In-vitro microCT validation of preoperative cochlear duct length estimation

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Abstract:

Variation in human cochlear dimension must be considered when selecting a patient-suitable electrode array for cochlear implantation. A promising way of cochlear duct length (CDL) prediction utilizes statistical properties of variations in cochlear morphology. In this work, CDL values estimated by statistically derived equations were validated using three-dimensional measurements in micro-CT data sets of seven human temporal bones with implanted electrode arrays. Further, the lateral wall length (LWL) was assessed manually and compared to the prediction of Escudé's equation. Comparison showed good congruency of the measured and predicted CDL and LWL at one turn length (basal turn). Deviations of about 5 % were observed in CDL at 1.5 turn lengths, as well in LWL at 1.5 and 2 turn lengths. Results suggest that CDL prediction based on a single radiographic measurement of the cochlea could support surgeons in electrode array selection, but further investigation with increased sample size is necessary.

Key words: Cochlear implantation, Insertion depth, Escudé's equation

1 Problem

Knowledge of the patient-specific cochlear duct length (CDL) is particularly important when precise intracochlear electrode array placement is desired. In cases with no residual hearing the surgeon aims to insert the electrode array as deeply as possible in order to achieve a full coverage of the sensory range. In contrast, in cases of patients with residual hearing, electrode arrays are designed to be placed only partially within the cochlea (electric-acoustic stimulation, up to 1.5 turns). Provided that a resistance-free (and atraumatic) insertion can be achieved, the usage of an electrode array with suitable length is crucial for optimal implant placement in both patients with and without residual hearing. Nevertheless, an electrode array inserted the same length in two different cochleae, may result in a completely different insertion depth angle due to variations of the cochlear size.

In this context, a preoperative estimation of the CDL could help the surgeon to choose an electrode array suitable for the patient's anatomy and therefore increase the patient's benefit after implantation. The utilization of statistical correlation between the length of the organ of Corti and the size of the cochlea seems to be a possible method for preoperative CDL estimation. The longest diameter of the basal turn (distance 'A') through the round window (RW) and the modiolar axis can be determined by single plane assessments in preoperative radiographs acquired as part of the routine clinical procedure. Based on previous work on cochlear size variation, statistical equations were formulated allowing for an estimation of the CDL at 1, 1.5, 2 turn lengths (TL) of the cochlea [1-7].

This work aims to validate the CDL prediction equations using in-vitro three-dimensional measurements in micro-computed tomography (μCT) datasets. Moreover, measurements of the cochlear lateral wall length (LWL) will be compared to the determination of Escudé's equation [8].

2 Materials and Methods

In a preceding study, 1.8 mm diameter direct cochlear access (DCA) tunnels were drilled by an image-guided robotic system in eight Thiel-embalmed human temporal bones (both sides of four heads). The robot system was specifically constructed for surgeries on the lateral skull base and has a targeting accuracy of 0.15 ± 0.08 mm at the RW [9]. Four standard electrode arrays (31.5 mm) and four Flex^{28} electrode arrays (28 mm) provided by Med-El Corporation (Innsbruck, Austria) were implanted via the DCA tunnel at the RW. Electrode array insertion was stopped as soon as resistance was detected. Temporal bones were then excised and trimmed in order to fit in a specimen holder of 36 mm in

