ORIGINAL ARTICLE

3D Representation of the Human Cochlea with FLEX[EAS] Electrodes

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The aim of this study was to create a three-dimensional data set of the cochlea with an inserted FLEX[EAS] electrode for later computation of the mechanical wave propagation in the cochlea. Human temporal bones (n =2) were implanted with FLEX[EAS] electrodes and scanned with a high-resolution μ-computer-tomograph. These data were analyzed and used for 3D reconstruction. In addition all temporal bones underwent fixation methylmethacrylate embedding to allow cutting of the undecalcified bone with the electrode in situ. Histologic results were correlated to the 2D images. The 2D images showed the electrode entering the scala tympani through the round window or a cochleostomy without causing damage to the bone. 3D visualization demonstrated that insertion through a cochleostomy led to a straighter position of the electrode in the scala tympani than the insertion through the round window. Therefore we conclude that the position of the inserted electrode in the scala tympani is influenced by the surgical approach. This 3D model of the cochlea with inserted FLEX[EAS] electrodes will allow the study of the mechanical influence of cochlear implant electrodes on the wave propagation along the cochlear partition.

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Introduction

In electro-acoustic cochlear implantation, auditory nerve fibres originating from the portion of basilar membrane located above 1000 Hz, approximately, are stimulated electrically while fibres of lower frequencies receive their information through the physiological process of remaining hair cell transduction. Minimized trauma of cochlear structures consecutive to electrode insertion is therefore of great importance for successful hearing preservation in the low frequency range and effective electro-acoustic stimulation (EAS). When these requirements are fulfilled, EAS improves speech understanding to a larger amount than electric hearing or aided acoustic hearing alone[1,3] .

Different potential mechanisms exist that may lead to an electrode insertion trauma . [4,6] [i]Acoustic trauma due to drilling of the bone at the cochlea; [ii] mechanical damage due to electrode insertion; [iii] disturbance of homeostasis within the cochlear fluid spaces; [iv] acute or chronic bacterial infection; [v] fibrosis of the cochlea after implantation [4,7,8] . To minimize electrode insertion trauma and preserve residual hearing, numerous investigations were performed with focus on the improvement of surgical techniques, anatomic considerations of the cochlea, electrode modification as well as intra- and post-operative pharmaceutical therapy[9,12].

To increase the chance of hearing preservation, the electrode design was adapted to the needs of EAS[11]. Electrode arrays became even more atraumatic and shorter. To reach the region of 1,000 Hz characteristic frequency an insertion angle of about 360° is necessary. In a temporal bone study, Adunka et al. described a safe and atraumatic implantation of the FLEX[EAS] electrode (MED-EL, Innsbruck, Austria) into the scala tympani of about 360°. From a temporal bone study Verbist et al. concluded that the intrinsic cochlear morphology contributes to a higher risk for

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trauma of the basilar membrane at specific locations: at the base, at approximately 180° and after 400°[10] .

Even though a cochleostomy as well as the round window approach provide safe access to the scala tympani, the specific surgical approaches might influence the position of the electrode within the scala tympani. The intra-cochlear potion of the electrode array is assumed to alter the biomechanical properties of the inner ear and thus to affect the perception of acoustic stimuli. A computer aided 3D model is useful to investigate the intra-cochlear position of FLEX^{EAS} electrodes inserted either via a cochleostomy or the round window.

Materials and Methods

Preparation of the temporal bone

Human temporal bones (n=2) were frozen and preserved at -20°C. To avoid artefacts and shrinking processes, no additional preparation that could have increased the detectability of structures inside the cochlea was done. Three hours before scanning, the temporal bone was unfrozen and held at room temperature (20°C).

The preparation followed general surgical principles of cochlear implantation using a transmastoid approach with a posterior tympanotomy [14,15]. The electrode insertion was performed either via the round window or a cochleostomy. The cochleostomy was made anterior and inferior to the bony niche of the round window. The electrode was inserted gently and with minimal force up to the marker and fixed at the bone with modelling clay. To avoid artefacts, we inserted specially prepared FLEX^{EAS} electrodes without wires.

