Published in final edited form as:

Otol Neurotol. 2007 August ; 28(5): 641–648. doi:10.1097/mao.0b013e3180577949.

Anatomy of the Round Window and Hook Region of the Cochlea With Implications for Cochlear Implantation and Other Endocochlear Surgical Procedures

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Abstract

Hypothesis—The goal of this study was to create a three-dimensional model of the anatomy of the hook region to identify the optimal site for cochleostomy in cochlear implant surgery.

Background—The anatomy of the hook region is complex, and spatial relationships can be difficult to evaluate using two-dimensional histological slides or cadaveric temporal bones.

Methods—The right temporal bone of a 14-year-old adolescent boy was used to create a three-dimensional model. Sections containing the round window membrane (RWM) and surrounding cochlear structures were stained, digitized, and imported into a general purpose three-dimensional rendering and analysis software program (Amira, version 4.1). Three-dimensional models of the RWM, basilar membrane, osseous spiral lamina, spiral ligament, cochlear aqueduct, inferior cochlea vein, scala media, ductus reuniens, scala vestibuli, scala tympani, and surrounding bone were generated. The relationship between these structures and the RWM and adjacent otic capsule was evaluated. Histological sections from a different temporal bone were also analyzed. This temporal bone was sectioned in a plane perpendicular to the axis corresponding to the surgical view of the RWM, seen through the facial recess.

Results—The anteroinferior margin of the RWM or adjacent otic capsule was identified as the site for a cochleostomy that will avoid damage to critical cochlear structures and allow implantation directly into the scala tympani. The model can be downloaded from: <https://research.meei.harvard.edu/otopathology/3dmodels>.

Conclusion—This three-dimensional model has implications for surgical procedures to the inner ear that aim to minimize insertional trauma.

Keywords

Cochlear implants; Cochlear implantation; Round window; Three-dimensional imaging; Computer generated; Surgical procedures; Temporal bone; Histology

Recent studies have shown that residual acoustic hearing may be preserved after cochlear implantation (1–4). This may allow combined electric and acoustic stimulation of the same ear. Preliminary results of electroacoustic stimulation have shown improved overall performance in these patients (2–4).

At this time, there is limited knowledge on the factors that may influence the preservation of residual hearing during cochlear implant surgery. It is likely that implant-induced damage may adversely affect residual hearing. Therefore, surgical techniques and electrode design have focused on ways to minimize intracochlear damage during implantation (5,6). There is currently no consensus in the literature regarding the optimal site for cochleostomy in an effort to avoid insertional trauma during cochlear implantation. The recommended location of cochleostomy has ranged from different sites in the otic capsule to the round window membrane (RWM) itself (7–12).

To identify the optimal site, the relationship between anatomical structures in the hook region must be fully understood. The anatomy of this region has previously been studied using either histological sections of temporal bones or dissected cadaveric specimens (10,12–15).

Histological sections have the advantage of showing the anatomy in detail, but given their two-dimensional nature, make it difficult to evaluate the spatial relationships between anatomical structures. Moreover, measurements between structures are influenced by the angle at which the temporal bone is sectioned. Dissected cadaveric temporal bones can be used to evaluate spatial relationships to a degree, but again, it is difficult to quantify distances between structures.

The goal of this study was to address these issues by developing a three-dimensional model of the cochlear hook region. The model could then be used to assess the optimal site for cochleostomy. The model also has application for other surgical procedures related to the inner ear.

MATERIALS AND METHODS

Creating a Three-Dimensional Model of the Hook Region and Round Window of the Human Cochlea

A three-dimensional model was created using the right human temporal bone of a 14-year-old adolescent boy. This subject has been the focus of a previous study to create a three-dimensional virtual model of a human temporal bone (16). The specimen was fixed in formalin, decalcified in ethylenediamine tetra-acetic acid, embedded in celloidin, and serially sectioned in the axial plane at 20 μm . Every section was stained with hematoxylin and eosin and mounted on slides. Results of histological examination of this temporal bone were normal.

A total of 201 sections, which contained the round window and surrounding cochlear structures in the hook region, were used to create the model. Every stained section was digitized using a Nikon Super Cool Scan 4000 ED at a resolution of $5,590 \times 3,474$ pixels. The digitized images from the sections were cropped and resampled to $1,559 \times 895$ pixels and the digitized sections were imported into Amira 4.1 (Mercury Computer Systems/TGS, San Diego, CA, USA) with a final resolution of $12.66 \times 12.66 \times 20$ $\mu\text{m}/\text{voxel}$.