diameter. One cochlea was damaged during this preparation step. Electrode array insertion depth angles were found to be 606°±79° (n=7) [10].
Samples were scanned using a μCT device (μCT 40, SCANCO Medical AG, Brüttisellen, Switzerland) using a 70 kVp tube potential and 114 μA tube current. Determined by the size of the samples, a voxel size of 18 x 18 x 18 μm^3 was obtained. Thereafter, the cochlea was segmented using Amira 5 visualization software (VSG, Burlington, MA, USA) starting with a region growing algorithm. Subsequently, manual correction of imaging artifacts caused by the implanted electrode arrays (exponential edge-gradient effect) was performed.
Next, a 3D surface model was generated and a zero reference angle plane [11] intersecting the modiolar axis and the center of the RW was manually aligned as seen in fig. 1. The longest distance from the RW to the lateral wall of the basal turn was then measured in this plane (distance 'A', fig. 1). Further, the lateral wall length (LWL) was measured manually along the surface of the cochlea, following the outermost points of the cochlear turns. Starting from the zero reference angle plane, the LWL was obtained at 1 TL (360°), 1.5 TL (540°) and 2 TL (720°), as shown in fig. 2. For CDL measurement, a 3rd order spline (500 samples per turn) was fitted in the center of the segmented electrode array (as an approximation to the position of the organ of Corti). In case of array bending in the proximal part of the basal turn, the spline was aligned with respect to the lateral wall course (fig. 3). CDL at 2 TL was determined using overlaid μCT slices in order to locate the basilar membrane position if the electrode array was not inserted deeper than 1.5 TL.

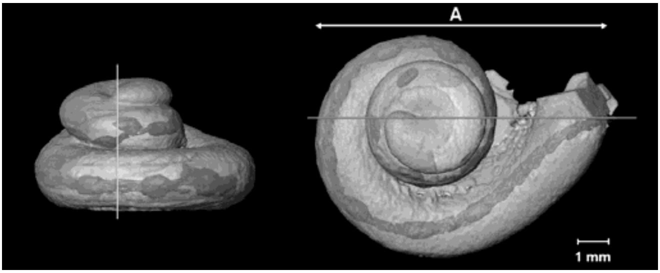

Figure 1: Surface model of a left human cochlea and implanted electrode array (dark gray). The zero reference angle plane is aligned through the modiolar axis and the center of the round window (RW), perpendicular to the basal turn. The distance 'A' is found between the RW center point and the outermost opposite surface of the basal turn.

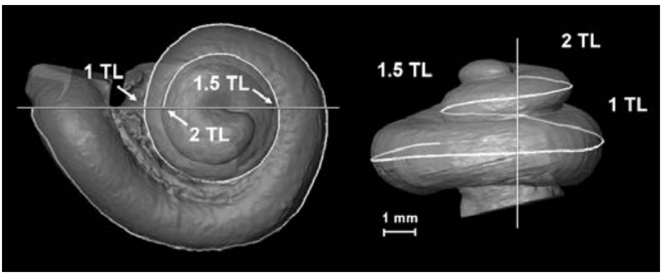

Figure 2: Surface model of a right human cochlea and lateral wall length measurement paths for 1, 1.5 and 2 turns (TL).

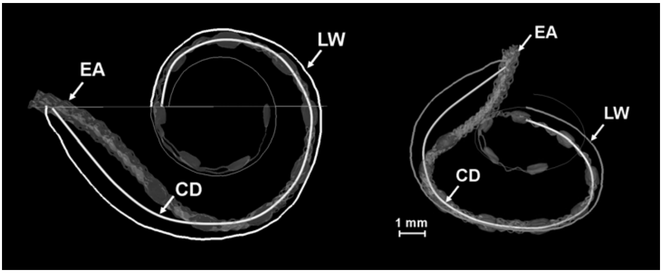

Figure 3: Measurement of cochlear duct length in the basal turn of a right human cochlea with implanted electrode array (EA). A spline (CD) is fitted in the center of the electrode array in order to approximate the position of the cochlear duct. In the proximal part of the basal turn electrode array bending lead to a deviation of the array position compared to the location of the organ of Corti. Therefore, the spline is positioned with respect to the course of the lateral wall (LW).

Based on the measured distance 'A' (mm), the CDL (mm) was computed at 1, 1.5 and 2 TL using following set of equations:

$$CDL_{OC,1TL} = 2.43 \cdot A - 2.43 \quad (1)$$
$$CDL_{OC,1.5TL} = 3.00 \cdot A - 3.02 \quad (2)$$
$$CDL_{OC,2TL} = 3.65 \cdot A - 3.63 \quad (3)$$

Further, the LWL (mm) was estimated by applying Escudé's equation (insertion depth angle θ in degrees) [8]:

$$LWL = 2.62 \cdot A \cdot \ln(1.0 + \theta/235) \quad (4)$$

3 Results

Lengths of distance 'A' were found to range within 8.86-9.77 mm, with a mean of 9.35±0.32 mm (n=7). At 1 TL, measured values showed correspondence with the lengths estimated by eqs. (1) and (4). Measurements revealed a deviation to the estimated CDL of about 1-1.5 mm and 0.5 mm at 1.5 TL and 2 TL, respectively. LWL measurements were found to deviate about 1 mm at 1.5 TL and 1.5 mm at 2 TL (fig. 4).

