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Effect of electrode impedance on spread of excitation and pitch perception using electrically coupled “dual-electrode” stimulation

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Abstract

Objective—In newer-generation Cochlear Ltd. cochlear implants, two adjacent electrodes can be electrically coupled to produce a single contact or “dual electrode” (DE). The goal of the present study was to evaluate whether relatively large impedance differences (>3.0 kOhms) between coupled electrodes affect the excitation pattern and pitch percepts produced by the DE.

Design—Fifteen electrode pairs in six recipients were tested. Neural spread-of-excitation (SOE) patterns and pitch perception were measured for adjacent physical electrodes (PEs) and the resulting DE to determine if the lower-impedance PE in the pair dominates the DE response pattern. Results were compared to a “normative sample” (impedance differences <3.0 kOhms) from two earlier studies.

Results—In general, SOE patterns for DEs more closely approximated those of the lower-impedance PE in each pair. The DE was more easily distinguished in pitch from the higher-impedance PE than the lower-impedance PE. The ECAP and perceptual results generally differed from those of the normative group.

Conclusions—Impedance differences between adjacent PEs should be considered if DE stimulation is implemented in future research studies or clinical coding strategies.

Keywords

cochlear implant; dual electrode; impedance; virtual channels; electrically evoked compound action potential; pitch ranking; electrode discrimination

INTRODUCTION

Several methods can be used to achieve intermediate pitch percepts in cochlear implants (CIs) to theoretically improve spectral representation of the signal (e.g., McDermott & McKay, 1994; Busby & Plant, 2005; Firszt et al., 2007). One of these methods is called “current steering,” which is commercially implemented in Advanced Bionics’ Fidelity 120

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processing strategy (e.g., Firszt et al., 2007; Koch et al., 2007). Current steering uses independent current sources to simultaneously stimulate adjacent¹ electrodes, resulting in summation of the respective electrical fields. The proportion of current delivered to the two electrodes can be varied to “steer” the location of the summed electric field. Another method, which is the focus of the present study, is known as “dual-electrode” (DE) stimulation. This method electrically couples two adjacent physical electrodes (PEs) to effectively create a single “electrode” that should produce an electrical field that is different from that of either of the two contributing PEs (Busby & Plant, 2005; Busby et al., 2008; Hughes & Goulson, 2011; Hughes et al., 2013). Newer-generation Cochlear Ltd. devices (CI24RE and later) have the capability for DE stimulation, although this feature is currently not FDA approved for clinical use.

Today’s CIs are constant-current devices, which adjust the voltage based on each electrode’s impedance to achieve a designated current. Local differences in the electrode-nerve interface and the surrounding tissue contribute to impedance differences across individual electrodes. Large differences in impedance between the coupled electrodes that form the DE therefore might affect the shape and location of the resulting electrical field and the subsequent excitation pattern because current takes the path of least resistance, and a single current source is used for DE stimulation.

Neural spread-of-excitation (SOE) patterns measured with the electrically evoked compound action potential (ECAP) have been described for DE stimulation (Busby et al., 2008; Hughes, & Goulson, 2011; Hughes et al., 2013). Results are similar to those reported for current steering (Saoji et al., 2009; Hughes, & Goulson, 2011; Snel-Bongers et al., 2012; Hughes et al., 2013), and show that DE stimulation can produce regions of excitation that are spatially separate from those produced by each PE alone. Generally, amplitudes for the DE SOE pattern are between those for the flanking PEs. Comparisons have also been made between PEs and DEs using pitch-based tasks (Busby & Plant, 2005; Busby et al., 2008; Goehring et al., 2014), which show that DEs can produce pitch percepts that are distinct from each PE. It should be noted, however, that the effects of impedance differences between electrodes that form the DE were not investigated in any of the aforementioned studies. It is therefore unclear whether impedance differences between adjacent PEs affect physiological excitation patterns and/or pitch percepts with DE stimulation.

The goal of this study was to determine whether ECAP SOE patterns and pitch percepts for DEs are affected by relative impedance differences between the flanking PEs. It was hypothesized that the lower-impedance PE in each pair (PE_L) will dominate the response patterns obtained with DE stimulation because the electric field will be biased toward the region with lower resistance. Specifically, large impedance differences between adjacent paired electrodes will result in ECAP SOE patterns for corresponding DEs that approximate the pattern of the PE_L . Furthermore, it was hypothesized that pitch percepts between the DE and the higher-impedance PE of each pair (PE_H) will be more easily distinguished because of greater separation of the respective excitation patterns, compared with the DE versus PE_L . Results from this study will be relevant for designing subsequent studies that involve DE

¹Current steering can be achieved between non-adjacent electrodes, but this capability is presently not clinically available.

stimulation, as well as for determining whether specific electrode pairs should be excluded in future clinical implementations of DE technology.

