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ORIGINAL RESEARCH

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Applications of visualizing cochlear basal turn in cochlear implantation

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Abstract

Objective: To report a reliable method in obtaining optimal cochlear basal turn and cross-section (c/s) of internal auditory canal (IAC) supporting Cochlear implantation (CI) procedure.

Materials and Methods: Computer tomography (CT) and magnetic resonance image (MRI) scans of potential CI candidates from 2018 to 2022 from the tertiary center were considered for analysis. Slicer software was used in three-dimensional (3D) segmentation of inner ear and for capturing the cochlear basal turn.

Results: A total of 1932 head scans were made available for the analysis and out of which 1866 scans had normal anatomy (NA) inner ear. Incomplete partition (IP) type-I was identified in 19 ears, IP type-II in 27 ears, IP type-III in 6 ears, cochlear hypoplasia (CH) type-I in 6 ears, CH type-II in 1 ear, CH type-III in 3 ears, and CH type-IV is 3 ears, and enlarged vestibular aqueduct syndrome in 1 ear. 3D segmented inner ear helped in successfully obtaining the cochlear basal turn and the c/s of IAC in all anatomical types. Time taken to capture the cochlear basal turn with the help of 3D segmented inner ear was <1 min. Within the NA category, five cases showed scalar ossification, and its extent was identified in the cochlear basal turn.

Conclusion: The identification and the extent of ossification in the scala tympani, shape of the basal turn, and the cochlear size measurement in cochlear basal turn has high clinical relevance as this helps in surgical planning and in choosing appropriate electrode length.

Level of evidence: Level 2 to the best of our understanding.

KEYWORDS

cochlear basal turn, Cochlear implantation, cochlear parameters

1 | INTRODUCTION

Cochlear implantation (CI) is a safe surgical procedure in the treatment of sensorineural hearing loss (SNHL) individuals.[1] Cochlear implant comprises of implantable and external components. The external processor comprises of audio-processor with the microphone that picks up the audio signal and breaks it down to frequency specific digital signal which is then transferred to implantable component through radio-frequency link. Implantable component comprises of implant stimulator and electrode array. The implant stimulator receives the signal and converts it to electrical impulses and is sent to electrode array to be delivered inside the scala tympani (ST) to stimulate the auditory neuronal elements. The auditory nerve bundle in the internal auditory canal (IAC) further takes electrical signal to be delivered it to the auditory cortex where it is perceived as sound.[2]

Literature reports that neuronal cell bodies inside the cochlea are distributed to an angular insertion depth of approximately 680°.[3–6] The linear length to achieve 680° of angular depth would vary depending on the overall size of the cochlea.[7] Measuring the full length of cochlea from clinical radiographs is almost an impossible task that has led to new methods in the indirect estimation of cochlear length through simple measurements like the basal turn diameter, which is also called as A-value.[8] This measurement is done in the oblique coronal view of the cochlear basal turn.

The accuracy of A-value depends on the resolution of the image itself as well as on the orientation of the oblique coronal view. Any misalignment in the oblique coronal view would lead to error in A-value measurement.[9] Oblique coronal view of the cochlear basal turn is also important in visualizing the extent of ossification in the ST due to meningitis infection that enters the cochlea mainly through the cochlear aqueduct. Most of the congenital inner ear malformation types have some degrees of cystic portion of the cochlea which can be seen clearly from the oblique coronal view of the cochlear basal turn.[10] Identifying the cystic portion helps in choosing an optimal length electrode that would prevent placing the electrode into cystic apical portion. For achieving all the above-mentioned goals demand for a method with which the optimal oblique coronal view of the cochlear basal turn could be visualized. The presence of cochlear nerve (CN) bundle in the IAC is a key structure to look for during the pre-operative image analysis prior to CI procedure, especially in the congenitally deaf subjects. Somewhere at the mid-length of IAC, the CN is visualized clearly, and its thickness could be measured. How accurately the mid-length of the IAC can be identified, and a cross-section is made to visualize the CN is a question, and this demands for a method with which the optimal oblique sagittal view of the IAC could be visualized.

