

Predicting Basal Cochlear Length for Electric-Acoustic Stimulation

Oliver Adunka, MD; Marc H. Unkelbach, MD; Martin G. Mack, MD, PhD; Andreas Radeloff, MD; Wolfgang Gstoettner, MD, PhD

Objective: To assess the feasibility and accuracy of predicting electrode insertion depth necessary in cochlear implantations for electric-acoustic stimulation by means of preoperative high-resolution computed tomography (HRCT).

Design: Human temporal bone study with evaluation of cochlear dimensions.

Setting: Tertiary care medical center.

Methods: Eight fresh human temporal bones were scanned, and basal cochlear structures were reconstructed and measured. Standard cochlear implantations with a free-fitting array were performed, and the bones then underwent histologic analysis using a technique that allows sectioning of undecalcified bones. Af-

ter embedding, all bones underwent conventional radiologic analysis with further insertion measurements. Preimplantation HRCT data were compared with radiologic and histologic data.

Results: Preimplantation HRCT-based measurements correlated very well with postimplantation radiologic data. A mean failure of 0.3 mm was found. Mean values for the first 360° ranged from 18.8 to 22.0 mm.

Conclusions: Preimplantation HRCT-based prediction of cochlear implant insertion depths is both feasible and accurate. It is especially useful when aiming for hearing preservation, where insertion depths of 360° are necessary.

Arch Otolaryngol Head Neck Surg. 2005;131:488-492

OVER THE LAST 5 YEARS, A new implantation method, the combined electric-acoustic stimulation (EAS) of the inner ear, has been successfully implemented in several clinical studies.¹⁻⁴ This method provides bimodal stimulation with a cochlear implant and a conventional hearing aid in the same ear. Candidates for EAS have relatively good residual hearing in the low frequencies (corresponding to apical parts of the cochlea) but substantial hearing loss in the high-frequency range, which makes adequate speech recognition impossible, even with high-power hearing aids. To ensure bimodal stimulation, at least some residual hearing must be preserved, and apical cochlear damage should be minimized. To this end, a properly performed EAS procedure stimulates the basal cochlear regions electrically while leaving the more apical portions free of an electrode carrier.¹ These apical areas are responsible for low-frequency hearing and contain still-working structures, which can be stimu-

lated with or without a conventional hearing aid, depending on the extent of residual function.

The aim of EAS surgery therefore is to insert the cochlear implant array one full turn so that it enters the 1000-Hz region,⁵ which defines the end of electric and the beginning of acoustic stimulation. Anatomically, a 360° insertion into the scala tympani corresponds to an insertion depth of about 20 mm measured from the round window membrane.⁵ However, considerable morphologic variations have been described.^{6,7} Accordingly, when placing implants during our clinical EAS trial, we found significant variations of insertion degrees at constant surgical depths (millimeters). In 1 patient, for instance, a 20-mm insertion corresponded to only 180° (unpublished data, 2004).

In temporal bone studies, deep electrode insertions of more than 360° significantly increased the risk of cochlear trauma.⁸⁻¹³ Shallower insertions, on the other hand, are believed to result in poor implant hearing performance.^{14,15} For EAS

Author Affiliations:

Departments of Otorhinolaryngology (Drs Adunka, Unkelbach, Radeloff, and Gstoettner) and Diagnostic and Interventional Radiology (Dr Mack), J.W. Goethe University, Frankfurt am Main, Germany.
Financial Disclosure: None.

Table. Characteristics of Temporal Bones Fitted With Cochlear Implants*

Bone† No./Sex/Age, y	Side	Insertion Depth			Distance to 360°, mm		
		Surgical, mm	Histologic, °	Radio, °	Radio	HRCT	Failure
1/M/23	Left	31	630	600	21.3	21.34	0.04
2/M/23	Right	31.5	540	600	20.3	20.31	0.01
3/M/38	Right	24.5	360	360	21.6	22.03	0.43
4/M/38	Left	31	540	540	19.5	20.13	0.63
5/F/24	Right	25.5	450	405	19.2	19.29	0.09
6/F/39	Right	31.5	540	600	21.9	21.19	0.71
7/F/39	Left	21	400	360	19.2	19.34	0.14
8/F/59	Left	20	360	360	19.2	18.77	0.43
Min	NA	20	360	360	19.2	18.77	0.01
Max	NA	31.5	630	600	21.9	22.03	0.71
Mean (SD)	NA	27.0 (4.9)	477.5 (99.5)	478.1 (116.9)	20.3 (1.2)	20.3 (1.1)	0.3 (0.3)

Abbreviations: HRCT, high-resolution computed tomographic; Max, maximum; Min, minimum; NA, not applicable; Radio, radiographic.

