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Authors
Danielian, Arman
Ishiyama, Gail
Lopez, Ivan A
et al.

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Morphometric Linear and Angular Measurements of the Human Cochlea in Implant Patients Using 3-Dimensional Reconstruction

Arman Danielian[a,*], **Gail Ishiyama**[b,*], **Ivan A Lopez**[a], **Akira Ishiyama**[a]

[a]UCLA David Geffen School of Medicine Department of Head and Neck Surgery, Los Angeles, CA, 90095, USA

[b]UCLA David Geffen School of Medicine Department of Neurology, Los Angeles, CA, 90095, USA

Abstract

The present study is the first to evaluate the spiral ganglion neurons (SGNs) and the linear and angular measurements of the cochlea in temporal bones of cochlear implant (CI) recipients. There are no studies evaluating the morphometric measures in subjects after long-term CI use, and this study fills in this gap in current knowledge, greatly important for the design of CI electrodes. Amira based 3-D reconstructions of the cochlea were generated from stained histopathological slides of 15 celloidin-embedded human temporal bones. The SGN angular distance from the round window exhibited a narrow range from 684°-704°, corresponding to linear distances of 17.87 and 34.48 mm along the inner and outer wall of the scala tympani. The first turn measured an average of 14.21 mm along the inner wall and 23.92 mm along the outer wall. The outer wall average for the second turn was 11.11mm and for the partial third apical turn was only 4.49 mm. The range for cochlear duct angular distance was 876° to 1051°, with a mean of 2.63 turns, corresponding to an average linear distance of 39.53 mm, ranging from 35.44 mm to 43.57 mm. 6 out of 15 temporal bones demonstrated better preservation of SGN in the middle and apical segments of Rosenthal's canal. The present study demonstrates that the anatomy of the cochlea of CI patients does not differ significantly from that of normative subjects and establishes measurements using the round window as the 0 ° reference point, an important surgical landmark. The relevance of the measurements to cochlear implant design are discussed.

Keywords

Spiral ganglion neurons; cochlear implant; electrode design; temporal bone; cochlea

1. Introduction

The spatial distribution of spiral ganglion neurons (SGNs) has important implications for cochlear implantation as SGNs play a crucial role in sound perception for cochlear implant

CORRESPONDING AUTHOR: Akira Ishiyama, M.D., ishiyama@ucla.edu, 35-64 Rehabilitation Center, 1000 Veteran Avenue, Los Angeles CA 90095, Phone: 310-825-5331, Fax: 310-206-1513.
*Equal contribution to the manuscript

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(CI) recipients (Allitt et al., 2012; Clark et al., 2013). The angular and linear length of the SGN within Rosenthal's canal (RC), the inner and outer wall lengths of segmental turns of the cochlea and the entire cochlear duct (CD) are important anatomical landmarks for determining the ideal electrode array length (Adunka and Kiefer, 2006; Ariyasu et al., 1989; Avci et al., 2014; Hochmair et al., 2015; Holden et al., 2013; Kiefer et al., 2014; Koch et al., 2017; Kós et al., 2005; Landry et al., 2011; Leake et al., 1999; O'Connell et al., 2016; Roland and Wright, 2006). Prior morphometric studies used temporal bones from normal hearing subjects of varied age groups. However, the varied disease processes causing profound hearing loss, and the effects of cochlear implant surgery and of long-term implantation are unknown. There are no prior detailed morphometric analyses of the inner ear cochlea from patients who received the CI. The use of morphometric measurements from normal hearing subjects for the design of CI length and dimensions assumes that deafened cochleae have unchanged dimensions from normal hearing cochleae. Additionally, most prior studies have not obtained measurements using the round window set at 0° reference point, which is of relevance to the CI surgeon given that the RW approach is preferred over the cochleostomy approach (Ishiyama et al., 2016). The present study investigates the angular and linear lengths of the inner wall (IW) and outer wall (OW) at the termination of the SGN, segmental quarter turns of the cochlea, and the entire CD length in 15 temporal bones (TBs) from patients who received a CI for profound deafness with causes ranging from otosclerosis, meningitis, congenital hearing loss, and ototoxicity.

The coordinate system of the cochlea adopted for the present study was created by a Consensus panel in 2010 to set a standardized protocol for cochlear measurements. The Verbist criteria sets the center of the round window (RW) as the 0° reference point with the plane of rotation set around the z-axis, which extends from the helicotrema to the base, reflecting the complex 3-dimensional geometry of the human cochlea. The y-axis originates at the center of the round window, travels through the modiolus and terminates at the outer border of the basal turn establishing the 0° and 180° reference points. The x-axis is perpendicular to the y-axis and establishes the 90° and 270° reference points. Using the RW as the 0° reference point has direct relevance to cochlear implant insertion lengths as the preferred surgical approach is through the RW (Ishiyama et al. 2016) and the insertion length in mm is defined as the length from the point of insertion.

There are two prior studies investigating the microanatomy of SGNs using 3-dimensional reconstruction of serial histology sections. Ariyasu et al. (1989) generated 3-D reconstructions using 25 µm hematoxylin and eosin (H & E) stained sections from two temporal bones, and reported that RC makes 1 ¾ (630°) turns and terminates by the middle of the 2nd turn of the OC. Kawano et al. (1996) generated computer-aided 3-D reconstructions using 3 µm thickness H&E sections every 130 µm from 8 male temporal bones, and described a range of 1 ¾ to 2 turns (630°-720°, mean 676.8°) for the angular distance of the SGN. Both of these studies were conducted before the introduction of the updated coordinate system by Verbist et al. (2010). Avci et al. (2014) applied the updated Verbist coordinate system to 3-D reconstructions from micro computed tomography (CT) images of 16 postmortem fresh frozen TBs. For better visualization of the fine structures of the cochlea, the cochlear perilymphatic fluid was removed prior to fixation which affected the most apical half-turn of the scalae in some cases. Avci reported a range of 510° to 615°, with a mean of 565° for Rosenthal's canal (RC) which contains the SGNs. With regard to linear length measurements, it is widely agreed that 3-D renderings of the cochlea provide the most accurate method of studying cochlear anatomy as it takes into account the complex geometry of the cochlea and is not affected by viewing angle and cutting angle differences (Alexiades et al., 2015; Kawano et al., 1996; Koch et al., 2017; Sridhar et al., 2006; Stakhovskaya et al., 2007; Takagi and Sando, 1989).

The purpose of this study is to determine the cochlear duct (CD) length, the angular and linear distances of SGNs in RC, and the linear lengths of the first, second and apical turns using the round window as the 0° reference point. The relative regional preservation of the SGN somata in CI patients was assessed. Amira 6.5, a computer based 3-dimensional reconstruction system, was applied to analyze stained histopathological sections of archival human temporal bones (TB) examined under light microscopy in 15 patients with a history of CI. The results were analyzed for differences in the angular and linear distance of the anatomical structures in male vs. female, and in right vs. left cochlea. The linear length of the first turn was compared with the linear length of the second turn, and with the linear length of the total cochlear duct for correlations. The morphometric findings are analyzed with respect to prior studies that had been conducted in normative subjects who had no history of audiovestibular disorders.

2. Materials and Methods

2.1. Temporal Bone Harvesting

Included in this study are 15 human temporal bones (HTBs) from patients who had received a cochlear implant for ototoxicity, meningitis, otosclerosis, hereditary hearing loss, or unknown causes. The Institutional Review Board (IRB) of UCLA approved this study (IRB protocol #10–001449). All methods used in this study are in accordance with NIH and IRB guidelines and regulations. Appropriate informed consent had been obtained from each patient before inclusion in the study. The temporal bone donors were part of a National Institute of Health funded National Temporal Bone Laboratory at UCLA through the National Institute on Deafness and Other Communication Disorders. The medical history for each of the patients who had donated their temporal bones is maintained and preserved in a secured electronic database.

HTB processing: The temporal bones had been removed postmortem using the block method (Schuknecht, 1993) and placed in 10% neutral buffered formalin for four weeks, the HTBs were then decalcified in EDTA until shown by X-ray to be free of calcium. Embedding was done in increasingly concentrated celloidin to allow complete penetration. To minimize extraction movement and the effect of chloroform-induced swelling of the silicone, the electrode was removed just before the specimen was placed in hardening chloroform. Polymerization of celloidin is allowed by exposing the temporal bones (placed in a desiccator) to fumes of chloroform for 4 weeks. The celloidin block was then cut into 20-micron sections of which every tenth was mounted and stained with hematoxylin and eosin (H & E). The stained human temporal bone sections were examined using a light microscope (Nikon Alphaphot YS) and all images were captured using a digital camera (Optromics).