Digital imaging and communications in medicine (DICOM) viewer, a software is necessary to visualize radiographs in three different planes namely the axial, coronal, and the sagittal. Manual orientation of these three different planes is needed to visualize the cochlear basal turn in the oblique coronal plane and the cross-section (c/s) of IAC in the oblique sagittal plane. Blindly orienting these three different planes without any reference point would lead to nowhere. This is where the three-dimensional (3D) segmentation of the inner ear could act as the reference point with which the coronal plane can be optimally aligned to the cochlear basal turn as well as perpendicular to the IAC.

The aim of this study is to evaluate the usefulness of 3D segmentation of the inner ear in optimally aligning the coronal plane to visualize cochlear basal turn and c/s of IAC in different inner ear anatomical types.

2 | MATERIALS AND METHODS

2.1 | Materials

The computer tomography (CT) and magnetic resonance image (MRI) scans of potential CI candidates from 2018 to 2022 from St. Petersburg ENT and Speech Research Institute were considered for analysis. The images were analyzed using 3D slicer software, version 5.3.0., freeware (https://www-slicer-org).

2.2 | Methods

2.2.1 | 3D segmentation of inner ear

The 3D segmentation of the inner ear was performed by SS, FA, JV, and AK during a workshop session at St. Petersburg ENT and Speech Research Institute. A detailed description of 3D segmentation is given in detail elsewhere,[11] setting a tight grayscale threshold to capture the fluid-filled inner ear and avoid capturing undesired structures around it (refer Figure 1). This step was supervised by AD who has 7 years of experience 3D segmenting inner ear from clinical CT scans as demonstrated earlier.[11]

2.2.2 | Cochlear basal turn

Using the reformat module of 3D slicer software, rotating the coronal plane (Green slice) using the slider (PA) under the rotation feature brings the coronal plane in-line with the cochlear basal turn as shown in Figure 2A. This step was supervised by experienced CI surgeons VK and RP.

2.2.3 | Cross-section of Internal auditory canal

Bringing the coronal plane further down to the mid-length of the IAC shows the c/s of IAC with the CN bundle as shown in Figure 2B.

2.2.4 | Ethics declarations

The study was conducted in accordance with the declaration of Helsinki and approved by the local institutional review board of St. Petersburg ENT and Speech Research Institute (IRB_23_001).

3 | RESULTS

3.1 | Inner ear anatomical types identified

A total of 1932 head scans of CI patients were identified from the radiology database between the time 2018 and 2022. Table 1 summarizes the inner ear anatomical types identified from the head scans.

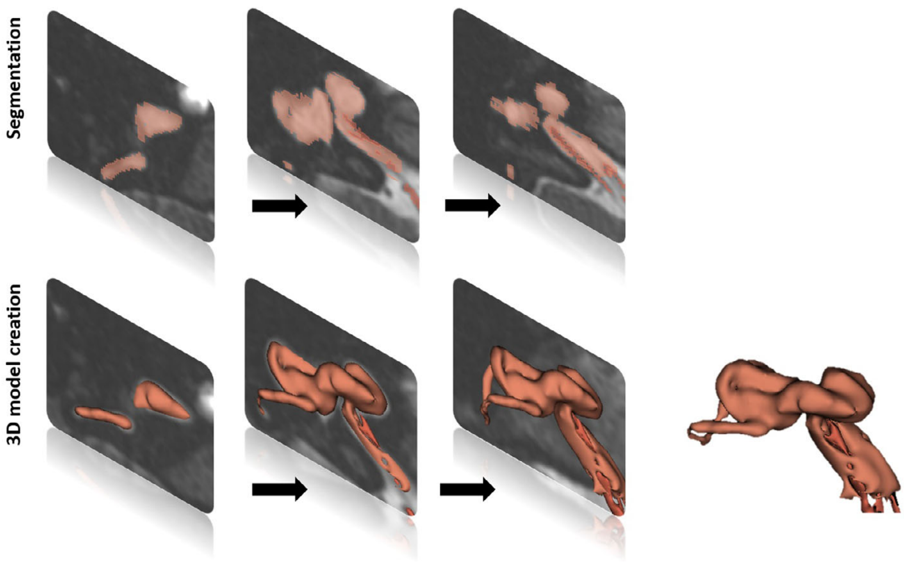

FIGURE 1 3D segmentation of inner ear. Capturing the inner ear structures manually from each slice to create a 3D model of the inner ear.

