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The Role of Electrode Placement in Bilateral Simultaneously Cochlear Implanted Adult Patients

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Short title: Role of Electrode Placement in Bilateral CIs

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ABSTRACT

Objective: To evaluate the influence on hearing performance of the electrode placement in adult patients simultaneously and bilaterally cochlear implanted.

Study Design: Case series with planned data collection

Setting: Tertiary referral university centers

Subjects and Methods: The postoperative CT scan of nineteen patients simultaneously and bilaterally implanted with a long straight electrode array was studied. The size of the cochlea was measured considering the major cochlear diameter and the cochlear height. The electrode-to-modiolus distance for the electrodes positioned at 180- and 360-degrees, and the angular depth of insertion of the array were also measured. Speech perception was assessed at 1-year and at 5-years postimplantation using disyllabic words lists in quiet and in noise, with the speech coming from the front, and a cocktail-party background noise coming from 5 loudspeakers.

Results: At 1-year postimplantation, the electrode-to-modiolus distance at 180-degrees was correlated with the speech perception scores in both quiet and noise. In patients with a full electrode insertion, no correlation was found between the angular depth of insertion and hearing performance. The speech perception scores in noise gradually declined as a function of the number of inserted and active electrodes. No relationship between electrode position and speech scores was found at 5-years postimplantation.

Conclusion: In adult patients simultaneously and bilaterally implanted, the use of a long straight array, the full electrode array insertion, and the proximity to the modiolus might be determining factors to obtain the best speech performance at 1-year, without influence on the speech scores after long-term use.

Key words: bilateral implantation, speech perception, electrode position, cochlear implant, angular depth of insertion, cochlear size

INTRODUCTION

The preservation of the inner ear structures during the insertion of cochlear implant, together with the identification of the ideal site of stimulation in the cochlea, should allow the best hearing performance. As a consequence, the quality of insertion of the cochlear implants has been extensively studied during the last decades[1-5]. In this context, three parameters have been more accurately investigated: the translocation of the array with the subsequent basilar membrane rupture, the depth of insertion of the electrode array, and the proximity of the electrodes to the spiral ganglion cells. To date, it is not clear how the position of the electrode in the cochlea can impact the hearing performance results, since many variables may influence this outcome. All the currently available electrode arrays have their own specific length, diameter, shape, and physical properties that influence the trajectory during the insertion and determine the final position in the cochlear lumen. Furthermore, variations in human cochlear anatomy, as well as the intersubject variability, have been described in several studies[6-8], whereas little is known about the intrasubject difference, i.e. the differences between the two ears.

Considering the hearing performance after cochlear implantation, intraindividuals variability in speech perception scores has been demonstrated among bilaterally cochlear implanted recipients[9,10]. In fact, in a prospective multicenter study, poor performance of one or both ears was reported at 1-year postimplantation in about 40% of simultaneously implanted patients with similar hearing loss history between the two ears (hearing deprivation, duration of deafness, etiology)[10]. An explanation for poor hearing performance and/or asymmetry between the two ears could be differences in the electrode position within the cochlea[5]. The aim of the present study is to explore the correlation between speech performance and electrode placement parameters in patients simultaneous and bilaterally implanted, and to investigate whether cochlear anatomy differences could explain inter- and intraindividual differences in hearing performance.

MATERIALS AND METHODS

Selection criteria and subjects

Study participants were 19 adult patients presenting a post-lingual bilateral profound or total hearing loss. Specific subject demographics are summarized in Table 1. The duration of deafness, of hearing deprivation, of hearing aid use, and the etiologies were similar for both ears. Enrolling criteria, speech perception evaluation setting, and results at 1- and at 5-years have been previously reported[10,11]. To be implanted, patients were required to have a maximum of 10% open set disyllabic word recognition score in quiet at 60 dB in the best-aided condition, a difference of profound hearing loss duration between the two ears of less than 5 years, and no malformations of the cochlea. Speech perception tests in quiet and in noise (SNR of +15 dB, +10 dB and +5 dB) were performed before implantation, at 1-year, and 5-years after activation. Responses were scored as the percentage of words correctly identified. All patients underwent bilateral implantation by expert otologists (more than 100 CI procedures) in a simultaneous surgical procedure with the same device (MED-EL Combi 40+, Standard Electrode Array, 31 mm length; Innsbruck, Austria).

A multi-slice helical CT scan (500 µm slice thickness), was realized in the immediate postoperative period.

All participants gave their informed written consent, and the study was approved by the local ethical committee (Saint-Louis, Paris, No. 61D0/22/A).

Radiological analysis

The DICOM (Digital Imaging and Communications in Medicine) data were analyzed by Osirix program (Osirix v 4.0 64-bit; Pixmeo Sarl, Bernex, Switzerland). This program allowed multiplanar reconstructions of cochlear anatomy and position of the arrays in the cochlea. All the images, acquired by different CT scans in the different centers, were reconstructed with 0.1 mm increments in order to standardize the measurement technique and reduce the error of measurement. To examine the cochlear sizes and their relationship with the insertion depth, a three-dimensional coordinate system was used, in accordance with the consensus of cochlear coordinates[12], with the exception of the cochlear height that was measured in a reformatted coronal view. The largest cochlear diameter (distance A) going from the center of the round window membrane to the opposite lateral wall[13], was calculated on a plane perpendicular to the modiolus axis and coplanar to the basal turn, named 'cochlear view' by Xu et al.[14] (Fig. 1A). The cochlear height was measured from the mid-point of the basal turn to the mid-point of the apical turn on a coronal section[15,16] (Fig. 1B). The electrode-to-modiolus distances (EMD) for electrodes positioned at 180- and 360-degrees were measured on the mid-modiolar plane, crossing the mid of the round window (Fig. 1C). The angular depth of insertion of the array was measured in the 'cochlear view' (slice thick of 5 mm), considering the mid-point of the round window as the 0-degrees reference (Fig. 1D). To minimize the error, all the measurements were performed blindly by an otologist, each measurement was repeated three times in nonconsecutive days, and the mean value was then considered.