*C40+ standard arrays (MED-EL, Innsbruck, Austria) were used for all implantations.

†Temporal bones 1 and 2 were harvested from a single cadaver, as were bones 3 and 4 and bones 6 and 7; nonetheless, note the intra-individual variations in size.

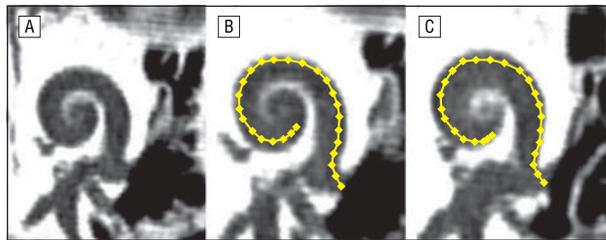


Figure 1. High-resolution computed tomography–based 3-dimensional placement of reference points in temporal bone No. 7. A, Reconstructed cochlea prior to point placement. B and C, Cochlea after reference points are set according to the greatest outline extent of the cochlea in each area. All evaluations were begun at the middle of the round window membrane owing to the absence of other anatomic landmarks that would allow an exact definition of the cochleostomy.

therefore, an atraumatic 360° insertion is essential to both preserve hearing and achieve full function of the cochlear implant. The aim of this study was to evaluate a reliable preoperative radiologic method to measure the basal cochlear size and determine the optimum insertion depth for EAS cochlear implantations.

METHODS

Eight fresh human temporal bones were harvested up to 24 hours post mortem. To evaluate the accuracy of the described technique, preimplantation high-resolution computed tomography (HRCT) reconstructions were compared with postimplantation conventional radiographic analyses. Additionally, electrode locations were histologically determined. Detailed data on all processed temporal bones are listed in the **Table**.

COMPUTED TOMOGRAPHY

To predict the basal size of the cochlea, we used HRCT imaging and reconstruction. Each bone underwent scanning with a multislice computed tomography scanner (Somatom Volume Zoom; Siemens, Erlangen, Germany). A spiral scan with a 4 × 0.5-mm collimation was performed in each specimen. Data were reconstructed with a slice thickness of 0.5 mm and an increment of 0.2 mm using a bony reconstruction algorithm. All



Figure 2. Linear reconstruction of the first full cochlear turn. Note the labyrinth on the left side of the picture and the cochlear aqueduct more apically. The calculation of the measured distance is software automated.

images were displayed in a bony window. The outline of the outer cochlear wall was marked using 3-dimensional reconstruction software until the functional 360° region, as defined by Marsh et al,¹⁶ was reached. The measurement itself was done blindly by 2 experienced and independent radiologists.

Reference points were 3-dimensionally defined using the rendering software. First, serial layers 90° to the cochlear axis every 0.5 mm were defined. Then, each layer was screened to determine the greatest extent of the designated cochlear portion. Reference points were set within their specific layers. The 3-dimensional data set was required to correctly determine the exact outlines of the desired cochlear section because 2-dimensional data from only 1 layer would not adequately represent the complex cochlear anatomy.

Reference points were set slightly toward the modiolus to approximate the future electrode position along the outer scala tympani wall (**Figure 1**). Intervals of about 0.5 mm were used because the electrode diameter varies from 0.5 mm at the tip to 0.8 mm at the basal end. Great variations have been reported in the area of the round window itself.¹⁷⁻¹⁹ It was extremely important to define a starting point to be used equally in all bones. Since no radiologically defined landmarks regarding the site of the cochleostomy existed before implantation, the middle of the round window membrane was chosen for starting each measurement (first reference point). Over the desired cochlear length, about 25 to 30 reference points were required for each specimen.

Linear reconstruction of the defined cochlear sequence followed. The software provided an automated measuring algorithm between the first (round window membrane) and the last (360° region) reference points. **Figure 1** illustrates the point placement procedure. **Figure 2** shows a basal cochlear linear reconstruction.