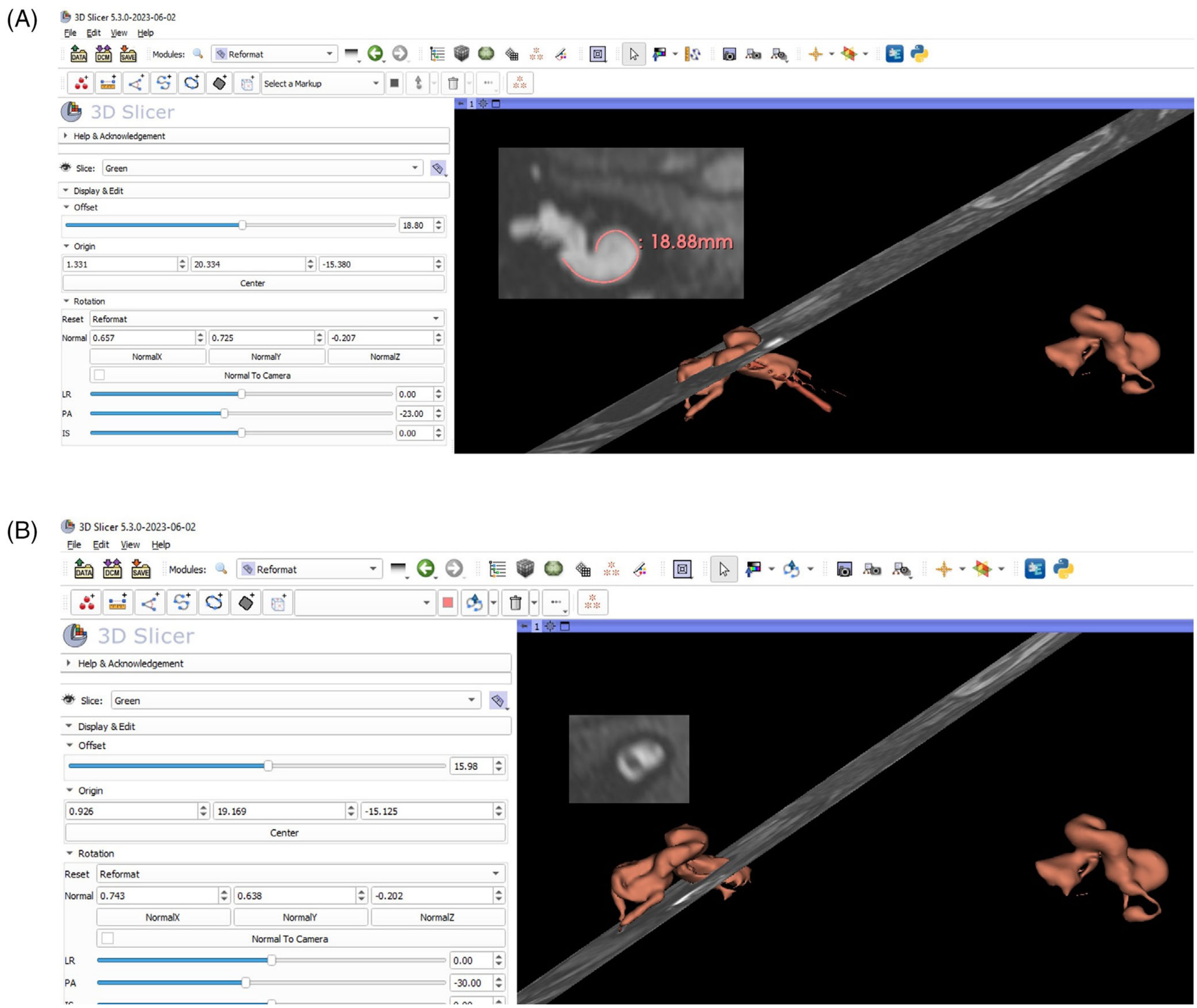

FIGURE 2 Rotating the coronal plane to bring in-line with the cochlear basal turn (A). Moving the oblique coronal plane down to the IAC to visualize the cochlear nerve (B).

TABLE 1 Inner ear anatomical types identified.

Anatomical type	Number of patients
Normal anatomy	1866 (5 ossified)
Incomplete partition (IP) type I	19
IP type II	27
IP type III	6
Cochlear hypoplasia (CH) type I	6
CH type II	1
CH type III	3
CH type IV	3
Enlarged vestibular aqueduct (EVA)	1

A total of 66 cases of different inner ear malformation (IEM) types were identified making the incidence rate of IEM as (66/1932) 3.5% within the SNHL population of Russia. Within the IEM types, IP type II was seen in 41% of the patients followed by IP type I in 29% of the patients. IP type III and CH type I were seen each in 9% of the patients. While CT scans were available for all patients, MRI scans were available only for few patients.

