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Insertion Depth and Cochlear Implant Speech Recognition Outcomes: A Comparative Study of 28- and 31.5-mm Lateral Wall Arrays

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Abstract

Objectives: 1) To compare speech recognition outcomes between cochlear implant (CI) recipients of 28- and 31.5-mm lateral wall electrode arrays, and 2) to characterize the relationship between angular insertion depth (AID) and speech recognition.

Study Design: Retrospective review.

Setting: Tertiary academic referral center.

Patients: Seventy-five adult CI recipients of fully inserted 28-mm (n=28) or 31.5-mm (n=47) lateral wall arrays listening with a CI-alone device.

Interventions: Cochlear implantation with postoperative computed tomography.

Main Outcome Measures: Consonant-nucleus-consonant (CNC) word recognition assessed with the CI-alone at 12 months post-activation.

Results: The mean AID of the most apical electrode contact for the 31.5-mm array recipients was significantly deeper than the 28-mm array recipients (628° vs 571°, $p < 0.001$). Following 12 months of listening experience, mean CNC word scores were significantly better for recipients of 31.5-mm arrays compared with those implanted with 28-mm arrays (59.5% vs 48.3%, $p = 0.004$; Cohen's $d = 0.70$; 95% CI [0.22, 1.18]). There was a significant positive correlation between AID and CNC word scores (r=0.372, p=0.001), with a plateau in performance observed around 600°.

Conclusions: Cochlear implant recipients implanted with a 31.5-mm array experienced better speech recognition than those with a 28-mm array at 12 months post-activation. Deeper insertion of a lateral wall array appears to confer speech recognition benefit up to ~600°, with a plateau in performance observed thereafter. These data provide preliminary evidence of the insertion

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MWC, MTD, and BPO designed experiments. Implanting surgeons were HCP, KDB, MMD and BPO. MWC, MTD, and BPO wrote the paper, and all authors contributed significantly to analysis and revisions leading to its final form.

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depth necessary to optimize speech recognition outcomes for lateral wall electrode arrays among CI-alone users.

INTRODUCTION

Substantial variability in speech recognition performance among cochlear implant (CI) recipients can be attributed to factors influencing the status and auditory processing abilities at the peripheral and central levels (1–5). With regard to peripheral factors, prior studies have largely focused on the relationship between variables associated with electrode array location and speech recognition performance; these variables include but are not limited to angular insertion depth (AID) (6–10), modiolar proximity (1,11,12), and scalar location (1,13–16). The impact of insertion depth on speech recognition remains controversial, in part because any potential benefit of a deeper insertion must be balanced with increased risk of trauma to the cochlear apex. Further, insertion depth is of considerable interest to surgeons when selecting an array from options that differ in design and length, as it remains an easily modifiable variable when compared to other factors (e.g., scalar location and modiolar proximity) that are more challenging to control.

Previous studies investigating the influence of electrode array insertion depth on speech recognition are conflicting, with some demonstrating a decrement in performance with deeper insertions (1,4,13), and others showing a benefit (6–9,15,17,18). Importantly, recent work has established that there are likely differential effects dependent on array design (i.e., lateral wall vs pre-curved) (10,11). When restricting this analysis to lateral wall arrays, studies have shown a positive correlation between AID and speech recognition (6–10,15,18). This is generally understood to be related to beneficial effects of a closer alignment between the electric speech information and tonotopic organization of the cochlea (18–24), in addition to distributing speech information across greater channel spacing – theoretically allowing for excitation of discrete neuronal populations (e.g., reduced channel interaction) (18).

In a prospective trial that investigated the effect of insertion depth on speech recognition, Buchman et al. (8) demonstrated a trend for better performance among 31.5-mm array recipients when compared to those implanted with a 24-mm array. Though enrollment was halted due to an interim analysis demonstrating superior performance for recipients of longer arrays, this study provided some evidence to suggest the benefit of a deeper insertion of a lateral wall array for speech recognition. In a long-term follow-up of this cohort, the benefit conferred by a long array continued to persist following years of CI listening experience (25).

Other studies have similarly demonstrated that deeper insertions confer speech recognition benefit among lateral wall array recipients, but the correlations that support these data are arguably driven by the cohort of relatively shallow insertions that consistently performs poorly (18). While these data provide reason to prefer a 31.5-mm electrode array over a 24-mm array for conventional CI recipients without residual hearing, the ideal insertion depth required to achieve optimal performance still remains incompletely characterized. The relationship between AID and speech recognition performance is likely non-linear, such that at a certain depth the risks of apical trauma (26) and reduced spatial selectivity in the apex (27–29) may either negate or outweigh the benefit of closer tonotopic alignment and reduced channel interaction with a deep insertion of a long lateral wall array. Given this, the purpose of the present study was twofold: The first aim was to compare speech recognition between CI recipients of longer (28 mm and 31.5 mm) electrode arrays, which should have substantial variability yet some overlap in AID between groups (18), while controlling for other variables known to affect outcomes (e.g., age at implantation (1,3,30–34), preoperative unaided hearing detection thresholds (35–37), and duration of hearing loss (3–5,38,39)). The second aim was to characterize the relationship between AID and speech recognition among longer lateral wall array recipients, with the goal of better understanding the insertion depth required to optimize performance.

