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Role of electrode placement as a contributor to variability in cochlear implant outcomes

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Abstract

Hypothesis—Suboptimal cochlear implant (CI) electrode array placement may reduce presentation of coded information to the central nervous system and consequently limit speech recognition.

Background—Generally, mean speech reception scores for CI recipients are similar across different CI systems, yet large outcome variation is observed among recipients implanted with the same device. These observations suggest significant recipient-dependent factors influence speech reception performance. This study examines electrode array insertion depth and scalar placement as recipient-dependent factors affecting outcome.

Methods—Scalar location and depth of insertion of intracochlear electrodes were measured in 14 patients implanted with Advanced Bionics electrode arrays and whose word recognition scores varied broadly. Electrode position was measured using computed tomographic images of the cochlea and correlated with stable monosyllabic word recognition scores.

Results—Electrode placement, primarily in terms of depth of insertion and scala tympani vs. scala vestibuli location, varies widely across subjects. Lower outcome scores are associated with greater insertion depth and greater number of contacts being located in scala vestibuli. Three patterns of scalar placement are observed suggesting variability in insertion dynamics arising from surgical technique.

Conclusion—A significant portion of variability in word recognition scores across a broad range of performance levels of CI subjects is explained by variability in scalar location and insertion depth of the electrode array. We suggest that this variability in electrode placement can be reduced and average speech reception improved by better selection of cochleostomy sites, revised insertion approaches, and control of insertion depth during surgical placement of the array.

Keywords

Cochlear implantation; Outcome variability; Electrode placement; Insertion depth; Computed tomography; Scalar Placement

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Despite the use of different electrode designs and processing algorithms across clinically-applied cochlear implant (CI) systems, the average speech-reception abilities of CI recipients are similar across devices. However, within the same device wide variability in speech-reception is seen across individuals (1), suggesting that significant recipient-dependent factors limit overall speech reception at the individual level. Numerous recipient-specific factors have been identified as affecting word recognition, including duration of deafness and duration of CI use (2-4), residual preoperative speech recognition (3,4), pre/postlingual status (5), choice of electrode coupling (6,7), choice of processing algorithm (8,9), and method and quality of fitting (10). Age at implantation has been found to have a small negative (2) or no (11) influence in older populations. Other factors, known to vary across subjects but have not been demonstrated to influence speech reception significantly, include medio-lateral placement of electrodes within scala tympani (ST) (12), spiral ganglion cell survival (13,14), morphological

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changes in surviving ganglion cells (15), inconsistent psychophysical percepts (16), and compromised central pathways (17,18).

This study examines variability in intracochlear electrode array scalar placement and insertion depth as possible contributing factors to variability in word recognition in the context of two questions, including (1) whether the intended placement goals for the array were achieved during insertion, and (2) if the array was sub-optimally placed, have the functional aspects of the array been altered from its intended operation?

Postmortem histological observations of the temporal bones of CI recipients have revealed intracochlear fibrous growth, bone formation, scala vestibuli (SV) invasion, fractures of the osseous spiral lamina, and disruption of the basilar partition at the cochleostomy site (19-25). These studies have shown that even in the presence of cochlear structural disruption, useful CI outcomes can be obtained by stimulation of modest numbers of surviving ganglion cells. More recent studies involving in situ embedding and sectioning of the electrode array in place provide a better assessment of conditions immediately post mortem. These studies have confirmed earlier findings, but have found no significant correlation between the numbers of surviving ganglion cells and performance (14,26-28). This suggests that the status of the central nervous system (CNS) might play a greater role than previously thought (28) and/or other peripheral factors contribute significantly to outcome variability.

Given numerous reports of cochlear damage during test insertions into fresh temporal bones (29-34), increased damage risk in the apical cochlea with deep insertions (29-35), variability in insertion depths (36,37), and observation of array migration from ST to SV during insertion (29,30,32,33,38), it is likely that tissue trauma occurs during insertion; as a result, electrode placement fails to achieve intended surgical goals. Thus the intended functional representation of information by the electrode array might be substantially altered. Consequently, we hypothesize that observed variability in electrode placement across individual recipients will account for a significant portion of variability in speech reception across the same subjects.

Recent advances in radiologic assessment of CI electrode placement in vivo (12,39-46) and measurement of intracochlear physiological potentials with current CI devices offer new opportunities to relate outcomes to the anatomical and physiological details of the electrode-nerve interface. In this study recipients were examined using high-resolution, computed tomography (CT) imaging. Measures of tonotopic electrode discrimination, and consonant-vowel nucleus-consonant (CNC) word recognition were also made. Data presentation and analysis in this paper will examine the effects of electrode position and tonotopic electrode discrimination on CNC word recognition.