Due to the test tube's limited size of 17 mm, the temporal bone specimen had to be sawed and milled for fitting after implantation. Due to this fixed restriction, the semicircular canals could not be conserved.

CT Scans and 3D Reconstruction

For the CT scans we used a commercial µ-Computer-Tomograph (µCT50, Scanco, Bruetisellen, Switzerland). For 3D reconstruction the Digital Imaging and Communications in Medicine (DICOM) image data (5.9 µm and 10.8 µm resolution) delivered by the µCT was imported into the Image Processing Software AMIRA® 5.2.2. After Segmentation of the µCT slices, reconstruction of a three-dimensional data set was performed.

Measuring

The measuring algorithm was used to define distances of anatomical structures in mm. Since the evaluation on 2D slices was not very useful due to the fact that the lengths of objects heavily depended on the cutting plane, the measuring was done using the reconstructed 3D objects. For correct measurements, the orthographic display was activated. Since the cochlea had no symmetries, the correct measurement of distances and angles was difficult. For the measurements of angles a top view of the cochlea in the axis of the modiolus was chosen.

Histology

After radiographic scanning the temporal bones were embedded in methylmethacrylate. Subsequently the bones were sectioned undecalcified and examined macroscopically and histologically.

Results

The µCT data of the cochlea with 5.9 µm (Fig. 1) and 10.8 µm (Fig. 2) resolution display bone in white, air in black and soft tissue in gray colour. The electrode is represented in gray. The first sequence of images shows the cuts through the cochlea starting at the vestibular (posterior) side showing the round window and the stapes footplate and ends at the anterior end of the basal winding of the cochlea.

Figure 1a demonstrates the anatomical relationship between the round window, the basal turn of the cochlea and the electrode. The soft tissues, e.g. the ligamentum spirale that constitutes together with the basilar membrane the cochlear partition, cannot be distinguished in the µCT scan. The slices show the electrode entering scala tympani through the round window without causing any apparent damage to the bone (Fig. 1b-d).

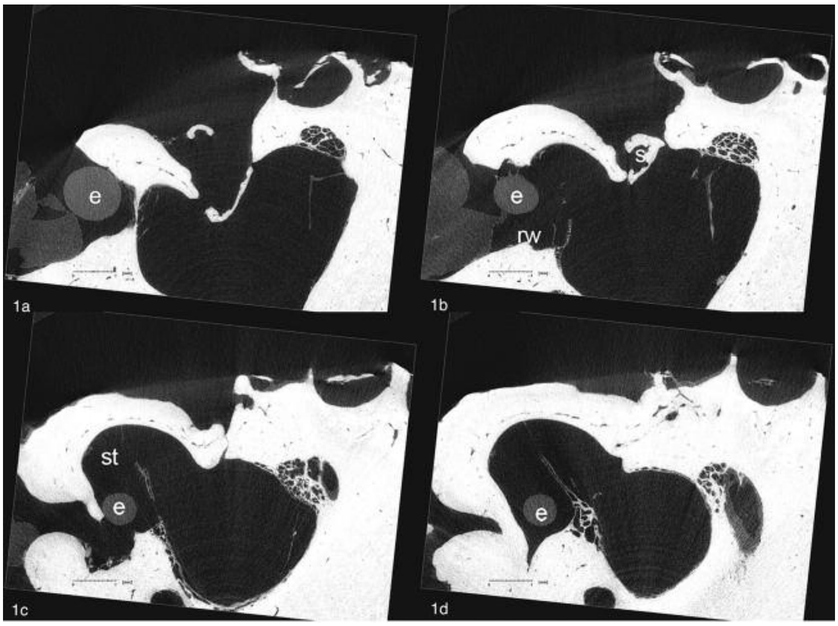

Figure 1. 2D µCT data of the cochlea with 5.9 µm resolution show the electrode entering scala tympani through the round window.