2.2. 3-D Reconstruction of the Cochlea using Amira 6.5

A total of 15 temporal bones were used in this study. There were 8 male and 7 female subjects; and there were 7 right and 8 left temporal bones. The digital images captured from serial sections were reconstructed into 3-D reconstructions. Images (between 28–39 sections per specimen) were taken from the entirety of the cochlea using a light microscopy objective (1x), total magnification 10x. The images were aligned using identifying landmarks (fiduciary points), including the cochlea, internal auditory canal, saccule, and semicircular canals, with the Fiji (Fiji Is Just ImageJ) software program, using the TrakEM2 plugin. Hyperstacks of the aligned images were then created on Fiji to account for the nine unstained sections between every H&E section. The hyperstack was then loaded onto Amira (version 6.5.0) where 3-D reconstructions were generated. Using the 'Segmentation' tool of Amira, the entire cochlea was segmented on every H & E slide in the hyperstack. Once the entire cochlea was segmented, the volume between segmented sections was interpolated to create a complete 3-D rendering of the cochlea. To input the dimensions of each voxel on Amira, 1x images taken with the light microscope were measured to determine microns per pixel.

2.3. Angular Distance

The coordinate system of the cochlea adopted for the present study was created by a Consensus panel in 2010 (Verbist et al., 2010). In brief: The center of the round window is to be set as the 0° reference point and the plane of rotation is to be set around the z-axis. A line originating at the center of the round window traveling through the modiolus and terminating at the outer border of the basal turn establishes the 0° and 180° reference points (y-axis). The x-axis is perpendicular to the y-axis and establishes the 90° and 270° reference points. The z-axis extends from the helicotrema to the base and through the intersection of the x-and y-axis. The coordinate system used for the 3-D reconstruction is demonstrated in Figure 1.

The 3-D reconstructions of the cochlea were used to determine the angular distance of the SGNs and the cochlear duct. Evaluation for the presence of SGNs at cochlear turns was determined by examining H&E sections at 10x magnification. Serial sections of the modiolus, where SGNs extend most apically were examined, and the cochlear turn adjacent to the most apical SGNs was marked to measure degree of rotation on the 3-D rendering. To generate a complete 3-D representation of SGN distribution in the cochlea (Figure 2), spiral ganglion neurons were segmented on each H & E section of the hyperstack and volumes in between were interpolated, in the same manner described previously for the cochlear segmentation. The round window was also segmented and surface area interpolated, so that the 0° reference point could be identified. 'Surfaces' of the individual structures were generated and combined to create a model containing the cochlea, SGNs, and round window (Figure 2). Angular measures were then made using Amira's 2-D angle tool while positioning the 3-D reconstruction in the 'cochlear view' (Figure 1), defined as viewing the cochlea through the z-axis from the helicotrema to the base of the cochlea.

2.4. Linear Distance Measurements

Linear distance measurements of interest were the lengths from the round window to the termination of the SGNs along the outer and inner wall of the scala tympani, the length of Rosenthal's canal along the inner wall of the scala tympani (Figure 3), and cochlear duct length along the outer wall. Measurements were made on Amira, using the 'B-spline' and 'Curve editor' tools. Using the 3-D reconstruction of the cochlea superimposed on its histology sections individual points were marked along desired landmarks. Figure 3A illustrates the outer (red point) and inner wall (black point) points on a histology section. Once all points for the entire length were marked, the 'line set to spatial graph' feature was applied to create a best fit line traveling through all the points. Finally, the 'spatial graph statistics' feature was utilized to generate the measurements.

2.5. Spiral ganglion neuron preservation

Spiral ganglion cell estimates were obtained as described by Linthicum and Fayad (2009). In brief: A template reconstruction was made for each cochlea section counted. The number of neurons seen in each portion of the slide were represented in the template reconstruction. The total number of neurons was added for each section and multiplied by 10 given that every tenth sections is counted and multiplied by 0.9 to account for cells that maybe double counted because of the profile being present in adjacent sections. A recent study confirmed that estimates obtained using the profile count method of estimating cell number for human SGN with a correction factor of 0.91 matched with 3-dimensional reconstruction derived counts (Robert and Linthicum, 2016).

Consecutive H&E sections of the mid-modiolus were examined and compared to identify differences in preservation of the SGN somata at the different segments of Rosenthal's canal (basal, middle, and apical).

2.6. Statistical Analysis

All statistical analysis was performed on SPSS software (version 24.0.0.0). Mean and standard deviations were calculated with the descriptive statistics function. Independent samples t-tests were conducted to compare angular and linear distance measures between males and females and between left and right cochlea. Levene's test for equality of variances was utilized to test for homogeneity of variances. Pearson correlation coefficients were computed to assess the relationship between two variables. Scatterplots were generated on Microsoft Excel. The significance threshold was set at $p<0.05$.

3. Results

3.1. SGN Angular Distance

Analysis of the 3-D reconstructions of the 15 temporal bones revealed a narrow range of SGN angular distances from the round window (Table 2). Angular distances ranged from 684°-704° (1.89 – 1.95 turns), with a mean of 695° (1.93 turns, sd = 5.78). There was no significant difference in angular distance between males (mean = 696°, sd = 5.39) and females (mean = 694°, sd = 6.36); $t(13) = 0.811$, $p = 0.432$. There was no significant difference in SGN angular distance between the right (mean = 695°, sd = 4.66) and left sides (mean = 695°, sd = 6.95); $t(13) = 0.10$, $p = 0.91$.

3.2. SGN Linear Distance

The linear lengths of the outer wall (OW) (outermost point within the scala tympani) and the inner wall (IW) (innermost point within the scala tympani), running alongside the length of the SGNs were measured (Figure 3). With the RW as 0°, the linear distances along the IW and OW of the scala tympani were measured every 90° to the termination of the SGNs (Table 2 and 3). The mean linear OW distance along the SGN was 34.48 mm, ranging from 31.38 to 36.44 mm (sd = 1.55). The mean linear IW distance along the SGN was 17.87 mm, ranging from 16.34 to 18.92 mm (sd = 0.79). The mean RC length was 15.89 mm, ranging from 14.44 – 16.97 mm (sd = 0.77). There was no difference in linear lengths for laterality and gender of temporal bones. The SGN linear distance for the OW in males (mean = 34.02 mm, sd = 1.83) and females (mean = 35.01 mm, sd = 1.03) was not significantly different $t(13) = -1.25$, $p = 0.23$. The SGN linear distance for the OW on the right (mean = 34.87 mm, sd = 1.55) and left (mean = 34.13 mm, sd = 1.56) was not significantly different $t(13) = 0.91$, $p = 0.37$. Similarly, the SGN linear distance for the IW in males (mean = 18.01 mm, sd = 0.85) and females (mean = 17.71 mm, sd = 0.75) was not significantly different $t(13) = 0.71$, $p=0.48$. The SGN linear distance for the right (mean = 17.96 mm, sd = 0.88) and left (mean = 17.80 mm, sd = 0.75) was not significantly different $t(13) = 0.39$, $p = 0.69$.

3.3. Segmental and Cumulative Lengths of the Inner and Outer Wall

The segmental and cumulative lengths and fractions of the total at every quarter turn (90°) were measured and detailed in Table 3. Each successive 90° increment was smaller, and each successive turn was also smaller in mm length. The IW length for the first half turn (from 0° to 180°) was 9.98 mm, and for the second half turn (from 180° to 360°) was 4.21 mm. Similarly, the OW length for the first half turn (from 0° to 180°) was 14.46 mm and for the second half turn (from 180° to 360°) was 9.44 mm. The distance from 360° to 540° (1 full turn to 1 ½ turns), measured 6.44 mm along the OW, and only 2.47 mm along the IW. Of note, there is a wide difference in the IW length and OW length for the same angular distance: there is an average of 16.61 mm difference between the OW (34.48 mm) and IW (17.87 mm) lengths up to the termination of SGNs, with the greatest intraindividual difference in TB 13 which was 18.25 mm.

3.4. Inner Wall and Outer Wall Linear Distance: First Turn and Second Turn

The average linear distance along the IW and the OW at 360°, or one full turn was 14.21 mm and 23.92 mm, respectively. The IW length ranged from 12.87 to 15.44 mm at 360°, with 2.57 mm difference between the smallest and largest first turn (18% of average IW length). The OW length ranged from 21.57 to 25.60 mm at 360 °, with a 4.03 mm difference between the smallest and largest first turn (17% of average OW length). The average cumulative OW length of 23.92 mm corresponds to 69 % of the total linear distance from the round window to SGN termination, while the average cumulative IW length of 14.21 mm corresponds with 79 % of the total linear distance from round window to SGN termination.

The second turn measured an average of 11.11 mm at the OW, but an average of only 3.25 mm for the first ¾ of the second turn (270 °) at the IW. The segmental lengths of the first turn, second turn, and final partial third turn of the CD at the OW of the scala tympani were measured. The first turn of the CD averaged 23.92 mm, the second turn averaged 11.11mm, and the last partial third turn averaged only 4.49 mm.