MATERIALS AND METHODS

Fourteen subjects in the CI program at Washington University School of Medicine (WUSM) and previously implanted with either the Advanced Bionics (AB) Clarion C-II or 90K implant systems were studied. Operations had been performed by four surgeons affiliated with WUSM and one from another medical center. The surgical techniques used were standard procedures through the mastoid and facial recess. Cochleostomies were placed anterior and inferior to the round window (RW) niche to enter the ST. The 14 subjects who agreed to participate were obtained from a pool of 24 adult AB CI users whose word recognition scores (47) spanned a range from poor-to-excellent. Those who agreed to participate were available to participate in multiple research sessions over a 2−4 month period. CNC word scores at the time of selection were stable and had been collected at least 4 months (range: 4−36 months) post CI activation. The CNC word scores for these subjects, identified as S1 through S14 in descending order of CNC scores, are shown in Figure 1 relative to other adult AB and Nucleus CI recipients

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implanted during the same time period at WUSM. Demographic and performance measures for both groups are presented in Table 1 and show no significant differences. An electrode discrimination task was performed with each subject using standard clinical software. After loudness balancing at a comfortable level, paired pulse train stimuli on adjacent electrodes were presented in random order to determine if the subjects could discriminate pitch between electrodes. Subjects were screened to have no overt history that suggests an unusually compromised CNS (i.e. meningitis, pre/perilingual deafness, dementia, etc). All human study protocols were approved by the WUSM Institutional Review Board in accordance with the Helsinki Declaration. Informed consent was obtained from all studied subjects including those whose image data are presented in Figure 3.

A two-step procedure, as described in detail in a previous publication (41), using pre and post-operative high resolution CT images was employed to determine the electrode position in each subject's implanted cochlea. Post-operative CT images alone are inadequate due to metal artifact bloom generated by the electrode array, which obscures the adjacent cochlear anatomy needed to determine position. Using well-defined anatomical landmarks, a pre-operative CT image voxel space optimized for anatomical detail was co-registered with a post-operative CT image space optimized for resolution of the electrode (47). The electrode was then segmented from the post-operative image data and copied into the pre-operative image space to provide a composite image of electrode placement within an individual's cochlea. Electrode placement was quantified in terms of (1) angular insertion depth of the center of each contact relative to rotation about the midmodiolar axis beginning at the basal end of the cochlear canal and (2) scalar location of each contact as to whether it is located below the basilar membrane (BM) in ST or above it in the combined space of SV and scala media (SM) which is simply designated as SV. Since the BM and other fine soft tissue structure within the cochlear canal are not resolved in the pre-operative CT image, the scalar designation is determined by comparing a midmodiolar section through each contact to that of an equivalent section of a high resolution cochlear atlas generated from an optically-sectioned donor cochlea (41). While individual cochleae differ in the exact shape and length of the cochlear spiral, the position of the BM at a given location within the cochlea is consistent enough to allow for a determination of the BM location in the pre-operative CT image In most cases the electrode contact is clearly in ST or SV and their scalar designation can easily be made. Contacts that are in the region where the array transitions from ST to SV have a higher degree of uncertainty as to scalar location, but in most cases this transition involves only one or two contacts.

RESULTS

Figure 2 shows electrode placements in all 14 subjects in order of decreasing word recognition from S1 to S14. Each panel shows the positions of electrode array contacts in terms of distance relative to the lateral scalar bony wall, scalar position (black electrodes are in ST; white electrodes are in SV), and depth of insertion. In general, note the marker contact (square box) is inserted well beyond the cochleostomy in many subjects and the presence of at least some contacts in SV in all subjects. Figure 3 shows electrode placements for additional subjects implanted with the Nucleus 24 and Contour arrays and the MedEl array all obtained using the same CT imaging methodology used to generate Figure 2. Figure 3 is included to show the generality in electrode array placement variability across all manufacturers' devices; however, these subjects are not included in the present analysis of outcome dependencies.

Figure 4 compares angular insertion depths and scalar locations of individual electrode contacts across subjects ranked in order of *CNC Word Recognition* scores. For each subject angular insertion depth of each electrode contact relative to the center of the beginning of the cochlear canal (41,44) is shown as a horizontal line of symbols. Variation in interelectrode angular distances is related to a decrease in the radius of curvature of the cochlea from base to apex

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combined with variability in medio-lateral placement of the array longitudinally. Only the effects of angular insertion depth are considered in this paper. The effects of medio-lateral placement on outcome involves estimation of the location of the inner modiolar wall and ganglion cell locations, neither of which is directly visible in the present CT analysis. These effects will be addressed in a separate paper.

Three patterns of longitudinal distribution of contacts across ST and SV are observed (Figure 4). These patterns, (*Insertion Pattern* - B, M, and A for Basal, Middle and Apical, respectively), are named for the region where the array first enters SV. For Pattern B (S6, S8, and S11-S14) all contacts are located in SV beginning in the basal cochlea. For Pattern M (S1, S3-S5, S7 and S9) the array begins in ST and transitions to and remains in SV at or slightly beyond 180° insertion depth. S3 is classified as Pattern M based on clear intrusion of the array into SV at approximately 200° insertion depth, whereas the array position wavers between ST and SV in the basal region possibly due to buckling. Finally, Pattern A (S2 and S10, both with positioner POS) is characterized by the array transitioning from ST to SV in the apical region beyond 360° insertion depth. The other subject with a positioner, S11, has Pattern B. An additional metric, *Scalar Position*, is the general pattern of scalar electrode placement independent of where the array crosses longitudinally from ST to SV (see Figure 4 caption for description). A final metric, *Total SV Elect Count*, represents the total number of contacts in SV. All of these metrics, including presence (+) or absence (−) of pitch confusions or difficulty in making discriminations on the apical electrodes, *Pitch Confus*, are shown in Figure 4.

