated with micro-CT landmarks. While not visible in the clinical CT (100-μm voxels), the location of these landmarks can be inferred in the clinical CT (36-μm voxels) with reference to the OPFOS (6-μm voxels) atlas.

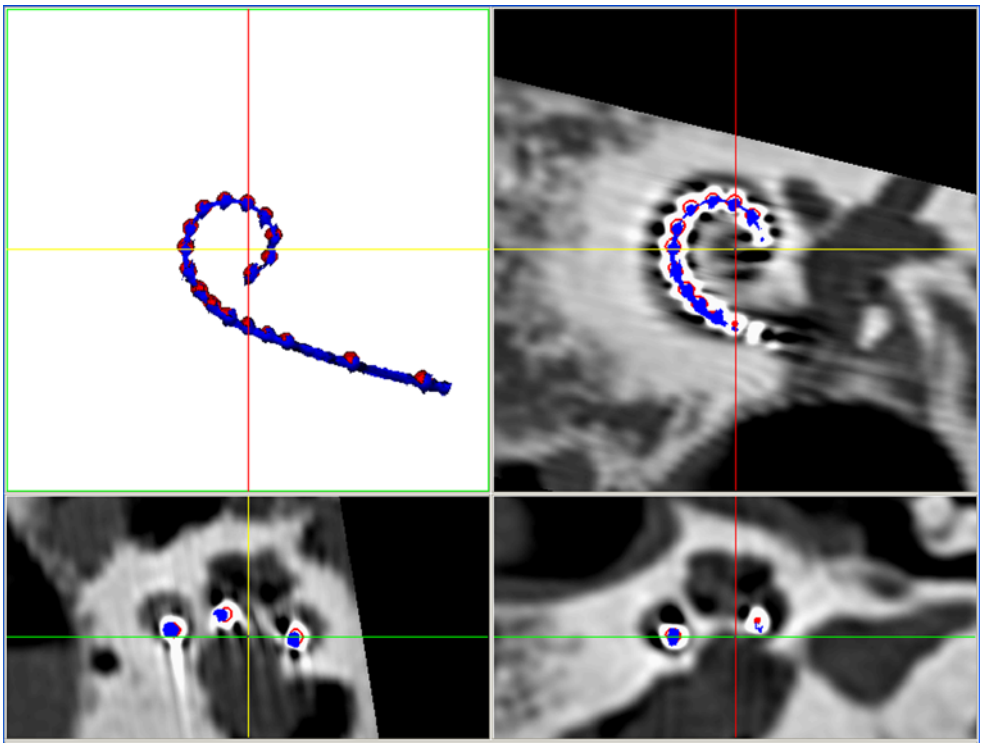

Fig. 4. Rendered view of coregistered micro-CT and clinical CT scans of an implanted electrode array. *Upper right*, **the rendered electrodes from the micro-CT scans (***blue***) are centered within the rendered electrodes from the clinical CT scanner (***red***). As shown in the three orthogonal sectional views, the micro-CT (***blue***) voxels lie within the thresholded array objects (***red outline***), which is symmetrically centered in the bloomed array volume from clinical CT.**

The result of registering image volumes is shown as a color rendering in Figure 4 for implanted temporal bone scans in a clinical and micro-CT scanner. The high-resolution micro-CT objects are well centered within the corresponding clinical CT objects, indicating excellent registration and a symmetric "blooming" of high-contrast objects. In Figure 5, a slice containing two cochlear walls from different scans of the same excised temporal bone are plotted, with excellent visual alignment.

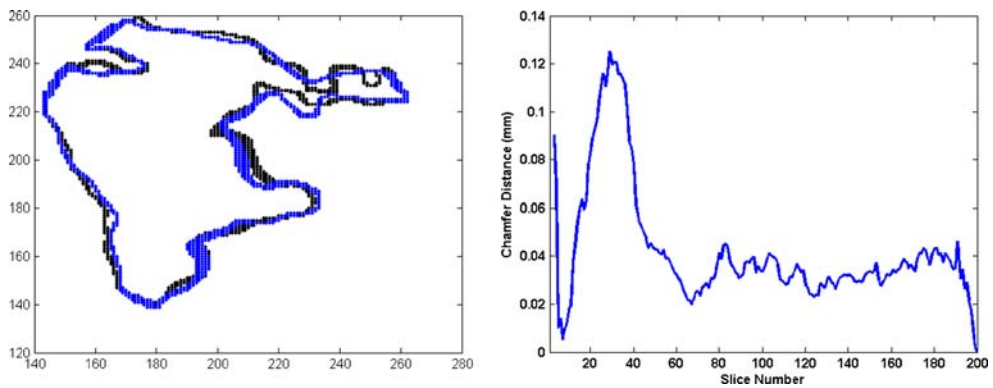

Fig. 5. Analysis of registered cochlear wall shells. *Left*, **plot of two registered wall outlines. A chamfer length, the distance to the closest neighboring wall point in the registered volume for each point on the wall, is computed. For this slice (corresponding to number 180 in right plot), the mean chamfer distance was 0.035 mm (SD = 0.06 mm), with a maximum individual distance of 0.2 mm.** *Right*, **plot of the average chamfer distance for each slice in the registered volume. The mean chamfer distance for the total volume was 0.042 mm. (In the first 50 slices, portions of the shell lay outside one of the segmented volumes, resulting in inflated estimates of closet distance.)**

The mean chamfer distance for the closest point to each point in the paired object was found to be 0.0425 mm (0.85 voxels). For the entire volume of 200 registered slices, the mean chamfer distance was 0.0424 mm (standard deviation 0.0245 mm), indicating overall alignment of better than one voxel, on average.

DISCUSSION

Recent advances in CT scanner design and the availability of powerful image processing software have improved the utility of CT scanning for cochlear implant patients. Improvements in spatial resolution now allow identification of electrodes and anatomical detail at the submillimeter level, providing important information for clinical workers. With enhanced image information, the ability to compare sequential views of a given patient is very beneficial, and the potential of using reference atlases or templates for extracting increased detail or research trends is promising. In addition, work continues for improving the underlying resolution and artifact level in CT images.[7]

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