3.5. Cochlear Duct

The length and angular distance of the cochlear duct along the OW were measured for each cochlea (Table 2). The cochlear duct lengths are measured at the outermost point within the scala tympani. The total cochlear duct angular distance ranged from 876° to 1051° (mean = 946.58° or 2.63 turns). Thus, the smallest apical third "turn" was less than half a turn (156°) and the largest apical turn was nearly a full turn (331°). There was a wide range of total cochlear duct (CD) lengths ranging from 35.44 to 43.57 mm, with a mean of 39.53 mm (sd = 2.04 mm). Dividing the SGN angular distance by the CD angular distance provides the percentage of the CD adjacent to SGN. (SGN/CD angular distance, Table 2), with an average of 74 percent, meaning RC extends to an average of 74 % of the cochlear duct length and the apical 26 % of the cochlear duct length does not contain SGN somata but may contain the afferent dendrites and innervated organ of Corti.

There were no differences for CD linear and angular distances dependent on TB laterality nor on gender. The linear distance of the CD in males (mean = 39.12 mm, sd = 2.55) and females (mean = 40.03 mm, sd=1.46) was not significantly different $t(13) = -0.82$, $p = 0.42$. The linear distance of the CD on the right side (mean = 40.02 mm, sd = 2.46) and the left side (mean = 39.13 mm, sd = 1.77) was not significantly different $t(13) = 0.81$, $p = 0.43$. The CD angular distance in males (mean = 951°, sd = 60.65) and females (mean = 941°, sd = 53.13) was not significantly different $t(13) = 0.34$, $p = 0.73$. The CD angular distance on the right side (mean = 952°, sd = 66.35) and the left (mean = 941°, sd = 48.20) did not significantly differ $t(13) = 0.35$, $p = 0.73$.

3.6. Correlations of Morphometric Measures Intraindividual TB

Correlations between 1st and 2nd OW length: A Pearson correlation coefficient was computed to assess the relationship between 1st and 2nd turn OW lengths. There was a near significant positive correlation between the two variables, $r = 0.48$, $p = 0.0673$, indicating that the smaller 1st turn is associated with a smaller 2nd turn, and the larger 1st turn is associated with a larger 2nd turn. The average 1st turn OW length was 2.15 times the length of the average 2nd turn OW length. A scatterplot summarizes the relationship (Figure 6).

Correlations between OW 1st turn / OW 2nd turn and total CD lengths: The cochlear duct length was significantly positively correlated with the OW 1st turn ($r = 0.77$, $p = 0.0008$) and OW 2nd turn ($r = 0.74$, $p = 0.0014$). A scatterplot displays the correlation between the CDL and OW 1st turn length (Figure 7).

Correlation between cochlear duct length and angular distance: There was also a positive correlation between the CDL and CD angular distance, $r = 0.51$, $p = 0.05$.

3.7. Preservation of Spiral Ganglion Neural Somata

Total SGN count and regional preservation of SGN somata within the different cochlear regions (i.e., basal, middle, and apical) was evaluated (Table 1). Total SGN somata counts ranged from 2244–24543 somata. Of the 15 TBs, there were 8 TBs which exhibited a similar degree of regional preservation of SGN in the basal, medial and apical turns. There were 7 TBs which demonstrated differential degrees of preservation depending on the cochlear region. Of those with differential preservation, 1 out of the 7 had the higher preservation in the apical turn, and 5 out of 7 had higher preservation in the apical and middle turns. Only 1 out of 7 demonstrated a higher degree of SGN somata preservation in the basal turn. Figure 4 demonstrates a TB with improving SGN somata preservation from basal to middle and apical regions (TB 6), which was the more common pattern of preservation. The present study indicates that a significant subset of implanted subjects exhibited a higher degree of preservation of SGN somata in the middle and apical cochlea. It is important to note that preservation of SGNs without regional variation does not necessarily indicate a high degree of overall preservation. For example, TBs 12 and 13 demonstrate similar preservation throughout the cochlear regions, but have only 2466 and 2244 total remaining SGNs, respectively. Figure 5 demonstrates the uniformly poor preservation of SGNs in RC throughout the cochlea in TB 13.

4. Discussion

The present study determines the linear and angular measurements of major landmarks in the human cochlea in CI recipients demonstrating that the anatomy of the cochlea in CI recipients does not differ significantly from that of normative subjects. It is important to confirm that cochlear anatomy in CI recipients is similar to normative, and to evaluate for potential effects of CI surgery and long-term cochlear implantation on the anatomy of the cochlea. It is possible that long-term implantation causes fibrotic changes affecting the ability to measure accurately the location of the most lateral point in the scala tympani (OW). Measurements were made using the Verbist et al. (2010) coordinates by conducting 3-D reconstructive analysis on serial human TB histopathology sections. There were no significant differences between male and female, nor between right and left sides in any of the cochlea measurements. The mean SGN angular distance was 695.22° with a relatively narrow range of 683.6° to 703.8° from the RW. Prior investigations using 3-D reconstruction have reported similar angular distances of the SGN ranging from 565° to 720°, with the 0° reference set at varying landmarks (Ariyasu et al. 1989; Kawano et al. 1996). Avci et al. (2014) using the Verbist criteria reported a mean SGN angular length of 565° which is a significant 130° less than the present study. This may be due to the suboptimal resolution in the ability to visualize the SGN somata when using micro CT compared with visualization under light microscopy. Stakhovskaya et al. (2007) used serial surface preparations to report an SGN angular length of 630° to 720° with the 0° reference point set at 1 mm from the basal end of the organ of Corti. The present study corroborates the SGN angular distance of 695° (1.93 turns) in CI recipients using the Verbist criteria.

The present study demonstrated a RC length of 14.44 to 16.97 mm (mean = 15.89 mm) in CI recipients, corroborating prior normative data by Stakhovskaya et al. (2007) (14.35 to 16.33

mm, mean = 15.49 mm) and Kawano et al. (1996) (14.73 to 18.38 mm, mean = 15.98 mm). In the present study, the percentage ratio of the length of RC in mm to the total CD length in mm ranged from 34% to 46%, with an average of 40% (sd = 3%) in accordance with measurements in normatives by Stakhovskaya et al. (2007) (40 to 43%) and Kawano et al. (1996) (41.1 to 49.7%).

The OW linear distance from the RW to the termination of SGN ranged from 31.38 to 36.44 mm, averaging 34.48 mm and the IW distance ranged from 16.34 to 18.92 mm, averaging 17.87 mm. This would indicate that a 18mm perimodiolar CI would cover most of the SGN if in close proximity to the IW but that coverage would require the perimodiolar implant to reach 1.93 turns. For the lateral wall CI, an average of 34 mm length would be needed to cover the SGN if in close proximity to the OW (the outermost wall in the scala tympani). The percent of CD angular length containing SGNs ranged from 65% to 80% with an average of 74%, suggesting that on average, the apical 26 percent of the cochlea is innervated by SGNs from more basal turns. However, it is important to note that because of the interindividual varying linear lengths in the cochlea, the longest mm electrode required for coverage of the SGN (36.44 mm in TB 8) is longer than the length of the entire cochlear duct of 35.44 mm in TB 3.

Of relevance to electroacoustic stimulation with goal of preserving residual hearing, the implant array at one full turn likely enters the 1000 Hz region, which defines the end of electric CI stimulation and the beginning of acoustic stimulation (Greenwood, 1961; Stakhovskaya et al., 2007). In the present study of CI recipients, the first turn corresponds to OW lengths ranging from 21.57 to 25.60 mm, averaging 23.92 mm, and IW lengths ranging from 12.87 to 15.44 mm, averaging 14.21 mm. These lengths are in line with the normative data by Kawano et al. (1996) which reported a first turn average OW length of 23.32 mm (sd = 1.52) and an IW length of 13.53 mm (sd = 1.16). The length from the present study, however, is longer than those obtained by Avci et al. (2014) which reported the lateral wall (similar to our OW) at 360° averaged 21.0 mm. It is notable from the present study that the difference between the average IW (14.21mm) and OW length (23.92mm) at 360 ° is 9.71 mm and therefore depending on whether the CI electrodes are placed medially or laterally within the scala tympani, the degree of angular insertion for a given length of electrode can vary greatly. Additionally, the difference between the largest and smallest cochlea was 2.57 mm for the IW and 4.03 mm for the OW lengths up to 360° indicative of significant interindividual differences in lengths for the same angular measurement.

The angular length of the entire CD ranged from 876.2° to 1051.8° (2.43 to 2.92 turns), averaging 946.6° (2.63 turns), with no cochlea reaching a full 3 turns. These findings are comparable to those reported by Avci et al. (2014) which reported that the CD ranged from 859° to 1024°, averaging 949° (2.64 turns) and Kawano et al. (1996) which reported a range of 945 ° to 1080 °, averaging 968 (2.69 turns). Of note, only one TB reached a full 3 turns in a study by Kawano et al. (1996). The total CD length was significantly positively correlated with the OW 1st turn and with OW 2nd turn indicating a proportional relationship. The CD angular distance was correlated with total CD length, which indicates that cochlea with a higher degree of extension of the apical turn have also longer length. There was a near significant positive correlation between the 1st turn OW length and 2nd turn OW length, indicating that a smaller 1st turn is associated with a smaller 2nd turn, and a larger 1st turn is associated with a larger 2nd turn. These findings suggest that there is a proportionate relationship between the OW 1st turn length (mm) and OW 2nd turn length (mm), as well as a proportional relationship between the OW turn lengths and total CD length.