Bivariant and partial correlations (single-tailed) were computed to determine if *CNC Word Recognition* decreased with measured variables describing electrode placement (angular insertion depths of selected basal (E12) and apical (E1) electrodes = *Basal Elect Angular Depth* and *Apical Elect Angular Depth*; length of the inserted portion of the array from the apical-most contact to cochleostomy = *Insertion Length*; subject demographic descriptors [age at testing = *Age*; duration of CI use = *Duration CI Use*; duration of deafness = *Duration Deafness*], and presence or absence of confusion and/or subtle distinctions in pitch discrimination of apical contacts = *Pitch Confus*). *CNC Word Recognition* decreased significantly (Spearman, $p \leq 0.05$) with increases in Pitch Confus, Basal Elect Angular Depth, Scalar Position, Total SV Elect Count, and *Age* and a shift in *Insertion Pattern* from pattern M to B. Non significant variables included: Duration CI Use, Duration Deafness, Apical Elect Angular Depth, and *Insertion Length.* In addition, increases in *Basal Elect Angular Depth* were significantly related to increases in *Scalar Position* and *Total SV Elect Count* and *Insertion Pattern* shift from M to B. Using partial correlations to control for covariance with other factors, *CNC Word Recognition* was found to significantly decrease with *Scalar Position* when controlling for *Age*. When controlling for *Age* and *Scalar Position, CNC Word Recognition* was significantly reduced by *Total SV Elect Count* and a shift in *Insertion Pattern* from M to B.

Linear regression analysis using step-wise introduction of independent factors (SPSS 15.0 for Windows) yielded three statistically significant models of *CNC Word Recognition* (Table 2). These regression models indicated that *Scalar Position, Age* and *Total SV Elect Count* can each account for significant portions of the overall variance in *CNC Word Recognition* as reflected by R^2 scores. Combined together in Model 3 these factors accounted for almost 83% of the outcome variance. Recall that *Basal Electrode Angular Depth* was significantly related to *Scalar Position* and *Total SV Elect Count*, suggesting that there are combined effects of deep insertion and SV array invasion in reducing word recognition.

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DISCUSSION

These results support the hypothesis that intracochlear electrode array placement accounts for a significant portion of variability in word recognition observed across CI recipients. This study, conducted in subjects with the AB system, confirms earlier reports in Nucleus subjects of dislocation of electrode arrays from ST into SV and the consequent negative impact on outcome (39,48). The present study extends these findings by describing variability in insertion depth, primarily deep insertion, and its deleterious effect on outcome.

Variability in electrode insertion depth across subjects is shown in Figure 4. Insertion depth is quantified by the measures *Basal Elect Angular Depth* and *Apical Elect Angular Depth*. While these two measures are strongly coupled by both referencing locations along the same linear electrode array, they are disassociated by variation in depth and trajectory of the array within the cochlea. In particular, angular depths between adjacent contacts may vary as a consequence of the diminishing radius of curvature of the cochlea apically and variation in the medio-lateral locus of the array longitudinally relative to the medial wall. In general, variability in *Basal Elect Angular Depth* is a more direct measure of variability in insertion depth arising from the surgical insertion process itself, including conditions controlled directly by the surgeon. In the present study *CNC Word Recognition* decreases significantly with increases in *Basal Elect Angular Depth*; however, there is a confounding dependence on *Age* as older subjects had lower speech recognition scores. Although age at implantation has been found to have a small negative (2) or no (11) influence in older populations, *Basal Elect Angular Depth* is no longer significantly related to reductions in *CNC Word Recognition* after controlling for *Age*, whereas *Scalar Position* remains significantly associated. In a separate, but similar, study involving subjects from the larger cohort of Nucleus recipients (Figure 1) a significant negative relation between CNC outcome and array insertion depth was found (49). Consequently, we infer that *Basal Elect Angular Depth* is the primary contributor to reduced word recognition, although *Age* cannot be ruled out with the current sample. Finally, it is worth noting that increases in insertion depth (*Basal Elect Angular Depth*) are significantly related to greater numbers of electrodes being located in SV (*Insertion Pattern, Scalar Position* and *Total SV Elect Count*), which significantly correlates with reduced CNC scores as discussed later.

Mechanistically, deep insertions may affect word recognition by effects at both the basal and apical ends of the electrode array. Basally, deep insertions may leave the cochlear region from the hook to the first turn devoid of electrode contacts, sacrificing possible basal stimulation sites along the tonotopic axis. This approximate region is shown as Zone B (Figure 4) where the electrode placement for S11 is a prime example, having loss of up to four basal stimulation sites compared to S1's insertion. Other subjects experiencing similar, but not as severe, loss of possible basal stimulation sites are S2, S4, S8, and S12-S14. Apically, deep insertions may increase mechanical trauma close to the apex as the cochlear canal cross-sectional area diminishes and the radius of curvature of the cochlea increases. In addition, stimulation selectivity may diminish as the apical-most cell cluster of the spiral ganglion is approached. This approximate apical region is shown as Zone A (Figure 4). Psychophysical electrode pitch ranking tests indicate that 8 of 14 subjects have difficulty or cannot discriminate their apical contacts. Of these 8 subjects, 6 have deep insertions with electrodes in Zone A. These findings are consistent with a recent report describing apical pitch confusions in MedEl patients with deeply inserted arrays (50). Although concern in the field about potential detrimental effects of the offset between normal acoustic characteristic frequencies and actual tonotopic position of electrode contacts coding those frequencies (51-53) implies that deeper insertion of present electrode designs is indicated, evidence from this study suggests that deeper insertions will likely be deleterious to outcome.

