Published in final edited form as:

Otol Neurotol. 2019 June ; 40(5): 617–624. doi:10.1097/MAO.0000000000002204.

Further evidence of the relationship between cochlear implant electrode positioning and hearing outcomes

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Abstract

Background: Post-operative imaging studies by numerous groups have revealed that final CI electrode position impacts audiological outcomes with scalar location consistently shown to be a significant factor. Modiolar proximity has been less extensively studied, and findings regarding the effect of insertion depth have been inconsistent.

Methods: Using previously developed automated algorithms, we determined CI electrode position in an IRB-approved database of 220 CI ears. Generalized linear models (GLM) were used to analyze the relationship between audiological outcomes and factors including age, duration of CI use, device type, and electrode position.

Results: For pre-curved arrays, GLM revealed that scalar position, modiolar proximity, base insertion depth, and gender were significant factors for CNC words ($R=0.43$, $p < 0.001$, $N=92$ arrays), while scalar position, modiolar proximity, age, and postlingual onset of deafness were significant for BKB-SIN ($R=0.51$, $p < 0.001$, $N=85$) scores. Other factors were not significant in the final model after controlling for these variables. For straight arrays, we found the insertion depth, postlingual deafness, and length of CI use to be highly significant ($R=0.47$, $p < 0.001$) factors for CNC words (91 arrays), while for BKB-SIN scores the most significant ($R=0.47$, $p < 0.001$) factors were insertion depth, younger age, and postlingual deafness (89 arrays).

Conclusion: Our results confirm the significance of electrode positioning in audiological outcomes. The most significant positional predictors of outcome for precurved arrays were full ST insertion and the modiolar distance, while for the lateral wall arrays the depth of insertion was the most significant factor.

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INTRODUCTION

Cochlear implants (CI) are neuroprosthetics that have been adopted as standard of care treatment for patients with at least a moderate sloping to profound sensorineural hearing loss. Average speech recognition scores in quiet are approximately 60% correct for Consonant-Nucleus-Consonant (CNC) monosyllabic word scores and 70% for AzBio sentence recognition tests in quiet¹⁻⁴. However, despite the remarkable effectiveness of CIs in the general population, there is a considerable degree of unexplained variability in patient outcomes⁵. It is important to know exactly how demographic and surgical factors affect outcomes, so that both patient counseling and surgical practices can be better tailored to the specific conditions of each individual patient.

Many studies have been undertaken by different groups to determine the causes of CI performance outcome variability for adult recipients. Certain factors have been consistently found to be significant. The duration of deafness prior to CI implantation has been repeatedly found to be strongly and negatively correlated with outcome for postlingually deafened CI users⁵⁻¹¹. A longer duration of untreated deafness can reduce cell survival in the cochlea and affect residual speech processing capabilities. The length of use of the implant is defined as the duration between the surgical implantation and the testing date, which reflects familiarity with the device and hence improved acclimatization. A longer length of use generally has a strong positive effect on outcomes^{6,12-14}. Age at implantation and the age at the onset of deafness have a noteworthy effect in the adult population only after age 60^{6,9}. The effect of age at CI implantation is less strongly correlated with outcomes, although it should be noted that across studies, the definition of “younger” and “older” users is not consistent. Holden et al. 2013⁵ found a significant difference in mean CNC word scores between users less than and more than 65 years of age.

Preimplantation cognitive factors are also thought to affect CI outcomes since they reflect cognitive adaptability of patients. However, these factors have not been routinely studied in CI recipients, and different measures used across studies makes conclusions difficult. The general consensus is that better performance in certain cognitive functions, like visuo-spatial processing tasks and verbal learning measures, is correlated with better word recognition; however, there is no evidence that general intellectual capacity is linked to better outcomes¹⁵⁻¹⁷. The etiology of hearing loss is another important factor that can indicate the degree of neuronal survival, which is thought to directly affect hearing performance. Nadol et al. demonstrated a strong correlation between the causes of hearing loss with preserved spiral ganglion cell count^{18,19}. Patients who have hearing loss due to toxicity or sudden idiopathic deafness likely have more residual nerve cells in the cochlea, and can thus be expected to have a better performance with CIs, compared to patients with labyrinthitis ossificans, congenital, or genetic causes of hearing loss. Blamey et al. 1996⁶ found similar results in terms of poorer performance of patients affected by labyrinthitis, but did not find any direct correlation of surviving ganglion cell numbers and performance. More recently, electrophysiological responses measured either at extracochlear²⁰ or intracochlear²¹ locations have been used as a surrogate for neural survival and/or health, and better outcomes are found to be correlated with better electrophysiological responses.