While within the individual cochlea, there are proportionate relationships between the 1st, 2nd turns and total CD lengths, there were great *interindividual* differences in not only the number of turns of the cochlea, but also in the total cochlear duct length, and lengths of given angular distances. In the present study of CI recipients, total CD length measured along the scala tympani OW ranged from 35.44 to 43.57 mm, averaging 39.53 mm with a range of 8.13 mm between the shortest and longest total CD. Kawano et al. (1996) also reported a wide range in CD lengths ranging from 37.93 to 43.81 mm, a 5.88 mm difference in only 8 subjects.

Determining the angular and linear distance of the SGN and cochlear landmarks from the RW is important as the RW can be visualized on imaging and it is a surgical landmark used for electrode insertion in the RW approach. However, predicting the corresponding length in mm for a given angular distance can be difficult as the length near the OW is much greater than that near the IW, and the average length of the first turn is much greater than that of the second turn. Each successive 90° increment becomes smaller and smaller. The first turn measures 23.92 mm in the OW which is approximately 60% of the total CD length of 39.53 mm. In comparison, the second turn of the OW is 11.11mm and the complete length of the first and second turns at 35.03 mm represents approximately 89% of the total CD length. The last apical partial third turn measures only 4.49 mm in the CD. The lengths along the IW are much shorter than those for the OW, as the first turn IW length measures 14.21 mm and the length for the ¾ of the second turn at the IW averages only 3.24mm. In the design of electrodes, it is of importance that a recent study has demonstrated that longer electrode insertions exhibited a higher degree of inner ear damage due to translocation (Ishiyama et al. 2019).

Estimates of the surviving SGN somata in the implanted temporal bones ranged from 2244–24543, and regional differential preservation of SGN somata in 6 out of the 15 human temporal bones exhibited better preservation in the middle and apical turns. These findings are consistent with the findings by Nadol (1997) which demonstrated that hearing-impaired individuals have more degeneration of SGNs in the basal segments than apical. However, SGN degeneration may also result from implant associated damage. Fayad et al. (2009) noted that intracochlear damage and new bone formation was concentrated in the basal region where the electrode was located. In that study, on average, segment I (basal cochlea) of the implanted side had 35% fewer spiral ganglion cells than the non-implanted side. Preventing degeneration of SGNs is important in cochlear implantation outcomes as speech performance word scores have been shown to positively correlate with residual SGN counts (Kamakura and Nadol, 2016). Regional SGN degeneration may reflect the effects of intracochlear damage due to CI electrodes or a primary effect of the hearing loss.

5. Conclusions

The present study findings corroborate previous measurements using the Verbist et al. (2010) criteria and validate the measurements of the cochlea in CI recipients. We report an angular SGN range of 684° to 704° (mean 695°; 1.93 turns) and an average RC linear distance of 15.89 mm, corresponding to an OW length of 31.38 to 36.44 mm (average = 34.48 mm) and an IW length of 16.34 to 18.92 mm (average = 17.87 mm). Each successive turn was smaller with the first turn measuring an average of 23.92 mm along the OW, the second turn measuring 11.11 mm, and the partial third apical turn measuring only 4.49 mm. The linear measurement of the first turn (0° to 360°) of the IW ranged from 12.87 to 15.44 mm, and of the OW, ranged from 21.57 to 25.60 mm. The average cochlea had 2.63 turns, corresponding to an average length of the total cochlear duct of 39.53 mm. There were significant correlations between the OW length of the first turn and total CD length, and near significant positive correlation between the 1st turn length and the 2nd turn length. There was a wide range of cochlear duct lengths such that the longest OW length at SGN coverage was longer than the smallest cochlea's total CD length. There was better relative preservation of the middle and apical SGNs in 40% of the 15 TBs and equal regional preservation in 53%.

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References

Adunka O, Kiefer J, 2006 Impact of electrode insertion depth on intracochlear trauma. Otolaryngol. - Head Neck Surg 135, 374–382. 10.1016/j.otohns.2006.05.002 [PubMed: 16949967]

Alexiades G, Dhanasingh A, Jolly C, 2015 Method to estimate the complete and two-turn cochlear duct length. Otol. Neurotol 36, 904–907. 10.1097/MAO.0000000000000620 [PubMed: 25299827]

Allitt BJ, Morgan SJ, Bell S, Nayagam DAX, Arhatari B, Clark GM, Paolini AG, 2012 Midbrain responses to micro-stimulation of the cochlea using high density thin-film arrays. Hear. Res 287, 30–42. 10.1016/j.heares.2012.04.004 [PubMed: 22531007]

Ariyasu L, Galey F, Hilsinger R, Byl F, 1989 Computer-generated three-dimensional reconstruction of the cochlea. Otolaryngol. - Head Neck Surg 100, 87–91. 10.1177/019459988910000201 [PubMed: 2495514]

Avci E, Nauwelaers T, Lenarz T, Hamacher V, Kral A, 2014 Variations in microanatomy of the human cochlea. J. Comp. Neurol 522, 3245–3261. 10.1002/cne.23594 [PubMed: 24668424]

Clark GM, Clark JCM, Furness JB, 2013 The evolving science of cochlear implants. JAMA - J. Am. Med. Assoc 310, 1225–1226. 10.1001/jama.2013.278142

Fayad J, Makarem AO, Linthicum FH, 2009 Histopathological Assessment of Fibrosis and New Bone Formation in Implanted Human Temporal Bones Using 3D-Reconstruction. Otolaryngol. - Head Neck Surg 141, 247–252. 10.1016/j.otohns.2009.03.031 [PubMed: 19643260]

Greenwood D, 1961 Critical Bandwidth and the Frequency Coordinates of the Basilar Membrane. J. Acoust. Soc. Am 33, 1344–1356.

Hochmair I, Hochmair E, Nopp P, Waller M, Jolly C, 2015 Deep electrode insertion and sound coding in cochlear implants. Hear. Res 322, 14–23. 10.1016/j.heares.2014.10.006 [PubMed: 25456089]

Holden LK, Au D, Finley CC, Ph D, Firszt JB, Timothy A, Brenner C, Potts LG, Gotter BD, Vanderhoof SS, Mispagel K, Heydebrand G, Skinner M, 2013 Factors affecting open-set word recognition in adults with cochlear implants. Ear Hear 34, 342–60. 10.1097/AUD.0b013e3182741aa7 [PubMed: 23348845]

Ishiyama A, Doherty J, Ishiyama G, Quesnel A, Lopez I, Linthicum F, 2016 Post Hybrid Cochlear Implant Hearing Loss and Endolymphatic Hydrops. Otol Neurotol 37, 1516–1521. 10.1097/MAO.0000000000001199 [PubMed: 27608418]

Ishiyama A, Ishiyama G, Lopez IA, Linthicum FH, 2019 Temporal Bone Histopathology of First-Generation Cochlear Implant Electrode Translocation. Otol. Neurotol 40, e581–e591. 10.1097/mao.0000000000002247 [PubMed: 31058752]

Kamakura T, Nadol JJ, 2016 Correlation between word recognition score and intracochlear new bone and fibrous tissue after cochlear implantation in the human. Hear Res 339, 132–41. 10.1016/j.heares.2016.06.015 [PubMed: 27371868]

Kawano A, Seldon HL, Clark GM, 1996 Computer-aided three-dimensional reconstruction in human cochlear maps: measurement of the lengths of organ of corti, outer wall, and Rosenthal's canal. Ann. Otol. Rhinol. Laryngol 105, 701–9. 10.1177/000348949610500906 [PubMed: 8800056]

Kiefer J, Gstoettner W, Baumgartner W, Marcel S, Tillein J, Ye Q, Ilberg C. Von, 2014 Conservation of low-frequency hearing in cochlear implantation. Acta Otolaryngol. 124, 272–80. 10.1080/00016480310000755a

Koch RW, Ladak HM, Elfarnawany M, Agrawal SK, 2017 Measuring Cochlear Duct Length - A historical analysis of methods and results. J. Otolaryngol. - Head Neck Surg 46, 1–11. 10.1186/s40463-017-0194-2 [PubMed: 28057072]

Kós MI, Boëx C, Sigrist A, Guyot JP, Pelizzone M, 2005 Measurements of electrode position inside the cochlea for different cochlear implant systems. Acta Otolaryngol. 125, 474–480. 10.1080/00016480510039995 [PubMed: 16092536]