MATERIALS AND METHODS

Subjects

ECAP SOE patterns, pitch ranking, and electrode discrimination were measured for 15 electrode sets (each consisting of two adjacent PEs and the resulting DE) with relatively large impedance² differences, measured in six recipients with newer-generation Cochlear Ltd. Devices (Cochlear Ltd., Macquarie, NSW, Australia). Subject demographics and test electrodes are shown in Table 1. Adjacent PEs with impedance differences of at least 3.0 kOhms (MP1+2) were selected for testing. This criterion was established by taking impedance values from a random sample of 20 previous research participants or clinical patients (from which the six subjects in the present study were drawn) who exhibited variable impedance patterns that were within the normal range specified by the manufacturer. The mean impedance difference between all adjacent PE pairs for the sample (21 pairs times 20 recipients) was 1.2 kOhms (SD = 0.41). The 3.0-kOhm criterion represented the first whole number that was greater than two standard deviations above the mean. Of this sample, 37/420 PE pairs (8.8%) exceeded the 3-kOhm criterion. Electrodes with short or open circuits were excluded from the calculations used to determine the inclusion criterion and for the study itself.

ECAP Measures

ECAP SOE patterns were measured for adjacent PEs and the resulting DE using a fixed probe and varied masker with the standard forward-masking subtraction technique for artifact reduction, as described in Hughes, and Goulson (2011) and Hughes et al. (2013). The Custom Sound EP (v. 3.2) software was used with the experimental “Dual-Electrode” mode enabled. Stimuli were delivered through a laboratory Freedom speech processor interfaced with a programming pod. The following default stimulus and recording parameters were used: 25 µsec/phase pulse width, 7 µsec interphase gap, 50 dB gain, 122 µsec delay, 80 Hz probe rate, 400 µsec masker-probe interval, MP1 stimulus indifferent electrode, MP2 recording indifferent electrode, and 100 sweeps. For the DE, the recording location was two electrode positions apical to the more basal electrode in the physical pair (software default). Masker and probe current levels (CL) were generally equal to a subjective judgment of “loud” (rating of 8 on a 10-point scale) for each electrode. If the CL for a rating of “8” differed within each electrode set, the lowest CL across the set of three probe electrodes (adjacent PEs and the resulting DE) was used to avoid potentially confounding effects of stimulus level across SOE functions being compared (Hughes, & Goulson, 2011). Maskers were only applied to PEs, except when the masker and probe were both delivered to the DE being tested. ECAP amplitudes were calculated as the difference in voltage between the N1 and P2 peaks. To allow for comparisons across SOE functions within a set as well as across subjects, ECAP amplitudes were normalized to the single

²The Custom Sound software measures electrode impedance at the end of the first phase of a 25-µsec/phase biphasic current pulse; therefore, impedances reflect both resistive and capacitive components (Clark, 2003; Hughes, 2013).

highest amplitude within each set. This method preserves the spatial relationships between functions within a set, but controls for overall differences in amplitudes across subjects and electrode sets (Hughes, 2008). The degree of spatial separation between ECAP SOE functions in each electrode set (denoted Σ) was calculated using the method described previously (Hughes, 2008; Hughes et al., 2013). Briefly, Σ represents the absolute value of the difference in normalized ECAP amplitude between two SOE functions, summed across all masker electrodes. Missing data points (e.g., for the recording electrode) were interpolated from adjacent masker electrodes.