Statistical analysis

Values are expressed as means ± standard error of the mean (SEM). For correlations between cochlear anatomy and cochlear array localization, and its relation with speech perception scores, Pearson's correlation coefficient (r) was calculated, and the ANOVA was used to test the slope of the linear regression line. One-way ANOVA was used to analyze the influence of the number of activated electrodes on speech performance. Student's t-test was used for comparisons between groups (male/female, right/left cochleae, full/partial insertions). For all comparisons, $p<0.05$ was considered as significant. All statistical analyses were performed using IBM SPSS for Windows (v 22.0, SPSS Inc., Chicago, Illinois, USA).

RESULTS

The mean speech performance in quiet and noise have previously been reported[10]. At 1-year post-implantation, 7 patients were poor performers (speech perception scores in quiet < 60% in bilateral condition). Among the good performers, 9 patients obtained asymmetrical performance (difference of speech scores in quiet between the two ears ≥20%).

Cochlear anatomy and electrode position

The cochlear anatomical data are reported in Table 2. The distance A was positively correlated with the cochlear height (r=0.52, $p=0.0007$, data not shown). Surprisingly, the distance A and the cochlear height were different between the two ears (difference of mean distance A: 0.22±0.05 mm, $p=0.04$; difference of mean cochlear height: 0.3±0.06 mm, p=0.001, Student's *t* tests); no right or left ear predominance was observed. The distance A and the cochlear height were different as well between male and female ears, the males having a diameter and a cochlear height greater than females ($p=0.0001$, Student's *t* tests).

A full insertion of the electrode array was achieved in 26 ears, and a partial insertion in 12 ears (3 patients with a bilateral partial insertion, and 6 patients with a unilateral partial insertion). In ears with an incomplete insertion, the number of extra-cochlear electrodes ranged from 1 to 4. The size of the cochlea (i.e. distance A and cochlear height) was similar between the ears with a full insertion and ears with a partial insertion (Table 3).

In the 26 ears with a full electrode insertion, the angular depth of insertion in the cochlea varied widely [510-880-degrees] (Fig 2), and was negatively correlated with the distance A (r=-0.55, *p*=0.003) (Fig. 3A), on the other hand no correlation was found with the cochlear height (Fig 3B). The EMD was positively correlated with the distance A at both 180- (r=0.47, *p*=0.0004) and 360-degrees (r=0.66, *p*=0.0002, Fig. 3C), and with the cochlear height at 360-degrees (r=0.6, *p*=0.001, Fig. 3D). The EMD distance at 180- and at 360-degrees was not correlated with the angular depth of insertion. These results indicate that in large cochleae (distance A), the electrode array was less deeply inserted and more distant from the modiolus at the basal turn (EMD at 180-degrees and 360-degrees). In the present study, the distance A was sufficient to define the cochlear size and reliable for the prediction of the position of the implant within the cochlea.

Correlation between electrode position and speech perception

At 1-year after cochlear implantation (38 implanted ears), speech perception scores were negatively correlated with EMD at 180-degreess both in quiet (r=-0.34, *p*=0.02) and in noise (SNR +15 dB: r=-0.44, p=0.006; SNR +10 dB: r=-0.63, *p*=0.0005; SNR+5 dB: r = -0.52, *p*=0.01, Fig. 4). The greater the EMD was, the poorer was the performance. No correlation was observed at 360-degrees. The number of inserted electrodes was correlated with speech perception in noise at SNR +15 dB and SNR +10 dB (ANOVA, *p*=0.02); the speech perception scores in noise gradually decreased as a function of the number of inserted electrodes (post hoc Dunnett's t test p=0.02) (Table 3). Considering the obvious interdependence between the number of intracochlear electrodes and the depth of insertion, we analyzed the influence of electrode position on hearing outcomes among the 26 ears with a full insertion of the electrode array. No correlation was found between the speech perception scores and the angular depth of insertion, both in quiet and in noise, whereas the speech perception scores were negatively correlated with EMD at 180-degreess both in quiet (r=-0.38, *p*=0.048) and in noise (SNR +15 dB: r=-0.4, *p*=0.049; SNR +10 dB: r = -0.62, *p*=0.006; SNR+5 dB: r=-0.51, *p*=0.032, data not shown).

A multifactorial ANOVA was performed and failed to demonstrate that the anatomic cochlear variations (distance A, cochlear height), and the different electrode position (EMD at 180- and 360-degrees) between the two ears, were the reason of the asymmetric speech score (difference ≥20% between better and poorer ear) at 1-year in 9 patients.