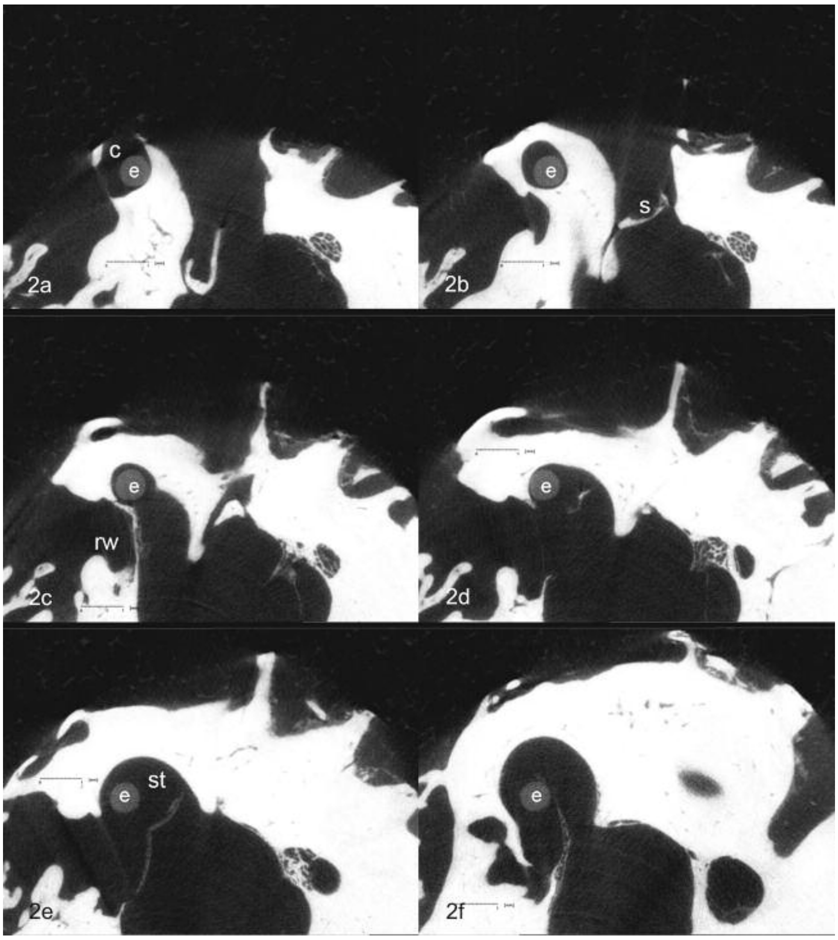

Figure 2. 2D µCT data of the cochlea with 10.8 µm resolution show the electrode entering scala tympani through a cochleostomy

The thin bony band (crista fenestrae cochleae) that surrounds the membrana tympani secundaria separating the scala tympani and the cavitas tympanica can be seen. Behind that a structure of similar morphology in this domain (cochlear partition) begins. Fig. 1B shows the position of the cochleostomy related to the oval window and the round window. In the following slices, the electrode can be visualised within the scala tympani.

Figure 2 shows part of the temporal bone with the contours of the cochlea inside. The spaces that, in physiological conditions, contain endolymph and perilymph, the stapes, the round window, the lamina spiralis ossea and the FLEX^{EAS} electrodes are clearly identifiable. Figure 3 demonstrates the position of the electrode along the scala tympani, after insertion through the round window (Fig. 3a) or cochleostomy (Fig 3b). The rotated view at 90° is shown in Figs. 3c,d. The two modes of insertion lead to different positions of the electrode within the scala tympani. Insertion through the round window causes a bending of the electrode towards the modiolus at the very basal turn of the cochlea at about 18.5°. In the further course, the electrode contacts the outer bony wall between 166.9° and 246° (Fig. 3c). The insertion through the cochleostomy leads to a more straight position of the electrode in the basal part of the cochlea, slightly touching the medial wall more apically (79.6°) than with the insertion through the round window. In the further course, the electrode contacts the outer bony wall between 150.2° and 180° (Fig. 3d). There is no apparent impact on the integrity of fine structures in the inner ear, e.g. osseous spiral lamina.