Psychophysical Measures

Psychophysical measures (described further in Goehring et al., 2014) consisted of pitch ranking and electrode discrimination, which were tested using a custom program utilizing Nucleus Implant Communicator routines (NIC v. 2, Cochlear Ltd.). Stimuli for both tasks were 300-ms, 1000-pps pulse trains (25 μ sec/phase, 7- μ sec interphase gap) delivered in monopolar mode with a 5% current-level rove above and below a rating of “7” (loud but comfortable). Results for both tasks were based on 2–4 blocks of 54 trials. Prior to each task, stimuli for comparison electrode pairs were loudness balanced using a 2-interval forced-choice (IFC) double-staircase procedure (Jesteadt, 1980). Pitch ranking was measured using a 2IFC procedure in which subjects chose the interval that sounded higher in pitch (Busby & Plant, 2005); correct-answer feedback was not provided. The three electrodes in each set (PE_L , PE_H , and the resulting DE) were each paired and compared 18 times each (each electrode occurred an equal number of times in the first and second intervals). Percent correct was calculated from the number of trials in which the more basal electrode was chosen as higher in pitch. Electrode discrimination was measured for the same pairs tested with pitch ranking, using a 3IFC procedure in which subjects were instructed to select the interval that sounded different in pitch while ignoring loudness cues; correct-answer feedback was provided. Within each trial, two electrodes in each set were randomly assigned to each of the three intervals. Percent correct was calculated for each electrode pair per block.

“Normative” Data

ECAP and pitch data from a larger group reported in two earlier studies (Hughes et al., 2013; Goehring et al., 2014) were used to compare with the trends seen in the present data set. ECAP Σ data from 16 subjects from Hughes et al. (2013) and pitch data from 13 subjects³ from Goehring et al. (2014) were re-analyzed as a function of impedance differences (DE , PE_L , PE_H) and compared with the data from the present study. Data from two electrode sets in two subjects from the present study (F10, set 17/18 and F15, set 17/18) had been reported in the earlier studies. Because these two electrode sets exceeded the 3.0-kOhm criterion, they were excluded from the “normative” data reported here. Otherwise, each subject contributed data for three electrode sets (basal, middle, apical). The mean difference in PE-PE impedance for this larger group was 0.56 kOhms (range: 0.03–2.44).

³These 13 subjects were also part of the Hughes et al. (2013) study.

Statistical Analysis

For each of the three outcome measures (ECAP Σ , pitch ranking, electrode discrimination), results were analyzed using a one-way repeated-measures analysis of variance (RM ANOVA) with comparison pair (DE vs. PE_L, PE_L vs. PE_H, and DE vs. PE_H) as the within-subjects factor. For subjects with data from more than one electrode set (N5, F10, F13; see Table 1), data for each outcome measure were averaged across electrode sets for each comparison pair so that each subject contributed one data point for each factor comparison in the ANOVA ($N = 6$). The rationale for this approach was because (1) there were an unequal number of electrode pairs among subjects and the N was too small to consider electrode set location as a factor, and (2) it was not a goal to examine differences across specific electrode sets. Means across electrode sets within subjects were likewise calculated for the normative group ($N = 16$ for ECAP and $N = 13$ for pitch data). Bonferroni adjustments were made for all post-hoc pairwise comparisons.

RESULTS

Figure 1 shows ECAP SOE patterns for adjacent PEs and the resulting DE for 14 of the 15 electrode sets listed in Table 1. Data for electrode set 2/3 for subject F13 are not shown because ECAPs could not be measured for E3. In each panel, the SOE pattern for the PE_L is shown with black circles, the DE with black squares, and the PE_H with white circles. Impedance values (MP1+2) for each electrode are noted in the corresponding figure legends. Examples in which the black symbols overlap are consistent with the hypothesis that the PE_L dominates the response patterns obtained with DE stimulation. There were nine electrode sets from six subjects that exhibited the hypothesized trend; these are shown in the top three rows of Fig. 1. The bottom two rows of Fig. 1 show the remaining five electrode sets from two subjects that did not clearly exhibit the hypothesized trend. Of the latter group, two electrode sets (F10, set 20/21 and F13, set 15/16) demonstrated no discernible separation of SOE patterns across the three probe functions, although the DE for set 15/16 (F13) did overlap with the PE_L along the basal portion of the function (consistent with the hypothesis). For F10 (set 16/17), the DE function generally fell between those of the PEs, which is the expected trend for PEs with similar impedances. The remaining two data sets (F10, set 19/20 and F13, set 18/19) demonstrated broader functions for the DE than for either of the two PEs.