Landry T, Wise A, Fallon J, Shepherd R, 2011 Spiral ganglion neuron survival and function in the deafened cochlea following chornic neurotrophic treatment. Hear 282, 303–313. 10.1016/j.heares.2011.06.007

Leake PA, Hradek GT, Snyder RL, 1999 Chronic electrical stimulation by a cochlear implant promotes survival of spiral ganglion neurons after neonatal deafness. J Comp Neurol 412, 543–62. [PubMed: 10464355]

Linthicum FJ, Fayad J, 2009 Spiral ganglioni cell loss is unrelated to segmental cochlear system degeneration in humans. Otol Neurotol 30, 418–422. [PubMed: 19326501]

Nadol J, 1997 Patterns of neural degeneration in the human cochlea and auditory nerve: Implications for cochlear implantation. Otolaryngol. - Head Neck Surg 117, 220–228. 10.1016/S0194-5998(97)70178-5 [PubMed: 9334769]

O'Connell B, Cakir A, Hunter J, Francis D, Noble J, Labadie R, Zuniga G, Dawant B, Rivas A, Wanna G, 2016 Electrode Location and Angular Insertion Depth are Predictors of Audiologic Outcomes in Cochlear Implantation. Otol Neurotol 37, 1016–23. 10.1097/MAO.0000000000001125 [PubMed: 27348391]

Robert ME and Linthicum FH, 2016 Empirical derivation of correction factors for human spiral ganglion cell nucleus and nucleolus count units. Otolaryngol. Head Neck Surg 154 (1) 157–163. [PubMed: 26378184]

Roland P, Wright C, 2006 Surgical aspects of cochlear implantation: mechanisms of insertional trauma. Adv Otorhinolaryngol 64, 11–30. 10.1159/000094642 [PubMed: 16891834]

Sridhar D, Stakhovskaya O, Leake PA, 2006 A frequency-position function for the human cochlear spiral ganglion. Audiol. Neurotol 11, 16–20. 10.1159/000095609

Stakhovskaya O, Sridhar D, Bonham BH, Leake PA, 2007 Frequency map for the human cochlear spiral ganglion: Implications for cochlear implants. JARO - J. Assoc. Res. Otolaryngol 8, 220–233. 10.1007/s10162-007-0076-9 [PubMed: 17318276]

Takagi A, Sando I, 1989 Computer-aided three-dimensional reconstruction: A method of measuring temporal bone structures including the length of the cochlea. Ann. Otol. Rhinol. Laryngol 98, 515–522. 10.1177/000348948909800705 [PubMed: 2751211]

Verbist B, Skinner M, Cohen L, Leake P, James C, Boex C, Holden T, Finley C, Roland P, Roland JJ, Haller M, Patrick J, Jolly C, Faltys M, Briaire J, Frijns J, 2010 Consensus panel on a cochlear coordinate system applicable in histologic, physiologic, and radiologic studies of the human cochlea. Otol Neurotol 31, 722–30. 10.1097/MAO.0b013e3181d279e0 [PubMed: 20147866]

HIGHLIGHTS

- 3-Dimensional reconstruction of the cochlea and Rosenthal's canal to study microanatomy in cochlear implant recipients.
- Angular SGN range from the round window was 695°, corresponding to outer and inner wall length of 34.48mm and 17.87mm.
- The first turn averaged 14.21 mm at the inner wall and 23.92 mm along the outer wall.
- Large interindividual variability for linear measures.

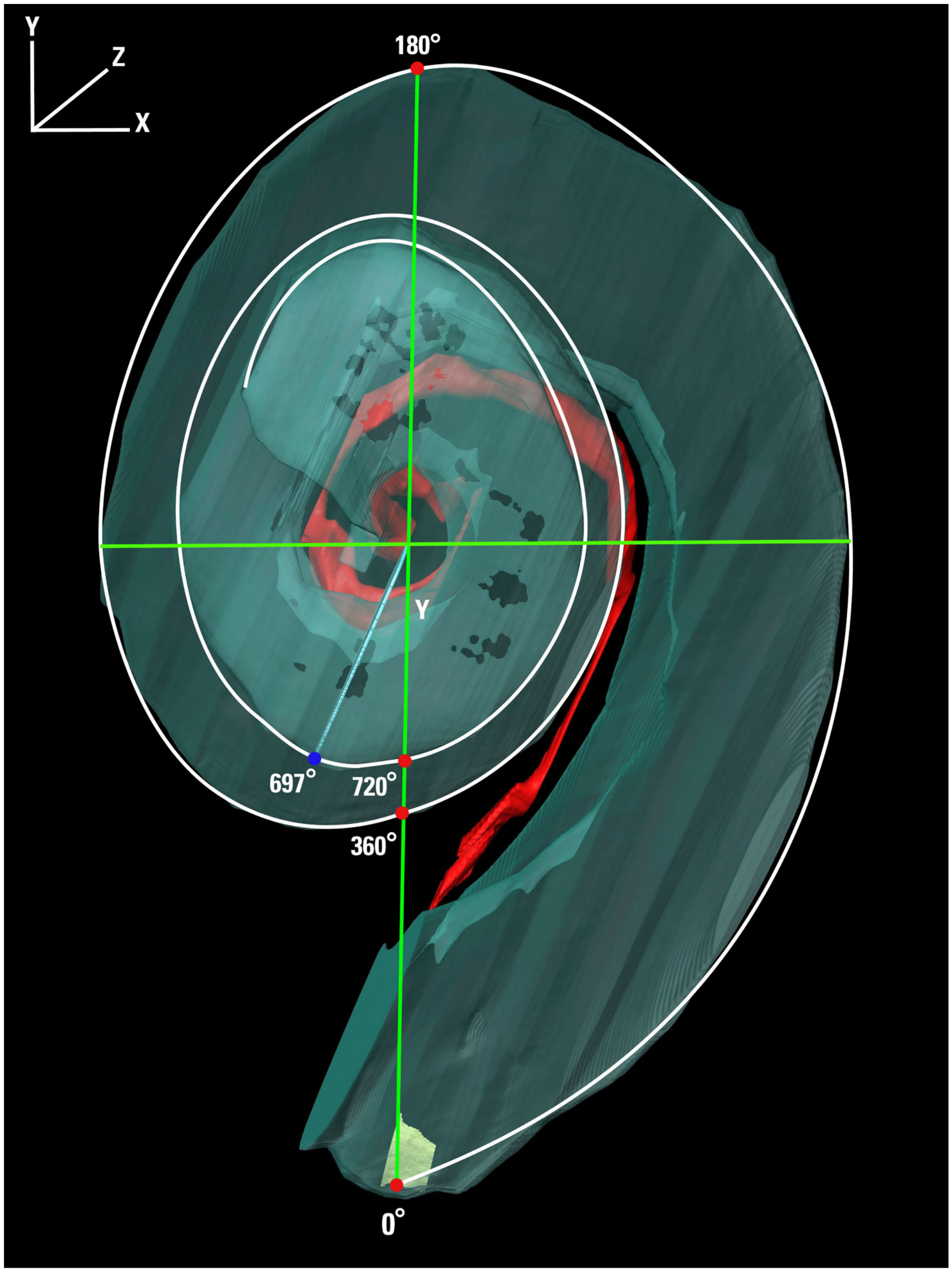

Figure 1.
'Cochlear view' of 3-D reconstruction of right temporal bone demonstrating the coordinate system used for measuring SGN angular distance. The 0° reference angle is located at the center of the round window and the angle of rotation is around the z-axis which travels from the helicotrema to the base of the cochlea through the intersection of the x-and y-axis (green lines). The y-axis is represented by the green line extending between 0° and 180°. The x-axis is the other green line perpendicular to the y-axis. This temporal bone has spiral ganglion neurons extending to 697° indicated by the blue dot. Red (spiral ganglion neurons); yellow (round window); orthogonal xyz coordinates with respect to human anatomy.