The ligamentum spirale as well as the basilar membrane can be distinguished histologically (Fig. 4). The electrode is located within the scala tympani with no apparent impact on the inner ear structures.

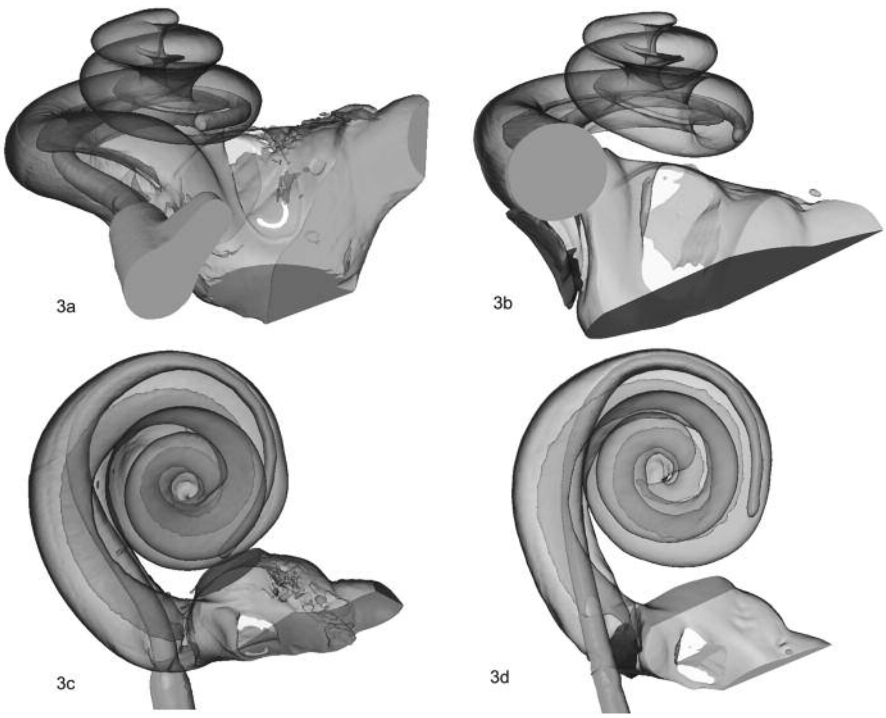

Figure 3. 3D reconstruction of the segmented data illustrates the fluid filled volumes blue, the stapes, the round window, the lamina spiralis ossea and the FLEXEAS electrodes. Figure 3a shows insertion of the electrode through the round window and Figure 3b through a cochleostomy. Figures 3c,d demonstrates a 90° rotated view compared to Figures 3a,b. Figure 3c shows insertion of the electrode through the round window and Figure 3d through a cochleostomy

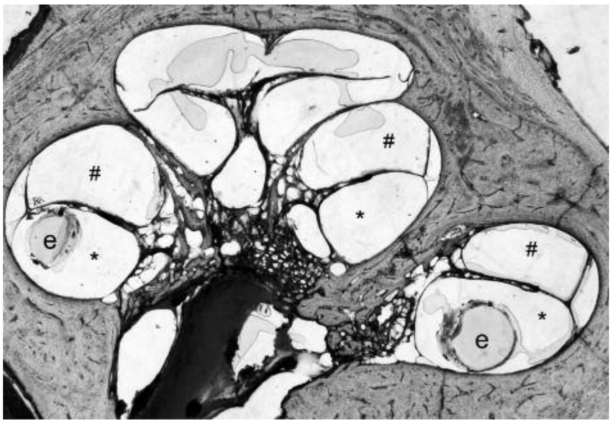

Figure 4. Histology of the cochlea, electrode inserted via the round window, electrode inside the scala tympani without any lesion to the inner ear structures

Discussion

In this study we could demonstrate that both, the round window approach and a cochleostomy give safe access to the scala tympani.

