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Cochlear Implant Speech Processor Frequency Allocations May Influence Pitch Perception

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Abstract

Objective—To investigate the effects of assigning cochlear implant speech processor frequencies normally associated with more apical cochlear locations to the shallow insertion depths of the Iowa/Nucleus Hybrid electrode.

Study design—Subjects using the Hybrid implant for more than one year were tested on speech recognition with CNC words and consonant stimuli. Pitch sensations of individual electrodes were also measured electrically through the implant and acoustically in the contralateral ear.

Setting—Tertiary Care Center

Results—Most subjects showed large improvements in speech recognition within 12 months after implantation. Further, after longer periods of 24+ months, some individuals were able to achieve high levels of consonant discrimination with electric only processing comparable to long-electrode patients with deeper electrode insertions. Pitch perceptions obtained from individual electrodes in these subjects were closer to the frequency map assigned an electrode than the place-frequency predicted from cochlear location.

Conclusions—These results suggest that over time, pitch sensations may be determined more by the implant map than by cochlear location. In other words, the brain may adapt to spectral mismatches by re-mapping pitch. Further, patients perform well with shifted frequency allocations for speech recognition. The successful application of shifted frequency allocations also supports the idea of shallower insertions and greater preservation of residual hearing for all cochlear implants, regardless of the patient's frequency range of usable residual hearing.

Introduction

In order to approximate the frequency tonotopicity of the normal cochlea, each electrode in a cochlear implant is positioned at a different location in the cochlea. Correct allocation of acoustic frequency to each electrode and location of stimulation may be important for speech recognition. Several studies in normal hearing listeners have shown detrimental effects of presenting speech spectrally shifted to the “wrong” cochlear place¹⁻³. Other studies suggest that listeners can adapt over time to spectrally shifted speech⁴⁻⁵. Implant users may also adapt partially to shifted frequency mappings⁶.

This question becomes increasingly relevant as we consider a new generation of implants designed to preserve residual hearing. One such type of implant is the Iowa/Nucleus Hybrid cochlear implant. At 10 mm long and only 0.2×0.4 mm in diameter, its insertion is limited to the lower basal turn of the cochlea. This short-electrode design provides electric speech information with just 6 electrodes to damaged high-frequency regions of the cochlea, which can be combined with the residual low-frequency acoustic hearing⁷.

This type of implant is well-suited for a common form of hearing loss, a mild-moderate hearing loss at low frequencies sloping to a severe-profound hearing loss at higher frequencies. In previously published results, residual hearing has been preserved to within an average of 13 dB in 48 Hybrid implant recipients⁸. The combination of electrical speech processing and the residual acoustic hearing has enabled this group of adults to improve their CNC word understanding from an average of 32% with 2 hearing aids to 72% with the use of 2 hearing aids and the Hybrid implant. Furthermore, because of the better frequency resolution of the preserved residual hearing, Hybrid patients perform significantly better than long electrode patients at melody recognition⁹ and at understanding speech in background babble¹⁰.

One concern about inserting the Hybrid implant only 10 mm into the scala tympani is that the limited length of the electrode limits access to the low frequency region of the cochlea. In the event that residual hearing is completely lost, low-frequency information could theoretically be provided through the most apical electrodes. However, this is not a useful option if severely shifted speech processor frequency allocations are detrimental to speech recognition.

In this paper, we describe long-term speech scores of a subset of Hybrid patients from the FDA multicenter clinical trial under various modes of stimulation: implant with binaural residual hearing (combined), implant with ipsilateral residual hearing (A+E), and implant alone (E). We also describe pitch sensations obtained from individual electrodes in these subjects over time, and how these pitch sensations may depend on the speech processor frequency allocations to each electrode.

Materials and Methods

Subjects

These studies were conducted according to the guidelines for the protection of human subjects as set forth by the Institutional Review Board (IRB) of the University of Iowa, and the methods employed were approved by that IRB.

