Published in final edited form as:

Ear Hear. 2010 April ; 31(2): 195–201. doi:10.1097/AUD.0b013e3181c4758d.

Frequency overlap between electric and acoustic stimulation and speech-perception benefit in patients with combined electric and acoustic stimulation

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Abstract

Objectives—Our aim was to assess, for patients with a cochlear implant in one ear and low-frequency acoustic hearing in the contralateral ear, whether reducing the overlap in frequencies conveyed in the acoustic signal and those analyzed by the cochlear implant speech processor would improve speech recognition.

Design—The recognition of monosyllabic words in quiet and sentences in noise was evaluated in three listening configurations: electric stimulation alone, acoustic stimulation alone, and combined electric and acoustic stimulation. The acoustic stimuli were either unfiltered or low-pass (LP) filtered at 250 Hz, 500 Hz, or 750 Hz. The electric stimuli were either unfiltered or high-pass (HP) filtered at 250 Hz, 500 Hz or 750 Hz. In the combined condition the unfiltered acoustic signal was paired with the unfiltered electric signal, the 250 LP acoustic signal was paired with the 250 Hz HP electric signal, the 500 Hz LP acoustic signal was paired with the 500 Hz HP electric signal and the 750 Hz LP acoustic signal was paired with the 750 Hz HP electric signal.

Results—For both acoustic and electric signals performance increased as the bandwidth increased. The highest level of performance in the combined condition was observed in the unfiltered acoustic plus unfiltered electric condition.

Conclusions—Reducing the overlap in frequency representation between acoustic and electric stimulation does not increase speech understanding scores for patients who have residual hearing in the ear contralateral to the implant. We find that acoustic information below 250 Hz significantly improves performance for patients who combine electric and acoustic stimulation and accounts for the majority of the speech-perception benefit when acoustic stimulation is combined with electric stimulation.

It is now well established that cochlear implant patients who have low-frequency acoustic hearing, either in the ear contralateral to the implant or in the same ear as the implant, benefit significantly from the combination of acoustic and electric stimulation (e.g., Shallop et al, 1992; Armstrong et al., 1997; von Ilberg et al., 1999; Tyler et al., 2002; Ching et al., 2004; Gantz, & Turner, 2004; Gstöettner et al., 2004; Kiefer et al., 2004; Turner et al., 2004; Kong, Stichney & Zeng, 2005; Gifford et al., 2007; Dorman et al., 2008; Mok et al., 2008). Both speech understanding in quiet and speech understanding in noise are improved significantly when patients have access to both electric (E) and acoustic (A) stimulation (EAS).

Many EAS patients have acoustic sensitivity to frequencies over the range 125 Hz to 500-750 Hz. If the cochlear implant signal processors for these patients are configured in the default configurations, then, depending on the manufacturer, input filters will respond to frequencies between 200-300 Hz at the low-frequency end of the spectrum and to 5-7 kHz at the high-frequency end. If this is the case, then frequencies between approximately 250 Hz and 750 Hz

will have both an acoustic representation and an electric representation. Lawson et al. (2000) described this situation as one of ‘stimulus overlap’ and suggested, without elaboration, that stimulus overlap might have either a negative effect on speech understanding or a beneficial effect.

Concern about a negative effect of stimulus overlap dates to the first publication on an EAS patient with significant low-frequency hearing (von Ilberg et al., 1999). In the same paper in which they described the synergy between electric and acoustic hearing, von Ilberg et al. (1999) described experiments with cats in which tuning curves were measured for single fibers in conditions of acoustic stimulation, electric stimulation and combined electric and acoustic stimulation. Overall, there were no major changes in response area in EAS conditions as compared to acoustic only conditions. von Ilberg et al. (1999) concluded that simultaneous electric and acoustic stimulation of the auditory system ‘does not substantially impair information transfer.’

Wilson’s research group at Research Triangle Institute has probed the issue of stimulus overlap in several ways. Brill et al. (2001) measured the thresholds of acoustic stimuli with and without concurrent stimulation at electrode 1. In the presence of electrical stimulation, auditory thresholds were little altered. On the other hand, acoustic broad band noise had a substantial effect on the threshold of an electric stimulus.

In the type of experiment reported in this paper, Wilson et al. (2002) manipulated the electrical bandwidth for five ipsilateral EAS patients (electric and acoustic stimulation to the same ear) to create conditions that optimized or minimized stimulus overlap. To maximize stimulus overlap the electric bandwidth was set to 350 - 5500 Hz. To minimize overlap the electric bandwidth was set to 600 – 5500 Hz. Speech recognition scores were significantly higher in the minimum overlap condition than in the maximum overlap condition for one patient. Using similar filter conditions, Kiefer et al. (2005) reported that only 1 of 11 patients performed better in the minimum overlap condition.