Recently, studies have shown that the final CI position also has a significant association with hearing outcomes. Specifically, studies have consistently established that a scalar translocation of the array across the basilar membrane from scala tympani (ST) to scala vestibuli (SV) is strongly associated with poorer hearing outcomes.^{5,22–26} Some studies report no correlation between outcomes and positioning of the array in ST,^{27,28} but they agree that small sample sizes might have made it difficult to find a significant correlation. On the other hand, findings conflict regarding depth of insertion of the CI array into the cochlea. While a number of studies^{23,25,29,30} conclude that monosyllabic word scores were positively correlated with insertion depth of the most basal electrode, Khan et al. 2005³¹ and Lee et al. 2010³² did not find any significant correlation of insertion depth. Finley et al. 2008²⁴ and Holden et al. 2013⁵, on the other hand, found a negative correlation of depth with outcomes. Possible reasons for this variability are that the effect differs for straight vs precurved arrays and that the relationship may not be monotonic, i.e., insertions that are too deep and ones that are too shallow both have negative effects on outcomes.

One other factor of electrode positioning that has not been extensively studied is the distance of the electrode array to the modiolus. Until recently, there were no tools available to automatically and accurately measure this distance on a large scale, which explains why this factor has not been included in many studies. Modiolar proximity is expected to lead to improved hearing outcomes since the spiral ganglion cells are housed in the modiolus, and reducing the distance leads to lower charge requirement for upper stimulation levels³³, which can, in turn, reduce spread of excitation and channel interaction³⁴. Holden et al. 2013⁵ measured the modiolar proximity in terms of a unitless “wrapping factor” and concluded that a closely wrapped array, i.e. an array that is positioned closer to the modiolus, leads to significantly higher word recognition scores. On a set of 25 ears with MED-EL (ME) implants, Esquia-Medina et al. 2013²⁸ confirmed that hearing outcomes and average electrode to modiolus proximity were strongly and positively correlated 6 months after implantation. However, this correlation does not hold at 12 months, possibly due to the effects of training and acclimatization in the long term. Further investigation is required to evaluate the role of modiolar distance in affecting hearing outcomes over time.

The objective of our current study is to model the variance in audiological scores as a function of electrode position, specifically modiolar distance, scalar location, and insertion depth. A potential drawback of most of the large sample studies in this field is that they are multicenter studies with inconsistent definitions of similar measures. Our study is based on data curated from a single center (7 full time equivalent audiologists practicing at a single physical site and 7 surgeons who perform cochlear implants at adjacent adult and pediatric hospitals) which has consistent metrics and CI programming techniques. Based on the literature discussed above, we hypothesized a priori that full ST insertion and closer modiolar proximity would be strongly and positively correlated with audiology outcomes.

MATERIALS AND METHODS

Data on 220 CI ears were obtained from an IRB-approved database of adult CI users who underwent post-operative CT scanning. A wide variety of implants, both straight and precurved, are represented in our dataset (see Table 1), from manufacturers Advanced