MATERIALS AND METHODS

Subjects

The study-site Institutional Review Board approved the retrospective review of post-lingually deafened adult CI recipients that underwent postoperative cone-beam CT of the temporal bone. Subjects that underwent unilateral implantation with a MED-EL GmbH (Innsbruck, Austria) Flex28 (array length = 28 mm; active stimulation range = 23.1 mm; contact number = 12; electrode contact spacing = 2.1 mm) or FlexSOFT/Standard electrode array (array length = 31.5 mm; active stimulation range = 26.4 mm; contact number = 12; electrode contact spacing = 2.4 mm) were eligible for inclusion. FlexSOFT and Standard electrode array recipients were treated as one group, as both arrays have the same noted specifications for length, active stimulation range, and electrode contact spacing. The Flex28 array was typically selected for CI candidates with better preoperative unaided low-frequency hearing detection thresholds. During the study period, cochlear duct length was not considered in the array selection process. Subjects with evidence of cochlear malformation, partial insertion (defined as at least 1 electrode contact extracochlear on review of postoperative imaging), listening with an electric-acoustic stimulation (EAS) device, or less than 1 year of follow-up were excluded from the analysis.

Postoperative Imaging Analysis

The postoperative temporal bone cone-beam CT obtained for each subject was reviewed using OTOPLAN, an otologic imaging software developed by CAScination AG (Bern, Switzerland) in collaboration with MED-EL GmbH, as previously described (40). Following identification of the center of the round window and mid-modiolar axis in the user-defined cochlear view (41), AID was determined for the most apical electrode contact.

Postoperative Speech Recognition

Aided speech recognition, as measured by consonant-nucleus-consonant (CNC) words (42), was assessed in a sound-treated booth with the listener seated approximately 1 meter from the sound source at 0° azimuth. Recorded materials were presented at 60 dB SPL. Each subject was tested with the CI-alone in their familiar, everyday map. Masking was presented to the contralateral ear via an insert earphone when warranted to isolate the input to the CI-ear. The present analysis used the scores obtained at the 12-month post-activation interval.

Statistical Analysis

The D'Agostino-Pearson omnibus test was used to evaluate normality for continuous variables. Normally distributed data are reported as means ± standard deviations and non-parametric data are reported as medians (interquartile ranges). To compare variables between 28-mm and 31.5-mm array recipients, an independent t-test and Mann-Whitney *U* test was used for normally distributed and non-parametric data, respectively. Effect size was calculated using Cohen's *d*, with an effect size of 0.2 to 0.49 considered small, 0.5 to 0.79 medium, 0.8 to 1.29 large, and greater than 1.3 being very large (43). Comparisons between categorical variables (i.e., gender and side of implantation) were evaluated with χ^2 analysis. Pearson correlation was used to assess the relationship between AID and speech recognition. Statistical analyses were performed with SPSS version 26 (IBM Corp, Armonk, New York). All tests were two-tailed, and statistical significance was defined as $\alpha < 0.05$.

RESULTS

Demographics

Demographics for 75 CI recipients that met inclusion criteria are shown in Table 1. Of the subjects included, 28 were implanted with a 28-mm array and 47 with a 31.5-mm array. Three subjects with an incomplete insertion (28 mm, $n = 1$; 31.5 mm, $n = 2$), defined as at least 1 electrode contact being extracochlear on postoperative imaging, were excluded. The median age at implantation for the entire group was 64.3 years (interquartile range [IQR], 56.6 – 73.5 years), with no significant difference in age between groups ($p = 0.824$). There were no significant differences between groups for gender ($p = 0.881$), side of implantation ($p = 0.294$), preoperative pure-tone average (PTA; 500, 1000, and 2000 Hz) ($p = 0.490$), or duration of hearing loss ($p = 0.430$). As expected, subjects implanted with a 28-mm array had significantly better preoperative low-frequency pure-tone average (LFPTA; 250 and 500 Hz) ($p = 0.006$)

Angular Insertion Depth

Figure 1 plots AID of the most apical electrode contact for individual subjects by array. The AID across the entire cohort ranged from 443° to 738°, with a mean of 607° ± 58.1°. The mean AID of the most apical electrode contact for 31.5-mm array recipients (628°) was significantly deeper than 28-mm array recipients (571°; $t_{(73)} = 4.64$, $p < 0.001$)

Speech Recognition

The median aided preoperative speech recognition, as measured by CNC words, was similar between 28-mm and 31.5-mm array recipients (4.0% vs 4.0%, $p = 0.336$). Figure 2 plots postoperative performance on CNC words in quiet at the 12-month post-activation interval for each group. At the group level, mean performance was significantly better for 31.5-mm array recipients (59.5%) compared to 28-mm array recipients (48.3%; $t_{(73)} = 2.95$, $p = 0.004$, Cohen's $d = 0.70$; 95% CI [0.22, 1.18]).

Relationship Between Insertion Depth and Speech Recognition

Given the variability in AID (Fig. 1) and post-activation performance (Fig. 2), we sought to analyze the relationship between AID and speech recognition. Figure 3 plots CNC word scores as a function of AID. For all subjects, there was a positive correlation between AID and CNC word scores ($r = 0.372$, $p = 0.001$) at 12 months post-activation. This pattern of significance remained unchanged for partial correlations between CNC and AID while controlling for age at implantation, preoperative PTA, preoperative LFPTA, or duration of hearing loss ($p \leq 0.003$). When analyzed separately by array length, a positive correlation remained for 28-mm array recipients ($r = 0.496$, $p = 0.007$) but not 31.5-mm array recipients ($r = 0.026$, $p = 0.862$), raising the possibility that performance plateaus beyond a certain AID. To investigate this, a binned analysis was carried out to approximate the insertion depth at which performance may plateau. Figure 4 plots a histogram of AID across subjects with mean CNC word scores for each bin. The left y-axis and grey bars indicate the number of subjects in each bin. The right y-axis and black circles with error bars indicate the mean CNC word scores with standard deviations for each bin. These results suggest that there is an improvement in speech recognition up to ~600°, with benefit remaining stable for deeper insertion depths.

