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Research paper

Cochlear length determination using Cone Beam Computed Tomography in a clinical setting

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ABSTRACT

Indications for cochlear implants are determined by audiological and medical considerations. Clinical imaging is therefore an integral element for anatomical evaluation in terms of medical considerations. Several authors have discussed the variability of cochlear shape, especially cochlear length. Cochlear length is, however, an increasingly recognized parameter in terms of preoperative evaluation. This study introduces a methodology to determine individual cochlear length in clinical setting by using Cone Beam Computed Tomography. Cochlear length determination was performed retrospectively with an OsiriX curved 3D Multiplanar Reconstruction tool on subjects who underwent temporal bone imaging from January 2011 to February 2013. Cochlear length was defined as the spiral route from the center-distal point of the bony round window along the lateral wall towards the helicotrema, which is the endpoint of the measurement. Cochlear length was measured in 436 temporal bones (218 left ears, 218 right ears, 218 subjects). The mean cochlear length was 37.6 mm (SD: ± 1.93 mm), median was 37.6 mm, range 32–43.5 mm. The cochlear length had a normal distribution. A significant difference was found between cochlear length by gender ($p < .0001$), but not between the left and right cochlea ($p = .301$) or according to age. Consideration of the cochlear length in clinical data may be an insufficiently represented parameter in cochlear implant treatment. Literature shows the impact of electrode insertion depth on residual hearing preservation and speech performance. Individual evaluation of the cochlear implant electrode choice may be the next step in personalized cochlear implant treatment as a valuable addition to existing audiological and surgical evaluation. The cochlear length determination methodology presented herein is a reproducible and clinically available parameter. Indeed, revealing a significant cochlear length span width, especially according to gender differences, may be assumed as hardly ignorable.

1. Introduction

A cochlear implant (CI) is a hearing device for people with severe or profound hearing loss. A CI electrically stimulates the spiral ganglion cells via an intracochlear electrode. The CI electrode has to be placed into the cochlea by a surgical approach through a mastoidectomy and delineation of the facial recess. The facial recess is the anatomical space between the chorda tympani and the facial nerve in the mastoid portion. This is the entry area to middle ear and the round window of the cochlea. The scala tympani is the anatomic target structure by which the electrode is positioned. Cochlear implantation (and subsequent rehabilitation) typically allows even children with prelingual deafness to develop spoken language understanding and production (Colletti et al., 2012 Jul; De Raeve and 2010 Oct). Many studies have concentrated on electrode insertion and have analyzed the electrode tilt properties that may lead to a scalar change from scala tympani into scala vestibuli during insertion (Adunka et al., 2004; Gstöttner et al., 2005 Sep; Adunka et al., 2006 Sep; Aschendorff et al., April 2007; Finley et al., 2008 Oct; Gani et al., 2007 Mar; Welling et al., 1993 Sep). This tilt may result in penetrating the basilar membrane. They considered insertion force measurements in correlation to real life behavior using radioscopy and a

Abbreviations: CBCT, Cone Beam Computed Tomography; CI, Cochlear implants; CL, Cochlear length; CT, Computed Tomography; MPR, Multiplanar Reconstruction; MRI, Magnetic Resonance Imaging; OW, Outer wall; OW-CL, Outer wall cochlear length; PPC, Pearson product–moment correlation coefficient

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histological assessment of the situation after implantation (specimen preparation, fluoroscopy, microCT, etc.). A large sample size of temporal bones allows a statistical value to be established. In particular, one would like to generate a normal distribution of anatomic variations in order to evaluate specific electrode properties. Several studies have shown that insertion depth varies, even within the same surgical procedure, in the temporal bone laboratory (Finley et al., 2008 Oct; Adunka et al., 2005 Jun 1; Ketten et al., 1998 Nov).

Determining and defining cochlear length (CL) has so far proven difficult because there exists neither 1) a consensus on which anatomical landmarks cochlear length should be measured from nor 2) a consistent nomenclature with which to describe these landmarks (although this is not the case with the organ of Corti, length of basilar membrane, or the length of the spiral lamina).

The importance of CL has been mentioned in insertion depth studies: insertion trauma in cochlear implantation strongly correlates to insertion depth (Welling et al., 1993 Sep; Shepherd et al., 1985 Feb; Kennedy, 1987 Jan), shallow insertion is related to worse speech performance in CI-rehabilitation (Hochmair et al., 2003 Jun), and deep CI-insertion significantly reduces the likelihood of residual hearing preservation (Adunka et al., 2004; Gstöttner et al., 2005 Sep; Gstoettner et al., 1997 Mar).

Furthermore, by comparing electrode placement in specimens after CI-insertion, Adunka et al. found that there is indirect indication for interindividual scala tympani length differences and concluded that using the manufacturer's data for insertion depth did not lead to comparable intracochlear placement (Adunka et al., 2005 Jun 1). On the contrary, they showed significantly different insertion angles (Gstöttner et al., 2005 Sep; Welling et al., 1993 Sep; Shepherd et al., 1985 Feb; Kennedy, 1987 Jan; Hochmair et al., 2003 Jun).