Bionics (AB) (Valencia, California), Cochlear (CO) (Sydney, New South Wales, Australia) and MED-EL (ME) (Innsbruck, Austria). To segment the cochlear anatomy, we used a non-rigid shape model of intracochlear structures defined using high resolution μ CTs of 10 cochlea specimens. Automated algorithms were used to non-rigidly register the model to new patient CT images to localize intra-cochlear structures with mean errors of approximately 0.2 mm^{35–37}. Since our automated image analysis techniques require normal cochlear anatomy, we ensured that there were no malformed cochleae in our dataset. The CI electrodes were localized on postoperative CTs using automated algorithms as well, with mean localization errors of approximately 0.13 mm^{38,39}. First, a set of candidate points for the electrodes were found in the CT based on intensity and shape features, and then a path joining the most viable candidate points is found representing the electrode array. Rigid coregistration of the preoperative and the postoperative images provided us with the locations of the implanted electrodes with reference to the intracochlear structures. Specifically, we measure one continuous modiolar proximity variable (mean distance from intra-cochlear electrodes to the modiolus), one categorical scalar location variable (whether the implant is fully positioned in the ST with no electrodes in the SV), and two continuous insertion depth variables (angular depth of the tip of the array and depth of the most basal electrode as a linear distance from the opening of the cochlea). These positional measurements relate the post-surgical electrode position to the intracochlear structures and are independent of the actual number of electrodes or inter-electrode spacing of the arrays so that they can be generically applied across array types. These measurements are illustrated in figure 1. Besides positional factors, we also controlled for demographic factors including age at implantation, gender, prelingual onset of deafness, and length of use of the device. Audiological outcome measures used were the CNC monosyllabic word scores, measured in terms of percent correct⁴⁰, and Bamford-Kawal-Bench Sentences in Noise (BKB-SIN) scores⁴¹, measured in terms of the signal-to-noise ratio (SNR) in dB at which sentences could be recognized with 50% accuracy. Speech recognition at lower SNR corresponds to better hearing in noise, and thus a lower BKB-SIN score indicates better performance. The factors are summarized in Table 2. It should be noted that not every patient had both CNC and BKB-SIN scores. As is evident from the numbers in Table 2, only a subset of patient ears used in the CNC model was used in fitting the BKB-SIN model.

To analyze how each of the factors is associated with hearing outcome, stepwise multiple regression was carried out with backward elimination of the weakly correlated factors (Pearson correlation coefficients of all factors with outcomes are listed in Table 3). Since our dataset does not have data for all factors from every patient ear, missing data were excluded at every step of the fitting process based on the factors present in the model at the current step. Factors with p value above the critical p value of 0.15 were eliminated in steps until all remaining factors were below the critical value and resulted in an overall significant model assessed by an F-test ($p < 0.05$). This generalized linear model (GLM) is the simplest linear model that provides the best explanation of the variability of postoperative audiological scores. No interaction terms were included, assuming additivity of all factors. All computations were carried out in MATLAB (Mathworks, Natick, MA USA).

RESULTS

A GLM model was built for CNC word recognition, in percent correct, for precurved arrays using data from a total of 92 patients with CI experience in the range 6 months to 13 years (mean $\pm$ st.dev. = 2.75 ± 2.42 years). The significant factors predictive of better CNC performance in the least-fit GLM were full ST insertion, closer distance of the electrodes to the modiolus, male gender, and shallower base insertion depth (Table 4). For BKB-SIN sentence recognition, available for 85 precurved arrays, we observed similar significant factors – full ST insertion and lower (i.e. closer) average modiolar distance of the array, along with younger age at implantation and postlingual onset of deafness.

For straight arrays, the significant predictors of better CNC word scores for 91 cases that had between 2 months and 16 years of use (mean $\pm$ st.dev. = 2.87 ± 3.57 years) were deeper insertion depth, postlingual onset of deafness, and longer duration of CI experience (Table 5). Better BKB-SIN values (obtained from 89 cases) for straight arrays were significantly modeled by deeper insertion depth, younger age at implantation, and postlingual onset of deafness.

DISCUSSION

Pre-curved (a.k.a. perimodiolar) electrodes:

For precurved arrays, variables associated with higher potential for CNC word recognition include gender (males>females), full ST placement, lower (i.e. closer) average modiolar distance, and deeper insertion depth. BKB-SIN scores were also significantly affected by ST scalar positioning and mean modiolar distance, but not by insertion depth. Although the aim of the implantation is to place the CI array fully into ST, a number of factors — such as electrode design, surgical approach, and patient-specific cochlea shape — can lead to one or more of the electrodes to break through the basilar and Reissner's membranes and pass into SV. Figure 1 shows an example of a full ST placement (c) and a translocation into SV (d). Note that even a direct SV insertion is more traumatic than an ST insertion⁴². In our linear model, we define a CI array as being a “full ST insertion” if no electrodes are located in SV. It has been well established that positioning the electrode array entirely in the ST limits trauma to the intracochlear structures and improves hearing outcomes²⁶. The findings herein corroborate this notion, with an estimated difference of 10.28-percentage points in CNC word scores and 3.25 dB in BKB-SIN SNR-50 scores between a full ST insertion and an insertion with translocation into SV. Of note here is that the 3.25 dB difference for BKB-SIN SNR-50 is clinically significant given that the 95% confidence interval data for this measure places the critical difference at 3.1 dB for adult CI users administered 2 paired lists⁴⁰. Independently, scalar location accounts for 7% and 9% of the variability of the CNC word scores and BKB-SIN scores, respectively (Table 3).