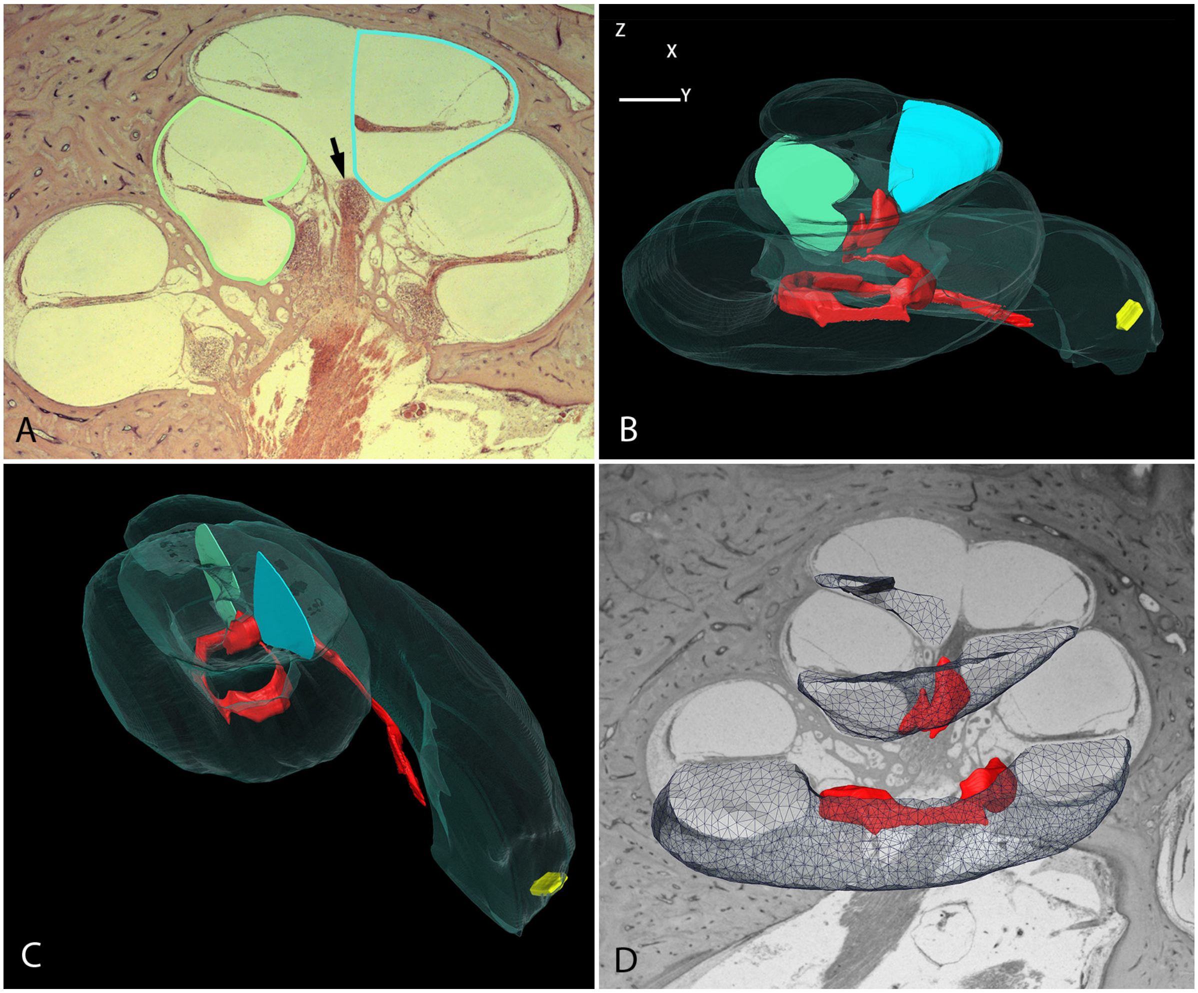

Figure 2.
3-D reconstruction of unimplanted cochlea and its SGNs. (A) H&E of modiolus at 2x magnification demonstrating most apical reaching spiral ganglion neurons. (B) View of 3-D model from the same orientation as Figure 2a. SGNs (red) are observed extending to 697° from the round window. (C) Superior view of 3-D rendering. (D) 3-D reconstruction of scala tympani and SGNs superimposed on a modiolar histology section. Red (spiral ganglion neurons); yellow (round window); green (517.1° turn of cochlea); blue (697.1° turn of cochlea); black arrow (apical SGNs); xyz coordinates described in Figure 1.

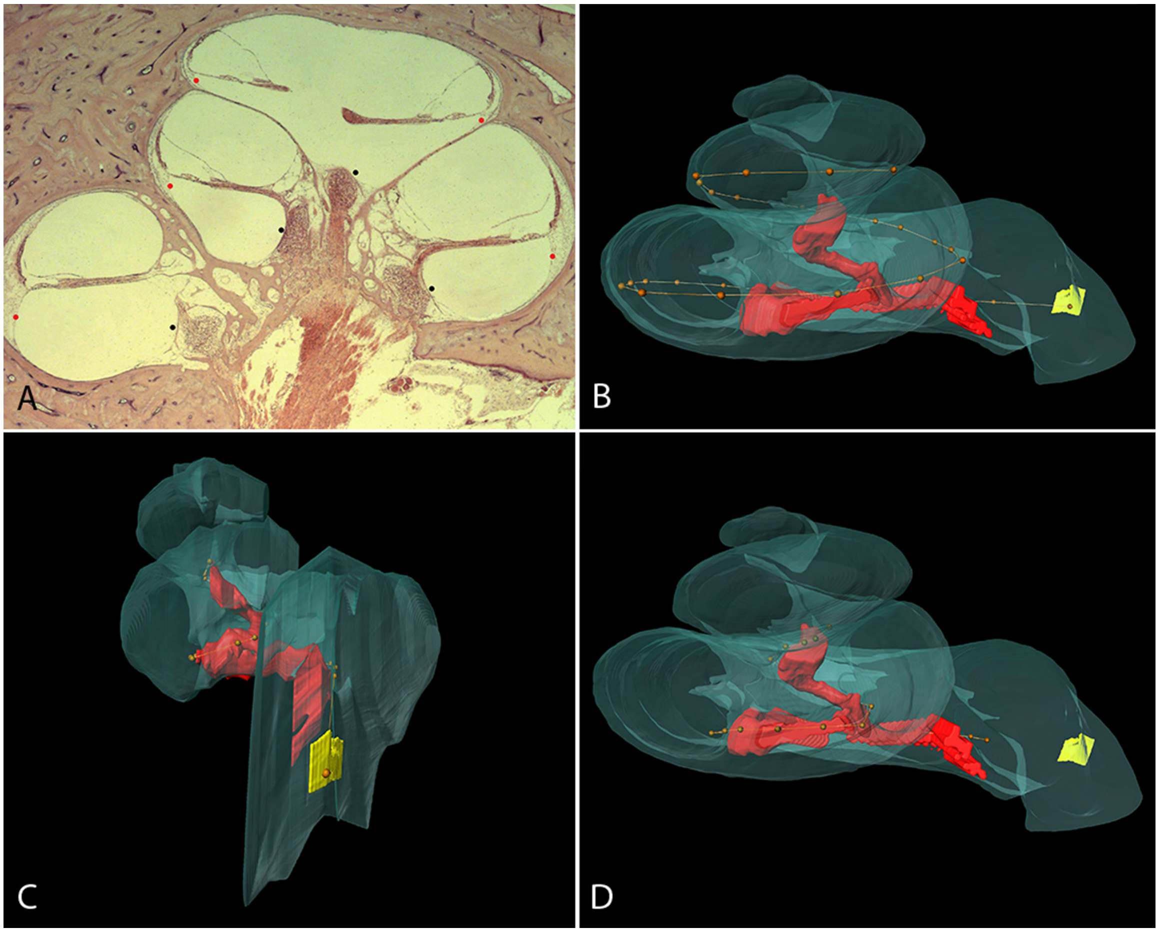

Figure 3.

Linear measures of Temporal Bone 5. (A) 2x magnification of modiolus with red and black dots indicating outer and inner wall of scala tympani, respectively. (B) Linear distance from the round window to the termination of SGNs along the outer wall of the scala tympani. (C) Linear distance from round window to termination of SGNs along the inner wall. (D) Length of Rosenthal's canal along the inner wall.