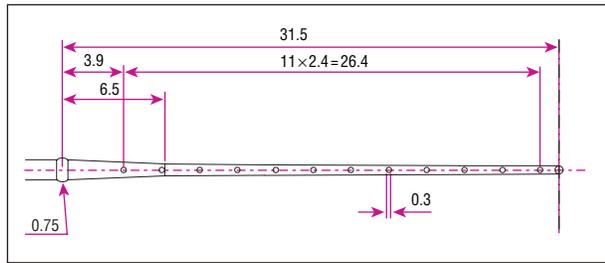


Figure 3. Technical drawing of the C40+ standard electrode (MED-EL, Innsbruck, Austria). This drawing served as basis for the evaluation of the inserted length to the 360° region using the conventional radiologic method. All numbers represent millimeters.



Figure 4. Conventional radiographic analysis of the embedded bone. The length of the implanted array can be clearly evaluated using the landmarks of the electrode carrier. A represents the 360° point. B is the site of the cochleostomy. The difference between compact bone of the labyrinthine capsula and air containing middle ear spaces can be used to determine the exact location of the cochleostomy. The contacts are 800 μm long, and their centers are 2.4 mm apart.

SURGICAL TECHNIQUE AND ELECTRODE ARRAY

After preimplantation HRCT, all bones underwent cochlear implant electrode insertion via a standard mastoidectomy–posterior tympanotomy approach. The cochleostomy was drilled anterior and inferior to the round window membrane to reduce the risk of primary electrode misplacements.

For all implantations, we used C40+ standard arrays (MED-EL, Innsbruck, Austria). This electrode is intended for deep intracochlear implantations and features a total intracochlear length of 31.5 mm. The distance from the very tip of the array to the middle of the first electrode contact is 1.2 mm. Each contact and all the wires are made of a platinum-iridium alloy (50:50). Contacts are 800 μm long and lie in 12 pairs on both sides of the electrode body, which is made of medical-grade silicone. Contacts are placed 2.4 mm apart (measured from the middle of each contact). Several experiments on the insertion trauma of this array have been performed.^{9,10} All studies showed a very atraumatic electrode that normally lies against the outer wall of the cochlea when properly handled.

HISTOLOGIC PREPARATION

Temporal bone histologic analysis was used to assess the intracochlear position of the array to ensure that no dislocations into the scala vestibuli occurred. Such dislocations would make exact comparisons between preoperative and postimplantation data impossible owing to the anatomically smaller scala vestibuli.

All bones that underwent cochlear implantation were fixed with an ascending series of alcohol (70%-100% ethanol), followed by embedding in polymethylmethacrylate. This embedding procedure allows sectioning of undecalcified bone with the electrode in situ. A special grinding-polishing technique was used to enhance the quality of histologic slides. A detailed description of the procedure is found in Plenck.²⁰

CONVENTIONAL RADIOGRAPHY

All histologic blocks were evaluated using conventional radiograms, which served as postimplantation controls. Using the described radiologic evaluation technique¹⁶ for the determination of cochlear implant insertion depth, we determined the intracochlear length of each implantation to the 360° area. The electrode contacts served as landmarks. Since all arrays feature the same contact spacing and distribution dimensions, accurate evaluations of insertion depths were possible. An imaginary line was drawn from the center of the cochlea to the point of the round window membrane, according to the procedure described by Xu et al.²¹ Then the point where this line crossed the electrode in the middle cochlear turn was defined as the 360° point. The distance from the round window to the 360° point was measured using the electrode dimensions provided by the manufacturer. This measurement served as the radiologic control. A technical drawing is shown in **Figure 3**. An illustration of the measuring procedure is shown in **Figure 4**.

HISTOLOGIC EVALUATION

Intracochlear electrode position and resulting trauma were evaluated histologically with a well-established grading scheme.²² Only electrodes lying on the outer cochlear wall in the scala tympani were included in this study.

RESULTS

Bones were harvested from 5 human cadavers whose mean age at death was 35.4 years (range, 23-59 years). Four right and 4 left cochleas were used for implantation.

Preimplantation HRCT reconstruction was easily performed in every bone. Linear reconstruction revealed ana-

tomic details of the cochlea and adjacent structures such as the cochlear aqueduct and the vestibulum. Using the described linear reconstruction method, we determined the average basal cochlear length to be 20.3 mm (range, 18.8-22.0 mm).

Postimplantation radiography of each specimen clearly allowed evaluation of the cochlear orientation within the embedded bone. Also, radiologic insertion depths and lengths of the implanted arrays from the cochleostomy to the 360° region were calculated using the technical drawings provided by MED-EL. For the 8 specimens, values for the implanted length to the 360° point ranged from 19.2 to 21.9 mm, with an average of 20.3 mm.