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Several mechanisms, acting separately or in combination, may explain why word recognition is reduced by SV compared to ST placement. One is direct mechanical damage to cochlear tissues resulting in loss of surviving ganglion cells (54). Others may be altered distribution of longitudinal and medial electrical current pathways due to SV placement, disruption of BM, and/or close proximity of contacts to the habenula (55). Yet another is increased likelihood of cross-turn stimulation when a contact is located in SV as opposed to ST. In this case, a SV electrode is approximately equidistant from ganglion cells located adjacent to the medial ST wall of both the current cochlear turn and the next higher cochlear turn, increasing the likelihood that stimulation would excite ganglion cells associated with both turns. It is important to note that the average performance of S6 and S8, even with all contacts in SV, is consistent with observations that intentional insertion into SV can result in little trauma (38) and produce favorable outcomes (56-58). It is likely that multiple mechanisms could be active and could vary regionally within the cochlea depending on electrode array insertion pattern.

Insight into why SV electrode placement occurs is suggested by examination of the *Insertion Pattern* metric. Three patterns are observed, each suggesting a separate mechanism involving insertion of the electrode array. Pattern A (S2 or S10, Figure 2), in which contacts move into SV from ST in the apical end of the cochlea, is closest to the ideal of full ST insertion. In this case, the array appears to have followed a ST trajectory up to the most apical part of the cochlea, at which point it migrates into SV as the cochlear radius and scalar cross section diminish. With Pattern M (S1 or S4, Figure 2) the array appears to have tracked through the basal cochlea along a straight trajectory where the ST cross section is relatively large, but as the array tip touches the outer ST wall slightly beyond 180° of angular insertion depth, the tip is deflected upward through the BM into SV, where it remains for the rest of the insertion. Pattern M is characteristic of tearing of the spiral ligament in the lower basal turn reported by other investigators (31,34,35). With Pattern B (S6 or S11, Figure 2), where most contacts are located in SV, the cochleostomy appears to have been made too high along the lateral cochlear wall, causing the array to either enter directly into the basal-most SV or into ST directly below the BM and at a trajectory that causes penetration of the BM into SV. In either case the array remains in SV during the full insertion.

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These patterns may well be dictated by the mechanical properties of the array itself. This cannot be ruled out and has been the topic of past investigations (59,60). Figures 2 and 3 show that similar electrode *Insertion Patterns* involving variability in depth of insertion and scalar placement are observed across all manufacturers' devices, as confirmed by other studies (32, 33,39,48). Preliminary results from a larger cohort of subjects implanted with the Nucleus system show similar sensitivity of speech recognition to both scalar placement and insertion depth (49). Similar results have been reported for the MedEl device (50), at least with regard to insertion depth.

An additional factor contributing to variability in electrode placement is the size of the cochlea itself. Variation in cochlear size and topology across subjects is well known from anatomical and radiographic studies (61-63). Escude and colleagues have described variation in insertion depth with increased size of the basal turn due to longer trajectories for straight electrode arrays and altered insertion dynamics for perimodiolar arrays (36). The present data were analyzed in similar fashion and showed that while cochlear size and gender variation were similar to that reported by Escude *et al.*, no statistically-significant correlation between cochlear size and apical-most insertion depth or outcome measures were found in the present data. This finding is most likely because the Escude et al. study limited linear insertion depth across subjects, whereas in the present study cochlear size-dependent effects are essentially masked by large uncontrolled variation in linear insertion depth.

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We hypothesize that variability in electrode placement can at minimum be improved by better selection of cochleostomy sites and control of insertion depth during surgical placement of the array, and consequently, average word recognition scores for the general CI population would improve. The degree of improvement that may be expected in averaged speech recognition scores was estimated from the current data. Assuming that surgical improvements could eliminate initial electrode placement in SV, Regression Model 3 (Table 2) predicts an average *CNC Word Recognition* of 81.9% (SD = 19.1) when the independent variables of *Scalar Position* and *Total SV Elect Count* are assumed to be 1.0 and 0, respectively, as compared to the actual *CNC Word Recognition* average of 46.1% (SD = 26.1) for the 14 subjects (Average *Age, Scalar Position* and *Total SV Elect Count* of 61.5, 2.39 and 10.1, respectively). This represents a significant estimated 35.8 point improvement in average *CNC Word Recognition* scores (p=0.000, paired t-test) as a result of improved surgical placements into SV without translocation into ST and with control of insertion depth. Although the magnitude of this improvement is surprisingly large, is dependent on many underlying assumptions in the simple regression model, and is probably subject to numerous limiting factors (e.g. ceiling effects in word recognition testing), the implication is that the potential payoff for improvement in surgical placement is very large.

