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Comparison of Skull Radiograph and Computed Tomography Measurements of Cochlear Implant Insertion Angles

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Introduction

The measurement of the post-insertion position of cochlear implant (CI) electrode arrays is of interest due to its clinical and research implications (1). Intracochlear electrode position can be used to study pitch perception, is associated with clinical outcomes (2) and has been used to help program CI speech processors in a way that optimizes electrode frequency mapping based on each electrodes' position within the cochlea (3).

In live subjects, calculating this position requires imaging studies that can visualize the implanted cochlea. Options for high-resolution imaging of the temporal bone include computed tomography (CT), magnetic resonance imaging (MRI), and three-dimensional (3D) reconstruction. These imaging modalities are frequently used for preoperative evaluation of patients who are to undergo cochlear implantation, but have significant limitations in the post-operative period. The evaluation of electrode position using MRI is limited due to the metal contained in the implanted receiver/decoder and the electrodes themselves. Post-implantation CT imaging of the temporal bone is often utilized but does include increased radiation exposure, which is a particular concern in the pediatric population. It also requires reformatting of the CT images which can distort measurements of electrode position.

Plain-film radiographs can easily be obtained immediately after implantation intraoperatively, in order to confirm proper position of the CI electrode array. This is performed routinely in many cochlear implant centers, including our own institution (4). Xu et al used measurements from CT imaging and 3D reconstruction to delineate the typical orientation of the cochlea in the skull and to design a "cochlear view" for radiography that would optimize the utility of images for measurement of the longitudinal and angular position of CI electrodes (5). This requires an adjustment of the median sagittal plane of the head to form an angle of 50 degrees with the plane of the film. In this orientation, the x-ray beam is approximately parallel to the axis of the cochlea. This view shows the intracochlear

electrode as a two-dimensional spiral (Figure 1). The error introduced by nonstandardized angles of radiograph acquisition appears to be limited (6).

When viewing these radiographs, trained clinicians can reliably identify the superior semicircular canal and its arcuate eminence and the vestibule, which together with the estimated modiolus and the electrode are landmarks that can be used to calculate the approximate location of the round window (Figure 2). Using a reference line, an angular expression of cochlear insertion can be calculated. Svrakic et al. showed excellent intra- and inter-rater concordance for angular depth of insertion calculations using this method (6). Based on a consensus panel, which defined a 3D cylindrical coordinate system of the cochlea choosing a z-axis through the modiolus and x and y coordinates to assign various points along the cochlea, the zero reference angle has been established at the center of the round window (7).

Because expected frequency can be expressed as a function of fractional length along the organ of Corti (8) and fractional length is related to angle along the organ (9), this measurement is widely applicable in the study and care of patients with CI. Examples include comparing angles of insertion to assess for overly deep or shallow insertions for patients with poor post-implantation speech perception, or programming speech processors based on expected frequencies given electrode location. Given the relative high speed, safety, and low cost of plain-film post insertion radiograph of the temporal bone compared to CT, we sought to determine whether measurement of angle of insertion based on radiographs was comparable to measurement using CT. A “gold standard” was then needed to represent the true locations of electrodes within the cochlea against which radiograph-based and CT-based measurements could be compared. CI electrode positioning within the temporal bone can be studied using a “microgrinding technique” to create histologic sections that preserve the location of each electrode within the cochlea (10); we used a similar method to serve as the gold standard for electrode position measurement in this study.

Materials and Methods

Ten cadaveric temporal bones were isolated. Using dummy electrodes, cochlear implantation was performed on the bones by an attending neurotologist. Five bones were implanted with perimodiolar electrodes (Contour Advance TM, Cochlear, Sydney, Australia) and five were implanted with lateral wall electrodes (Slim Straight, Cochlear). The insertion depths of the electrodes were purposefully varied to reflect a variety of clinical conditions. A cyanoacrylate glue was used to fixate the electrodes adjacent to its entry into the cochlea as well as the remainder of the lead at the facial recess and within the mastoid cavity. Each bone was imaged with a radiograph and computed tomography. Angular depth of insertion was measured independently for each bone in the x-ray and CT modalities by a neurotologist and a neuroradiologist, respectively.