DISCUSSION

Despite considerable advances in the field of cochlear implantation, speech recognition outcomes remain highly variable (1–5). Several previous studies have shown that the spatial positioning of the electrode array can account for a portion of this variability (6,15,44,45), and more specifically, a positive linear correlation has been demonstrated between AID and speech recognition among CI recipients of lateral wall electrode arrays (6,7). In a prospective trial, Buchman et al. (8) reported better word recognition in quiet and sentence recognition in noise for CI recipients of a 31.5-mm array as compared to those implanted with a 24-mm array. Though these results imply benefit with a deeper insertion of a lateral wall electrode array, it has been hypothesized that linear modeling may not capture the true relationship between AID and speech recognition, as performance may either plateau or even decline beyond a certain insertion depth (11). The present study sought to build upon the aforementioned literature to evaluate whether there is an optimal insertion depth for lateral wall array recipients listening in the CI-alone condition, and demonstrated that 1) on average, 31.5-mm array recipients experience better word recognition in quiet than those implanted with a 28-mm array, and 2) performance generally improves with increasing insertion depth and appears to plateau around 600°.

In contrast to the present findings, Rivas et al. (46) examined the relationship between AID and CNC word scores among 16 CI recipients of a 28-mm array and demonstrated a plateau in performance beyond 450°. By also analyzing data from recipients of 31.5-mm arrays and expanding the sample size ($n = 75$), we identified a deeper insertion depth at which CNC word scores plateau. The findings herein have important clinical implications in that it generally requires a 31.5-mm array to consistently achieve an insertion depth of ~600° (Fig. 1), which is further demonstrated by better mean performance among recipients of a 31.5-mm array in comparison to those implanted with a 28-mm array (Fig. 2).

These findings have additional relevance in the preoperative consideration of cochlear morphology when choosing the optimal array length for CI candidates. Specifically, measurement of cochlear duct length preoperatively will allow for identification of patients with relatively smaller cochlea. In cases destined for the CI-alone condition, the optimal array may not be the longest array available, but rather one that will reach but not extend much beyond the 600° region. Continued analysis of these data, from both our center and others, will be important as increasing interest is being given to preoperative electrode array selection based on patient specific cochlear morphology.

While the present dataset offers interesting insight into the benefits of a deeper insertion, it raises several questions that remain unanswered. Theoretically, the mechanism of speech recognition benefit conferred with a deeper insertion of a longer lateral wall array may be attributed to 1) a closer alignment between default electric frequency filters and the tonotopic place of stimulation (i.e., reduced frequency-to-place mismatch) (18,19) and 2) greater spatial separation between adjacent electrode contacts, which could improve spectral resolution (18). Given that the human spiral ganglion has been shown to extend to 630–720° (47,48), speech recognition might be expected to continue to improve beyond 600° in consideration of the described mechanisms. Perhaps the observed plateau supports more recent data using synchrotron radiation phase-contrast imaging to suggest that the spiral ganglion may have greater apical compression and not extend as far as previously demonstrated (49). If this is the case, spatial selectivity in the apex may be limited due to the spiral ganglion morphology in the second cochlear turn (27–29). The true frequency map of the human cochlea remains an active area of investigation; however, the present results may provide some support for the more recent frequency map described with synchrotron imaging (49,50).

The present findings could also be interpreted in light of prior literature highlighting the role of neural plasticity in adapting to frequency-to-place mismatch associated with shallower insertion depths. Prior CI-alone simulation studies have demonstrated tolerance to spectral shifts of up to 3 mm (20,22,51). With regard to pitch perception, Reiss et al. (52) demonstrated that CI users may be able to adapt to spectral shifts as large as 3 octaves. However, there is likely a limit to plasticity, with some users experiencing incomplete adaptation, even following extensive listening experience (53–57). Our results could suggest that while CI users may be able to tolerate a certain degree of frequency-to-place mismatch, it likely continues to limit speech recognition outcomes after 1 year of device use.

Another possible explanation for these findings is that at a certain insertion depth detrimental effects related to not only reduced spatial selectivity in the apex (27–29) but also increased risk of apical trauma (26) may either negate or outweigh benefits gained with a deeper insertion. Interestingly, we did not observe a decline in performance for the range of AIDs in the present sample, and although anecdotal, the subject with the deepest insertion (738°) had an above average speech recognition score (68% vs 55.3%). Ultimately, this highlights our incomplete understanding of beneficial and/or detrimental effects of apical stimulation and the need for future research.

There are limitations of this study that deserve mention. The retrospective design and electrode array selection bias contributed to unequal sample sizes between the 28- and 31.5-mm groups. As such, a prospective evaluation is warranted to confirm these findings. Additionally, electric frequency filters were not controlled, and prospective studies evaluating the effects of matching frequency filters to the tonotopic place of stimulation are currently underway (58). Lastly, further studies are needed to elucidate the actual mechanism contributing to the observed non-linear speech recognition benefit with increasing insertion depth.