Minimization of the effects of suboptimal electrode insertion is actively being pursued by our group and other investigators. These approaches include surgical revision to correct for overly deep insertion (64), improved selection of cochleostomy sites (60,65-69), and minimization of electrode insertion trauma through refined insertion angles (66,69,70). Using the RW niche as the landmark for the cochleostomy may explain some of the observed variability in the cochleostomy site. Full exposure of the RW and placement of the cochleostomy inferior and anterior to the RW annulus may improve ST insertions. Although cochleostomy placement anteroinferior to the RW appears critical to consistent and desired placement in ST, placement too inferior to the RW increases the likelihood of surgical damage to the cochlear aqueduct and inferior cochlear vein (66,67,69,71). Careful preoperative evaluation of the relative anatomy of the facial nerve, chorda tympani, orientation of the basal turn and midmodiolar axis based on high-resolution preoperative CT scans to plan surgical techniques may be beneficial. The insertion angle, in addition to cochleostomy placement, must be considered. This angle is at least in part related to the insertion tools used to place the array and the mechanical properties of the array itself.

In conclusion, this study shows that a significant portion of the variability in word recognition scores across a broad range of performance levels of CI subjects is explained by variability in scalar placement and insertion depth of the electrode array. Improved cochleostomy site selection, revised insertion approaches, and better control of array insertion depth can minimize the deleterious effects of both these electrode placement factors on speech reception. Significant improvements in speech recognition are expected as a consequence of these surgical improvements.

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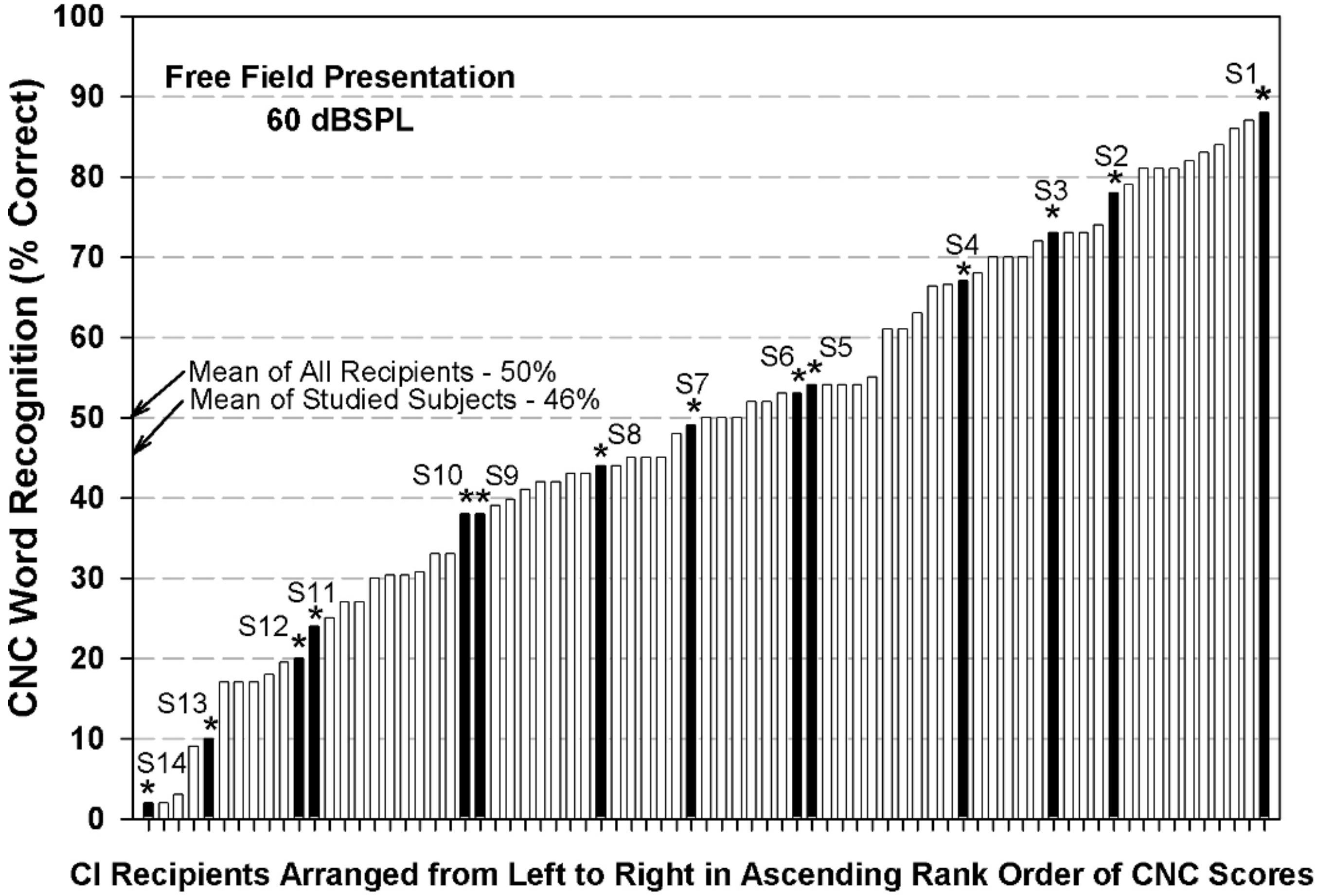

FIG. 1.
Rank order presentation of post activation CNC word recognition scores for a selection of Nucleus and Advanced Bionics adult CI recipients at WU School of Medicine. Scores are interpolated to 6 months post activation based on longitudinally collected data, unless otherwise noted. Black bars indicate scores for the subset of individuals with the AB device who participated in this study. These subjects are numbered (S#) in descending rank order of each individual's CNC score at entry into study. At entry into the study all subjects had stable CNC performance and at least 4 months of experience post activation.