Histologic evaluation of all 8 bones demonstrated scala tympani insertions in every specimen (**Figure 5**). Histologically evaluated insertion depths ranged from 360° to 630° (mean ± SD, 477.5° ± 99.5°). Insertion depths evaluated via conventional radiography ranged from 360° to 600° (mean ± SD, 478.1° ± 116.9°). No anatomic abnormalities or cochlear ossifications were observed during implantation. All arrays were inserted as far as possible. Although insertion maneuvers were performed beyond the point of first resistance, smooth and nonforceful procedures were achieved in all bones. A mean ± SD insertion depth of 27.0 ± 4.9 mm (range, 20.0-31.5 mm) was reached.

Comparing the results of the preimplantation and postimplantation measurements, a mean ± SD failure of 0.3 ± 0.28 mm in predicting the correct length of the basal turn of the cochlea was observed. The maximum failure was 0.7 mm.

COMMENT

Preoperative HRCT scans of the temporal bone are routinely used prior to every cochlear implantation^{16,21} to identify possible anomalies of the temporal bone and inner ear structures and adapt the surgical procedure accordingly. In conventional implantation, the aim of the surgeon is to place the electrode array as deeply as possible into the scala tympani of the cochlea to stimulate apically located neural structures.^{14,15} For EAS implantations, however, limited insertions of exactly 1 full cochlear turn (360°) are anticipated to provide safe and efficient insertions.

For regular cochlear implantations, HRCT data only serve to identify the bony structures of the mastoid, the fallopian canal, the bony labyrinth capsule, and adjacent middle ear structures. In the present report, the accuracy of an additional clinical application of preimplantation HRCT data is evaluated—the prediction of basal cochlear dimensions necessary for EAS surgery. Using the described technique, our data show that preoperative predictions were reliable, showing a mean failure of only 0.3 mm and a strong positive correlation ($r = 0.93$).

Although dealing with only 8 human temporal bones, our data demonstrate the great anatomic variations of the cochlea, which has also been reported elsewhere.^{6,7} The length of the basal cochlear portions to the 360° region ranged from 18.8 to 22.0 mm, showing a variation of 3.2 mm. Based on an average length of 20.3 mm in the present study, this variation represents only 16%. A shall-



Figure 5. Histologic specimen of temporal bone 7 with cochlear implant in place. The C40+ standard electrode array (MED-EL, Innsbruck, Austria) lies against the outer wall of the scala tympani. Note the wires within the electrode body indicating the location of the sectioning plane and the absence of cochlear trauma.

low insertion, however, might lead to poor performance of a cochlear implant alone whereas insertions beyond the 360° point could contribute to increased cochlear trauma as shown in numerous temporal bone experiments.⁹⁻¹³

In contrast to our method, intraoperative fluoroscopy offers an alternative approach that allows for intraoperative observation of electrode insertion.²³ The dynamic character of this method offers the possibility to adapt surgical maneuvers in real time to perform accurate 360° insertions. However, additional radiation is applied to the patient—and the surgeon—with the fluoroscopy technique, and the device must be available in the otology theater. Our method of using preimplantation HRCT data also provides exact, pinpoint implantations and is easy to use. Furthermore, it eliminates exposure to added radiation and requires no extra device in the operating room.

To our knowledge, this is the first report dealing with the prediction of cochlear dimensions prior to cochlear implantation. Our data showed excellent correlation between preoperative HRCT-assisted measurements and postimplantation radiography. Therefore, we think that this method should be used in every EAS implantation procedure. With the growing clinical implementation of

EAS, this is an issue of gaining importance, and additional investigations in this matter should be performed. However, detailed knowledge of the electrode dimensions is fundamental for the correct implementation of this technique.

Submitted for Publication: November 19, 2004; accepted February 19, 2005.

Correspondence: Oliver Adunka, MD, Otorhinolaryngology Department, University Clinic Frankfurt am Main, Theodor Stern Kai 7, D-60590 Frankfurt am Main, Germany (adunka@em.uni-frankfurt.de).