The tonotopy of the cochlea is expressed mathematically in the Greenwood function. The frequency mapping in CI recipients is based upon the principles of tonotopy. Several studies have examined the influence of the exact intercochlear electrode placement on subjects' hearing ability (Boëx et al., 2006 Jun; Dorman et al., 2007 Jun; Noble et al., 2013 Sep). As has been demonstrated in individual cases (Noble et al., 2013 Sep), there are new approaches that an image-based mapping of frequencies leads to improved speech understanding. Noble et al. (Noble et al., 2013 Sep) adapted an atlas, based on an anatomic model, to the subject's individual computed tomography (CT) temporal bone data. With this, they were able to locate and assess the scala tympani and vestibuli although a conventional CT is not capable of imaging these anatomical landmarks.

CL determination is also important because short cochleae may be at greater risk than long cochleae of suffering intraoperative trauma; this is because the scala tympani narrows towards the apex.

Methodologies which use CT and Magnetic Resonance Imaging (MRI) are generally based on a volume generated by one or both of these modalities and distance measurements of defined internal landmarks (Colletti et al., 2012 Jul; De Raeve and 2010 Oct; Hochmair et al., 2003 Jun; Gstoettner et al., 1997 Mar). By using three histological and one CT-based method, Miller et al. (Miller and 2007 Apr) showed that the organ of Corti is not significantly larger in males (34 mm) than in females (33 mm).

With enlarged indications for CI-treatment in patients with functional residual hearing and manufacturers who have responded by expanding their portfolio of CI-array lengths and diameters – MED-EL™ provides 20, 24, 28 and 31.5 mm long electrodes (FLEX[20], FLEX[24], FLEX[28], and Standard) and Cochlear™ provides 15, 16, and 20 mm long electrodes (Hybrid™ L24 and CI422) – individual CI-treatment is a central point of interest (Lenarz et al., 2009, 2006, 2013 Dec; Helbig et al., 2011 Jun). In principle, it seems to be difficult to use terms with direct connection to CL without having a metric reference to CL. That is why a simple and easy method to perform individual intracochlear length measurements is needed.

The goal of this paper is to evaluate a methodology that uses a clinically available high-resolution imaging modality to determine CL in a clinical setting.

2. Material and methods

2.1. Subjects

Eligible subjects were those who underwent an anatomical evaluation of their temporal bones as part of a routine clinical visit for differential diagnosis of hearing loss and/or tinnitus between January 2011 and February 2013. Potential subjects were excluded if they 1) had acquired or congenital pathologies of the temporal bone and inner ear, 2) used a hearing implant, especially a CI, in one of their temporal bones, or 3) did not have measurable cochlea in both temporal bones, 4) did have a sufficient conventional CT of the temporal bones.

2.2. Procedure

The distal bony rim of the round window was the starting point of the CL measurement (see Fig. 1). The curve was set up three-dimensionally along the outer edge of the bony cochlea in projection of the osseous spiral lamina (see Figs. 2–4). The endpoint was defined by the helicotrema (see Figs. 4 and 5).

Temporal bone cone beam computed tomography (CBCT) data were collected with 1) a stationary Xoran MiniCAT (Ann Arbor, Michigan) equipped with a 536 x 536 matrix detector resulting in 0.3 mm^3 isotropic voxel (125 kVp, 7 mA) and 2) a mobile Xoran xCAT (Ann Arbor, Michigan) with a 536 $\times$ 536 matrix detector resulting in 0.3 mm^3 isotropic voxel (120 kVp, 7 mA).

DICOM data processing was performed with OsiriX MD (Pixmeo, Los Angeles, California) using 3D curved MPR. OsiriX is open source imaging software for Mac OS X.

The Multiplanar Reconstruction (MPR) interface provides 4 windows, 1 for each section and 1 for the uncoiled spiral in the lower right window (Figs. 1–5). The first section was set within and parallel to the basal turn in the top right window, the second section was set through the round window at either the top or the bottom left window. The third section was defined by Sections 1 and 2. For a standardized view, window width was set to 4600 Hounsfield Units (HU) and window leveling was set to 1095 HU.

Data was statistically analyzed for differences in CL between gender, age, and temporal bone side (left or right).

2.3. Ethics

The local medical ethics committees of the Hannover Medical School (Hannover, Germany) approved the described procedure.

3. Results

CL was measured in both temporal bones of 218 subjects (114 female and 104 male), resulting in 436 measurements. The statistical power was observed as 1.0 in Pillai's trace, Wilk's Lambda, Hotelling's trace, and Ray's largest root.

The Kolmogorov–Smirnov test confirmed the normal distribution of the CL data (Fig. 6; $p = .887$).

CL ranged from 32 to 43.2 mm (see Figs. 8 and 10).