At 5-years post-implantation, most of the patients (85%) achieved good speech performance (speech perception score ≥60% in quiet in bilateral condition); the speech score of the poorer ear in noise continued to improve over time, and the majority of the patients with poor speech scores improved their performance both in quiet and in noise[11]. Studying the relationship between the electrode insertion parameters and the hearing outcomes, no correlation was found at 5-years postimplantation between speech perception scores and the angular depth of insertion, both in the entire sample and in the group with full insertion of the electrode array. In contrast to what observed at 1-year postimplantation, the EMD was not correlated with speech perception scores, both at 180-degrees and 360-degrees (data not shown).

DISCUSSION

We have previously shown that in adult patients simultaneously and bilaterally implanted, poor or asymmetrical hearing performance at 1-year postimplantation are present in 40% of cases, and that the speech scores of the poorer ear continues to improve over time[10,11]. In the present study, we demonstrate that both the distance between electrode array and modiolus at 180-degrees, and the number of inserted electrodes, are important variables that influence the early achievement of the best speech perception scores. The variability in cochlear anatomy could explain the differences in hearing outcomes between patients; nevertheless we failed to demonstrate an influence of cochlear geometry on intraindividual speech perception asymmetry, probably due to the small number of patients with asymmetric speech scores.

The variability in cochlear anatomy influences electrode array position

Several studies investigated the influence of cochlear anatomy on electrode array position within the cochlea[17-21]. Important variations in the first segment of the scala tympani, such as unusual narrowing or constriction, have been reported. The basal end of the cochlea is in fact of major interest in cochlear implant surgery; it bends in three dimensions, resembling to a ‘‘fish hook’’, and in some cases its anatomical variations lead to a difficulty for the surgeon to choose the ideal cochleostomy site in order to reach the scala tympani without damaging any inner ear structure[7].

In this study the cochlear size was assessed using the major cochlear diameter of the basal turn, that is assumed to be a good predictor of the length of the two first turns of the cochlea[22,23,24], and using the cochlear height; our results are in line with the data present in literature[6,8,13,15,16]. These two measures are clearly correlated to each other, meaning that a greater basal turn diameter is associated to a higher cochlea. Both distance A and cochlear height vary with sex, males having bigger cochlea compared to females, as already described in the literature[13,16,20]. Additionally, we observed an asymmetry between the two ears in distance A (0.22 mm), that was only described by Escude et al.[13], and in cochlear height (0.3 mm). No ear predominance was found, as previously reported[16,20,23-25].

In patients implanted with long (31 mm) and straight electrode arrays, we demonstrated that as expected, the smaller the diameter of the cochlea is, the closer is the electrode array to the modiolus at the basal turn, and the deeper is the array insertion. The depth of array insertion was strongly correlated (r=-0.63) with the major cochlear diameter measurement, with a shallower insertion in bigger cochlea and deeper insertion in smaller cochlea. Van der Marel et al.[20] found a weaker correlation (Pearson's r = -0.3) analyzing 362 cochleae implanted with Advanced Bionics implants. In other studies, a more significant correlation between depth of insertion and cochlear diameter was found using straight electrodes[21,26].

An incomplete insertion of the electrode array was observed in 12/38 ears (32%). This observation is in accordance with a histopathological study, which reported the 52% of incomplete insertion in absence of intrascalar bony or soft tissue that could explain a partial insertion[27]. The anatomical study of Rask-Andersen et al.[7] describes a narrowing of the cochlear duct or a sharp bend of cochlear coiling between the first and the second turn as another possible cause for incomplete insertion. No significant difference in the size of the cochlea between ears with incomplete and complete insertions was found in our study, nevertheless it should be noticed that the three cochleae with 4 electrodes outside, had a smaller distance A than the other ears (see Table 3). On the base of the cochlear length equation based on distance A value (Alexiades et al.[24]), we can assume that a 31 mm length array was too long to be totally inserted in these three ears. At the present, different lengths of cochlear arrays are available, and it is crucial to measure the distance A before implantation in order to adapt the type (and length) of the electrode array to be implanted.

Is the electrode position related to speech perception?

If we consider the ears with full insertion of the electrode array, despite a large variation of the angular depth of insertion, no correlation was found between this variable and the hearing performance. This observation is consistent with a histological analysis over a series of 27 temporal bone specimens of subjects with cochlear implant[28]. Van der Marel et al.[29] analyzed six position-related variables including the angular and linear insertion depth of the array and did not find any correlation with speech outcomes at 2-years postoperative. In a prospective randomized study including 13 patients, Buchman et al.[30] didn't find a difference in speech scores between MedEl standard array (mean angular depth of insertion 657-degrees) and medium array (mean angular depth of insertion 423-degrees), although better performance was found in the standard array group when 6 more patients were included retrospectively. On the contrary, other studies reported poorer performance in case of deeper insertions[31], explained by the increased number of electrodes in the scala vestibuli, reduced pitch discrimination, decreased basal stimulation[32], and pitch confusion at apical contacts[33]. The negative correlation between the electrode angular depth of insertion and hearing outcomes found by Yukawa et al.[34] may be explained by the presence of confounding factors, such as the lower number of activated electrodes in case of partial insertion. Indeed, in the present study, in case of incomplete insertion, the speech perception scores in noise at 1-year decreased as a function of the number of inserted electrodes (see Table 3).