In contrast Fraysse et al. (2006) reported that 7 of 9 ipsilateral EAS patients preferred minimum stimulus overlap. However, over a span of 1 to 3 months speech recognition scores were equivalent for the minimum and maximum overlap configurations. Vermeire, Anderson, Flynn and Van de Heyning (2008) reported consistent beneficial effects on speech intelligibility of reduced stimulus overlap. These researchers investigated the influence of different cochlear implant configurations and hearing aid fittings on sentence recognition in noise at +5, +10 and +15 dB SNR in four subjects with electric and acoustic hearing in the same ear. The results showed that the minimum overlap condition allowed the best scores in three out of four subjects.

The conflicting results of the studies reviewed above led us to revisit the issue of stimulus overlap in patients who combine electric and acoustic stimulation. In this paper we examine the issue of stimulus overlap for EAS patients for whom electric and acoustic information is delivered to *different* ears. EAS patients of this type are more numerous by several orders of magnitude than EAS patients who receive electric and acoustic stimulation in the same ear. For that reason our results have relevance to a large number of patients.

We evaluated the recognition of monosyllabic words in quiet and sentences in noise in three listening configurations: electric stimulation alone, acoustic stimulation alone, and combined electric and acoustic stimulation. The acoustic stimuli were either unfiltered (wideband) or LP filtered at 250 Hz, 500 Hz, or 750 Hz. The electric stimuli were either wideband or HP filtered at 250 Hz, 500 Hz or 750 Hz. In the combined condition the wideband acoustic signal was paired with the wideband electric signal, the LP 250 Hz acoustic signal was paired with the HP 250 Hz electric signal, the LP 500 Hz acoustic signal was paired with the HP 500 Hz electric

signal and the LP 750 Hz acoustic signal was paired with the HP 750 Hz electric signal. The central issue in this experiment was whether, in the combined conditions, any of the LP acoustic plus HP electric signals yielded higher scores than the wideband acoustic plus wideband electric signal.

METHOD

Listeners

Eight, adult, postlingually-deafened, cochlear implant users were recruited. All were fitted with a conventional implant in one ear and seven subjects used a hearing aid in the contralateral ear. One (Subject 6) did not choose to wear a hearing aid. All subjects had residual hearing with thresholds ≤ 65 dB HL at 500 Hz and below, and thresholds ≥ 65 dB HL at 1000 Hz and above. The individual audiograms for the nonimplanted ears are shown in Figure 1. Table 1 displays demographic information for each subject. At the time of testing, all subjects had at least 4 months experience with electric stimulation (range = 4 months to 5 years) and all subjects except for S6 had at least 5 years of experience with amplification prior to implantation. Informed consent procedures were approved by the Institutional Review Board at Arizona State University.

Speech stimuli and test conditions

Monosyllabic word recognition was tested using the CNC word lists (Peterson & Lehiste, 1962). Sentence recognition was tested using the AzBio sentences (Spahr & Dorman, 2005) organized into 33 lists of 20 sentences (Gifford, Shallop & Peterson, 2008). These sentences, with 6 to 10 words, were recorded by 4 talkers (2 male & 2 female) using a casual speaking style. The sentence lists were constructed to have an equal number of sentences spoken by each of the talkers and to have a similar level of intelligibility.

The recognition of CNC words in quiet and AzBio sentences in the presence of a competing 20-talker babble at +10 dB SNR was evaluated in three stimulation conditions: (i) E stimulation alone - signals were presented via direct input to the cochlear implant; (ii) A stimulation alone - signals were presented via earphone to the non-implanted ear; and (iii) EAS - signals were simultaneously presented to the implanted ear via direct input and to the non-implanted ear via earphone.

In both the E and EAS conditions, the electric signals presented to the cochlear implant were high-pass filtered at 250 Hz, 500 Hz or 750 Hz, or presented wideband. The actual bandwidth of the wideband electric signal was subject to the default configuration of each subject's cochlear implant signal processor, in which the band pass of the input filters was typically configured at 250-350 Hz at the low-frequency end and 5-7 kHz at the high frequency end. In the both A and EAS conditions, the acoustic signals were low-pass filtered at 250 Hz, 500 Hz, or 750 Hz, or presented wideband. The bandwidth of the wideband acoustic signal was 0-10k Hz. All filters were implemented in MATLAB by specifying a 256th order FIR filter to achieve a 90-dB/octave roll-off. The conditions are described by the filter cutoff frequency: (i) 250LP, 500LP, 750LP, and wideband for the A conditions; (ii) 250HP, 500HP, 750HP and wideband for the E conditions; and (iii) 250+250, 500+500, 750+750, and wideband+wideband for the EAS conditions. Because the low-frequency cutoff for the most apical electrode of subjects' cochlear implant signal processors was, depending on the manufacturer, configured between 200-300 Hz (see Table 1), the 250HP and wideband for the E conditions were essentially identical. The 250HP for the E condition was included in the present study in order to retain a symmetrical design across the A, E, and EAS conditions.