CONCLUSIONS

The present study examined speech recognition outcomes between 28-mm and 31.5-mm lateral wall array recipients and the relationship between AID and postoperative performance. Following 12 months of CI listening experience, mean word recognition scores in quiet were significantly better among 31.5-mm array recipients when compared to those implanted with a 28-mm array. Deeper insertion of a lateral wall array conferred speech recognition benefit up to ~600°, with a plateau observed thereafter. Future studies are needed to fully elucidate the mechanisms behind these findings.

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REFERENCES

1. 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. [PubMed: 23348845]
2. Blamey P, Arndt P, Bergeron F et al. Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants. Audiol Neurootol 1996;1:293–306. [PubMed: 9390810]
3. Blamey P, Artieres F, Baskent D et al. Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants: an update with 2251 patients. Audiol Neurootol 2013;18:36–47. [PubMed: 23095305]
4. Lazard DS, Vincent C, Venail F et al. Pre-, per- and postoperative factors affecting performance of postlinguistically deaf adults using cochlear implants: a new conceptual model over time. PLoS One 2012;7:e48739. [PubMed: 23152797]
5. Gantz BJ, Woodworth GG, Knutson JF et al. Multivariate predictors of audiological success with multichannel cochlear implants. Ann Otol Rhinol Laryngol 1993;102:909–16. [PubMed: 8285510]
6. O'Connell BP, Hunter JB, Haynes DS et al. Insertion depth impacts speech perception and hearing preservation for lateral wall electrodes. Laryngoscope 2017;127:2352–7. [PubMed: 28304096]
7. Morrel WG, Holder JT, Dawant BM et al. Effect of Scala Tympani Height on Insertion Depth of Straight Cochlear Implant Electrodes. Otolaryngol Head Neck Surg 2020;162:718–24. [PubMed: 32093543]
8. Buchman CA, Dillon MT, King ER et al. Influence of cochlear implant insertion depth on performance: a prospective randomized trial. Otol Neurotol 2014;35:1773–9. [PubMed: 25122601]
9. Hochmair I, Arnold W, Nopp P et al. Deep electrode insertion in cochlear implants: apical morphology, electrodes and speech perception results. Acta Otolaryngol 2003;123:612–7. [PubMed: 12875584]

10. Canfarotta MW, O'Connell BP, Giardina CK et al. Relationship Between Electrocochleography, Angular Insertion Depth, and Cochlear Implant Speech Perception Outcomes. Ear Hear 2021;42:941–8. [PubMed: 33369942]
11. Chakravorti S, Noble JH, Gifford RH et al. Further Evidence of the Relationship Between Cochlear Implant Electrode Positioning and Hearing Outcomes. Otol Neurotol 2019;40:617–24. [PubMed: 31083083]
12. Esquia Medina GN, Borel S, Nguyen Y et al. Is electrode-modiolus distance a prognostic factor for hearing performances after cochlear implant surgery? Audiol Neurootol 2013;18:406–13. [PubMed: 24157488]
13. 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. [PubMed: 18667935]
14. 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. [PubMed: 17542465]
15. O'Connell BP, Cakir A, Hunter JB et al. Electrode Location and Angular Insertion Depth Are Predictors of Audiologic Outcomes in Cochlear Implantation. Otol Neurotol 2016;37:1016–23. [PubMed: 27348391]
16. Aschendorff A, Kromeier J, Klenzner T et al. Quality control after insertion of the nucleus contour and contour advance electrode in adults. Ear Hear 2007;28:75S–9S. [PubMed: 17496653]
17. Yukawa K, Cohen L, Blamey P et al. Effects of insertion depth of cochlear implant electrodes upon speech perception. Audiol Neurootol 2004;9:163–72. [PubMed: 15084821]
18. Canfarotta MW, Dillon MT, Buss E et al. Frequency-to-Place Mismatch: Characterizing Variability and the Influence on Speech Perception Outcomes in Cochlear Implant Recipients. Ear Hear 2020;41:1349–61. [PubMed: 32205726]
19. Landsberger DM, Svrakic M, Roland JT Jr. et al. The Relationship Between Insertion Angles, Default Frequency Allocations, and Spiral Ganglion Place Pitch in Cochlear Implants. Ear Hear 2015;36:e207–13. [PubMed: 25860624]
20. Dorman MF, Loizou PC, Rainey D. Simulating the effect of cochlear-implant electrode insertion depth on speech understanding. J Acoust Soc Am 1997;102:2993–6. [PubMed: 9373986]
21. Fu QJ, Shannon RV. Effects of electrode location and spacing on phoneme recognition with the Nucleus-22 cochlear implant. Ear Hear 1999;20:321–31. [PubMed: 10466568]
22. Li T, Fu QJ. Effects of spectral shifting on speech perception in noise. Hear Res 2010;270:81–8. [PubMed: 20868733]
23. Baskent D, Shannon RV. Speech recognition under conditions of frequency-place compression and expansion. J Acoust Soc Am 2003;113:2064–76. [PubMed: 12703717]
24. Baskent D, Shannon RV. Interactions between cochlear implant electrode insertion depth and frequency-place mapping. J Acoust Soc Am 2005;117:1405–16. [PubMed: 15807028]
25. Canfarotta MW, Dillon MT, Buchman CA et al. Long-Term Influence of Electrode Array Length on Speech Recognition in Cochlear Implant Users. Laryngoscope 2021;131:892–7. [PubMed: 32738069]
26. Adunka O, Kiefer J. Impact of electrode insertion depth on intracochlear trauma. Otolaryngol Head Neck Surg 2006;135:374–82. [PubMed: 16949967]
27. Landsberger DM, Mertens G, Punte AK et al. Perceptual changes in place of stimulation with long cochlear implant electrode arrays. J Acoust Soc Am 2014;135:EL75–81. [PubMed: 25234918]
28. Kalkman RK, Briaire JJ, Dekker DM et al. Place pitch versus electrode location in a realistic computational model of the implanted human cochlea. Hear Res 2014;315:10–24. [PubMed: 24975087]
29. Arnoldner C, Riss D, Baumgartner WD et al. Cochlear implant channel separation and its influence on speech perception--implications for a new electrode design. Audiol Neurootol 2007;12:313–24. [PubMed: 17536200]
30. Murr AT, Canfarotta MW, O'Connell BP et al. Speech Recognition as a Function of Age and Listening Experience in Adult Cochlear Implant Users. Laryngoscope 2021.
31. Roberts DS, Lin HW, Herrmann BS et al. Differential cochlear implant outcomes in older adults. Laryngoscope 2013;123:1952–6. [PubMed: 23737286]