3.2 | 3D segmentation of inner ear

The first and the last horizontal panels of Figure 3 showcase the 3D segmented image of inner ear of all the anatomical types in both oblique coronal (first row) and axial planes (last row). This result shows that 3D segmentation is possible from both CT and MRI scans. MRI helps capturing the complete vestibular aqueduct sac as shown under the IP type II anatomical type within Figure 3 marked with (*) symbol.

3.3 | Capturing the cochlear basal turn

Using the reformat module and rotating the coronal plane in both *x*- and *y*-axis following the basal turn in the 3D segmented image, the oblique coronal plane is established to capture the cochlear basal turn in all anatomical types as shown in the second row in Figure 3. Normal anatomy, EVAS, and CH type III show the cochlear turn close to 540°, whereas for all other anatomical types, the cochlear lumen is seen as less than 540°.

3.4 | Cross-section of IAC

The cochlear basal turn is simply moved down to the mid-length of the IAC to visualize the CN. Third row in Figure 3 shows cross-sectional view of IAC to visualize the cochlear nerve in 6 different anatomical types for which the MRI was available. CN is seen in NA, EVAS, IP-II, and IP-III as pointed out by white arrow in Figure 3.

3.5 | Detecting scalar ossification in the cochlear basal turn

Out of five ossified cases within the normal anatomy group, one case of round window (RW) ossification (refer Figure 4A), one case of ST ossification only in the basal turn (refer Figure 4B), one case identified with ossification at the RW entrance and in the third quadrant of the basal turn (refer Figure 4C), and two cases of complete ST ossification (refer Figure 4D,E) were detected. In all these cases, scala vestibuli (SV) was seen without any ossification.

3.6 | Studying the shape of the basal turn

Oblique coronal plane capturing the cochlear basal turn showed a huge variation in the shape of basal turn within the normal anatomy group. Figure 5 is a collection of selected samples that showed variation in the shape of the basal turn. An elliptical-shaped basal turn extending along the A-value (refer Figure 5A), a round-shaped basal turn (refer Figure 5B), an elliptical-shaped basal turn extending opposite to the A-value (refer Figure 5C), and a triangular-shaped basal turn (refer Figure 5D) was observed.

3.7 | Usefulness of 3D segmented image of inner ear

The 3D segmented inner ear was used as a guide/reference to rotate the coronal plane to capture the cochlear basal turn as shown in Figure 6A. This took less than a minute to capture the cochlear basal turn. By scrolling down the oblique coronal plane brings the c/s of IAC to visualize the CN. In the absence of a 3D segmented inner ear as shown in Figure 6B, it was difficult to rotate the coronal plane to bring it in-line with the cochlear basal turn and it took more than a minute. Still the cochlear basal turn is not as good as the one captured using the 3D segmented inner ear as guide. Also, the c/s of the IAC did not clearly show the distinct nerve bundles. Please refer to the supplementary screen capture video clips (Videos S1 and S2) to see how the cochlear basal turn was captured with and without the guide of 3D segmented inner ear.

4 | DISCUSSION

4.1 | Earlier work on the measurement of cochlear parameters

Adunka et al. in 2005 reported for the first time that the basal turn length (BTL) can be manually measured from the oblique coronal plane cutting through the basal turn of the cochlea.[12] They did mention that it was difficult to capture the cochlear basal turn accurately from a single layer as the cochlea has a complex anatomy. Their motivation for measuring the BTL was to estimate the electrode length to cover only the basal turn in cases with good low-frequency residual hearing. Escude et al. in 2006 reported for the first time that the diameter of