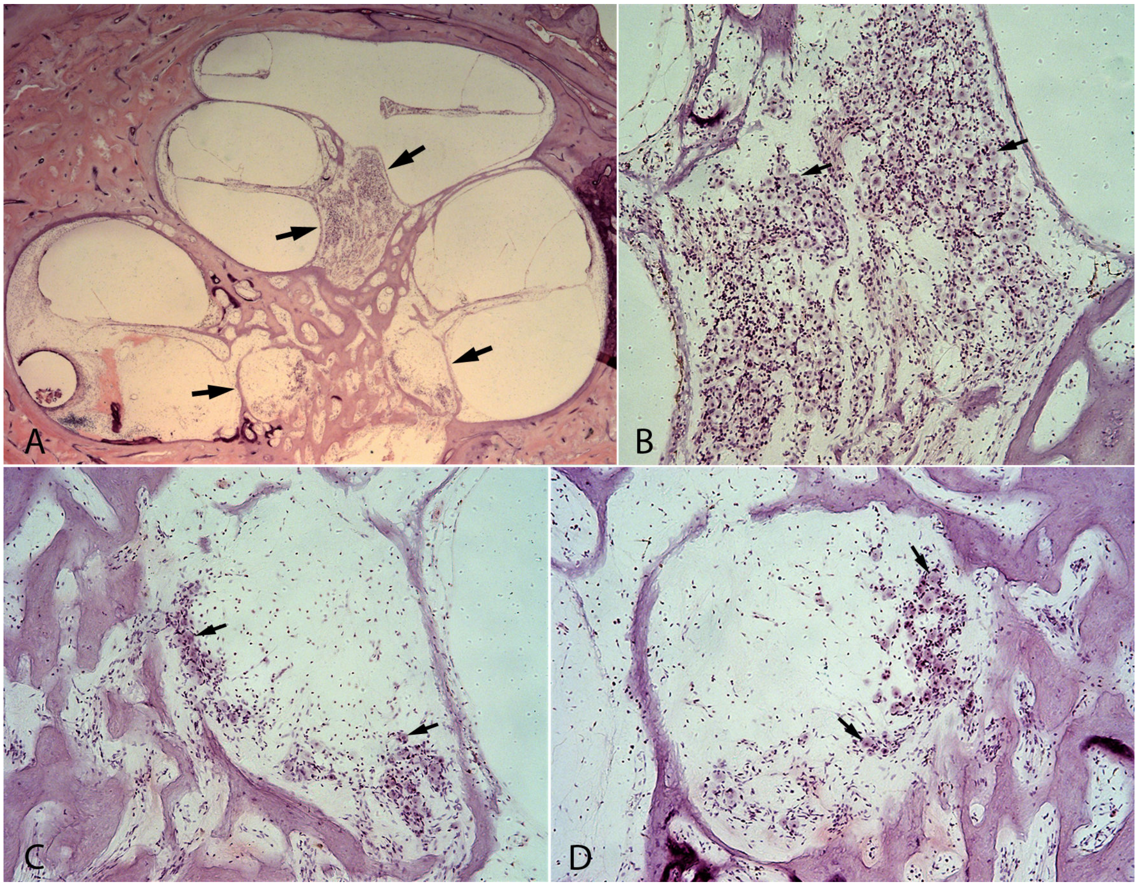

Figure 4.

Temporal Bone 6 in Table 1 demonstrating better SGN somata preservation in the middle and apical regions of RC. (A) H&E of the modiolus at 2x magnification. From superior to inferior, the black arrows are pointing to the apical, middle, upper basal, and lower basal SGNs respectively. (B) 10x magnification of apical and middle SGNs from Figure 4A. Individual spiral ganglion soma are identified by the black arrows. (C) 10x magnification of the upper basal turn of RC from Figure 3A. (D) 10x magnification of the lower basal turn of RC. There is better preservation of the neural somata and elements in the apical and middle regions, compared to the basilar counterparts.

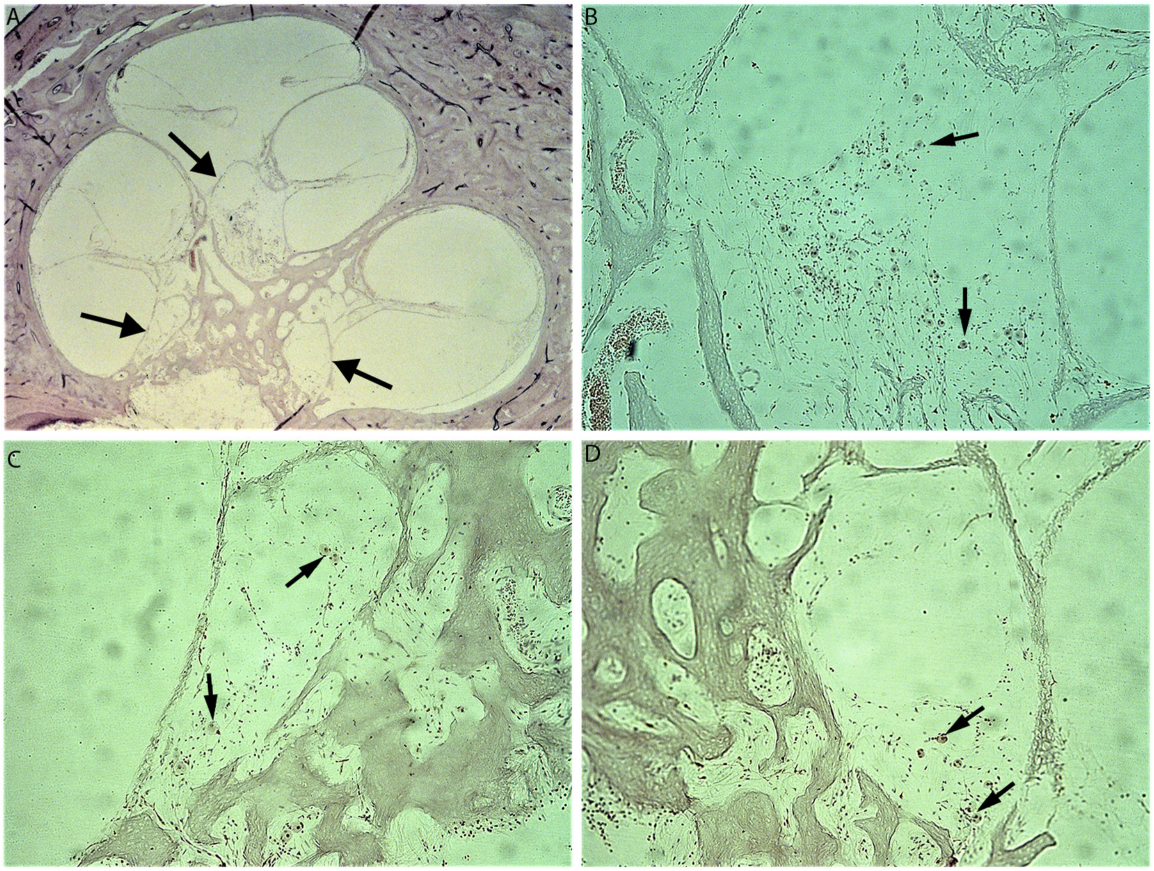

Figure 5:

Temporal Bone 13 from Table 1 demonstrating similar SGN somata preservation throughout Rosenthal's canal, but very poor preservation of somata throughout the entire cochlea. (A) H&E of modiolus at 2x magnification with arrows identifying different segments of Rosenthal's canal; from superior to inferior, the black arrows point to the apical and middle, upper basal, and lower basal segments. (B) 10x magnification of apical and middle turn SGNs from Figure 5A with black arrows pointing to individual soma. (C) 10x magnification of upper basal turn SGNs from Figure 5A. (D) 10x magnification of lower basal turn SGNs from Figure 5A.

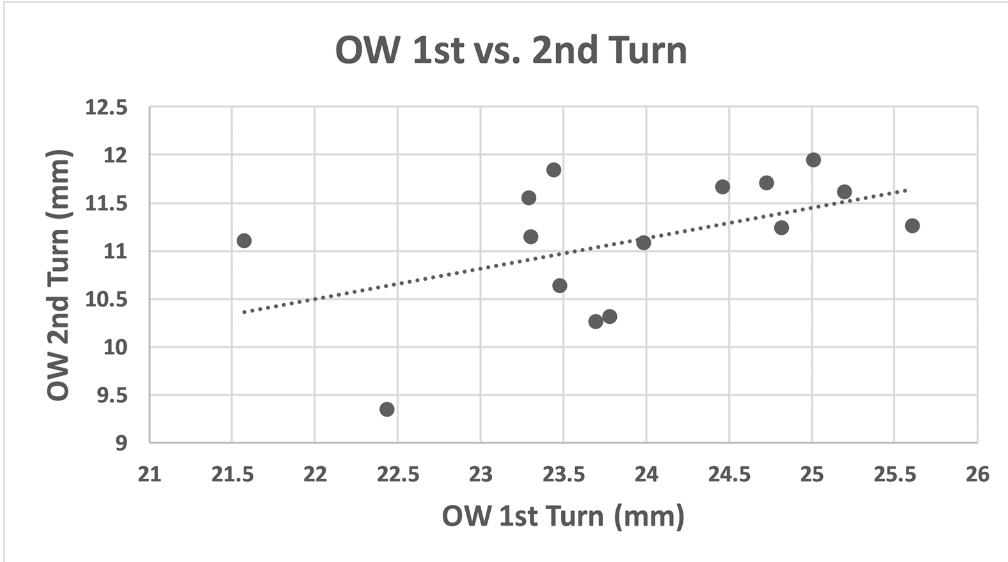

Figure 6:

Relationship between outer wall (OW) 1st and 2nd turn. Results of a Pearson correlation indicated there was a positive association, approaching significance, between the OW 1st turn and OW 2nd turn, (r(13)= 0.48, p=0.07). Overall, larger OW 1st turns correlated with larger OW 2nd turns.