32. Sladen DP, Zappler A. Older and younger adult cochlear implant users: speech recognition in quiet and noise, quality of life, and music perception. Am J Audiol 2015;24:31–9. [PubMed: 25239296]
33. Beyea JA, McMullen KP, Harris MS et al. Cochlear Implants in Adults: Effects of Age and Duration of Deafness on Speech Recognition. Otol Neurotol 2016;37:1238–45. [PubMed: 27466894]
34. Lin FR, Chien WW, Li L et al. Cochlear implantation in older adults. Medicine (Baltimore) 2012;91:229–41. [PubMed: 22932787]
35. Francis HW, Yeagle JD, Bowditch S et al. Cochlear implant outcome is not influenced by the choice of ear. Ear Hear 2005;26:7S–16S. [PubMed: 16082263]
36. Holden LK, Firszt JB, Reeder RM et al. Factors Affecting Outcomes in Cochlear Implant Recipients Implanted With a Perimodiolar Electrode Array Located in Scala Tympani. Otol Neurotol 2016;37:1662–8. [PubMed: 27755365]
37. Fabie JE, Keller RG, Hatch JL et al. Evaluation of Outcome Variability Associated With Lateral Wall, Mid-scalar, and Perimodiolar Electrode Arrays When Controlling for Preoperative Patient Characteristics. Otol Neurotol 2018;39:1122–8. [PubMed: 30106854]
38. Green KM, Bhatt Y, Mawman DJ et al. Predictors of audiological outcome following cochlear implantation in adults. Cochlear Implants Int 2007;8:1–11. [PubMed: 17479968]
39. Rubinstein JT, Parkinson WS, Tyler RS et al. Residual speech recognition and cochlear implant performance: effects of implantation criteria. Am J Otol 1999;20:445–52. [PubMed: 10431885]
40. Canfarotta MW, Dillon MT, Buss E et al. Validating a New Tablet-based Tool in the Determination of Cochlear Implant Angular Insertion Depth. Otol Neurotol 2019;40:1006–10. [PubMed: 31290802]
41. 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. [PubMed: 20147866]
42. Peterson GE, Lehiste I. Revised CNC lists for auditory tests. J Speech Hear Disord 1962;27:62–70. [PubMed: 14485785]
43. Sullivan GM, Feinn R. Using Effect Size-or Why the P Value Is Not Enough. J Grad Med Educ 2012;4:279–82. [PubMed: 23997866]
44. O'Connell BP, Hunter JB, Wanna GB. The importance of electrode location in cochlear implantation. Laryngoscope Investig Otolaryngol 2016;1:169–74.
45. Buchner A, Illg A, Majdani O et al. Investigation of the effect of cochlear implant electrode length on speech comprehension in quiet and noise compared with the results with users of electro-acoustic-stimulation, a retrospective analysis. PLoS One 2017;12:e0174900. [PubMed: 28505158]
46. Rivas A, Cakir A, Hunter JB et al. Automatic Cochlear Duct Length Estimation for Selection of Cochlear Implant Electrode Arrays. Otol Neurotol 2017;38:339–46. [PubMed: 28146009]
47. Stakhovskaya O, Sridhar D, Bonham BH et al. Frequency map for the human cochlear spiral ganglion: implications for cochlear implants. J Assoc Res Otolaryngol 2007;8:220–33. [PubMed: 17318276]
48. Dhanasingh AE, Rajan G, van de Heyning P. Presence of the spiral ganglion cell bodies beyond the basal turn of the human cochlea. Cochlear Implants Int 2020;21:145–52. [PubMed: 31771498]
49. Li H, Schart-Moren N, Rohani SA et al. Synchrotron Radiation-Based Reconstruction of the Human Spiral Ganglion: Implications for Cochlear Implantation. Ear Hear 2020;41:173–81. [PubMed: 31008733]
50. Li H, Helpard L, Ekeroot J et al. Three-dimensional tonotopic mapping of the human cochlea based on synchrotron radiation phase-contrast imaging. Sci Rep 2021;11:4437. [PubMed: 33627724]
51. Shannon RV, Zeng FG, Wygonski J. Speech recognition with altered spectral distribution of envelope cues. J Acoust Soc Am 1998;104:2467–76. [PubMed: 10491708]
52. Reiss LA, Turner CW, Erenberg SR et al. Changes in pitch with a cochlear implant over time. J Assoc Res Otolaryngol 2007;8:241–57. [PubMed: 17347777]