Twenty adult Hybrid cochlear implant subjects, with ages ranging from 29 to 75 at age of implantation, participated in this study. Of these, 17 were implanted at Iowa and 3 (subjects 12, 15, and 20) were implanted elsewhere as part of the multicenter clinical trial.

The Hybrid subjects' ages, durations of implant use, average residual hearing and change in hearing loss after implantation, hearing aid use, processor type, and MAP frequency allocation range are shown in Table 1. Though there are only 20 subjects, the subject

numbers in Table I number as high as 25 because more than 20 Hybrid patients were studied at Iowa. No data for the other 5 subjects (subjects 9, 13, 14, 22, and 23) was collected for this study; 4 of these subjects were implanted elsewhere with data only collected for another study at their single visit, and 1 subject did not like the implant, became a non-user, and did not return for further testing.

Note the relatively low MAP frequency allocation ranges compared to the actual implant intracochlear location. The Hybrid implant is implanted approximately 10.5 mm from the cochlear base. When potential variability due to angle or cochlear length is accounted for, the Greenwood frequency-place function for the basilar membrane predicts a pitch sensation between 2800-4700 Hz for the most apical electrode¹²⁻¹³. The remaining electrodes would have correspondingly higher frequencies. Theoretically, the best frequency allocation range would be the one most similar to the normal place frequencies for those electrodes. In practice, Table 1 shows that given the choice of multiple allocations for the speech processor, Hybrid implant patients typically choose a lower and broader frequency allocation, most likely because the widest range of frequencies provides the greatest speech information.

Speech Recognition Testing

Speech perception was tested using subjects' everyday MAP frequency allocations (table of speech processor frequency allocations for each electrode) and signal processing strategies (all used ACE with rates ranging from 720 to 2400 pps). All subjects (N=20) were tested on consonant discrimination, but just the subjects from the Iowa section of the clinical trial (N=17) were tested on monosyllabic words.

Monosyllabic words—Subjects were tested on monosyllabic word recognition using Consonant-Nucleus-Consonant (CNC) word lists. The word list chosen was randomized across sessions, and in most cases presented twice and scores averaged over the two lists.

Performance was tested under three conditions: bilateral acoustic hearing without implant (aided or unaided), implant plus bilateral acoustic hearing (combined), and implant plus ipsilateral acoustic hearing (acoustic+electric). In the ipsilateral condition, the contralateral ear was plugged.

Consonants—Subjects were tested on discrimination of 16 consonants presented in a /a/-consonant-/a/ context and spoken by 4 different talkers¹⁴. Performance was tested under three conditions: ipsilateral acoustic-alone, acoustic+electric, and implant-alone (electric-only). The first two conditions were conducted via loudspeaker with the non-implant ear plugged *and* muffed (to provide >30 dB of attenuation, especially important for testing subjects with mild low-frequency hearing loss), while stimuli in the electric-only condition were presented via a direct electric connection. In most cases the consonant set was presented twice and scores averaged over the two presentations.

Electric to Acoustic Pitch Matches

Clinical software from Cochlear was used to stimulate a single electrode in the Hybrid implant, in this case electrode 6 or the most apical electrode in the implant. The electrode ground was monopolar (MP1+2). Electrical stimuli were presented at C-level, or “loud but comfortable” current level. A high pulse rate was used to “saturate” temporal effects on pitch perception, i.e. rates of at least 800 pulses per sec (pps), usually 1000 or 1200 pps, were used. No significant changes in pitch perception were observed with variations in current level or pulse rates above 800 pps¹¹.

Generally, three electric pulse trains were presented first, followed by an interstimulus interval delay, then three pulsed acoustic tones. Acoustic tones were randomly selected by the experimenter within a decreasing frequency range in order to bracket the matching pitch range. Subjects were instructed to rate whether the acoustic tone was higher, lower, or similar in pitch, while ignoring loudness. Acoustic tone frequency was varied until the range of similar pitches was bracketed. Data were not included if the patient was unable to perform acoustic-acoustic pitch ranking, or if the patient's responses were highly inconsistent within a single pitch matching session.

