Anatomic Studies of the Human Cochlea: Implications for Cochlear Implantation

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Siebenmann made corrosion casts of the human labyrinth using Woods metal and described its beautiful anatomy over one hundred years ago. Despite many anatomical studies of the human cochlea, there are few reports describing its anatomical variations. Such data are of value in cochlear implantation (CI). Cochlear implant electrodes on the market are designed either for a position along the inner modiolar wall (so-called peri-modiolar) or along the outer wall of scala tympani. Anatomic variations of the cochlea may influence its final position relative to the cochlea place/frequency map and final pitch discrimination. With less invasive surgical techniques and shorter electrodes, the fragile inner ear structures may also be conserved. Preservation of residual hearing is now a goal in all cochlear implant surgery and better knowledge about anatomical variation may limit intra-cochlear damage.

Our collection of plastic human inner ear molds contains 325 specimens (Fig. 1). These molds were made from unselected human temporal bones removed at autopsy. The applied method of casting temporal bone specimens was described by Wilbrand et al. and Rask-Andersen et al. Bone specimens are macerated using potassium hydroxide, boiling, hydrogen peroxide, and trypsin. The specimens are placed in a wax form, with orifices of the
inner ear canals left open. The casting material, a polyester resin or a silicone rubber material, is poured into the wax form. The specimens are placed in a low-pressure chamber for penetration into the multiple bony channels of the macerated bones. After hardening, bone is dissolved with hydrochloric acid. The inner ear structures are freed with a fine forceps in the case of the polyester preparations or with scissors in the case of the silicone material. The silicone and polyester resin material has a shrinkage factor of 0.6 to 1%. Several studies have been made here in Uppsala using this material by Dimopoulos and Muren and Wadin.

Measurement Procedure

Photographs are taken of each mold in different positions and width, length, and height of different turns is measured. Relevant anatomic variations such as unusual coiling patterns and asymmetries of individual turns that may influence the introduction of a CI electrode array can be appreciated. Computer-aided planimetry is performed and a ruler is used which is connected to a computer. We use the midpoint of the long diameter of the round window as a reference and starting point for measuring the length of the cochlea. A line is drawn through the central axis of the cochlea to a distant point of the first turn. A line is drawn at right angles to this line through the axis of the cochlea, dividing each turn of the cochlea into quadrants (Fig. 2). Quadrants 1 to 4 constitute the first turn; 5 to 8, the second; and 9 to 12, the third turn. The outer wall length of each quadrant is calculated. Error of measurement was estimated to be approximately 0.08 mm.

Results and Discussion

Each human cochlea was found to be individually shaped, with large variations of the dimensions and coiling characteristics in different cochleae. The estimated mean number of turns of the human cochlea was found to be 2.6 with a range from 2.2 to 2.9 (929 degrees; range, 774-1037 degrees). The number of quadrants varied from slightly more than 8 to 12.

The outer cochlear wall length ranged from 38.6 to 45.6 mm, with a mean length of 42.0 mm. Maximal radius of the round window (half diameter of round window) was estimated to be 1.1 mm, with a range from 0.3 to 1.6 mm. The mean length of the first turn (quadrants 1-4) was 22.6 mm, with a range from 20.3 to 24.3 mm, representing 53% of the total length (Fig. 3). The mean length of the turns are shown in the accompanying table. The mean height (diameter) of the cochlea was 3.9 mm, with a range from 3.3 to 4.8 mm. The internal diameter of the first turn varied broadly (1.6-2.6 mm). The mean width of the cochlea (first turn) was 6.8 mm with a range from 5.6 to 8.2 mm. The shape of the first turn of the cochlea seemed to be influenced by the coiling pattern. There were different positions of the central axis of the individual turns. Therefore, other authors have used different reference points.