The variability in the outcomes explained by the modiolar distance was 7% for both CNC words and BKB-SIN scores (Table 3). Since precurved arrays are designed to be positioned close to the modiolus, it is intuitive that deviations from this ideal position would significantly affect hearing outcomes. Based on our model estimates, positioning the array by an average of 0.5 mm away from the modiolus can decrease CNC scores by 21.65-

percentage points and BKB-SIN values by 5.75 dB. This agrees with the correlations reported in literature, specifically that reported by Holden et al. 2013.⁵ The other positional factor that has a significant but negative effect is the base insertion depth, with a coefficient of determination of 0.02. This is not entirely surprising because deeper insertions that push the array towards the lateral wall might make modiolar stimulations less effective for precurved arrays. For every 1 mm of additional insertion, the CNC word recognition decreases by 3.49-percentage points.

The other factors which are significant in the models are age at implantation, gender of the patient, and the indicator for prelingual deafness. The BKB-SIN performance in general is poorer with increasing age at implantation by about 1.2 dB for every 10 years of age difference at surgery, while prelingual deafness is associated with 3.84 dB poorer scores with all other factors constant. Our model suggests that CNC values were about 8.5-percentage points better in men than in women, which indicates that there might be some independent factor of electrode placement correlated with gender that we did not control for in the model, e.g., it is well known that male cochleae are larger on average than female cochleae⁴³. Further, since (a) prelingual deafness is found to be significant for straight arrays for both CNC and BKB-SIN scores and BKB-SIN scores for precurved arrays; and (b) there is a significant correlation between gender and prelingual deafness ($|R| = 0.25$, $p < 0.05$) in our dataset; it is possible that the gender variable is actually capturing the effect of prelingual deafness on CNC values for the precurved group. In total, these three demographic factors, along with the descriptors of electrode position, account for 18% of the variability of CNC scores and 26% of the variability of BKB-SIN scores (Table 3).

Implications for pre-curved (a.k.a. perimodiolar) electrodes:

The implications of this GLM are better understood with how expected hearing outcomes change with electrode position. Consider the demographic of postlingually deafened males who were implanted with a precurved array at 35 years of age and have 5 years of CI experience. According to our GLM, if a precurved array was ideally implanted with a full ST insertion, a mean modiolar distance of 0.18 mm, which is 2 standard deviations better than average, and at a base insertion depth of 0 mm, which is two standard deviations shallower than average, the expected CNC score and confidence interval are 82% [66%, 98%] for such patients. In contrast, population average positioning (modiolar distance = 0.48 mm, insertion depth = 2.32 mm) leads to an expected CNC score of 61% [53%, 69%] with a full ST placement or 51% [43%, 59%] with a scalar translocation. Finally, with a poor positioning of a scalar translocation, 0.78 mm mean modiolar distance, which is two standard deviations worse than average, and at a depth of 4.64 mm, which is two standard deviations deeper than average, the expected CNC score is 30% [15%, 45%]. Between an ideal electrode position (full ST insertion) and 0.18 mm modiolar distance to a poor placement of partial ST insertion and 0.78 mm modiolar distance, the expected score changes by over 50-percentage points with no overlap in confidence intervals. *This is a considerable change in predicted outcome, and illustrates the remarkable influence of the surgical process on user experience.*