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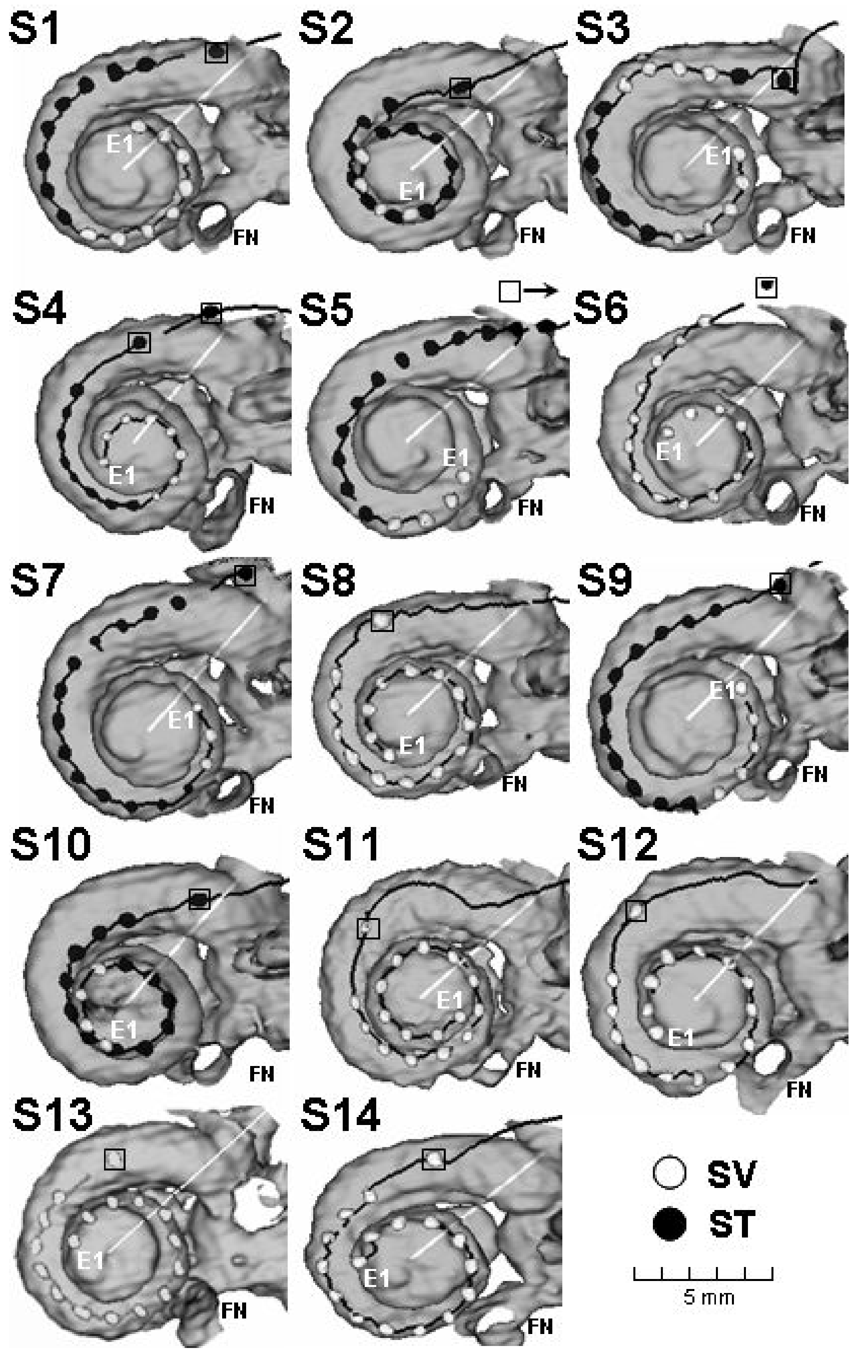

FIG. 2.

CT-based views of the boundary between the scalar fluid space and bony wall in each CI subject as seen from the apex of the cochlea along the midmodiolar axis. Electrode array styles are HiFocus® I (S2, S5, S10, and S11), HiFocus® Ij (S1, S3, S6-S9, S12-S14), and HiFocus® Helix (S4). The position and insertion depth of electrode contacts are shown relative to the bony wall. White contacts (○) are in SV, and black contacts (•) are in ST. Boxed contacts (□) are non stimulating marker contacts. The apical-most contact is marked as E1. Subjects S2, S10 and S11 have electrode positioners in place. The radial white line is the 0° reference from which angular insertion depth is measured and extends from the midmodiolar axis through the beginning of the cochlear canal.