The digitized two-dimensional sections were registered pair by pair using Amira's interactive alignment tool. This module allows consecutive images to be displayed in translucent colors while the alignment of one image is modified.

Once the two-dimensional sections were aligned, the anatomical structures of interest were extracted using Amira's segmentation tools. These structures included the following: the scala vestibuli, scala media, ductus reuniens, scala tympani, basilar membrane, RWM, cochlear aqueduct, primary osseous spiral lamina, spiral ligament, inferior cochlear vein, and surrounding bone.

Polygonal three-dimensional surface models of the segmented structures were generated and Amira's surface simplification algorithm was applied to smooth the model by removing redundant vertices and reducing the number of triangles in each model. The three-dimensional models can be displayed in Amira as shaded smooth surfaces with control over rotation and transparency.

The three-dimensional model created in this study has been packaged into a freeware, stand-alone application, which can be downloaded to either Windows-, Mac-, or Linux-based platforms from our institutional web site: <https://research.meei.harvard.edu/otopathology/3dmodels>.

Evaluating the Anatomical Relationships Between Structures in the Hook Region of the Cochlea

The anatomy of the hook region was evaluated using the RWM and adjacent otic capsule as references. These areas were selected as previous studies have suggested placing the cochleostomy either directly through the RWM or in the otic capsule anterior, inferior, or anteroinferior to the RWM (7–14). Using Amira's landmark editor, six points were placed on the model to represent potential sites of cochleostomy, three points evenly distributed across the surface of the RWM, and three points in the adjacent otic capsule (see Table 1).

Amira's measurement tools were used to measure the shortest distance between these reference points and other structures.

Histological Sections

To complement the three-dimensional model, a set of histological sections from a different temporal bone was analyzed. The right temporal bone of a 55-year-old man was used. The specimen was fixed in formalin, decalcified in ethylenediamine tetra-acetic acid, embedded in celloidin, and serially sectioned at 20 μm . Every section that contained the round window was stained with hematoxylin and eosin and mounted on slides.

The temporal bone was sectioned in a plane perpendicular to the axis corresponding to the surgical view of the RWM, seen through the facial recess. The plane of sectioning is illustrated in Figure 1 using images taken from the previously cited three-dimensional human temporal bone model (16).

RESULTS

Images taken from the three-dimensional model are shown in Figure 2. To orientate the reader to the view of the RWM seen through the facial recess, Figure 2A is a low-magnification image taken from the previously cited three-dimensional human temporal bone model (16). Figures 2B and C are images taken from the three-dimensional model created in this study.

Relevant structures that are located on the cochlear side of the RWM include the basilar membrane, spiral ligament, scala media, and osseous spiral lamina, all of which can be seen running anteriorly from the posterior margin of the RWM. The ductus reuniens is closely related to the posterior margin of the RWM, whereas the inferior cochlear vein and cochlear aqueduct are closely related to the inferior margin of the RWM.

Images of the temporal bone sections are shown in Figure 3. As shown in Figure 3A, at its posterior margin, the RWM is very close to other intracochlear structures, and the width and height of scala tympani are small. As one moves anteriorly and inferiorly (Figs. 3B–D), the width and height of the scala tympani increases, and the distance between the RWM and intracochlear structures therefore increases. A cochleostomy made in the otic capsule anterior

to the RWM at the midpoint of its vertical axis would allow insertion of an electrode array directly into the scala tympani without damage to other intracochlear structures (Fig. 3D). We will subsequently refer to this region as the anteroinferior margin of the RWM. There is a discrepancy over the nomenclature of the bony area adjacent to this region; some authors have referred to it as the crista fenestra (10,12,14,17) or crista semilunaris (13); others use the term postis anterior (18).

The measurements between points on the RWM or adjacent otic capsule and various intracochlear structures in this reconstructed temporal bone are presented in Figure 4. The posterior margin of the RWM (point A) is especially close to the scala media, scala vestibuli, and ductus reuniens. These structures are at risk from a cochleostomy situated posteriorly. As one moves from the posterior margin toward the anteroinferior margin of the RWM, the distances between these points and surrounding structures tends to increase (points A–C). Structures at risk from a cochleostomy anterior to the RWM (point D) include the spiral ligament, scala media, and basilar membrane, whereas a cochleostomy inferior to the RWM (point F) risks damaging the cochlear aqueduct and inferior cochlear vein. A cochleostomy adjacent to the anteroinferior margin of the RWM (point E) is 1 mm or more away from other intracochlear structures.