Lateral wall (a.k.a. straight) electrodes

The positional factor primarily predictive of better expected performance on CNC word tests with straight arrays is greater base insertion depth. It accounts for 10% and 8% of the variability in CNC word scores and BKB-SIN scores, respectively. An insertion that is deeper by 1 standard deviation of our sample, i.e. 2.4 mm, is associated with an improvement of 8.04-percentage points on the CNC score and 1.61 dB on the BKB-SIN score. This agrees with the strong positive correlation between basal insertion depth and audiological outcomes reported previously.^{23,25,29,30}

The significant biographic factors were similar to those found for precurved arrays – better BKB-SIN scores were associated with younger age at implantation and postlingual onset of deafness; and better CNC word scores were associated with longer duration of CI experience and postlingual onset of deafness. The effects of these factors agree with findings in prior studies – experience with the device is associated with better outcomes, while prelingual deafness and later age at implantation are associated with poorer outcomes, independent of electrode position. In total, the positional and demographic factors account for 22% of the variability of both CNC and BKB-SIN scores.

Implications for Lateral wall (a.k.a. straight) electrodes

To understand the impact of electrode position on CNC scores for lateral wall arrays, consider a demographic of postlingually deafened male or female individuals implanted with a straight array at 35 years of age and with 5 years of CI use when the audiological testing occurred. Our model predicts that if the implant was inserted to a depth of -3.4 mm, which is two standard deviations shallower than average, the expected CNC score would be 36% [25%, 47%]. If the array was inserted to a population average 1.42 mm, the expected CNC score would be 52% [46%, 59%]. If the array were inserted further to 6.24 mm, which is two standard deviations deeper than average, the expected score would be 68% [56%, 80%]. Our GLM predicts that deeper insertions are associated with significantly better expected outcomes. However, beyond the range of insertion depths in our dataset, there likely are rapidly diminishing benefits to deeper insertions given the increased likelihood of trauma to the apical walls of the cochlea and failure to achieve proper basal stimulation.²⁴

Implications for surgical procedures

We found using our GLM analysis for 35-year old, male patients with 5 years of CI use that if using a pre-curved electrode array, the expected outcome as a function of excellent, average with full ST positioning, average with scalar translocation, and poor electrode position are CNC scores of 82%, 61%, 51%, and 30% for mean $\pm$ 2 st. dev. in electrode positioning. On the other hand, the expected outcome when using a straight electrode array as a function of deep, average, and shallow electrode depth are CNC scores of 68%, 52%, and 36% for mean $\pm$ 2 st. dev. in electrode base insertion depth. What is the clinical impact of these predictions? For straight arrays, the likely cause for shallow insertions in our retrospective dataset is that the surgeon perceived resistance and wisely chose to stop the insertion procedure without further advancement to avoid potentially causing additional intra-cochlear trauma. This retrospective study does not show that further advancement of the array in such cases where resistance is felt would result in improved outcomes, and it is

quite possible to have the opposite effect due to increased intra-cochlear trauma. Similarly, it is also possible that the deeper insertions in our dataset were obtained when resistance was never perceived and less trauma occurred, in which case the direct cause for better outcomes could be reduced trauma, rather than increased depth. In this context, we can conclude that any advances to surgical techniques and array devices that permit deeper atraumatic insertion of the array should lead to improved outcomes. This could include techniques for patient customized selection of arrays that are appropriately sized for the patient's cochlea⁴⁴. For pre-curved arrays, advances to surgical technique and devices that permit reducing scalar translocations and obtaining more perimodiolar positioning of the array should lead to improved outcomes. For example, techniques for patient-customized electrode insertion procedure planning have shown promise for improving the modiolar positioning and scalar location of pre-curved arrays.^{45,46}

Limitations

Limitations of the current study include the demographic factors that were not modeled, including length of deafness, daily CI wear time, etiology, and cognitive factors, which will be explored in future work. As more data is collected, it will be possible in future analyses to further categorize results according to device type, as it is well known that cochlear implant design has an important impact on outcomes. After controlling for base insertion depth, tip insertion depth isn't a significant predictor of outcomes; however, the two are highly correlated. It is also of note that the relationship between insertion depth and outcomes is likely not monotonic. If the insertion is too shallow the outcomes are poor due to extracochlear electrodes and lack of low frequency stimulation; too deep and trauma could outweigh the benefits of a more complete frequency map. Supplemental online data from Rivas and Cakir et al.⁴⁴ with MedEl arrays show a trend of increasing outcomes with increased insertion depth for arrays inserted up to around 500 degrees, and beyond that point outcomes no longer improve with increasing depth. Thus, the use of linear modeling to capture this relationship is likely sub-optimal. Another potential confound for insertion depth due to the retrospective nature of our dataset is that it is likely that most shallow insertions in our dataset occurred because the surgeon perceived resistance and deliberately concluded the insertion procedure at a shallow depth. The perception of resistance suggests trauma could have occurred, which could impact hearing outcomes.