Considering the distance between the electrode array and the modiolus, it has been shown that a closer position to the spiral ganglion cells is associated with better speech perception[18,32]. This effect may be related to the minimization of channel interaction, which leads to reduction of electrical thresholds and/or improvement of the spatial selectivity. Our findings are in accordance with Esquia-Medina et al.[18] who reported a correlation between speech perception scores and average EMD of the 6 most basal electrodes of MED-EL devices (corresponding approximately to the region from 0- to 180-degrees) at 6 months, whereas no correlation was found at 12 months. In this study, as well as the present one, such relationship was not present for the electrode at 360-degrees, possibly due to the narrowing of the scala tympani from base to apex[35] that reduces the variability of the array position. This relationship between the EMD and the hearing performance could point out a preferential use of perimodiolar electrode array in order to obtain a rapid hearing rehabilitation. Nevertheless, Doshi et al.[36] reported no differences between speech perception outcomes at 3- and 9-months in patients implanted with either straight or perimodiolar electrodes array. A reason could be the more frequent dislocation from scala tympani to scala vestibuli in case of perimodiolar electrodes[37]. Although such scalar dislocation is difficult to assess in standard CT scan, it might negatively influence the cochlear implant outcome[4,5,33,38]. An aspect that has not been explored in this study is the surgeon's gesture. A recent study described a high intra- and inter-individual variability of the insertion axis of the array into the cochlea; yet, this variability was reduced among expert surgeons[39]. Since all the participants to the present study were senior otologists, we estimate that this doesn't represent a great factor of bias of the study; furthermore, how the insertion axis influences the trajectory of insertion or the final position of the array has not yet been described or reported. An additional limitation of this study could be represented by the migration of the array that can occur between 1- and 5-years. Nevertheless, in all patients the most basal electrodes remained activated with stable impedance values over time and providing auditory responses, thus an extrusion of the electrodes should be unlikely [40].

In conclusion, whereas 1-year results suggest that the number of inserted electrodes and the distance electrode-to-modiolus are related to good performance, these parameters does not influence the speech scores after long term use. In order to obtain a rapid hearing rehabilitation and the best results at 1-year, the preoperative measurement of the cochlear diameter (distance A) may guide the choice of the correct array length allowing a complete insertion. In case of unilateral implantation the choice of the side to be implanted should be oriented, in presence of equal clinical and audiological conditions of the two ears, to the smaller cochlear diameter.

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The authors report no conflicts of interest.

References

1. Shepherd RK, Hatsushika S, Clark GM. Electrical stimulation of the auditory nerve: the effect of electrode position on neural excitation. *Hear Res* 1993;66:108-20
2. Skinner MW, Ketten DR, Vannier MW, Gates GA, Yoffie RL, Kalender WA Determination of the position of nucleus cochlear implant electrodes in the inner ear. *Am J Otol*. 1994;15:644-51.
3. Skinner MW, Ketten DR, Holden LK, et al. CT-derived estimation of cochlear morphology and electrode array position in relation to word recognition in Nucleus-22 recipients. *J Assoc Res Otolaryngol*. 2002;3:332-50.
4. Aschendorff A, Kromeier J, Klenzner T, Laszig R. Quality control after insertion of the nucleus contour and contour advance electrode in adults. *Ear Hear* 2007; 28:75S-79S.
5. Holden LK, Finley CC, Firszt JB, et al. Factors affecting open-set word recognition in adults with cochlear implants. *Ear Hear* 2013;34:342-60

6. Erixon E, Högstorp H, Wadin K, Rask-Andersen H. Variational anatomy of the human cochlea: implications for cochlear implantation. *Otol Neurotol* 2009;30:14-22
7. Rask-Andersen H, Liu W, Erixon E, et al. Human cochlea: anatomical characteristics and their relevance for cochlear implantation. *Anat Rec (Hoboken)* 2012;295:1791-811.
8. Martinez-Monedero R, Niparko JK, Aygun N. Cochlear coiling pattern and orientation differences in cochlear implant candidates. *Otol Neurotol* 2011;32:1086-93
9. Litovsky RY, Parkinson A, Arcaroli J, Sammeth C. Simultaneous bilateral cochlear implantation in adults: a multicenter clinical study. *Ear Hear* 2006;27:714–731.
10. Mosnier I, Sterkers O, Bebear JP, et al. Speech performance and sound localization in a complex noisy environment in bilaterally implanted adult patients. *Audiol Neurootol* 2009;14:106-14.
11. De Seta D, Nguyen Y, Ferrary E, Sterkers O, Mosnier I. Does the Anatomy of the Cochlea influences the Hearing Outcomes in Simultaneous Bilateral Cochlear Implanted Adults? 38th ARO Meeting Abstract book. 2015 Vol 38. PS 330 p 195
12. Verbist BM, Skinner MW, Cohen LT, et al. Consensus panel on a cochlear coordinate system applicable in histologic, physiologic, and radiologic studies of the human cochlea *Otol Neurotol* 2010;31:722-30.
13. 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
14. Xu J, Xu SA, Cohen LT, Clark GM. Cochlear view: postoperative radiography for cochlear implantation. *Am J Otol* 2000;21:49-56.