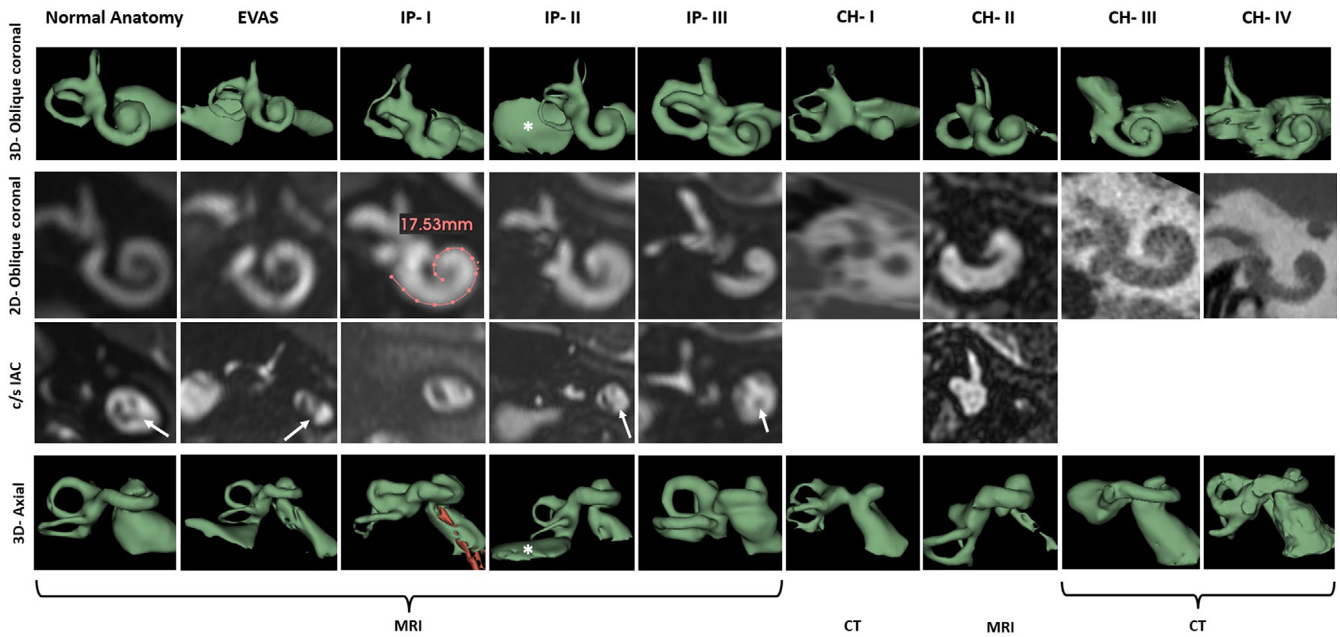

FIGURE 3 Visualization of inner ear of various anatomical types in different views. First row represents 3D model of inner ear in the oblique coronal plane. Second row represents 2D image of inner ear in the oblique coronal plane. Third row represents cross-sectional view of internal auditory canal to visualize the cochlear nerve. Fourth row represents 3D model of inner ear in the axial plane.

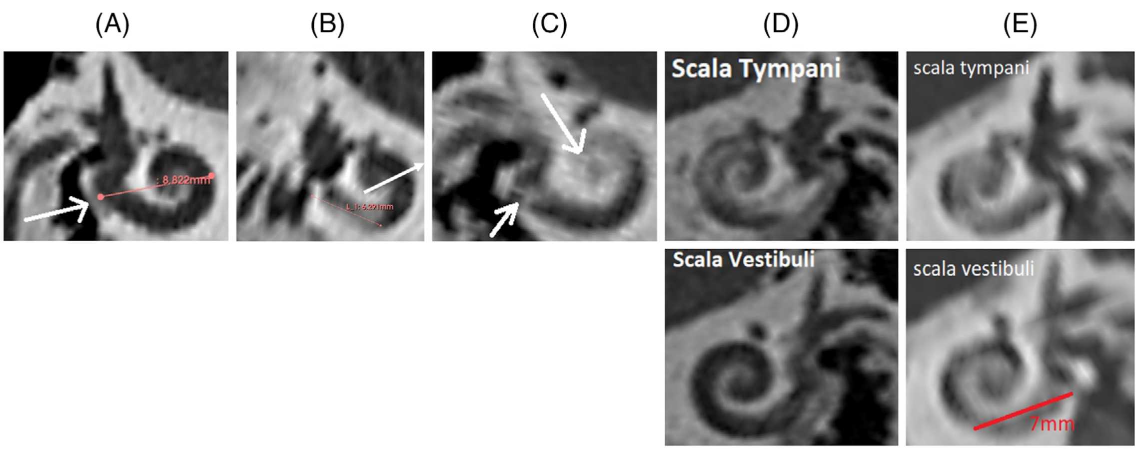

FIGURE 4 Detection of ossification using the oblique coronal plane. RW ossification (A), ossification at the cochlear entrance (B), ossification at the RW and in the third quadrant of the basal turn (C), and full ST ossification with no ossification in the SV (D and E).

cochlear basal turn (A-value) can be used to estimate the full length of the cochlea.[8] Their motivation for estimating the cochlear length is for choosing the best length electrode and for applying mapping the cochlear frequencies. It is essential to capture the cochlear basal turn as accurately as possible to make the A-value or the BTL measurements as it directly influences other applications of these measurements.