53. Reiss LA, Turner CW, Karsten SA et al. Plasticity in human pitch perception induced by tonotopically mismatched electro-acoustic stimulation. Neuroscience 2014;256:43–52. [PubMed: 24157931]
54. Sagi E, Fu QJ, Galvin JJ 3rd et al. A model of incomplete adaptation to a severely shifted frequency-to-electrode mapping by cochlear implant users. J Assoc Res Otolaryngol 2010;11:69–78. [PubMed: 19774412]
55. Svirsky MA, Silveira A, Neuburger H et al. Long-term auditory adaptation to a modified peripheral frequency map. Acta Otolaryngol 2004;124:381–6. [PubMed: 15224858]
56. Svirsky MA, Talavage TM, Sinha S et al. Gradual adaptation to auditory frequency mismatch. Hear Res 2015;322:163–70. [PubMed: 25445816]
57. Tan CT, Martin B, Svirsky MA. Pitch Matching between Electrical Stimulation of a Cochlear Implant and Acoustic Stimuli Presented to a Contralateral Ear with Residual Hearing. J Am Acad Audiol 2017;28:187–99. [PubMed: 28277210]
58. Dillon MT, Canfarotta MW, Buss E et al. Effectiveness of Place-based Mapping in Electric-Acoustic Stimulation Devices. Otol Neurotol 2021;42:197–202. [PubMed: 33885267]

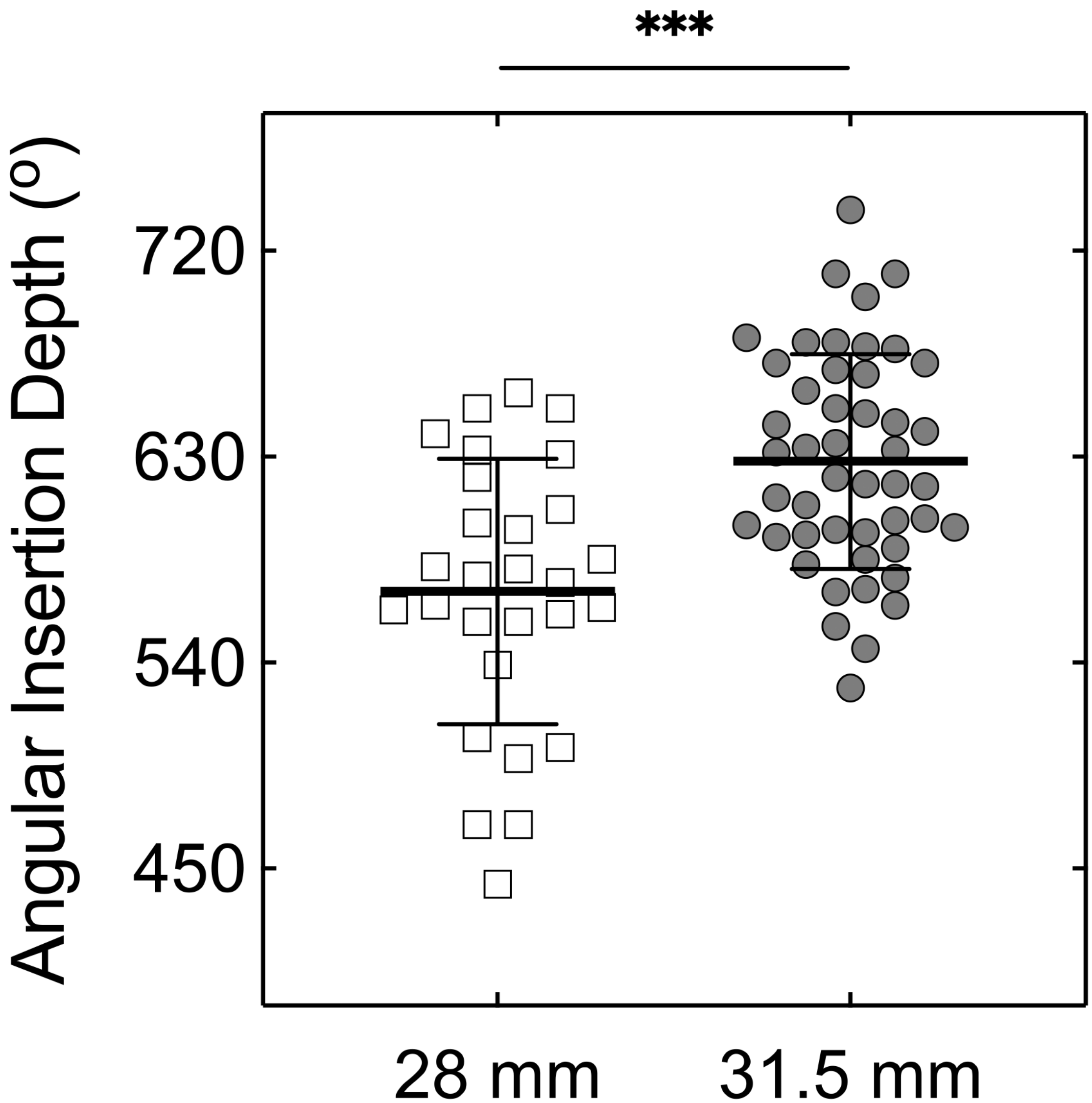

Figure 1.

Angular insertion depth of the most apical electrode contact for cochlear implant recipients of fully inserted 28-mm and 31.5-mm lateral wall electrode arrays. Individual values are plotted over the sample mean and standard deviation. ***, $p < 0.001$.