15. Purcell D, Johnson J, Fischbein N, Lalwani AK. Establishment of normative cochlear and vestibular measurements to aid in the diagnosis of inner ear malformations. *Otolaryngol Head Neck Surg* 2003;128:78-87
16. Mori MC, Chang KW. CT analysis demonstrates that cochlear height does not change with age. *AJNR Am J Neuroradiol* 2012;33:119-23.
17. Kawano A, Seldon HL, Clark GM. Computer-aided three-dimensional reconstruction in human cochlear maps: measurement of the lengths of organ of Corti, outer wall, inner wall, and Rosenthal's canal. *Ann Otol Rhinol Laryngol* 1996;105:701-9
18. Esquia Medina GN, Borel S, Nguyen Y, Ambert-Dahan E, Ferrary E, Sterkers O, Grayeli AB (2013) Is electrode-modiolus distance a prognostic factor for hearing performances after cochlear implant surgery? *Audiol Neurootol* 18:406-13.
19. Verbist BM, Ferrarini L, Briaire JJ, Zarowski A, Admiraal-Behloul F, Olofsen H, Reiber JH, Frijns JH Anatomic considerations of cochlear morphology and its implications for insertion trauma in cochlear implant surgery. *Otol Neurotol* 2009;30:471-7
20. van der Marel KS, Briaire JJ, Wolterbeek R, Snel-Bongers J, Verbist BM, Frijns JH Diversity in cochlear morphology and its influence on cochlear implant electrode position. *Ear Hear* 2014;35:e9-20.
21. Franke-Trieger A, Jolly C, Darbinjan A, Zahnert T, Mürbe D. Insertion depth angles of cochlear implant arrays with varying length: a temporal bone study. *Otol Neurotol* 2014;35:58-63.
22. Erixon E, Rask-Andersen H How to predict cochlear length before cochlear implantation surgery. *Acta Otolaryngol* 2013;133:1258-65

23. Singla A, Sahni D, Gupta AK, Aggarwal A, Gupta T. Surgical anatomy of the basal turn of the human cochlea as pertaining to cochlear implantation. *Otol Neurotol.* 2015;36:323-8.
24. Alexiades G, Dhanasingh A, Jolly C Method to Estimate the Complete and Two-Turn Cochlear Duct Length. *Otol Neurotol.* 2015;36:904-7.
25. Pelliccia P, Venail F, Bonafé A, Makeieff M, Iannetti G, Bartolomeo M, Mondain M. Cochlea size variability and implications in clinical practice. *Acta Otorhinolaryngol Ital* 2014;34:42-9.
26. Franke-Trieger A, Mürbe D. Estimation of insertion depth angle based on cochlea diameter and linear insertion depth: a prediction tool for the CI422. *Eur Arch Otorhinolaryngol*. 2015;272:3193-9.
27. Lee J, Nadol JB Jr, Eddington DK. Factors associated with incomplete insertion of electrodes in cochlear implant surgery: a histopathologic study. *Audiol Neurootol* 2011;16:69-81
28. Lee J, Nadol JB Jr, Eddington DK. Depth of electrode insertion and postoperative performance in humans with cochlear implants: a histopathologic study. *Audiol Neurootol* 2010;15:323-31
29. van der Marel KS, Briaire JJ, Verbist BM, Muurling TJ, Frijns JH. The Influence of Cochlear Implant Electrode Position on Performance. *Audiol Neurootol* 2015;20:202-211
30. Buchman CA, Dillon MT, King ER, Adunka MC, Adunka OF, Pillsbury HC Influence of cochlear implant insertion depth on performance: a prospective randomized trial. *Otol Neurotol* 2014;35:1773-9

31. Skinner MW, Holden TA, Whiting BR, et al. In vivo estimates of the position of advanced bionics electrode arrays in the human cochlea. *Ann Otol Rhinol Laryngol Suppl*. 2007;197:2-24

32. Finley CC, Holden TA, Holden LK, et al. Role of electrode placement as a contributor to variability in cochlear implant outcomes. *Otol Neurotol* 2008;29:920-8

33. Gani M, Valentini G, Sigrist A, Kós MI, Boëx C. Implications of deep electrode insertion on cochlear implant fitting. *J Assoc Res Otolaryngol* 2007;8:69–83

34. Yukawa K, Cohen L, Blamey P, Pyman B, Tungvachirakul V, O'Leary S. Effects of insertion depth of cochlear implant electrodes upon speech perception. *Audiol Neurotol* 2004;9:163–172.

35. Biedron S, Prescher A, Ilgner J, Westhofen M. The internal dimensions of the cochlear scalae with special reference to cochlear electrode insertion trauma. *Otol Neurotol* 2010;31:731-7

36. Doshi J, Johnson P, Mawman D, Green K, Bruce IA, Freeman S, Lloyd SK Straight versus modiolar hugging electrodes: does one perform better than the other? *Otol Neurotol* 2015;36:223-7.

37. Boyer E, Karkas A, Attye A, Lefournier V, Escude B, Schmerber S. Scalar Localization by Cone-Beam Computed Tomography of Cochlear Implant Carriers: A Comparative Study Between Straight and Periomodiolar Precurved Electrode Arrays. *Otol Neurotol* 2015;36:422-9.

38. Wanna GB, Noble JH, Carlson ML, et al. Impact of electrode design and surgical approach on scalar location and cochlear implant outcomes. *Laryngoscope* 2014;124 Suppl 6:S1-7.