4.2 | 3D segmentation of inner ear in the accuracy of cochlear parameters

Rotating the coronal plane without any reference point to bring it inline with the cochlear basal turn is time-consuming and in the worst case, it could lead to tilted view from which accurate measurements cannot be made. This was reflected in an earlier study in 2018 in which they used sub-optimal oblique coronal plane where the cochlear basal turn was not perpendicular to the point of view, from which the A-value measurement was made as shown in Figure 7A.[13] Figure 7B gives a comparison of cochlear basal turn captured in the optimal oblique coronal plane. Their conclusion from that study was the Indian population may have a smaller cochlear size compared to the rest of population. The accuracy of their A-value measurement could be questioned because of their A-value measurement in a sub-optimal oblique coronal plane.

Recently there were reports on the application of 3D segmentation of inner ear in the classification and identification of IEM types

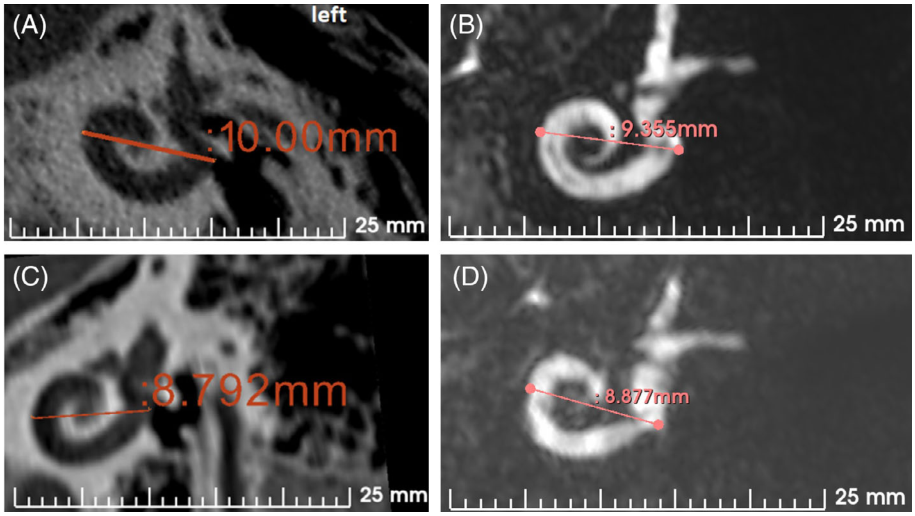

FIGURE 5 Shape of the cochlear basal turn. An elliptical-shaped basal turn extending along the A-value (A), a round-shaped basal turn (B), an elliptical shape basal turn extending opposite to the A-value (C), and a triangular-shaped basal turn (D).