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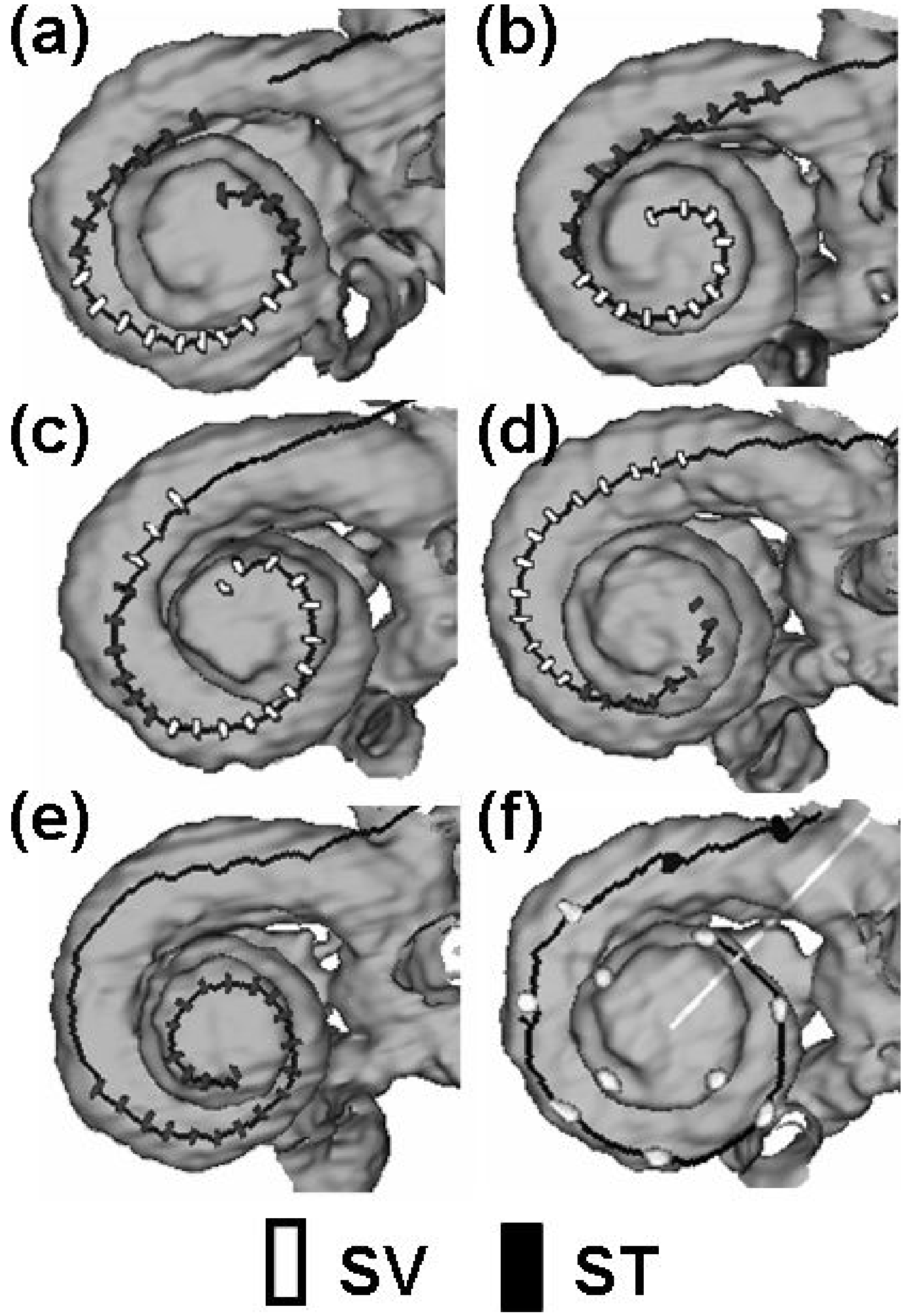

FIG. 3.
CT-based views similar to Fig. 2 showing electrode position and insertion depth in recipients of Nucleus and MedEl cochlear implant systems. These recipients are not participants in the present study but are included with those in Fig. 2 to illustrate that variability of electrode placement is not unique to a single electrode design and is possible with any manufacturer's devices. Displayed arrays are Nucleus Contour (a-c), Nucleus Contour Soft-Tip (d-e), and MedEl Combi 40+ (f).