DISCUSSION

The intracochlear damage caused by cochlear implantation has both immediate and delayed components. Immediate damage can occur at the site of cochleostomy, along the path of electrode trajectory and from disruption of the cochlear fluids. Delayed damage involves the functional loss of intracochlear structures and the host response resulting in inflammation, fibrosis, and new bone formation. These changes have been widely reported in histopathologic studies of postmortem cochlear implant recipients and in implanted cadaveric temporal bones (5,19–24).

This study addresses the potential for immediate damage caused by cochlear implantation. Common patterns of trauma to cochlear structures include destruction of the spiral ligament and organ of Corti, rupture of the basilar membrane and Reissner's membrane leading to electrode insertion into scala media or scala vestibuli, and fracture of the osseous spiral lamina (5,19–24). Insertional trauma to the ductus reuniens has been proposed as a mechanism to explain the high prevalence of cochlear hydrops and saccular collapse observed in the temporal bones of implant recipients (25).

The three-dimensional model illustrates the complex anatomy of the cochlea hook region. The close proximity of intracochlear structures to one another and the uncertainty about where to insert an electrode may account for the observed patterns of insertional trauma.

Looking through the facial recess (Fig. 2C), the section of the basilar membrane adjacent to the superior margin of the RWM is seen to occupy a vertical position but shifts position anteriorly to lie in a horizontal plane. Similarly, the osseous spiral lamina can be seen to rotate 90 degrees from a vertical position adjacent to RWM to a horizontal position in parallel with the basilar membrane. The scala tympani initially takes a steep inferior course as it spirals along the basal turn of the cochlea and in the ascending basal turn lies medial to the carotid artery (Fig. 2A).

To facilitate electrode insertion, adequate exposure of the RWM must be achieved. This can be accomplished by drilling away the shelf of bone overhanging the RWM seen in Figure 5A.

The optimal site of cochleostomy and direction of electrode insertion is illustrated in Figure 5B, using the dimensions of the largest currently used electrode (Table 2). As shown, a

cochleostomy sited at the anteroinferior margin of the RWM or in the otic capsule immediately adjacent to this location would minimize insertion trauma and allow direct entry into the scala tympani. The trajectory of electrode insertion should avoid both the osseous spiral lamina and the basilar membrane and parallel the long axis of the scala tympani (26).

Our results are consistent with and extend the results of some previous studies. Briggs et al. (12) compared the results of implant insertion at different locations in cadaveric temporal bones. They reported an atraumatic electrode insertion in all temporal bones where the cochleostomy was sited inferior to the RWM. Varying amounts of damage or insertion into scala media or vestibuli were seen with electrode insertions in the otic capsule at other locations. Structures that may be at risk of damage from a cochleostomy inferior to the RWM are the cochlear aqueduct and inferior cochlear vein. The functional role of the cochlear aqueduct in humans remains uncertain (27). However, there is evidence from animal studies that obstruction of the inferior cochlear vein can lead to loss of hair cells and degeneration of the stria vascularis (28).

Adunka et al. (8) have argued that atraumatic insertion can be achieved directly through the RWM. Their approach was to remove the anteroinferior overhang of the round window niche, drill down the crista fenestra, and incise the most lateral aspect of the RWM before insertion. This cochleostomy corresponds to the anteroinferior margin of the RWM.

Within the corporate literature, there has been a trend to recommend a cochleostomy anterior to the RWM (7). Previous studies have shown that if a cochleostomy is sited here, the electrode may be inserted into the scala media or scala vestibuli (29). Our model supports this conclusion by showing that the spiral ligament, scala media, and basilar membrane are most at risk from an anterior site of insertion.

The three-dimensional model used in the current study is based on reconstructing a single human temporal bone. There are likely to be interindividual variations in the anatomy of the hook region. However, reassuring evidence that the anatomical relationships identified from the model will persist between individuals can be found in evaluating the histological sections from a different temporal bone. The scala tympani can be seen to widen in width and height as one moves anteriorly and inferiorly along the RWM (Fig. 3). This means that the distance between the site of electrode insertion and other intracochlear structures will increase and suggests, such as the three-dimensional model, that the cochleostomy should be positioned at the anteroinferior margin of the RWM or in the adjacent otic capsule.