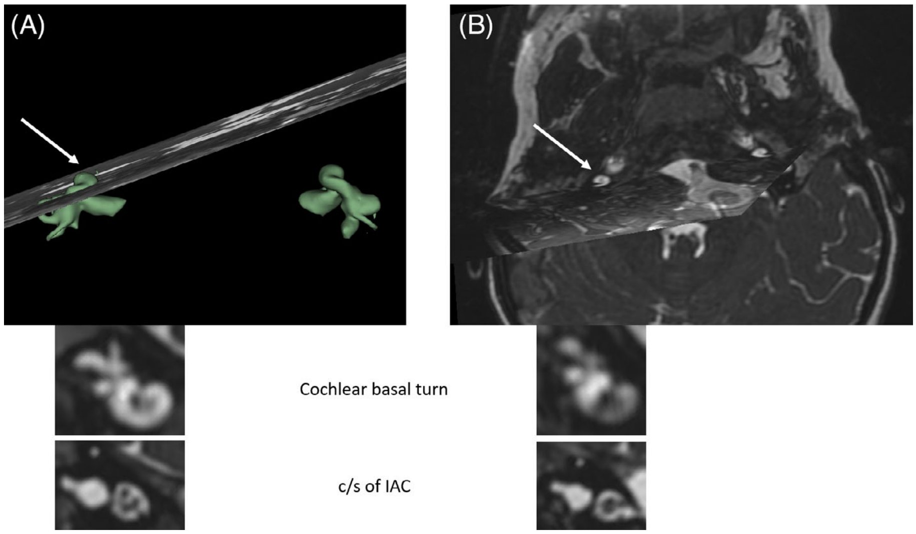

FIGURE 6 Rotation of the coronal plane with (A) and without (B) 3D segmented image as a guide to orient the coronal plane along the cochlear basal turn and the cross-section of IAC.

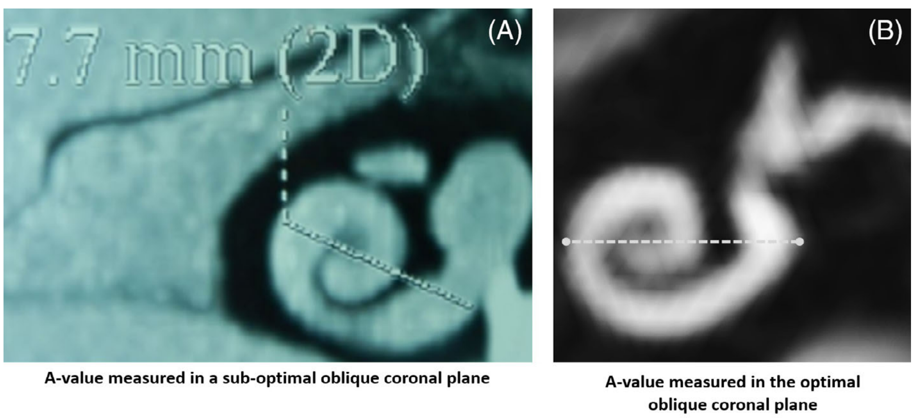

FIGURE 7 A-value measurement in a sub-optimal oblique coronal plane (A) (The rights in the material are owned by a third party[13]) and in the optimal oblique coronal plane (B).

and we successfully applied it in our own clinical practice.[14] This led to the idea of using 3D segmented inner ear as a guide to accurately capture the cochlear basal turn. While 3D segmentation of the inner ear itself is an effort of 5 min, it is worth the effort as the true cochlear basal turn can be established accurately.

4.3 | Applications of cochlear basal turn

Visualizing the cochlear basal turn has several clinical benefits namely, (i) measuring the BTL in cases of inner ear malformation types to choose an optimal electrode length as shown in Figure 3 (second row) under IP type I, (ii) confirming the presence of CN in the c/s of IAC if the oblique coronal plane can be brought down to the mid-length of the IAC as shown in the third row of Figure 3, (iii) measuring the extent of ossification in cases of ossification as shown in Figure 4, (iv) studying the shape of the basal turn as shown in Figure 5, and (v) estimating the cochlear size in general. The shape of the basal turn could theoretically predict the ease of electrode insertion in the case of straight free-fitting electrode type as well as the modiolar proximity in the case of pre-curved peri-modiolar electrode type.

4.4 | Limitations and outlook

Cochlear size variation has been well reported in the literature, but we did not systematically measure the cochlear size from all 1866 normal anatomy cases. Though Figure 6 shows cochlear size as measured by the A-value varying between 8.7 mm and 10 mm, the complete distribution of the cochlear size variation within the Russian population needs to be studied which is planned in our upcoming study. Also, we plan to measure the basal turn length to see its variation from all the samples of IEM types. We further plan to analyze the presence of CN bundle in the c/s of IAC in all inner ear anatomical types to see the occurrence of the absence of CN in any specific anatomical type. One other application of cochlear basal turn is in the post-operative identification of full or partial insertion of the electrode which will be studied in the future. There are commercial/research DICOM viewers like OTOPLAN from MED-EL[15] and Nautilus from Oticon[16] are available which could simplify the whole process of bringing the cochlear basal turn, but none of those were utilized in this study.