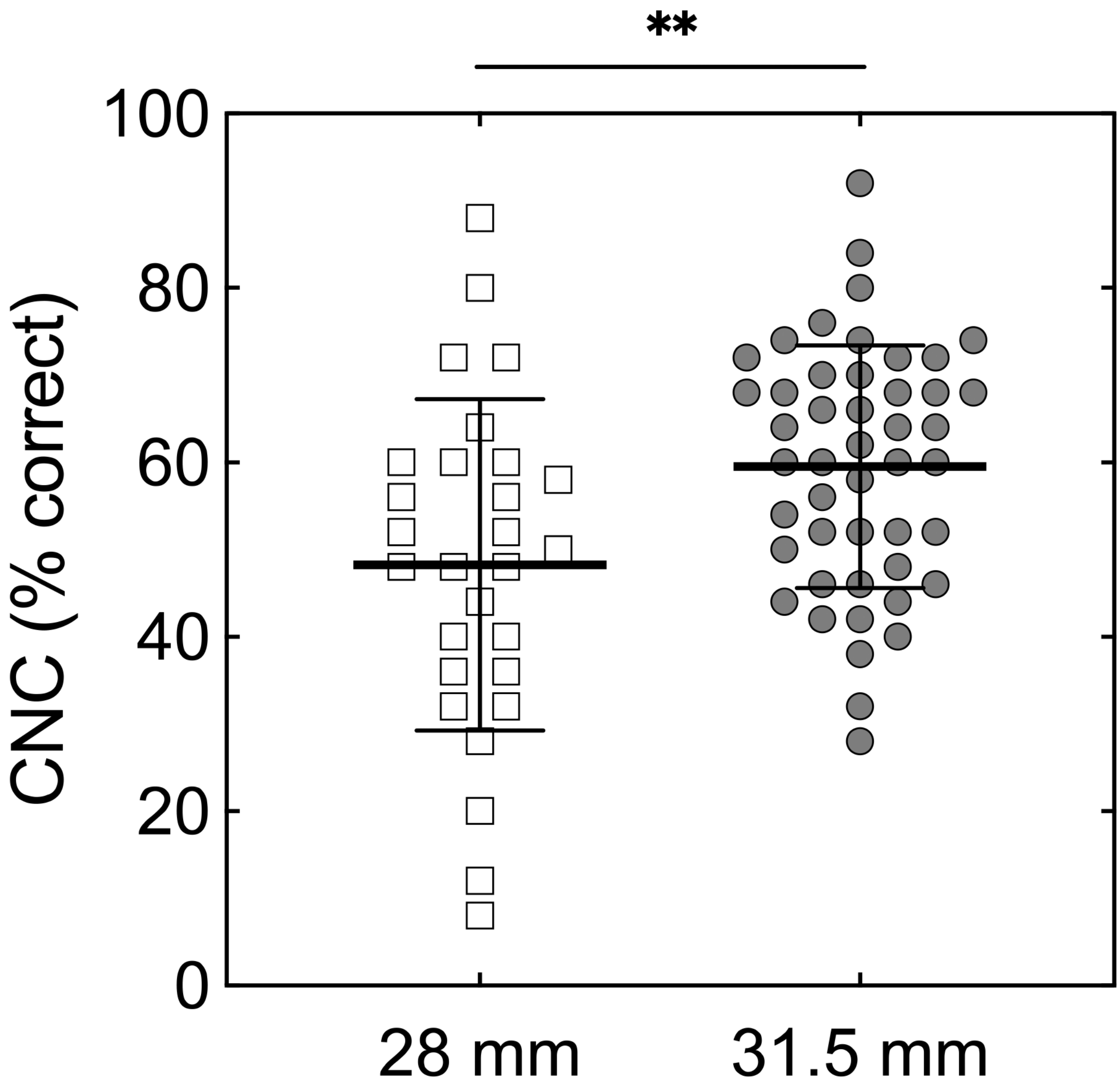

Figure 2.

Postoperative consonant-nucleus-consonant (CNC) word score in quiet at 12 months post-activation for cochlear implant recipients of fully inserted 28-mm and 31.5-mm lateral wall electrode arrays. Individual values are plotted over the sample mean and standard deviation. **, $p < 0.01$.

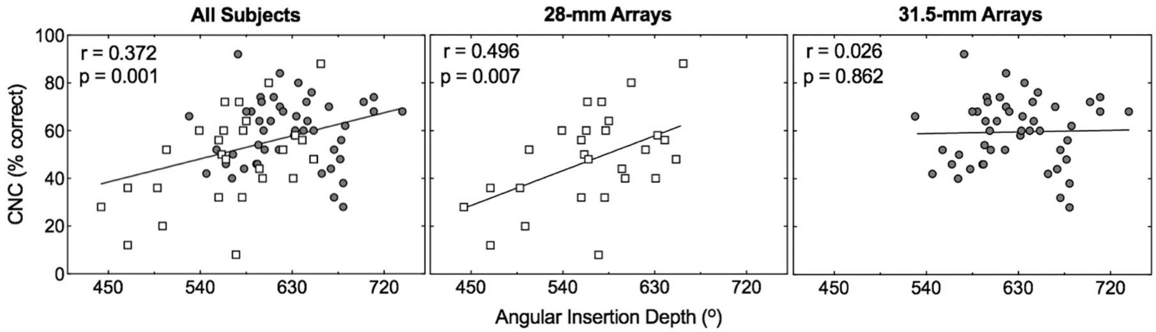

Figure 3.