Results

Speech Testing

The results of speech testing under the combined, ipsilateral acoustic+electric, and electric-only modes are shown at 12 and 24+ months in Figs. 1, 2, and 3 respectively. 24+ months means any duration of implant use greater than 24 months, the scores from the latest testing are shown with durations for each subject indicated in Table 1.

Fig. 1 compares CNC word recognition under bilateral acoustic-alone (black bars) and combined modes (patterned bars) for 17 patients implanted at Iowa. The mean combined scores are significantly higher than the mean bilateral acoustic-alone scores. In fact, 13/17 patients performed about twice as well or better with the implant than without it. For patients with data at both 12 and 24+ months, most of the improvements occurred within 12 months.

Note that in 3 cases, residual hearing thresholds worsened by more than 30 dB between 12 and 24+ months (Table 1), but 2/3 of these subjects still maintained their improved speech recognition scores (S1, S6).

Figure 2 shows speech scores under the ipsilateral acoustic+electric mode. The CNC word recognition using the ipsilateral ear alone (mean 62% at 24+ months) is typically lower than the combined scores shown in Fig. 1 (mean 73% at 24+ months), but still much improved compared to bilateral acoustic-alone (mean 35%). Similarly to the combined mode, scores did not show additional improvements between 12 and 24+ months.

Fig. 2b shows that acoustic+electric consonant discrimination was also typically improved compared to ipsilateral acoustic-alone. As with CNC words, little additional improvement

was seen between 12 and 24+ months. Note that a smaller proportion of subjects (9/19) showed a large benefit under consonant discrimination than with CNC words.

Fig. 3a shows that electric-only consonant discrimination was highly variable across subjects. The individual data show that unlike with acoustic+electric scores, subjects often continued improving with electric-only recognition, with improvements seen for 6/9 subjects between 12 and 24+ months.

Some individuals performed surprisingly well on consonant recognition with the implant-alone. Figures 3b and 3c compare the distributions of test scores for Hybrid patients at 12 and 24+ months with test scores for long-electrode patients using a similar device and speech processing strategy. Compared to long-electrode patients' scores, Hybrid patient scores were not significantly different from long-electrode patients at either 12 or 24+ months ($p=0.055$ and 0.26 , respectively; rank-sum test).

Pitch Measurements

The results of across-ear acoustic-electric pitch matches for the most apical electrode in the Hybrid implant, electrode 6, are shown in Figs. 4 and 5.

Fig. 4 shows averaged estimates of pitch sensations for individual subjects (indicated by symbol/line shade) over the time of implant use, from hookup up to 5 years. Clearly, many individuals showed marked changes in pitch sensation through their implant over time, as observed previously¹¹. Note in particular that many patients with early high pitch sensations (S2, S6, S7, S8, S11, S22) showed a systematic drop over time, while patients with early low pitch sensations (S16, S19) showed the opposite trend, a slight increase over time. Other subjects varied more considerably (S10, S21, S25). The trends of pitch changes from high to low, and low to high, are toward an intermediate zone between 500-1500 Hz. Because implant speech processor frequency-electrode mappings typically assign speech information from these frequencies to electrode 6, this suggests a relationship of the observed pitch changes over time to the speech processor map.

To investigate a hypothesis that pitch sensations move over time toward the electrode's assigned MAP frequency, we plotted early and late pitch sensations relative to the electrode's assigned MAP frequency (Fig. 5, black and gray bars, respectively; octaves are used as a relative measure, where the closer the value is to zero, the closer the pitch is to the MAP frequency). Figure 5 shows that for the majority of subjects, changes from early to late pitch sensations do approach the electrode MAP frequency (the value approaches zero). For 6/11 subjects the early pitch matches were outside of the electrode's average MAP frequency range (dashed horizontal lines), but late pitch matches moved into this range. For 3/11 subjects, pitch matches were stable with both early and late pitch matches inside the range.