To examine how the trends shown in Fig. 1 compared with those for electrode pairs with more equal impedances (<3.0 kOhms), data were examined from an earlier study (Hughes et al., 2013) that were collected for three of the subjects in the present study. Figure 2 shows ECAP SOE functions for seven electrode sets in those three subjects. Impedance differences between adjacent PEs averaged 0.72 kOhms (range: 0.07—1.22; electrode impedances are shown in each figure legend). For the majority of comparisons, the DE amplitudes occurred between those of the adjacent PEs (N5, sets 5/6 and 11/12; F15, sets 5/6 and 11/12) or the DE function was broader than either PE function (N5, set 17/18), consistent with previous studies (Busby et al., 2008; Hughes et al., 2013). For F10 set 5/6, there was minimal separation amongst all three probe functions. Only one electrode set (F10, set 11/12) exhibited a trend similar to those shown in the upper portion of Fig. 1. Interestingly, this

electrode pair had the largest PE impedance difference (1.22 kOhms) across all of the sets shown in Fig. 2.

Figure 3 shows the ECAP spatial separation index, Σ (top row), pitch ranking (middle), and electrode discrimination (bottom) results as a function of the difference in impedance between compared electrodes. The left column shows data from the present study (6 subjects; 14 electrode sets for ECAP data and 15 electrode sets for psychophysical data). The right column shows the “normative” ECAP data from Hughes et al. (2013; top panel) and psychophysical data from Goehring et al. (2014; middle and bottom panels). In both columns of graphs, the black, gray, and white symbols represent comparisons between the DE and PE_L, the two PEs, and the DE and PE_H, respectively. Individual data from electrode comparisons for the study group (in Table 1) are shown with smaller symbols in the left column of the figure. Mean data (± 1 SD) for each comparison are shown with enlarged diamonds (left column) or triangles (right column) and respective shading. As noted above in the Methods, data for each comparison pair (DE-PE_L, PE_L-PE_H, DE-PE_H) were averaged across electrode sets within subjects so that each subject contributed one value toward the mean for each group.

For the present hypothesis to be supported, we expected significantly larger values for the PE_L-PE_H comparison than for the DE-PE_L comparison, and we expected that the PE_L-PE_H and DE-PE_H comparisons would not differ significantly. The DE-PE_H comparison was expected to yield larger values than for the DE-PE_L comparison, although we anticipated that the differences might not be statistically significant. For the normative group, we expected significantly larger values for the PE_L-PE_H comparison than for either of the DE comparisons, and we expected that the DE comparisons would not differ significantly from each other.

Results for the ECAP data in the top left panel showed a significant main effect of comparison pair ($F[2] = 9.99, p = 0.004$). On average, the PE_L-PE_H comparison (gray symbols) demonstrated the greatest spatial separation ($\Sigma = 2.3$), followed by the DE-PE_H comparison ($\Sigma = 1.9$; white symbols), with the least amount of spatial separation for the DE-PE_L comparison ($\Sigma = 0.9$; black symbols), as expected. Post-hoc results were consistent with the hypothesis; Σ values were significantly larger for the PE_L-PE_H comparison than for the DE-PE_L comparison ($p = 0.005$), the DE-PE_H comparison also yielded significantly larger Σ values than for the DE-PE_L comparison ($p = 0.019$), and there was no significant difference in mean Σ values for the PE_L-PE_H comparison and the DE-PE_H comparison ($p = 0.29$). In contrast, ECAP data from the normative sample (Fig. 3, top right) showed significantly larger Σ values for the PE_L-PE_H comparison ($\Sigma = 1.7$; gray triangle) than for either the DE-PE_H ($\Sigma = 1.3$; white triangle; $p < 0.001$) or the DE-PE_L comparisons ($\Sigma = 1.2$; black triangle; $p < 0.001$), with no significant difference between the two DE-PE comparisons ($p = 0.32$), as expected.

Results for pitch ranking in the study group (Fig. 3, middle left) showed a borderline significant effect of comparison pair for pitch ranking ($F[2] = 4.09, p = 0.05$). None of the post-hoc comparisons were statistically significant. The test was underpowered (0.46), which means there is less likelihood of detecting a significant effect that really exists. The

results were, however, in the predicted direction. Performance was best for the PE_L - PE_H comparison (74.3%; gray symbols), closely followed by the DE - PE_H comparison (71.0%; white symbols), with poorest performance for the DE - PE_L comparison (59.7%; black symbols). Data from the normative sample (Fig. 3, middle right) were consistent with the hypothesis for that group. Pitch ranking was significantly better for the PE_L - PE_H comparison (77.3%; gray triangle) than for either the DE - PE_H (68.0%; white triangle; $p = 0.001$) or the DE - PE_L (67.5%; black triangle; $p = 0.001$) comparisons, with no significant difference between the two DE - PE comparisons ($p = 0.84$).