An unforeseen outcome was the individual design and proportions of the human cochlea. These variations should be taken into account when performing surgery on the cochlea because they may not always be comprehended from a preoperative CT scan as performed routinely. Unusual anatomy such as tilting or misalignment of
the first and second turns may account for difficulties for the electrode to glide upward and reach the second turn (Fig. 4). The width of the various turns differed greatly between individuals, and the cochlear height varied as much as 1.5 mm, representing one-third of the total height. There was also abrupt turning of the cochlea near the carotid area. In some instances, the carotid canal impinged on the anterior cochlear wall. This condition will influence the force generated by the tip of the electrode on the lateral wall when gliding up the first turn. The estimated mean number of turns of the human cochlea is in accordance with Hardy, who measured the organ of Corti on histological sections. The number of quadrants was in accordance with Kawano et al.\textsuperscript{9} who investigated 6 human temporal bones and performed sectioning and computer-aided 3-dimensional (3-D) reconstructions. They found the number of turns on average to be 2.69, with a range from 2.63 to 3. Cochleae with up to 3 turns were also described by Tian et al.\textsuperscript{10}

Kawano et al. estimated outer wall length to be 40.81 mm, which coincides with our data, wherein we also found individual differences of up to 7 mm. We calculated the length of the bony outer wall of the human cochlea, which is longer than the estimated length of the organ of Corti. The latter corresponds to the extension of the basilar membrane, which is generally around 34 mm. Our estimated values of the width and height of the first turn are in accordance with those reported by Dimopoulos and Muren\textsuperscript{4}. Stakhovskaya et al.\textsuperscript{11} presented measurements of cochlear width ranging from 6.9 to 8.2 mm, which is slightly more than we found as well as those obtained by Escude\textsuperscript{’} et al\textsuperscript{12}.

Analyses of the molds also confirmed the short distance between the upper first turn of the cochlea and the first (labyrinthine) portion of the facial nerve canal (Fig. 5). In one specimen, there was virtually no distance between the two structures, indicating that the neural fascicles of the facial nerve were almost in direct contact with the cochlear soft tissue. This may explain the facial nerve excitation or twitching when stimulating certain electrodes in this region, especially in patients with extensive cochlear otospongiosis or Paget’s disease.

An electrode runs considerably higher up into the cochlea if placed near the modiolus than along the outer wall because of the relatively large diameter of the first turn and small dimensions of the modiolus in the second and third turns. Rosenthal’s canal is well defined only in the first turn of the cochlea. Thus, neurons innervating hair cells in the basal turn coincide fairly well with the location of corresponding hair cells, whereas more apically, neurons merge into a less well-defined canal with less obvious and precise place/frequency alignment. Neurons innervating hair cells in the third turn are located more basally (Ariyasu et al\textsuperscript{13}). It is valuable to estimate the mean outer wall length of the first turn for patients undergoing CI surgery with combined acoustic and electric hearing \textsuperscript{14}.

\begin{table}
\centering
\begin{tabular}{|l|c|c|c|c|}
\hline
Outer wall length (mm) & Mean & Range & SD & n \\
\hline
Half diameter of the RW & 1.1 & 0.3-1.6 & 0.21 & 65 \\
First half of first turn & 13.5 & 12.1-15.0 & 0.73 & 67 \\
First turn (quadrant 1-4) & 22.6 & 20.3-24.3 & 0.83 & 65 \\
Second turn (quadrant 5-8) & 12.4 & 10.7-13.3 & 0.63 & 63 \\
Third turn (quadrant 9) & 6.1 & 1.5-8.2 & 1.40 & 58 \\
to 11 (12) & 42.0 & 38.6-45.6 & 1.96 & 58 \\
\hline
\end{tabular}
\caption{Outer wall length measurements.}
\end{table}

\textit{SD} indicates standard deviation, number of specimens; RW, round window. *The total length of the outer wall excluding the basal half of the RW.

\textbf{Fig. 3.} Diagram showing relative lengths of various quadrants of the human cochlea.

\textbf{Fig. 4.} Plastic mold of a human cochlea demonstrating the height of the second turns.
Fascinating construction most likely play an important role. Are known to date, the extensive anatomic variations of this system influence the distance of the array to the modiolus. Maximum insertion depth angle as defined by Xu et al. may be a better reference for the position of CI electrodes because it will not be influenced by the distance of the array to the modiolus.

The large variations in cochlear anatomy may question the use of a standard electrode with a fixed shape and favor the idea of using individual- or custom-shaped electrodes. When performing CI surgery for combined acoustic and electric hearing, it is necessary to consider the multiple anatomic variations. Despite attempts to preserve hearing after CI, a small group of patients appear to lose their residual hearing and become dependent on their implant. Although shallow insertion reduces the risk of damage to apical cochlear structures, a deep insertion of the array may improve CI performance in case residual hearing is lost. A radiological method to predict the required insertion depth to achieve a 360-degree insertion is therefore of value. Although not all factors leading to hearing loss after electrode insertion are known to date, the extensive anatomic variations of this fascinating construction most likely play an important role.