In conclusion, the application of three-dimensional modeling to archival human temporal bones, as described by the methods in the current study, has implications for evaluating the optimal site of cochleostomy in cochlear implantation. These techniques may prove useful in the future for evaluating other endocochlear surgical procedures as well as in the emerging field of drug delivery systems to the inner ear.

Acknowledgements

This study was supported by the following National Institutes of Health/National Institute on Deafness and Other Communication Disorders grants: P30 DC05209, 5 RO1DC00152, 1U24DC008559.

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FIG. 1.

Illustration showing the surgical view of the RWM, seen through the facial recess. The pointer in A points in a direction perpendicular to the plane of sectioning. This plane is shown in B. Ca, carotid artery; CA, cochlear aqueduct; CT, chorda tympani; EAC, external auditory canal; FN, facial nerve; I, incus; LSC, lateral semicircular canal; PSC, posterior semicircular canal; S, stapes; SM, scala media; SSC, superior semicircular canal; ST, scala tympani; RWM, round window membrane.

FIG. 2.

A, Illustration showing the RWM and surrounding structures seen through the facial recess. The red box represents the hook region of the cochlea that was modeled in this study. B, Anatomy of the round window and surrounding structures after removing the bone from the model. C, The RWM and spiral ligament have been removed from the model, and the scala tympani has been made transparent to show the intracochlear structures. BM, basilar membrane; CA, cochlear aqueduct; CT, chorda tympani; DR, ductus reuniens; EAC, external auditory canal; FN, facial nerve; I, incus; ICV, inferior cochlear vein; LSC, lateral semicircular canal; OSL, osseous spiral lamina; PSC, posterior semicircular canal; S, stapes; SL, spiral

ligament; SM, scala media; SSC, superior semicircular canal; ST, scala tympani; SV, scala vestibuli; RWM, round window membrane.

FIG. 3.

Histological sections showing a different temporal bone cut perpendicular to the surgical view of the round window. The plane of sectioning is shown at A. A, Section through the posterior margin of the RWM. B, Section through the middle of the RWM. C, Section through the anteroinferior margin of the RWM. D, Section through the otic capsule adjacent to the anteroinferior margin of the RWM. BM, basilar membrane; CA, cochlear aqueduct; DR, ductus reuniens; OSL, osseous spiral lamina; OW, oval window; PA, postis anterior; RWN, round window niche; RWM, round window membrane; Sa, saccule; SL, spiral ligament; SM, scala media; ST, scala tympani; SV, scala vestibuli.

FIG. 4.

Graph showing the shortest distance between points placed on the RWM and otic capsule and other intracochlear structures in the hook region. CA, cochlear aqueduct; SL, spiral ligament; ST, scala tympani; SV, scala vestibuli; RWM, round window membrane.

FIG. 5.

A, The RWM is shown within the round window niche. Note the relationship of the postis anterior/crista fenestra to the anteroinferior margin of the RWM. *B*, The optimal site of cochleostomy and direction of electrode insertion are shown. The circle represents the proximal diameter of the largest current electrode, which measures 1.3 mm. CA, cochlear aqueduct; ICV, inferior cochlear vein; MAC, mastoid air cells; PA/CF, postis anterior/crista fenestra; RWM, round window membrane; RWN, round window niche; SL, spiral ligament; ST, scala tympani; SV, scala vestibuli.

TABLE 1

Location of points on the round window membrane and otic capsule

Point	Location
A	Posterior margin of the RWM
B	Midpoint of the RWM
C	Anteroinferior margin of the RWM
D	Otic capsule adjacent to the anterior margin of the RWM
E	Otic capsule adjacent to the anteroinferior margin of the RWM
F	Otic capsule adjacent to the inferior margin of the RWM

RWM, round window membrane.

TABLE 2

Dimensions of currently used electrode arrays

Company	Electrode	Electrode array tip diameter (mm)	Electrode array proximal diameter (mm)
Advanced Bionics	HiFocus 1J	0.4	0.8
Advanced Bionics	HiFocus Helix	0.6	1.1
MED-EL	PULSAR CI ¹⁰⁰	0.5	1.3
Cochlear Corporation	Freedom Contour Advance	0.5	0.8
Cochlear Corporation	Freedom Straight	0.4	0.6
Cochlear Corporation	Nucleus Hybrid	0.2	0.4