Results for electrode discrimination in the study group (Fig. 3, bottom left) showed a significant main effect of comparison pair ($X^2[2] = 10.33$, $p = 0.002$; Friedman's RM ANOVA, due to non-normal distribution). On average, the PE_L - PE_H comparison (gray symbols) demonstrated the best performance (62.9%), followed by the DE - PE_H comparison (48.3%; white symbols), with the poorest performance for the DE - PE_L comparison (41.8%; black symbols), as expected. Post-hoc testing indicated significantly better performance for the PE_L - PE_H comparison than for the DE - PE_L comparison ($p = 0.008$) and no significant difference between the PE_L - PE_H and DE - PE_H comparisons, as hypothesized. Data from the normative sample (Fig. 3, bottom right) showed better performance for the PE_L - PE_H comparison (67.5%; gray triangle) than for either the DE - PE_H (53.2%; white triangle; $p < 0.001$) or the DE - PE_L (47.8%; black triangle; $p < 0.001$) comparisons, consistent with the hypothesis. However, performance for the DE - PE_H comparison was significantly better than for the DE - PE_L comparison ($p = 0.027$), which was unexpected.

DISCUSSION

The primary goal of this study was to examine whether relatively large impedance differences (>3.0 kOhms) between paired electrodes that form the DE result in a bias toward the PE_L , as measured physiologically and perceptually. In general, ECAP SOE patterns for the DE more closely approximated that of the PE_L , which supports the hypothesis that substantial impedance differences between coupled electrodes will typically bias the excitation pattern toward that of the PE_L . On average, pitch percepts between the DE and the PE_H were more easily distinguished than the DE versus the PE_L . These results are consistent with the hypothesis that the region of excitation for the DE will approximate that of the PE_L , making the two more difficult to distinguish on the basis of pitch. In contrast, comparisons for the normative group showed significant differences between the PE_L - PE_H comparison and both DE - PE comparisons, and generally no differences between the two DE - PE comparisons, consistent with a DE pattern that is approximately equally spaced between PE s (Busby et al., 2008; Hughes & Goulson, 2010). The exception was for electrode discrimination (Fig. 3, bottom right), which resulted in significantly more difficulty discriminating the DE from the PE_L than from the PE_H (consistent with the hypothesis for the study group). Although the PE impedance differences in the normative group were small, these results suggest that perhaps the electrode discrimination task is more sensitive to impedance differences between the PE s that form the DE .

An explicit comparison between the two pitch tasks was not a goal of the present study; however, it is worthwhile to note that percent-correct performance was better overall for

pitch ranking than for electrode discrimination for both the study group and the normative group. This result is likely due to procedural differences between tasks (i.e., different levels of chance associated with 2IFC vs. 3IFC). For the normative group, Goehring et al. (2014) converted percent correct for both tasks to d' so results for the two tasks could be compared. Applying corrections based on signal detection theory for M -alternative forced-choice tasks (Hacker & Ratcliff, 1979) yielded no significant differences between pitch ranking and electrode discrimination for each of the comparison pairs for the group. The d' conversions were not used in the present study because it was not the goal to directly compare results for the two pitch tasks. Further, d' conversions should not change results of electrode pair comparisons *within* a task.

As can be seen in the lower section of Fig. 1, patterns for five electrodes in two subjects did not conform to the expected trends. In two cases (F10, set 20/21 and F13, set 15/16) the patterns for the adjacent electrodes overlapped, which suggests less distinctive activation patterns perhaps due to poorer neural survival near those electrodes. (This was also the case for F10, set 5/6 in Fig. 2.) In two other cases in the study group (F10, set 19/20 and F13, set 18/19 in Fig. 1), as well as one example in the normative group (N5, set 17/18 in Fig. 2) the DE pattern was broader than either PE pattern. This observation is consistent with the findings of Busby et al. (2008; see their Fig. 4), who reported larger amplitudes on average for the DE than for the adjacent PEs. The authors suggested that the DE might have produced slightly broader excitation patterns than either PE; however, they found no significant differences in width of the SOE pattern (measured at 75% of the peak amplitude) between DE and PE patterns in their study. Hughes and Abbas (2006) suggested that the width of the function at a specified point does not adequately characterize the spread of the entire pattern, and supported this notion with an example in which two patterns of equal width (at 75% of the normalized amplitude) exhibited large differences in the overall spread and elevation of the edges of the respective patterns (see Fig. 7 in Hughes & Abbas, 2006). Thus, it appears that DE stimulation can produce broader patterns in some cases, although it is unclear why this occurs for some electrode pairs and not others.