To minimize insertional trauma during cochlear implantation the recommended location of a cochleostomy has ranged from different sites in the promontory to the round window membrane itself [9,16,17]. The need of residual hearing preservation in EAS promotes efforts to avoid cochlear damage and to gain safe access to the scala tympani. Thus, the round window is used as a surgical landmark to locate the scala tympani. From temporal bone studies, it seems that a cochleostomy located inferiorly and anteriorly to the round window leads to a safe insertion into scala tympani without any basal cochlear traumatisation[18]. Another option to gain access to the scala tympani is the round window itself. Although the position of the round window niche shows some variation, it is usually a well identifiable anatomical structure. During surgery, bony overhangs may limit visibility and access to the round window membrane and therefore have to be removed. Furthermore, drilling the posterior-superior lip of the round window niche and the anterior-inferior margin of the round window leads to a straighter access to the midportion of the scala tympani, which helps to protect the modiolar wall and the spiral ganglion cells during electrode insertion[9]. Compared with the cochleostomy, a round window insertion usually requires less drilling for accurate electrode insertion. This may lower the risk of acoustic trauma. However from a three-dimensional model created of the histology of one temporal bone Li et al. concluded that a cochleaostomy at the anteroinferior margin of the round window membrane is favourable[19].

In the present study we could demonstrate that insertion through an anterior and inferior cochleostomy leads to a straighter position of the electrode in the basal part of the cochlea slightly touching the medial wall. This does not occur when the electrode is inserted through the round window. In this approach, the electrode bends first against the modiolar wall before getting in contact with the outer bony wall. The different intracochlear electrode position may alter the biomechanical properties of the inner ear and thus affect the perception of acoustic stimuli. As a restriction, we have to state that the electrodes have no wires. This circumstance may affect the mechanical properties and therefore the likely performance of the electrode which may itself affect the electrode trajectory. However compared to the histological results of temporal bone studies using FLEX[EAS] electrodes with wires the electrodes of our study seem to have similar properties[13,20].

In an initial study, Skarzynski et al. report on preservation of residual hearing using the standard electrode array of the MED-EL Combi 40/40+ device in 21 out of 26 patients[21]. Only 5 of these 26 patients (19%) lost all measurable residual hearing after cochlear implantation. At the same time five other patients showed improved hearing in the lower frequencies between 125 and 500 Hz. The reason for this improvement was the transfer of acoustic energy to places apical to where the basilar membrane is fixed by the CI electrode[22,23].

Our three-dimensional model of the human cochlea based on realistic anatomical data may help to confirm these findings. The cochlea is a finely tuned biomechanical structure that spatially separates the frequency contents of acoustic signals. The acoustic energy enters the cochlea mainly via the oval window and initiates a travelling wave that extends along the basilar membrane. For each frequency, the travelling wave builds up a maximum displacement of the basilar membrane at a designated place that corresponds to the characteristic frequency of that location. The travelling wave is influenced by the presence of an electrode. As a restriction, we have to state that only two implanted cochleas were reconstructed. This is due to the time-consuming not-automated process of segmentation and reconstruction of the large amount of data. However, the presented 3D data gives us solid information of varying options for intracochlear electrode position.

The presented 3D model of the cochlea with inserted FLEX^{EAS} electrodes paves the way for the study of the mechanical influence of cochlear implant electrodes on the wave propagation along the cochlear partition. Simulation of the travelling wave using numerical methods such as the finite volume method will be performed in an upcoming study with this new reconstruction procedure in combination with our 3D model of an unimplanted cochlea .

Conclusion

With the use of high-resolution μCT data of human bones implanted with FLEX^{EAS} electrodes it was possible to create a data set which represents the three-dimensional geometry of the cochlea. This model of representation should lead to future development where further numerical calculations of the travelling wave ought to be performed within implanted cochleas.

In addition, the three-dimensional model illustrates the effect of the different positions of electrode insertion on the electrode trajectory within the scala tympani.

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