Discussion

Long-term speech recognition benefit

Clearly, for most patients, the Hybrid implant provides a significant benefit for speech recognition under everyday conditions, i.e. electric stimulation combined with bilateral

acoustic information. Specifically, word recognition scores are at least doubled in most subjects compared to pre-operative aided acoustic scores. This benefit remains high even under just ipsilateral acoustic+electric stimulation. Therefore, these patients are able to successfully integrate the acoustic and electric information from the same and opposite ears to understand speech.

When tested with consonant discrimination under the acoustic+electric mode, some patients showed a less measurable benefit than with CNC words. One likely reason for the difference may be the greater difficulty of the consonant test, due to the presence of multiple talkers and the lack of context cues, i.e. words, in the test. Another possible reason is that the CNC word test measures recognition of both vowels and consonants, and the implant may provide additional benefit for recognition of vowels.

Patients also performed comparatively well to long-electrode implant users on consonant discrimination with the implant alone (no acoustic information). This level of performance is surprising simply because of the fewer electrodes and limited range of nerve fibers stimulated. As will be discussed later, it is also surprising given the common spectral mismatch of MAPs to predicted place frequency of stimulation, as well as the mismatch to the residual acoustic hearing.

It should be noted that testing subjects in a condition that they do not use on a regular basis, i.e. implant + hearing aid on one side versus implant + binaural aids may not reflect true maximum achievable performance as the subject may require a significant period of adjustment to learn to use the limited information. Similarly, electric-only scores may not reflect the true maximum possible performance. In fact, the improvement in electric-only scores often appears to be correlated with a recent decrement in residual hearing. This trend is not directly observable when acoustic+electric scores are examined over time, as the overall score may remain the same while the relative contributions of acoustic and electric information are substantially altered with any decrement of residual hearing.

Potential for electric-only speech benefit

As mentioned in the introduction, one concern about the Hybrid implant has been the potential for complete loss of residual acoustic hearing. If low-frequency residual hearing is lost as a result of implantation trauma, the limited insertion depth means that electrical stimulation can only be provided to the basal, high frequency region of the cochlea, not the apical, low-frequency region. While there is the option of presenting the lost low-frequency information to the electrodes present in the cochlear base, several studies suggest detrimental effects of presenting speech spectrally shifted to the “wrong” place frequencies in normal hearing listeners¹⁻³ and regular implant users^{6,15},

The finding here that some Hybrid patients perform comparably to the best long-electrode implant users *with the implant alone* suggests otherwise.

This positive result is similar to more recent studies suggesting that normal hearing listeners can adapt over time to spectrally shifted speech⁴⁻⁵. In other words, the previous studies¹⁻³ may not have given subjects enough time to adapt to the new frequency shifts. Consistent

with this interpretation, Hybrid patients also required a significantly longer time to adapt to the frequency shifts, as indicated by the large improvement in speech recognition with the implant alone from 12 to 24+ months.

Relationship of speech processor maps to changes in perceived pitch over time

Since the most apical electrode in the Hybrid implant is implanted approximately 10.5 mm from the cochlear base, the Greenwood frequency-place function predicts a pitch sensation between 2800-4700 Hz¹²⁻¹³.

The finding here and in previous studies¹¹ suggests that pitch sensations perceived through a cochlear implant electrode are not necessarily fixed at the predicted cochlear place-frequency of stimulation, but may actually change systematically over time. Possible, but unlikely, explanations for these changes include diplacusis and changes in residual hearing¹¹. Another possibility suggested by the data in Fig. 5 is the spectral mismatch between the frequencies allocated to the electrode by the processor and what the patient is used to hearing, or between the allocated frequencies and the residual acoustic hearing. This mismatch may cause central changes such that the pitch perceived through each electrode changes over time to alleviate any perceived mismatch.