39. Torres R, Kazmitcheff G, Bernardeschi D, et al. Variability of the mental representation of the cochlear anatomy during cochlear implantation. *Eur Arch Otorhinolaryngol.* 2015 DOI 10.1007/s00405-015-3763-x

40. Johnston JD1, Scoffings D, Chung M, Baguley D, Donnelly NP, Axon PR, Gray RF, Tysome JR. Computed Tomography Estimation of Cochlear Duct Length Can Predict Full Insertion in Cochlear Implantation. *Otol Neurotol*. 2016;37:223-8.

FIGURES

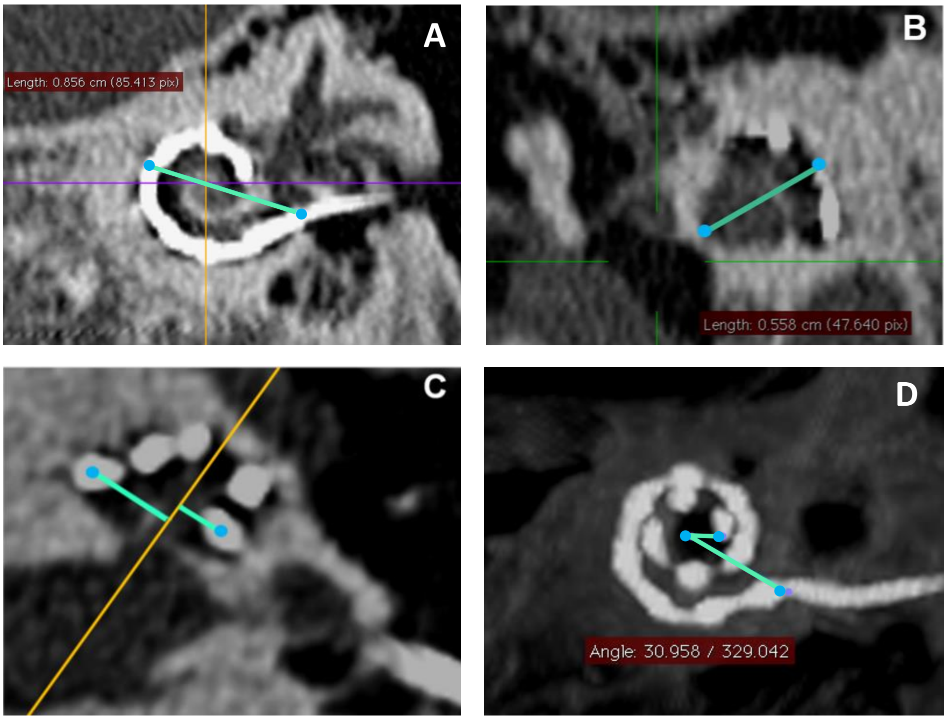

Figure 1: Radiological analysis (CT scan). A. Cochlear diameter (Distance A). B. The cochlear height was measured in the coronal reconstruction. C. The electrode-to-modiolus distance (EMD) at 180-degrees and 360-degrees. D. Angular depth of insertion.

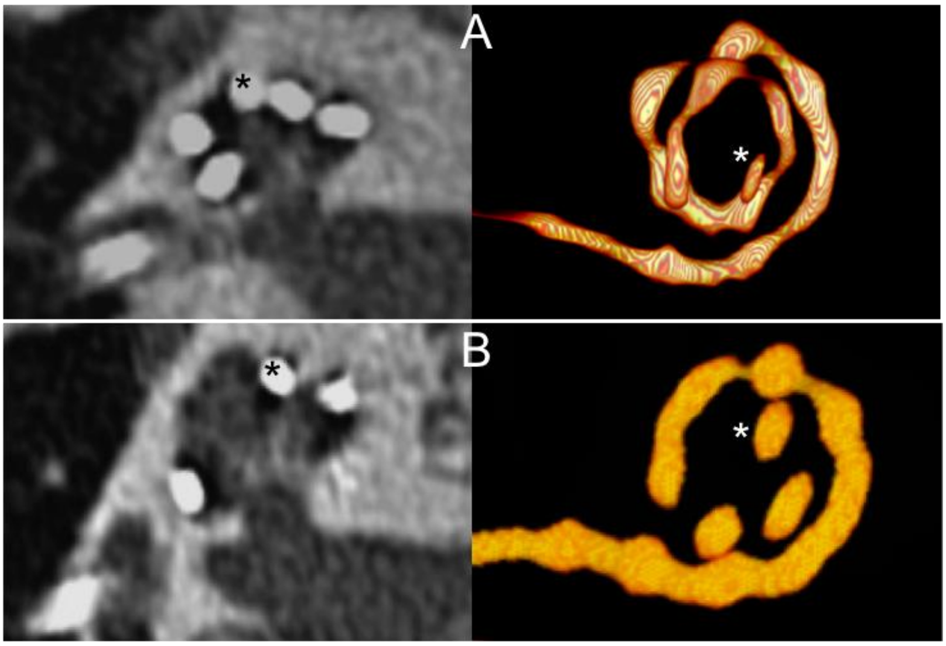

Figure 2: Variability of the angular depth of insertion among cochleae with complete array insertion in mid-modiolar cuts and 3D volumetric reconstruction of the array. A. 880-degrees insertion. B. 550-degrees insertion. The asterisks (*) represent the apical electrode.