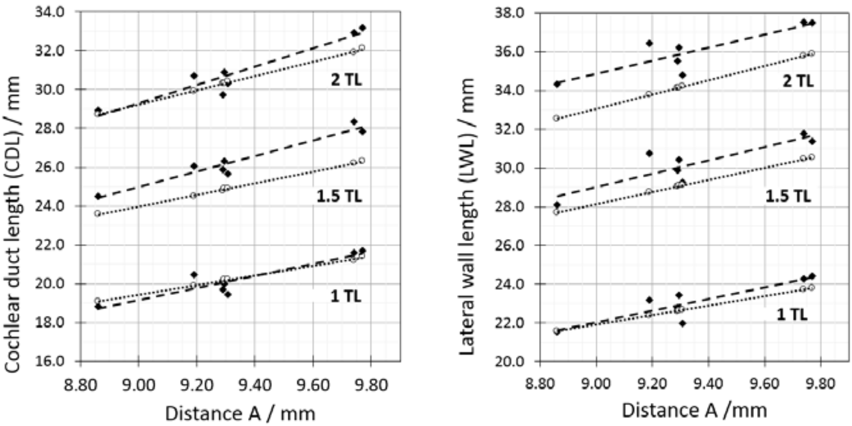

Fig. 4: Summary data for distance 'A', as well as the estimated (○) and the measured (♦) cochlear duct and lateral wall lengths. Linear regression is plotted for predicted (dotted lines) and measured (dashed lines) values at 1, 1.5 and 2 turn lengths (TL) of the samples (n=7).

4 Discussion

In this work, three-dimensional in-vitro measurements of the CDL and LWL of human cochleae were obtained and compared to values estimated by statistically derived equations. Although samples were taken from four human heads only, a high variability of the cochlear size, reflected by ‘A’, was observed. The cochlear size variation of the investigated samples (9.35±0.32 mm, n=7) are within the range reported in literature (6.8-10.3 mm, mean 8.55±0.57 mm, n=104 [6]).

The CDL was more or less congruent at 1 TL and 2 TL, whereas a deviation of approximately 5% was observed at 1.5 TL. This may be a result of either the measurement method (overestimation of the CDL at 1.5 TL), the impact of anatomical variations due to a small sample size or a deviation within the derived equations. Deviations of about 5% were observed for the LWL at 1.5 TL and 2 TL, which may again be caused by the measurement method or anatomical variation. Nevertheless, a trend of higher difference between the predicted and measured values for increasing angles can be seen.

These preliminary results suggest that a preoperative estimation of the CDL based on the measurement of a single value (distance ‘A’) is a practical approach for patient-specific electrode array selection in both cases with and without residual hearing. According to literature, the CDL of human cochleae ranges from 25 to 36 mm, with an average value of 31.5 mm (n=95) [1,2]. Currently there is no single free-fitting electrode array available which covers the whole CDL range. A short electrode array inserted into a cochlea with a long CDL is not sufficient in stimulating low frequency regions. Conversely, intracochlear damage may occur if a long electrode array is inserted into a cochlea with short CDL. Further, the risk of occurrence of extracochlear contacts is increased when electrode arrays longer than the CDL are inserted. In this context, findings of this study may help surgeons in reliably selecting a suitable electrode array length from portfolios provided by different CI manufacturers and ultimately increase the patient’s benefit.

In order to improve the method, further investigations with an increased sample size and statistical analysis are carried out. Moreover, the measurement accuracy of the presented method and the influence of lower imaging resolution of clinical data are evaluated.

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