The long time scales of these pitch changes, of 12 months or longer, are on the same scale observed for adaptation to using the implant alone. It is possible that the changes in pitch and electric-only speech perception are linked, although no correlation was observed over the short term¹¹. The larger variability in electric-only scores compared to acoustic+electric scores across subjects may also be related to patients' ability to adapt to spectral mismatches between pitch sensation and speech processing, or between speech heard acoustically and electrically; certain patients, e.g. older patients, may be less able to adapt.

Implications

Clearly, Hybrid implant patients are able to adapt to spectral mismatches introduced by providing a relatively broad speech frequency range to the high-frequency region of the cochlea. This adaptation may be possible because of changes in absolute pitch sensation over time for a given electrode, and may even drive the observed pitch changes.

This result implies that equivalent speech information can potentially be provided with a shorter electrode and a regular long electrode. Therefore, given the additional qualitative and background noise benefits of preserving residual hearing, a shorter version of the regular cochlear implant may be beneficial for regular implant candidates, as well as those targeted in the initial Hybrid clinical trial.

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Figure 1.

Comparison of CNC word recognition scores for Hybrid patients for pre-operative bilateral acoustic mode versus the combined mode (implant combined with bilateral acoustic, aided or unaided) after implantation. Shown are individual scores for the pre-operative, bilateral acoustic mode (black bars), the combined mode (striped bars) at 12 months; and the combined mode at 24+ months (stippled bars). Clearly, most patients show large improvements within 12 months.

Figure 2.

Distribution of speech scores for Hybrid patients tested under the Hybrid mode (ipsilateral acoustic+electric = A+E, i.e. implant combined with ipsilateral acoustic only). A) CNC word scores at 12 (striped bars) and 24+ months (stippled bars). While scores are slightly lower, results are similar to those for the combined mode. B) Consonant discrimination scores at 12 (striped bars) and 24+ months (stippled bars); ipsilateral acoustic-alone (A-alone) scores are shown for comparison (black bars).

Figure 3.

Electric-alone (implant-only) consonant discrimination scores. A) Consonant discrimination scores for individual Hybrid patients at 12 (striped bars) and 24+ months (stippled bars). Unlike the results for combined and Hybrid acoustic+electric modes in Figs. 1 and 2, there is often additional improvement between 12 and 24+ months. Also shown are comparisons of long-electrode and Hybrid scores at 12 months (B) and 24+ months (C). While the differences are not significant in either case (rank-sum test), the Hybrid scores at 24+ months (C, black bars; mean=51%, s.d.=20.7) are more similar in range to the long-electrode scores (B&C, gray bars; mean=51%, s.d.=16.7) than the Hybrid scores at 12 months (B, black bars; mean=38%, s.d.=18.7).

Figure 4.

Pitch sensations and speech performance of individual subjects plotted over time. Clearly, mean values of pitch matches of the most apical electrode (electrode 6) tended to change after 12 or more months of implant use (indicated by vertical dotted line), sometimes by more than 2 octaves. Different symbols and line shades indicate different individual subjects. Only mean values of pitch matches are shown for clarity.

Figure 5.

Relationships of pitch matches to the preferred processor MAP frequency bands for electrode 6 for individual subjects. Both early (black bars) and late (grey bars) pitch matches are shown. Pitch results are plotted relative to speech processor frequency allocation range, i.e. divided by the MAP band center frequency, to show how they are related to the frequency allocation. Octaves are used as a logarithmic measure of this difference. A value near 0 indicates that the pitch match was close to the band center frequency. The dashed horizontal dotted lines show the average range of the MAP frequency band for electrode 6. Standard deviations are indicated by vertical lines when multiple pitch matches were obtained. Only subjects with both early and late pitch match data are shown, with the months of implant use corresponding to these pitch matches indicated next to the bars. The data show that subjects often have pitch changes approaching the electrode map frequency.