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MEETINGS

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The NIDCD National Temporal Bone Registry is pleased to announce the availability of mini-travel fellowships. The fellowships provide travel funds for research technicians and young investigators to visit a temporal bone laboratory for a brief educational visit, lasting approximately one week. The emphasis is on the training of research assistants, technicians and junior faculty. The fellowships are available to:

1) U.S. hospital departments who aspire to start a new temporal bone laboratory
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Nobel Prize winner Robert Barany was the first Professor at the Dept. of Otorhinolaryngology (ORL) in Uppsala (1926-1936). He was awarded the prize in 1914 for his discovery of the caloric response, but due to the First World War he collected it in 1915 in Stockholm, and chose thereafter to stay in Uppsala. He was an ingenious scientist who combined clinical observation with physiological thinking. His work laid the foundation for future vestibular research in Uppsala that included Olof Nylen, Arne Sjöberg and Jan Stahle. Olof Nylen designed the first microscope for use in ear surgery.

It was under Professor Hans Engström (1968-1979) that Uppsala Clinic started to perform cellular inner ear research. Engström was an outstanding electron microscopist. He came from Karolinska Institute where he had worked under the famous anatomist Fritiof Sjöstrand; a pioneer in electron microscopy (Afzelius Björn. Sjöstrand FS. Memories, the development of Scandinavian electron microscopy. J Submicr Cytol Pathol. 2001;33:363-417). During its golden age (1951-1955) he developed a technique to cut thin sections using razor blades (Schick!) that were polished with a particular diamond powder using a glass plate inspected with epimicroscopy. Hans Engström was the first in the field of inner ear electron microscopy and was joined by Jan Wersäll, later chairman of the Dept. of ORL at Karolinska Hospital in Stockholm. Hans Engström brought his daughter Berit Engström into the field (today, a medical audiologist); also an excellent electron microscopist. Their beautiful studies of the organ of Corti are still classic.

Inner ear research continued under Jan Stahle’s chairmanship. He devoted his clinical career to problems around Meniere’s disease. Under his and Herrman Wilbrand’s (Professor in Otoradiology) guidance, the idea was developed to create a collection of human inner ear molds and dissections. The initiative was to delineate the miniscule structures of the human inner ear such as the vestibular and cochlear aqueducts and to observe their role in Meniere’s disease. These small canals were also associated with accessory canals housing blood vessels that were believed to play important roles for the turnover of inner ear fluid. Herrman Wilbrand had a deep interest in temporal bone anatomy and its radiological appearance and used polytomography before the era of modern CT. Our collaboration resulted in radio-anatomic correlations and new techniques to cast human inner ears using methacrylate and silicone with a low shrinkage factor. A collection was built with 325 corrosion casts performed by several collaborators at the Dept of Radiology. These casts are now at the Medical-History Museum and Dept. of ORL, and used for research and teaching. Little did we then understand the remarkable evolution of ORL with cochlear implants and auditory brainstem implants, and other bionic systems. Our collection can be used to understand the individual biological variations important for inner ear surgeons. Today, our research focuses on cell culture, structural analyses and proteomics of the human ear. We rely on animal data, as well as fresh human tissue obtained at surgery; the latter is scarce, which limits the investigations.
Recent studies have revealed (and perhaps a bit surprising) differences in molecular expression between animal and human material, which motivates some caution in generally extrapolating animal data to human. This seems particularly relevant for the auditory nervous system.

Scanning electron micrograph (SEM) of human cochlea and prestin immunolocalization. Specimen was directly fixed for SEM after removal at surgery. Surgery by Anders Kinnefors, Dept. ORL Uppsala. Microdissection by author. Labeling and SEM performed by author with Professor Kristian Pfaller, Innsbruck. Photoshop colorization (left image) by Rudolf Glueckert, Innsbruck. Inner hair cell (right image) and confocal microscopy (middle) by Professor Wei Liu, Dept. ORL Uppsala. (Surgical specimen was obtained during translotic skull base surgery for life-threatening petro-clival meningioma where inner ear was removed instead of drilled away. Ethical and informed consents were obtained from the patient and study was performed in accordance with the Helsinki declaration).

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