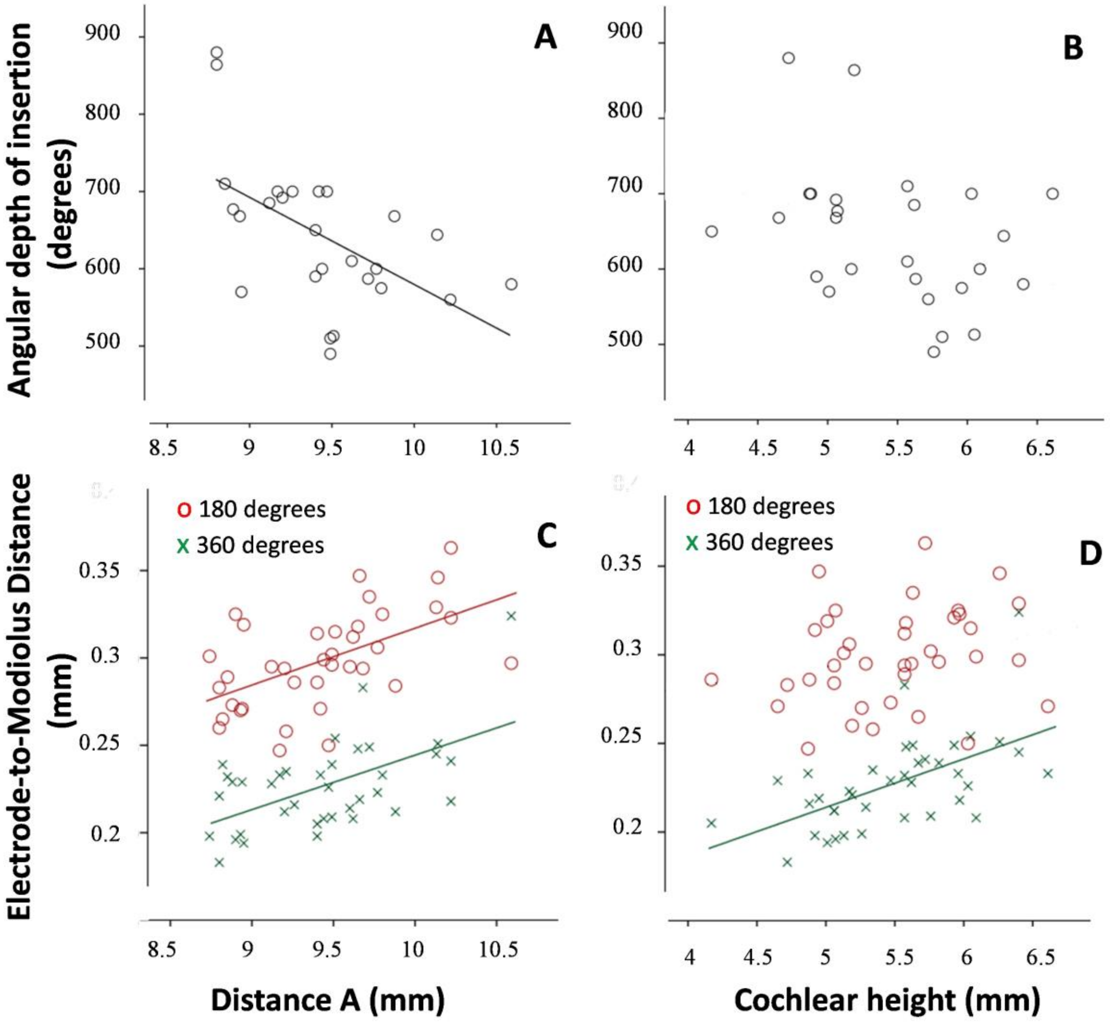

Figure 3: Correlation between the size of the cochlea (cochlear diameter, cochlear height) and the position of electrode array (Electrode-to-modiolus distance, angular depth of insertion). The lines represent the significant linear regression.

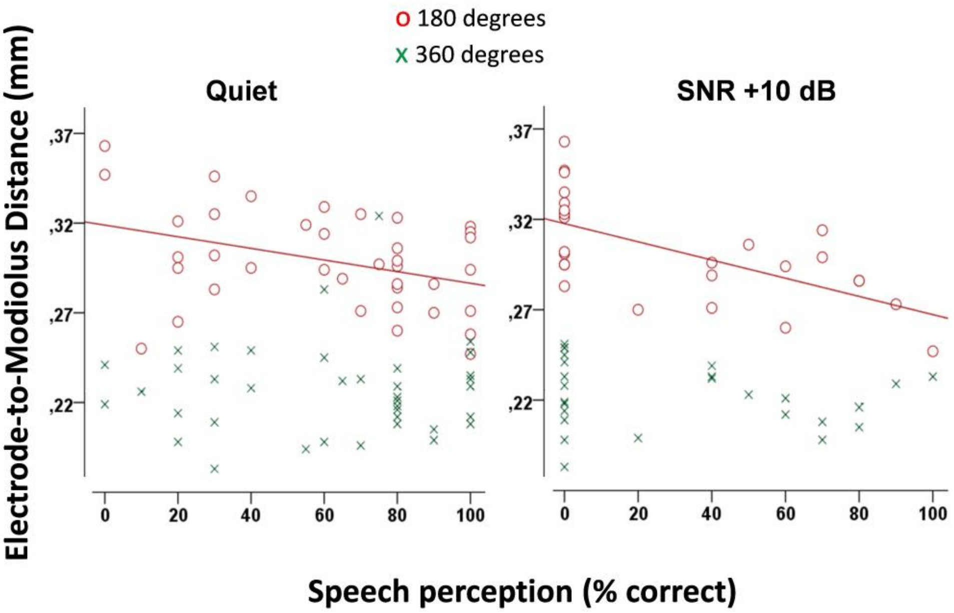

Figure 4: Correlations between the electrode array position and the speech perception scores in quiet and at SNR +10 dB at 1-year at 180-degrees. No correlation was found at 360-degrees. The lines represent the significant linear regression.