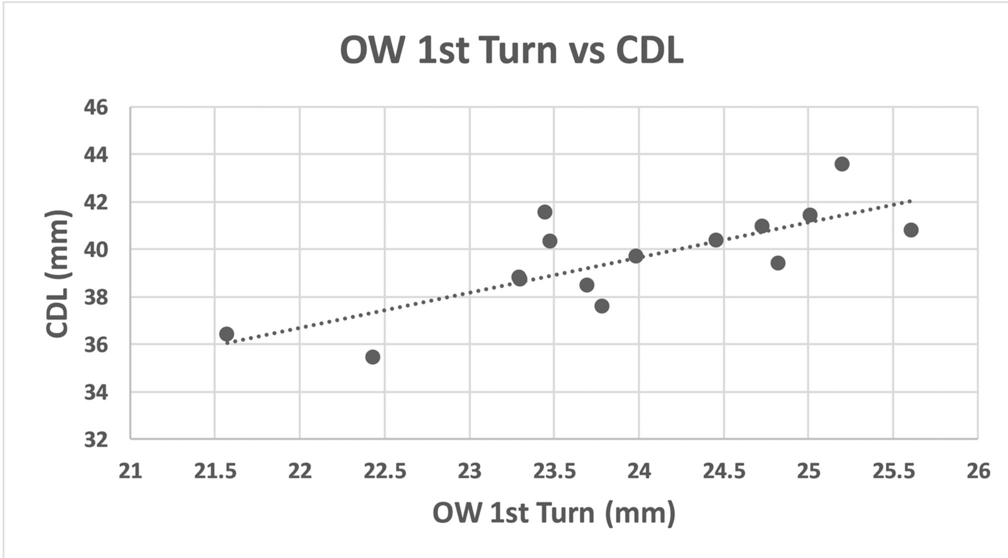

Figure 7:

Relationship between outer wall (OW) 1st turn and cochlear duct length (CDL). Results of a Pearson correlation indicating there is a significant positive association between the OW 1st turn and CDL, (r(13)= 0.77, p=0.0008). Overall, a larger OW 1st turn correlated with a larger CDL.

Table 1.

Age at death, sex, laterality, etiology of hearing loss, SGN estimate, and regional segments of RC with better neural element preservation for each temporal bone. In these temporal bones with cochlear implantation, 8 out of 15 had similar SGN somata preservation throughout RC, while 7/15 demonstrated differences. Of the 7 with differential preservation, 6 demonstrated better preservation of middle and apical somata. SGN estimates ranged from 2244–24543.

Temporal Bone	Age	Sex	Side	Etiology of Hearing Loss	Duration of Hearing Loss In Years	SGN Estimate	SGN Preservation :Regional Segments of Rosenthal's Canal
1	67	M	R	Otosclerosis	55	14022	same at all levels
2	79	M	L	SNHL (familial)	40	6435	Apex
3	78	M	L	SNHL	20	24543	same at all levels
4	63	M	R	Ototoxicity	6	18450	same at all levels
5	71	F	R	SNHL	Unknown	10307	middle and apex
6	87	M	R	Otosclerosis	Unknown	13693	middle and apex
7	75	M	L	Otosclerosis	50	10287	middle and apex
8	92	F	R	Otosclerosis	25	3966	same at all levels
9	87	F	L	SNHL (infectious)	46	13447	Base
10	87	F	R	SNHL (infectious)	46	18076	same at all levels
11	85	F	L	SNHL	Unknown	10903	middle and apex
12	76	F	R	SNHL (familial)	55	2466	same at all levels
13	76	F	L	SNHL (familial)	55	2244	same at all levels
14	60	M	L	Ototoxicity	1	8506	same at all levels
15	73	M	L	SNHL (genetic)	Unknown	9561	middle and apex

L-left ear; R-right ear; SNHL=sensorineural hearing loss

Table 2.

SGN angular distance (°), length of RC (mm), linear distance (mm) from round window to the termination of SGNs along the inner and outer wall of the scala tympani, and cochlear duct (CD) angular and linear distances along the outer wall for the 15 temporal bone specimens. Inner and outer wall linear distances for the 1st turn (360°) are also displayed. The SGN angular distance ranged between 683.6°-703.8° (1.89– 1.95 turns) with a mean of 695.22°, sd=5.78°). The length of RC along the inner wall (IW) ranged from 14.44–16.97 mm with a mean of 15.89 mm (sd = 0.82 mm). The mean distance from the round window to the termination of SGNs along the inner wall of scala tympani (SGN Inner Wall) and outer wall of scala tympani (SGN Outer Wall) was 17.87 mm and 34.48 mm, respectively. The mean angular distance for the cochlear duct was 946.58° (2.63 turns) which corresponded to an average cochlear duct length of 39.53 mm along the outer wall. 'SGN/CD Angular Distance' represents the percent of the cochlear duct adjacent to SGNs (dividing the SGN angular distance by the cochlear duct angular distance).

Temporal Bone ID	SGN Angular Distance	RC (mm)	SGN Inner Wall (mm)	SGN Outer Wall (mm)	Inner Wall at 1st Turn (mm)	Outer Wall at 1st Turn (mm)	Outer Wall at 2nd Turn (mm)	CD Angular Distance	CD Length (mm)	SGN/CD Angular Distance	RC/CD Length
1	701.8°	14.44	16.34	32.03	13.45	21.57	32.67	876.2°	36.40	0.80	0.40
2	688.6°	16.34	18.20	33.27	14.45	23.69	33.96	934.2°	38.45	0.74	0.43
3	697.8°	16.41	17.96	31.38	13.89	22.43	31.77	944.5°	35.44	0.74	0.46
4	698.4°	14.73	17.96	36.01	14.13	25.19	36.80	1036°	43.57	0.67	0.34
5	699.2°	16.08	18.24	33.72	14.45	23.78	34.09	945.2°	37.57	0.74	0.43
6	689.5°	16.97	18.92	35.66	15.44	24.82	36.06	911.2°	39.37	0.76	0.43
7	703.8°	16.89	18.83	33.62	14.38	23.47	34.11	1050.9°	40.30	0.67	0.42
8	695.9°	16.26	18.61	36.44	15.29	25.01	36.95	931.6°	41.41	0.75	0.39
9	683.6°	15.23	16.60	34.33	12.87	23.98	35.07	942°	39.69	0.73	0.38
10	692°	15.55	17.27	34.55	13.61	23.44	35.28	1051.8°	41.53	0.66	0.37
11	703.4°	15.11	17.07	34.27	13.54	23.29	34.83	883°	38.78	0.80	0.39
12	691°	16.14	18.43	35.71	14.51	24.46	36.12	912.9°	40.35	0.76	0.40
13	692.3°	16.13	17.80	36.05	14.08	24.73	36.43	921°	40.94	0.75	0.39
14	694.2°	16.70	18.56	36.33	15.20	25.60	36.86	922.6°	40.79	0.75	0.41
15	696.9°	15.40	17.35	33.84	13.81	23.30	34.44	935.6°	38.71	0.74	0.40
mean	695.22°	15.89	17.87	34.48	14.21	23.92	35.03	946.58°	39.53	0.74	0.40
sd	5.78°	0.77	0.79	1.55	0.72	1.08	1.55	55.47°	2.04	0.04	0.03
min	683.60°	14.44	16.34	31.38	12.87	21.57	31.77	876.20°	35.44	0.66	0.34
max	703.8°	16.97	18.92	36.44	15.44	25.60	36.95	1051.8°	43.57	0.80	0.46

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Table 3.

Average segmental and cumulative distances from the round window to SGN termination at every quarter turn. Cumulative fractions of the total length are also displayed every 90°. Average cochlear duct lengths (CDL), measured along the outer wall, for every full turn are described: 23.92mm (1st turn), 11.11mm (2nd turn), and 4.49mm (distance from 720° to CDL termination).

Degrees from Round Window	Interval Outer Wall (mm)	Cumulative Outer Wall (mm)	Fraction of Total	Inner Wall (mm)	Cumulative Inner Wall (mm)	Fraction of Total
0–90°	8.29 ± 0.65	8.29 ± 0.65	0.24	6.74 ± 0.56	6.74 ± 0.56	0.37
90–180°	6.16 ± 0.29	14.46 ± 0.77	0.41	3.24 ± 0.28	9.98 ± 0.59	0.55
180–270°	5.18 ± 0.27	19.65 ± 0.81	0.56	2.33 ± 0.27	12.32 ± 0.65	0.68
270–360°	4.26 ± 0.41	23.92 ± 1.08	0.69	1.88 ± 0.19	14.21 ± 0.72	0.79
360–450°	3.52 ± 0.33	27.44 ± 1.36	0.79	1.40 ± 0.16	15.61 ± 0.75	0.87
450–540°	2.92 ± 0.21	30.37 ± 1.46	0.88	1.07 ± 0.12	16.68 ± 0.76	0.93
540–630°	2.52 ± 0.22	32.90 ± 1.53	0.95	0.77 ± 0.09	17.46 ± 0.78	0.97
630-SGN termination	1.58 ± 0.24	34.48 ± 1.55	1	0.41 ± 0.08	17.87 ± 0.79	1

CDL	Interval (mm)	Cumulative (mm)	Minimum (mm)	Maximum (mm)
0–360°	23.92 ± 1.08	23.92 ± 1.08	21.57	25.60
360–720°	11.11 ± 0.71	35.03 ± 1.55	31.77	36.95
720° -CDL termination	4.49 ± 0.99	39.53 ± 2.04	35.44	43.17