5 | CONCLUSION

To the best of our knowledge, this is the first study reporting a reliable method to capture the true cochlear basal turn that has several clinical applications. The 3D segmented image of the inner ear ensures capturing of the true cochlear basal turn in every inner anatomical type. The identification and the extent of ossification in the ST has a high clinical relevance as this helps the operating surgeon to plan the surgery and to choose the appropriate electrode length. The huge variation in the shape of cochlear basal turn is reported for the first time and has clinical relevance in theoretically predicting the ease of electrode insertion and on the electrode modiolar proximity.

FUNDING INFORMATION

This study did not receive funding from any organization.

CONFLICT OF INTEREST STATEMENT

Andras Kedves and Anandhan Dhanasingh are full-time employees of a hearing implant organization (MED-EL) within research and development department with no marketing activities. All the other authors declare no conflict of interest and this study was performed truly for educational purpose.

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1. Deep NL, Dowling EM, Jethanamest D, Carlson ML. Cochlear implantation: An overview. *J Neurol Surg B Skull Base*. 2019;80(2):169-177. doi:10.1055/s-0038-1669411
2. Dhanasingh A, Hochmair I. Signal processing & audio processors. *Acta Otolaryngol*. 2021;141(suppl):106-134. doi:10.1080/00016489.2021.1888504
3. Guild SR, Crowe SJ, Bunch CC, Polvogt LM. Correlations of differences in the density of innervation of the organ of Corti with differences in the acuity of hearing, including evidence as to the location in the human cochlea of the receptors for certain tones. *Acta Otolaryngol*. 1931;15:269-308.
4. Dhanasingh AE, Rajan G, van de Heyning P. Presence of the spiral ganglion cell bodies beyond the basal turn of the human cochlea. *Cochlear Implants Int*. 2020;21(3):145-152. doi:10.1080/14670100.2019.1694226
5. Danielian A, Ishiyama G, Lopez IA, Ishiyama A. Morphometric linear and angular measurements of the human cochlea in implant patients using 3-dimensional reconstruction. *Hear Res*. 2020;386:107874. doi:10.1016/j.heares.2019.107874
6. Li H, Schart-Morén N, Rohani SA, Ladak HM, Rask-Andersen H, Agrawal S. Synchrotron radiation-based reconstruction of the human spiral ganglion: implications for Cochlear implantation. *Ear Hear*. 2020;41(1):173-181. doi:10.1097/AUD.0000000000000738
7. Dhanasingh A. Design of a cochlear implant electrode. *ENT Updates*. 2022;12(2):97-109.
8. Escudé B, James C, Deguine O, Cochard N, Eter E, Fraysse B. The size of the cochlea and predictions of insertion depth angles for cochlear implant electrodes. *Audiol Neurootol*. 2006;11(Suppl 1):27-33. doi:10.1159/000095611
9. Breitsprecher T, Dhanasingh A, Schulze M, et al. CT imaging-based approaches to cochlear duct length estimation—a human temporal bone study. *Eur Radiol*. 2022;32(2):1014-1023. doi:10.1007/s00330-021-08189-x
10. Alshalan A, Almuhawas F, Alhabib S, Hamed N, Abdelsamad Y, Dhanasingh A. Method to estimate the basal turn length in inner ear malformation types. *Sci Rep*. 2023;13(1):66. doi:10.1038/s41598-022-23911-5
11. Dhanasingh A, Dietz A, Jolly C, Roland P. Human inner-ear malformation types captured in 3D. *J Int Adv Otol*. 2019;15(1):77-82. doi:10.5152/iao.2019.6246
12. Adunka O, Unkelbach MH, Mack MG, Radeloff A, Gstoettner W. Predicting basal cochlear length for electric-acoustic stimulation. *Arch Otolaryngol Head Neck Surg*. 2005;131(6):488-492. doi:10.1001/archotol.131.6.488
13. Grover M, Sharma S, Singh SN, Kataria T, Lakhawat RS, Sharma MP. Measuring cochlear duct length in Asian population: worth giving a thought! *Eur Arch Otorhinolaryngol*. 2018;275(3):725-728. doi:10.1007/s00405-018-4868-9
14. Dhanasingh A, Erpenbeck D, Assadi MZ, et al. A novel method of identifying inner ear malformation types by pattern recognition in the mid modiolar section. *Sci Rep*. 2021;11(1):20868. doi:10.1038/s41598-021-00330-6
15. MED-EL. https://www.medel.pro/products/otoplan
16. Nautilus. https://nautilus.oticonmedical.com/#/login

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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