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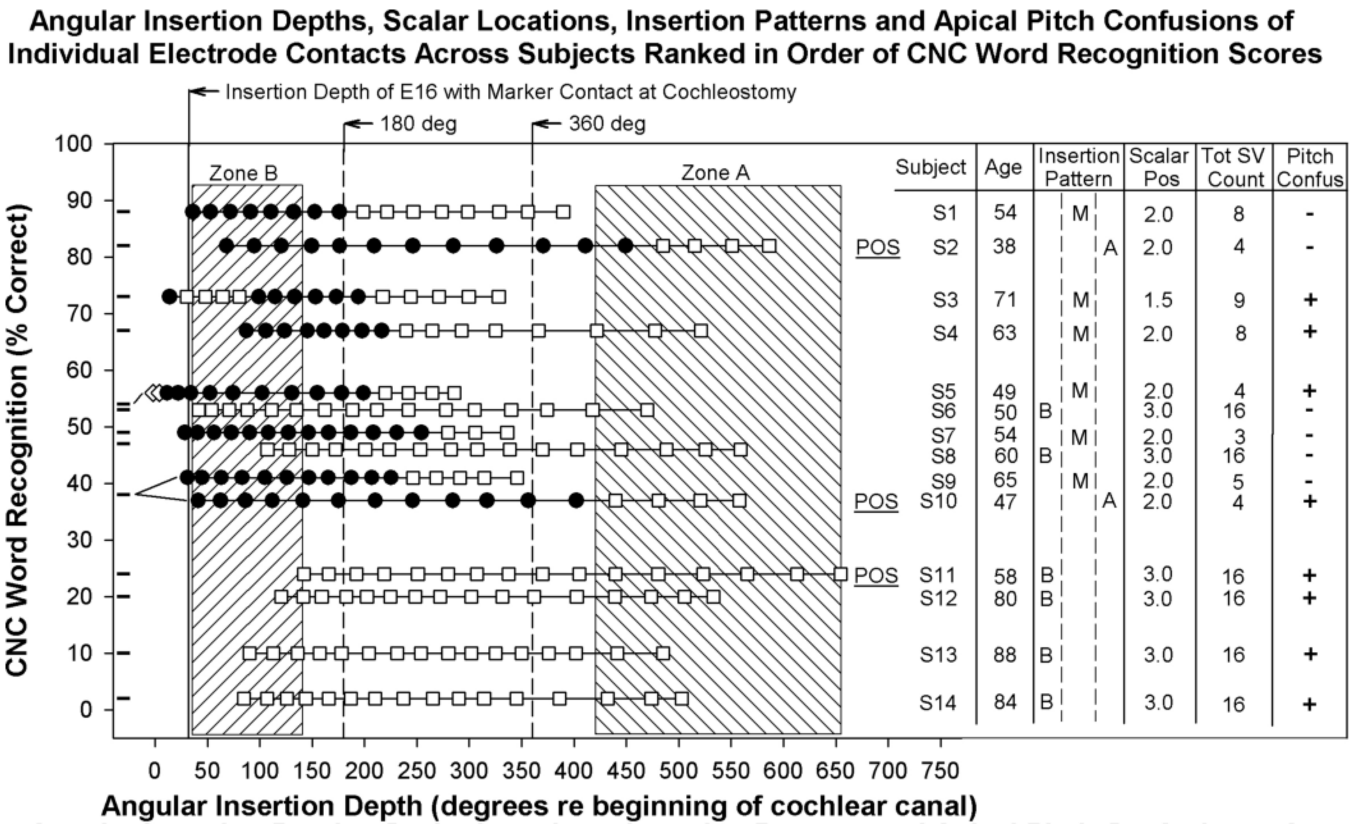

FIG. 4.

Angular insertion depths, scalar locations and insertion patterns of individual electrode contacts for subjects ranked in order of CNC word recognition scores. Each line of 16 symbols is located along the ordinate to indicate the subject's CNC Word Recognition score and mark the angular insertion depth of individual electrode contacts (E16 to E1, left-to-right). Open diamonds (◇) indicate contacts located outside of the cochlea (e.g. basal-most contacts for S5). Black circles (•) indicate electrode contacts located in ST, whereas white squares (□) indicate contacts located in SV. The vertical line at 34° insertion depth indicates the expected position of E16 for an array insertion with which the marker contact is positioned at a RW cochleostomy site. Columns to the right indicate presence of an electrode array positioner (POS), subject designation, age at time of the study, and four metrics, *Insertion Pattern*(A,B or M), *Scalar Position* (1 = All contacts in ST; 1.5 = Contacts initially in ST followed by a section of the array mapping into SV space and returning to ST; 2.0 = Initially ST then entering SV for the remainder of the cochlea; 2.5 = contacts are initially in SV followed by contacts mapping into ST and returning to SV; and 3.0 = All contacts in SV), *Total Number of Electrodes in SV*, and the *Occurrence of Apical Pitch Confusions* [present (+); absent (−)], each described in the text. Zone B and Zone A represent basal and apical cochlear regions, respectively, in which electrode function may be altered due to deep insertions.

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TABLE 1

Demographic and Performance Measures of Study and General Adult CI Populations at WU

Measure	Study Subjects	General Population
N	14	63
Age at Time of Study	60.3 ± 13.0	57.1 ± 17.0
Age at Onset of HL	23.9 ± 11.1	21.6 ± 19.2
Duration of Deafness	11.7 ± 10.9	18.4 ± 15.9
Duration of HA Use	19.8 ± 14.2	20.5 ± 14.8
Duration of CI Use	1.9 ± 1.6	2.1 ± 0.8
CNC Word Score	46.1 ± 26.1	50.2 ± 22.5

Measures are Means ± 1.0 SD. Units are years or % correct, as appropriate.

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TABLE 2

Linear Regression Models of CNC Word Recognition (% Correct)

Model No.	Model Description	R^2	Sig. Lev (p value)
1	$CNC_1 = A_1 + (B_1$*Scalar Position*$)$	0.494	0.005
2	$CNC_2 = A_2 + (B_2$*Scalar Position*$) + (C_2$*Age*$)$	0.662	0.003
3	$CNC_3 = A_3 + (B_3$*Scalar Position*$) + (C_3$*Age*$) + (D_3$*Total SV Elect Count*$)$	0.825	0.000

where $A_1 = 124$, $B_1 = -32.7$; $A_2 = 152$, $B_2 = -23.6$, $C_2 = -0.8$; $A_3 = 221$, $B_3 = -60.2$, $C_3 = -1.3$, $D_3 = 4.8$;