To take measurements, visual inspection of radiographs of the implanted bone was first performed. Reference lines were drawn on the radiographs using Microsoft PowerPoint 2016 (Microsoft Corporation, Redmond, WA, USA). Reference lines between the estimated apex of the superior semicircular canal and the vestibule were created; the round window

location was estimated at the point at which this line intersected the electrode lead. The modiolus was identified using visual estimation and the center of the electrode spiral. Following consensus panel recommendations (7), the line connecting the modiolus and the round window defined the 0 degree reference line. The angular depth of insertion was defined as the angle of rotation of the most distal electrode with respect to the 0 degree reference line (Figure 2). Angular measurements were completed using ImageJ (public domain, <http://rsbweb.nih.gov/ij/download.html>).

For measurement of computed tomography images, CT data was reformatted to create the Cochlear View as described by Xu et al (5) (Figure 3). The angular insertion depths of the ten specimens were then measured by a neuroradiologist blinded to the results of the radiograph measurements (Figure 4). Of note, the neurotologist was not aware of the results from this analysis when analyzing the plain films.

To provide a histologic gold standard against which to compare the measurements made using plain radiograph and CT, the temporal bones with their electrodes in place were fixated, dehydrated, and embedded in epoxy resin for histologic sectioning. Fixation was performed by opening the round and oval windows and perfusing the bones with a solution of buffered 10% formaldehyde + 10% ethanol. The temporal bones were then dehydrated in an ascending series of alcohols (70–100% ethanol) and 100% acetone. Subsequently all specimens were embedded in epoxy resin. (EPO-TEK 301, Epoxy Technology INC, Billerica, MA). Two holes were drilled at 90 degree angles through each of the blocks to create “fiducials” present in each slice to allow for correct spatial alignment during processing of images of the histologic slices. The epoxy blocks were transferred to a micro-grinding machine (Struers Tegramin-25, Struers Inc., Cleveland, OH) and ground down at 100 micron intervals. After each grinding layer, they were stained with eosin and toluidine blue, then examined and photographed using a stereomicroscope and digital camera. These sectioning steps were repeated until the entirety of the cochlea with the electrodes in place had been sectioned. Images were next aligned using the fiducials and ImageJ software to create three-dimensional image stacks for each specimen (Figure 5). Three-dimensional pixel coordinate locations were recorded for the round window center, modiolus, and each electrode. A MATLAB script (MATLAB, The MathWorks, Natick, 2014) was encoded to create 3D maps of all of these locations for each specimen, and to use them to calculate the angular position relative to the round window for the most apical electrode within each specimen.

One-way repeated measures ANOVA was used to determine if there were systematic differences between x-ray, CT, and histology-based estimates. Then, the accuracy of x-ray and CT measurements was estimated by comparing them to the histology-based estimates. The mean absolute error was calculated for each modality (x-ray and CT), and a paired-t test was run to compare the accuracy of the two modalities.

Results

Results of measurement for each specimen and for each modality can be found in Table 1. A scatterplot of x-ray-based and CT-based measurements as a function of histology-based

measurements is shown in Figure 6. Please note that the resin did not cure properly in two of the bones, making it impossible to obtain histology-based estimates in those cases. As Table 1 indicates, the average aDOI across all bones was very similar across modalities. The repeated measures ANOVA did not find significant differences between x-ray, CT, and histology estimates ($p=0.62$). Both x-ray and CT resulted in estimates that were reasonably close to the histology estimates. As Table 1 indicates, the mean absolute error was 12.6 degrees for x-ray data and even lower (9.7 degrees) for CT data. However, this difference was not significant either from a statistical standpoint (paired t-test, $p=0.39$), or when considered in practical or clinical terms.

Discussion

The finding that errors in calculated angular depth of insertion are small when using either post-insertion radiographs or CT is helpful. At many institutions, intra-operative post-insertion radiographs are obtained on each CI case to determine that there is no tip rollover or other malposition of the electrode. CT imaging generally requires a separate visit and has a greater associated cost. There is also a significant differential in radiation exposure when comparing plain radiograph to CT of the temporal bones. A range of 0.9–2.6 mSv per study for temporal bone CT has been described in the literature (10), compared to 8.4–22.7 microSv for lateral skull radiograph (12). This is particularly relevant in pediatric CI cases. Due to their longer life expectancy and increased sensitivity to radiation, children have a two to three-fold increase in risk of cancer compared to adults with the same radiation exposure (13). The lowest possible radiation dose should be used for all patients. Other imaging modalities such as CT or cone-beam CT do provide additional anatomical detail beyond angular insertion depth, and have been utilized in combination with anatomic imaging registration to estimate electrode scalar position.