CONCLUSIONS

Our results using 220 patient ears confirm the significant association between electrode positioning and audiological outcomes. Controlling for biographic factors like age at implantation, gender of patient, linguistic capabilities at the onset of deafness, and length of device use, the most significant predictors of outcome for precurved arrays were full ST insertion and the modiolar distance, while for the lateral wall arrays the depth of insertion was the most significant factor. We demonstrate how to use our linear model to determine the expected hearing outcome as a function of patient demographics and electrode position. A comprehensive knowledge of how each of these positional factors affects hearing outcomes for different demographics is critical in guiding patient counseling. These data also hold implications for future electrode design and support the importance of

development of improved methods for patient-customized surgical planning and guidance techniques^{45,46} and post-operative mapping techniques.^{47–49}

Acknowledgments

Funding: This work was supported in part by grants R01DC014462, R01DC008408, and R01DC014037, from the National Institute for Deafness and Communication Disorders and by grant UL1TR000445 from the National Center for Advancing Translational Sciences. The content is solely the responsibility of the authors and does not necessarily represent the official views of these institutes.

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Fig 1.

(a) Perimodiolar-positioned, pre-curved array and (b) lateral wall-positioned, straight array. Tip insertion depth of the array is measured in angle around the mid-modiolar axis to the most distal contact and is 365° in (a) and 358° in (b). In (c) and (d), examples of (c) full ST positioning and (d) scalar translocation of a CI array are shown. The structure in red is the scala tympani, and the structure in blue is the scala vestibuli. In (c), the array is completely positioned in the scala tympani. In (d), the apical part of the array has translocated into the scala vestibuli, which causes trauma to the intracochlear structures.

Table 1:

Straight and precurved Arrays included in the study

Manufacturer	Total arrays	Straight arrays	Precurved arrays
AB	50	Hifocus 1J (29)	MidScala (21)
CO	120	CO-422 (20), CO-ST (11)	Contour Advance (89)
ME	50	ME-24 (3), ME-28 (22), ME-MD (1), ME-ST (24)	--

Table 2:

Summary of factors included in each GLM. For numeric variables, ranges are shown in square brackets followed by mean $\pm$ 1 standard deviation

	Precurved Arrays		Straight Arrays	
	CNC words (%), N = 92	BKB-SIN (dB), N = 85	CNC Words (%), N = 91	BKB-SIN (dB), N = 89
Scores	[0, 98] 52.41 $\pm$ 24.97	[2.5, 23.5] 13.51 $\pm$ 6.05	[0, 100] 43.81 $\pm$ 25.49	[1.5, 23.5] 14.79 $\pm$ 5.62
Full scala tympani insertion	47 fully in ST, 45 partly or wholly in SV	42 fully in ST, 43 partly or wholly in SV	77 fully in ST, 11 partly or wholly in SV	72 fully in ST, 11 partly or wholly in SV
Mean modiolar distance (mm)	[0.16, 0.92] 0.48 $\pm$ 0.15	[0.16, 0.82] 0.47 $\pm$ 0.15	[0.44, 1.63] 1.16 $\pm$ 0.16	[0.44, 1.63] 1.16 $\pm$ 0.16
Base insertion depth (mm)	[−3.01, 6.30] 2.32 $\pm$ 1.16	[−3.01, 4.25] 2.26 $\pm$ 1.06	[−9.57, 4.60] 1.42 $\pm$ 2.41	[−9.57, 4.60] 1.36 $\pm$ 2.43
Tip insertion depth (degrees)	[115, 679] 376.4 $\pm$ 68.2	[115, 584] 371.4 $\pm$ 61.7	[217, 717] 453.9 $\pm$ 128.3	[217, 717] 454.3 $\pm$ 129.9
Age at implantation (yrs)	[12, 89] 57.1 $\pm$ 16.9	[12, 89] 57.9 $\pm$ 16.9	[7, 86] 56.1 $\pm$ 18.0	[7, 86] 56.0 $\pm$ 18.0
Gender	52 Males, 40 Females	50 Males, 35 Females	53 Males, 38 Females	51 Males, 38 Females
Prelingually deafened	13 Prelingually Deafened, 79 Postlingually Deafened	13 Prelingually Deafened, 72 Postlingually Deafened	18 Prelingually Deafened, 73 Postlingually Deafened	18 Prelingually Deafened, 71 Postlingually Deafened
Length of CI use (yrs)	[0.53, 12.92] 2.75 $\pm$ 2.42	[0.53, 12.92] 2.8 $\pm$ 2.5	[0.18, 16.55] 2.9 $\pm$ 3.6	[0.18, 16.55] 2.9 $\pm$ 3.6