As noted in the Introduction, previous studies examining ECAP SOE patterns and/or pitch related tasks using virtual channels (with DE stimulation or current steering) have not assessed the role of impedance on the results (Busby & Plant, 2005; Busby et al., 2008; Saoji et al., 2009; Hughes, & Goulson, 2011; Snel-Bongers et al., 2012; Hughes et al., 2013; Goehring et al., 2014). Local differences in the electrode-nerve interface and surrounding tissue will affect the path of current flow. Because the mechanism used to achieve DE stimulation (electrical coupling) does not utilize independent current sources or allow for “steering” of current (as with the Advanced Bionics Fidelity 120 strategies; e.g., Firszt et al., 2007), the electric field will follow the path of least resistance and more closely approximate that of the lower-impedance electrode in the pair. Theoretically, impedance differences between paired PEs should have no bias for devices that utilize independent current sources for current steering, which allow for controlled current from each contributing electrode regardless of individual electrode impedances. However, spread of excitation using current steering would still be subject to the resistive effects of the tissue surrounding the electrode

array. The effect of electrode impedance differences for paired PEs that utilize current steering remains to be investigated.

Although the data from the present study represent a rather small sample size, the results suggest that impedance differences between adjacent PEs should be considered if DE stimulation is implemented in future coding strategies or research studies. Perhaps future algorithms might disable specific DEs based on an empirically predetermined impedance difference between adjacent PEs. Regardless, DE stimulation yields lower impedances, which would be clinically beneficial for circumventing potential voltage compliance issues and reducing power consumption. Although the overall incidence of substantial impedance differences was small (8.8%), the present results provide valuable information to consider for development of future virtual-channel strategies.

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FIG. 1.

Electrically evoked compound action potential (ECAP) spread-of-excitation patterns for adjacent physical electrodes (circles) and the resulting dual electrode (squares) for 14 of the 15 electrode sets listed in Table 1. Data are not shown for set 2/3 for subject F13 because ECAPs could not be recorded for E3. Subject numbers, probe electrodes, and monopolar impedances are detailed on each graph. Graphs above the solid dividing line illustrate electrode sets that exhibited trends in the hypothesized direction.

FIG. 2.

Electrically evoked compound action potential (ECAP) spread-of-excitation patterns for seven electrode sets in three subjects with minimal impedance differences ($<3 \text{ k}\Omega$) between adjacent physical electrodes. Data are plotted as in Fig. 1.

FIG. 3.

Electrically evoked compound action potential (ECAP) separation index, Σ , (top row), percent correct for pitch ranking (middle row), and percent correct for electrode discrimination (bottom row) for all subjects and electrode pairs as a function of the impedance difference between contrasted pairs. Left column: Data from the study group with impedance differences >3.0 kOhms. Means and standard deviations for each comparison pair are shown with enlarged diamonds in respective shading and vertical bars. Right column: Data from the normative sample (<3.0 kOhms), reanalyzed from Hughes et

al. (2013) and Goehring et al. (2014). For both groups, means were calculated across electrode sets so that each subject contributed one value to the mean (see text). Comparisons that were significantly different are indicated with horizontal lines and asterisks.

Subject demographics and electrode sets tested. R=right, L=left, SNHL = sensorineural hearing loss. All ages and durations are in years, months.

Table 1

Subject	Device	Ear	Age at CI	Time post CI	Dur. Deaf	Etiology/ Onset	Electrode sets (> 3.0 kOhms difference)
N5	CI512	R	50, 8	1, 7	1, 0	Sudden SNHL	4/5, 12/13, 16/17, 18/19
F10	CI24RE(CA)	R	8, 3	6, 5	8, 3	Waardenburg Syndrome	16/17, 17/18, 19/20, 20/21
F13	CI24RE(CA)	L	35, 2	4, 2	8, 0	Unknown	2/3 *, 15/16, 18/19, 19/20
F15	CI24RE(CA)	L	22, 9	2, 2	22, 9	Congenital Unknown	17/18
F17	CI24RE(CA)	R	42, 11	6, 4	11, 0	Congenital, Progressive	1/2
FS22	CI422	L	13, 9	0, 3	12, 0	Menigitis	11/12

* Electrically evoked compound action potentials (ECAPs) could not be measured for E3.