Table 1: Patients Demographics (n = 19)

Age at implantation (yrs)	46 ± 3 [24-68]
Sex: Male/Female	5/14
Duration of hearing loss (yrs)	
Right ear	23.5 ± 3.0 [1-51]
Left ear	23.4 ± 3.2 [1-51]
Duration of profound hearing loss (yrs)	
Right ear	3.0 ± 0.5 [1-9]
Left ear	2.7 ± 0.5 [0-9]
Use of hearing aids before implantation	
Bilateral	12
Unilateral	1
None[a]	6
Duration of hearing aid use (yrs)	
Right ear	10 ± 3 [1-41]
Left ear	10 ± 3 [1-41]
Etiology[b]	
Unknown	6
Sudden hearing loss	6
Genetic/Familial	4
Traumatism	1
Otosclerosis	1
Meningitis	1

Values are expressed as mean ± SEM [range] or only number of patients

a. These patients never tried hearing aid because of sudden total bilateral hearing loss. b. Same etiology for both ears.

Table 2: Cochlea measurement and electrode array placement on CT scan (19 patients, 38 ears)

Distance A (mm), n = 38 ears	9.4 ± 0.08 [8.8 – 10.6]
Male (n = 10)	9.9 ± 0.12 [9.7-10.6]
Female (n = 28)	9.3 ± 0.07 [8.8-10.2] *
Ears with full insertion of electrode array (n = 26)	9.4 ± 0.09 [8.8-10.6]
Ears with partial insertion of electrode array (n = 12)	9.6 ± 0.16 [8.9-10.2]
Cochlear height (mm), n = 38	5.5 ± 0.09 [4.2 - 6.4]
Male (n = 10)	6 ± 0.09 [5.5 - 6.4]
Female (n = 28)	5.5 ± 0.09 [4.2 - 6.6] **
Ears with full insertion of electrode array (n = 26)	5.4 ± 0.12 [4.2 - 6.6]
Ears with partial insertion of electrode array (n = 12)	5.5 ± 0.13 [4.9 - 6.4]
Angular depth of insertion (degrees)	
Ears with full insertion (n = 26)	643 ± 93 [510 - 880]
Ears with partial insertion (n = 12)	403 ± 82 [318 - 590] **
Total (n = 38)	567 ± 23 [318 - 880]
EMD 180-degrees (mm)	
Ears with full insertion (n = 26)	0.29 ± 0.004 [0.25 - 0.36]
Ears with partial insertion (n = 12)	0.29 ± 0.008 [0.26 – 0.35]
EMD 360-degrees (mm)	
Ears with full insertion (n = 26)	0.22 ± 0.004 [0.18 - 0.32]
Ears with partial insertion (n = 12)	0.23 ± 0.006 [0.2 – 0.28]

Values are expressed as mean ± SEM [range]. A full electrode array insertion was achieved in 26 ears and a partial electrode array insertion in 12 ears. Comparison of distance A and cochlear height between males and females, and of angular depth of insertion between ears with full or partial insertion, * *p*<0.05, ***p*<0.001, Student's t test. EMD: electrode-to-modiolus distance

Table 3: number of inserted electrodes, cochlear measurements and speech perception score at 1 year

Inserted Electrodes	Distance A (mm)	Cochlear height (mm)	Speech score at 1-yr	
			Quiet	SNR +15 dB
Full insertion				
12 electrodes (26 ears, 16 patients)	9.4 ± 0.08 [8.8 - 10.6]	5.4 ± 0.12 [4.2 - 6.6]	64 ± 6	54 ± 7
Partial insertion				
11 electrodes (3 ears, 3 patients)	9.5 ± 0.14 [9.2 - 9.6]	5.2 ± 0.12 [5.3 - 4.9]	63 ± 27	46 ± 13
10 electrodes (4 ears, 4 patients)	9.7 ± 0.32 [8.8 - 10.2]	5.9 ± 0.19 [5.6 – 6.4]	52 ± 18	30 ± 4
9 electrodes (2 ears, 2 patients)	9.8 ± 0.13 [9.6-10.1]	5.7 ± 0.25 [5.6 – 5.9]	60 ± 40	15 ± 15
8 electrodes (3 ears, 2 patients)	8.8 ± 0.09 [8.7 – 8.9]	5.3 ± 0.17 [5.1 – 5.5]	43 ± 18	10 ± 10 *

Values are expressed as mean ± SEM [range]. The mean number of electrodes outside the cochlea was 2.4 (range: 1-4). More than 3 electrodes out of the cochlea influenced the speech scores in noise. * $p = 0.02$, One-way ANOVA, post hoc Dunnett's t test.