This study utilized a specific mode of CT reformatting along the cochlear view. It is possible that CT-derived measurements of angular depth of insertion could vary between institutions, which could affect correlation with radiograph-derived measurements, although consensus guidelines were followed (7). Also, images were taken of isolated cadaveric temporal bones rather than live patients with cochlear implants, which could theoretically change the quality and resolution of the images obtained for both modalities.

Cochlear implantation functionality depends on the tonotopic organization of the cochlea, so the accurate measurement of angular depth of insertion provides valuable information. Studies using plain radiographs to estimate this measurement have suggested that default frequencies of electrode arrays are often mismatched to the frequency that would be expected based on its location in the cochlea (1) and that deeper depth of insertion is correlated with worse low frequency hearing preservation (14). In another study, there was a strong relationship between greater insertion depth and improved performance (15). Angular depth of insertion has a variety of applications for clinical care and research.

Conclusions

Post-insertion radiographs provide a reliable measure of angular insertion depth when compared to measurements using CT imaging. This method appears suitable for both perimodiolar and lateral wall electrode designs; no significant difference in technique would be expected between the two subsets of electrode design. The present pilot study is admittedly small (only ten bones) and is not intended to characterize results across the full range of variability in the human cochlea. However, this study suggests electrode position can be reasonably estimated using post-insertion radiographs, which may prevent unnecessary radiation exposure and expense.

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Figure 1:

In the “cochlear view” radiograph, the x-ray beam is approximately parallel to the axis of the cochlea, and the electrode array appears as a two-dimensional spiral within the cochlea

Figure 2:
Reference lines from the estimated locations of the superior semicircular canal to the vestibule, the round window to the modiolus, and the most basal electrode to the modiolus are used to create measurements of angular depth of insertion from a radiograph of the implanted temporal bone

Figure 3:
Traditional temporal bone computed tomography can be reformatted to create the “cochlear view.” Arrow marks vestibule.

Figure 4:

Reformatted computed tomography along the plane of the “cochlear view” can be used to measure angular depth of insertion. Shown here is the angle created by the estimated position of the most basal electrode, the modiolus, and the round window.

Figure 5:

Each specimen was embedded in epoxy resin and sectioned at 100 micron intervals. After staining, images of each section were captured using a digital scientific camera and microscope, then aligned using the drilled fiducial holes and ImageJ software (drill hole fiducials marked with asterisks).

Angular depth of
insertion (degrees)

Figure 6:
Depth of insertion as estimated based on CT (red circle) and XR (yellow square) measurements, compared to the measurements as estimated based on the histologic gold standard (solid line).

Table 1:

As measured by CT, angle of insertion ranged from 366.8 – 515.0 degrees with a mean of 425.3 degrees. As measured by radiograph, angle of insertion ranged from 368.6 – 531.0 degrees with a mean of 423.4 degrees. Specimens 6 and 10 did not section properly due to incomplete hardening of the resin; thus histologic results were not computable. For the remaining specimens, as measured by histology, angle of insertion ranged from 377.6 to 497 degrees with a mean of 427.8 degrees. The mean absolute error when comparing measurements based on imaging modalities to ones based on histology was 9.7 degrees for CT-based measurements and 12.6 degrees for radiograph-based measurements.

Specimen #	Histology	CT	Abs. Error (CT v. Histology)	XR	Abs. Error (XR v. Histology)
1	424.7	414.9	9.8	412.9	11.8
2	391.2	392.6	1.5	379.2	12.0
3	377.6	366.8	10.8	368.6	9.0
4	407.9	406.1	1.8	396.2	11.7
5	488.7	463.6	25.1	472.9	15.8
6		441.1		451.9	
7	425.4	424.3	1.1	419.3	6.1
8	408.7	419	10.3	407.1	1.6
9	497	515	17.0	531.0	33.0
10		414.3		410.4	
average	427.8	425.3		423.4	
mean absolute error			9.7		12.6