Table 3:

Pearson correlation coefficients between factors and audiological scores. Numbers in bold indicate factors that are significant in GLM.

	Precurved Arrays				Straight Arrays			
	CNC words (N = 92)		BKB-SIN (N = 85)		CNC Words (N = 91)		BKB-SIN (N = 89)	
	R	p	R	p	R	p	R	p
Full scala tympani insertion	0.27	0.009	-0.30	0.004	-0.02	0.854	0.03	0.752
Mean modiolar distance	-0.27	0.006	0.27	0.008	0.15	0.140	-0.07	0.472
Base insertion depth	-0.14	0.178	0.01	0.926	0.31	0.002	-0.28	0.007
Tip insertion depth	0.08	0.450	-0.11	0.301	0.19	0.073	-0.12	0.241
Age at implantation	-0.22	0.022	0.29	0.004	-0.06	0.566	0.12	0.227
Gender	-0.09	0.361	0.12	0.231	-0.09	0.335	0.09	0.345
Prelingually deafened	-0.04	0.659	0.00	0.988	-0.26	0.005	0.24	0.014
Length of CI use	0.26	0.006	-0.19	0.053	0.12	0.231	-0.03	0.778
GLM	0.43	< 0.001	0.51	< 0.001	0.47	< 0.001	0.47	< 0.001

Table 4:

Model specifications for precurved arrays. Any ‘-’ indicates that the factor was not significant in the final GLM for the respective outcome measure.

	Precurved Arrays			
	CNC words (N = 92)		BKB-SIN (N = 85)	
	Estimate	<i>p</i>	Estimate	<i>p</i>
Intercept	79.58 %	< 0.001	2.04 dB	0.523
Full Scala Tympani Insertion	10.28 %	0.041	-3.25 dB	0.006
Gender	-8.49 %	0.088	-	-
Age At Implantation	-	-	0.12 dB/year	0.001
Prelingually Deafened	-	-	3.84 dB	0.031
Mean Modiolar Distance	-43.30 %/mm	0.008	11.50 dB/mm	0.005
Base Insertion Depth	-3.49 %/mm	0.107	-	-
F statistic vs constant model	F = 4.8, <i>p</i> = 0.002		F = 8.41, <i>p</i> < 0.001	

Table 5:

Model specifications for straight arrays. Any ‘-’ indicates that the factor was not significant in the final GLM for the respective outcome measure.

	Straight Arrays			
	CNC Words (N = 91)		BKB-SIN (N = 89)	
	Estimate	<i>p</i>	Estimate	<i>p</i>
Intercept	38.66 %	< 0.001	8.77dB	< 0.001
Age At Implantation	-	-	0.10 dB/year	0.003
Prelingually Deafened	-23.17 %	< 0.001	5.37 dB	0.001
Length of CI Use	1.73 %/year	0.018	-	-
Base Insertion Depth	3.35 %/mm	0.001	-0.67 dB/mm	0.004
F statistic vs constant model	F = 7.12, <i>p</i> < 0.001		F = 7.82, <i>p</i> < 0.001	