CNC word scores as a function of angular insertion depth for all subjects (left panel) and separated into those implanted with a 28-mm (middle panel) or 31.5-mm array (right panel). Text at the upper left of each panel indicates the correlation as illustrated with line fits. CNC; consonant-nucleus-consonant.

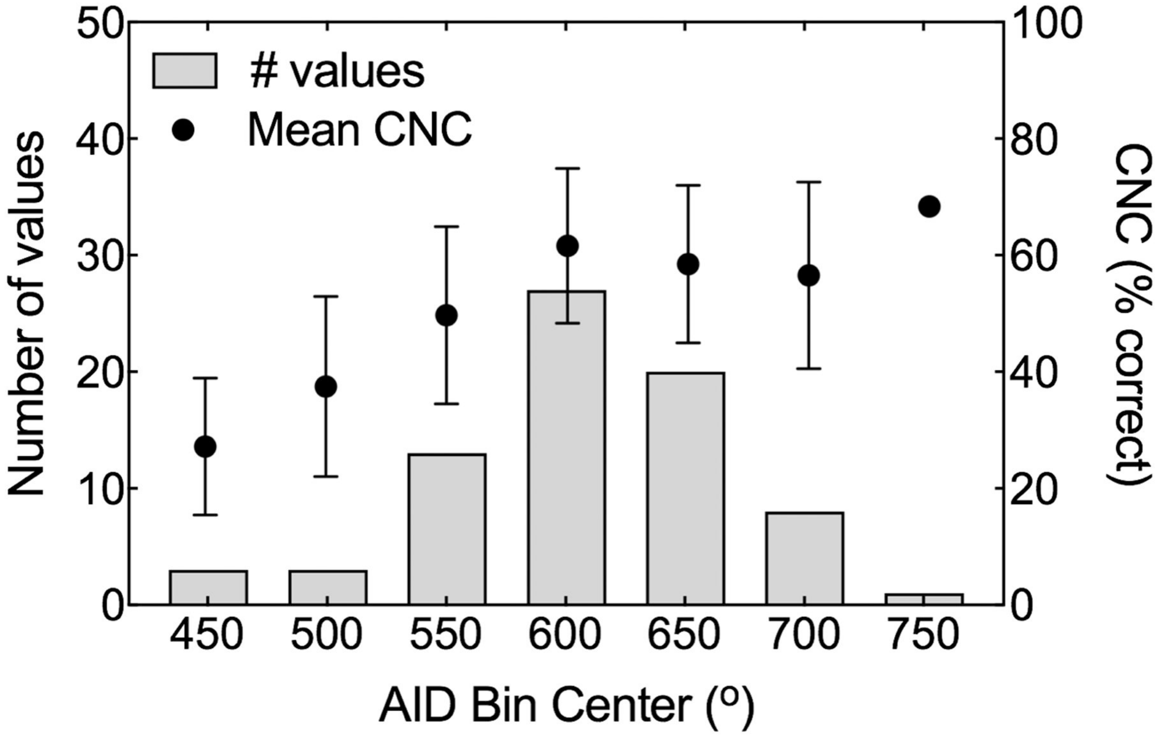

Figure 4.

Binned analysis of CNC word scores as a function of angular insertion depth. Left y-axis and grey bars indicate the number of subjects in each bin. Right y-axis and black circles with error bars indicate the mean CNC word score with standard deviations for each bin. CNC, consonant-nucleus-consonant; AID, angular insertion depth.

Table 1.

Demographic information for the study sample.

Variables	Array length		P value[‡]
	28-mm (n = 28)	31.5-mm (n = 47)	
Age (years)	65.0 (57.1 – 73.6)	63.6 (54.4 – 73.5)	0.824
Female (n)	13 (46.4%)	24 (51.1%)	0.881
Right ear (n)	15 (53.6%)	18 (38.3%)	0.294
Preoperative CNC (%)	4.0 (0 – 16)	4.0 (0 – 16)	0.336
Preoperative PTA (dB HL)	90.0 (75.0 – 98.3)	91.7 (78.3 – 103.3)	0.490
Preoperative LFPTA (dB HL)	70.0 (58.1 – 81.8)	85.0 (67.5 – 95.0)	**0.006**
AID (°)	571 ± 58.2	628 ± 46.9	**< 0.001**
Postoperative CNC (%)	48.3 ± 19.0	59.5 ± 13.9	**0.004**
Duration of hearing loss[§] (years)	10.0 (5.0 – 18.8)	9.0 (4.0 – 19.0)	0.430
Etiology			
Unknown	25	39	
Meniere's	1	5	
Noise induced hearing loss	1	1	
Usher's syndrome	1	1	
Temporal bone fracture	0	1	

[‡]Categorical variables are presented as n (%) and significance values determined with χ^2 analysis. For continuous variables, the D'Agostino-Pearson omnibus test was used to evaluate normality. Normally distributed data are presented as means ± standard deviations and non-parametric data are presented as medians (interquartile ranges), and significance was determined with an independent t-test and Mann-Whitney U test, respectively.

[§]Reported duration of severe-to-profound hearing loss in years.

Bold values indicate statistical significance ($p < 0.05$). CNC, consonant-nucleus-consonant; PTA, pure-tone average (500, 1000, and 2000 Hz); LFPTA, low-frequency pure-tone average (250 and 500 Hz); AID, angular insertion depth.