Hybrid Subjects Demographic Data

Table 1

Hybrid subjects' ages, durations of implant use at time of CNC word and consonant testing, average ipsilateral and contralateral residual hearing at latest testing, average change in ipsilateral residual hearing between pre-op or hookup to 12+ months of implant use, hearing aid use, speech processor, and lower and upper bounds of frequency range allocated to electrode 6 (the most apical electrode in the Hybrid implant array). The residual hearing measurements are averaged over 125, 250, 500, and 750 Hz. The lower bound for electrode 6 indicates the lower bound for the total speech processor MAP frequency range, as well. The upper bound for the total range is ~8000 Hz for all subjects. Note that most subjects have lower bounds for implant processor allocations of 1068 Hz and lower. Hearing aid use: b=both, c=contralateral only, i=ipsilateral only, n=no aids, t=used hearing aid(s) at first, - indicates only ipsilateral usage known. Single asterisk indicates only 5 electrodes activated in those subjects. Double asterisks indicates subject who was implanted with a regular long-electrode in the contralateral ear after the large loss of residual hearing in that ear, after 24 months of Hybrid use in the other ear. Plus sign indicates subject who lost hearing ~6 months after tested at 12 months; the speech data shown reflect performance before substantial loss of hearing

Subject ID	Age Implanted	Months CNC	Months a/C/a	Ipsi Mean HL, dB	Ipsi mean change in HL, dB	Contra Mean HL, dB	Contra mean change in HL, dB	Hearing aid use	Processor	Electrode 6 LB, Hz	Electrode 6 UB, Hz
1	57	60	60	72.5	33	65	25	c	SPRINT	688	1063
2	51	60	60	61.25	9	55	3	b	SPRINT	688	1063
3	29	48	39	56.25	14	48	21	bt	3G	688	1063
**4	57	24	37	75	40	89	59	bt	SPRINT	688	1063
5*	64	36	48	77.5	21	58	14	b	SPEAR	1000	1516
6*	48	36	36	77.5	38	49	10	i	SPEAR	750	1204
7	69	36	36	100	55	56	5	c	SPRINT	688	1063
8	65	36	36	40	15	25	4	b	SPRINT	1063	1438
10	65	24	37	52.5	-1	39	3	b	SPRINT	1063	1438
11	47	24	24	45	-1	46	3	bt	SPRINT	688	1063
12		DNT	12	56.25	13	45	-1	n-	SPEAR	750	1113
15		DNT	24	45	-3	46	0	i-	SPEAR	2000	2330
16	59	18	12	47.5	6	38	6	b	FREEDOM	688	1063
17	51	12	12	30	3	36	8	b	SPRINT	1063	1438
18+	55	12	12	105	56	43	3	b	FREEDOM	688	1063

Subject ID	Age Implanted	Months CNC	Months a/C/a	Ipsi Mean HL, dB	Ipsi mean change in HL, dB	Contra Mean HL, dB	Contra mean change in HL, dB	Hearing aid use	Processor	Electrode 6 LB, Hz	Electrode 6 UB, Hz
19	75	12	12	48.75	11	24	-3	b	FREEDOM	688	1063
20		DNT	15	57.5	15	41	6	b	SPEAR	750	1113
21	49	12	18	41.25	6	28	0	b	FREEDOM	688	1063
22	74	12	DNT	43.75	1	35	-4	b	FREEDOM	688	1063
25	49	12	12	23.75	1	23	3	b	FREEDOM	1063	1438

Hearing aid use: b=both, c=contralateral only, i=ipsilateral only, n=no aids, t=used hearing aid(s) at first, - indicates only ipsilateral usage known

* only 5 electrodes activated

** this subject was implanted with a regular long-electrode in the contralateral ear after the large loss of residual hearing in that ear, after 24 months of Hybrid use in the other ear.

+ this subject lost hearing ~6 months after tested at 12 months; the speech data shown reflect performance before substantial loss of hearing.