REFERENCES

1. von Ilberg C, Kiefer J, Tillein J, et al. Electric-acoustic stimulation of the auditory system. *ORL J Otorhinolaryngol Relat Spec.* 1999;61:334-340.
2. Kiefer J, Tillein J, von Ilberg C, et al. Fundamental aspects and first results of the clinical application of combined electric and acoustic stimulation of the auditory system. In: Kubo T, Takahashi Y, Iwaki T, eds. *Cochlear Implants: An Update.* The Hague, the Netherlands: Kugler publications; 2002:569-576.
3. Kiefer J, Gstoettner W, Baumgartner W, et al. Conservation of low-frequency hearing in cochlear implantation. *Acta Otolaryngol.* 2004;124:272-280.
4. Gstoettner W, Kiefer J, Baumgartner WD, Pok S, Peters S, Adunka O. Hearing preservation in cochlear implantation for electric acoustic stimulation. *Acta Otolaryngol.* 2004;124:348-352.
5. Otte J, Schunknecht HF, Kerr AG. Ganglion cell populations in normal and pathological human cochleae: implications for cochlear implantation. *Laryngoscope.* 1978;88:1231-1246.
6. Dimopoulos P, Muren C. Anatomic variations of the cochlea and relations to other temporal bone structures. *Acta Radiol.* 1990;31:439-444.
7. Zrunek M, Lischka M, Hochmair-Desoyer I, Burian K. Dimensions of the scala tympani in relation to the diameters of multichannel electrodes. *Arch Otorhinolaryngol.* 1980;229:159-165.
8. Adunka O, Kiefer J, Unkelbach MH, Lehnert T, Gstoettner W. Development and evaluation of an improved cochlear implant electrode design for electric and acoustic stimulation. *Laryngoscope.* 2004;114:1237-1241.
9. Gstoettner W, Plenck H, Franz P, et al. Cochlear implant deep electrode insertion: extent of insertional trauma. *Acta Otolaryngol.* 1997;117:274-277.
10. Gstoettner W, Franz P, Hamzavi J, Plenck H, Baumgartner W, Czerny C. Intracochlear position of cochlear implant electrodes. *Acta Otolaryngol.* 1999;119:229-233.
11. Kennedy DW. Multichannel intracochlear electrodes: mechanism of insertion trauma. *Laryngoscope.* 1987;97:42-49.
12. Shepherd RK, Pyman BC, Clark GM, Webb RL. Banded intracochlear electrode array: evaluation of insertion trauma in human temporal bones. *Ann Otol Rhinol Laryngol.* 1985;94:55-59.
13. Welling DB, Hinojosa R, Gantz BJ, Lee J. Insertional trauma of multichannel cochlear implants. *Laryngoscope.* 1993;103:995-1001.
14. Hochmair I, Arnold W, Nopp P, Jolly C, Müller J, Roland P. Deep electrode insertion in cochlear implants: apical morphology, electrodes and speech perception results. *Acta Otolaryngol.* 2003;123:612-617.
15. Friesen LM, Shannon RV, Slattery WH. Effects of electrode location on speech recognition with the nucleus-22 cochlear implant. *J Am Acad Audiol.* 2000;11:418-428.
16. Marsh MA, Xu J, Blamey PJ, et al. Radiologic evaluation of multichannel intracochlear implant insertion depth. *Am J Otol.* 1993;14:386-391.
17. Franz BKH, Clark GM, Bloom DM. Surgical anatomy of the round window with special reference to cochlear implantation. *J Laryngol Otol.* 1987;101:97-102.
18. Proctor B, Bollobas B, Niparko JK. *Ann Otol Rhinol Laryngol.* 1986;95:444-446 Anatomy of the round window niche.
19. Su WY, Marion MS, Hinojosa R, et al. Anatomical measurements of the cochlear aqueduct, round window membrane, round window niche, and facial recess. *Laryngoscope.* 1982;92:483-486.
20. Plenck H. The microscopic evaluation of hard tissue implants. In: Williams DF, ed. *Techniques of Biocompatibility Testing.* Boca Raton, Fla: CRC Press; 1986:35-81.
21. Xu J, Xu SA, Cohen LT, Clark GM. Cochlear view: postoperative radiography for cochlear implantation. *Am J Otol.* 2000;21:49-56.
22. Eshraghi AA, Yang NW, Balkany TJ. Comparative study of cochlear damage with three perimodiolar electrode designs. *Laryngoscope.* 2003;113:415-419.
23. Fishman AJ, Roland JT Jr, Alexiades G, Mierzewski J, Cohen NL. Fluoroscopically assisted cochlear implantation. *Otol Neurotol.* 2003;24:882-886.