Monosyllabic word (CNC) understanding in quiet and sentence (AzBio) understanding in noise was evaluated in a total of 12 conditions. Testing in all three listening configurations began with the wideband stimuli. Within each filtered condition in the three configurations, the condition order was randomized and counterbalanced among listeners. For both words and sentences, the list-to-condition assignments were randomized for each listener. However, with 10 CNC word lists and 12 conditions, the word lists used in the A-alone 250LP and 500LP condition, where recognition scores were < 10% correct, were also assigned to other listening conditions. A novel sentence list was used in each condition. Prior to testing, listeners were allowed a brief practice session in each condition.

Presentation of speech stimuli

Direct input to the cochlear implant in the E and EAS configurations was accomplished using the external audio patch cables provided by the cochlear implant companies. Listeners were tested using their 'everyday' speech coding program. The presentation level of the electric stimuli was verified as being 'comfortably loud' by each listener.

Signals were presented to the non-implanted ear in both the A and EAS configurations via an insert earphone (Etymotic ER-1). To accommodate for the different degrees of hearing loss in our population, acoustic signals were subjected to the frequency-gain characteristic prescribed by NAL-RP formula (see Appendix). The maximum gain applied to acoustic stimuli was limited to 50 dB at any frequency.

The final presentation level of the acoustic stimuli was determined by a loudness matching method to equate the electric and acoustic signals. This was accomplished by alternating the presentation of a wideband signal to the cochlear implant and the presentation of an amplified, wideband signal to the earphone. Listeners used a response card to indicate whether the sound presented through the earphone was louder or softer than the signal presented to the cochlear implant. The response card used a continuous scale, labeled with 'softer' and 'louder' at the end points and 'same' at the midpoint. The overall gain applied to the signal presented to the earphone was adjusted until the listener reported similar loudness in the two ears. The overall gain setting which yielded the equal loudness rating in the wideband setting was applied to all acoustic stimuli in filtered conditions for both the A-alone and EAS configurations.

RESULTS

CNC words

Figure 2 shows recognition accuracy for CNC words as a function of filter cutoff frequency and as a function of stimulation condition. A two-way repeated-measures ANOVA revealed a significant main effect for the filter cutoff frequency ($F_{(3,21)} = 95.2, p < 0.001$) and for the stimulation condition ($F_{(2,14)} = 23.4, p < 0.001$). There was a significant interaction ($F_{(6,42)} = 15.8, p < 0.001$).

Effects of filtering—An analysis of the main effect for the filter cutoff frequency revealed that the mean word recognition scores were influenced by the filter cutoff frequency for the A condition ($F_{(3,5)} = 11.5, p < 0.05$) and the E condition ($F_{(3,5)} = 7.1, p < 0.05$) but not for the EAS condition ($F_{(3,5)} = 4.4, p > 0.05$). A post hoc, pairwise comparison (Fisher's LSD) revealed that in the A condition the mean word recognition scores for the 250LP, 500LP, 750LP, and wideband conditions were significantly different from one another ($p < 0.05$). In the E condition, the mean word recognition scores for the 250HP, 500HP, and 750HP conditions were significantly different from one another ($p < 0.05$). The score for the wideband condition was not significantly different from that for the 250HP condition ($p > 0.05$) but was significantly higher than those for the 500HP and 750HP conditions ($p < 0.05$).

AzBio sentences at +10 dB SNR

Figure 3 shows recognition accuracy for AzBio sentences in noise at +10 dB SNR as a function of filter cutoff frequency and as a function of stimulation condition. A two-way repeated-measures ANOVA revealed significant a main effect for the filter cutoff frequency ($F_{(3,21)} = 19.2, p < 0.001$) and for the stimulation condition ($F_{(2,14)} = 53.3, p < 0.001$). There was a significant interaction ($F_{(6,42)} = 10.8, p < 0.001$).

Effects of filtering—An analysis of the main effect for the filter cutoff frequency revealed that the mean sentence recognition scores were influenced by the filter cutoff frequency for the A condition ($F_{(3, 5)} = 8.1, p < 0.05$) and the E condition ($F_{(3, 5)} = 48.7, p = 0.000$) but not for the EAS condition ($F_{(3, 5)} = 2.7, p > 0.05$). For the A condition a post hoc pairwise comparison (Fisher's LSD) revealed that the mean sentence recognition scores for the 250LP, 500LP, 750LP, and wideband conditions were significantly different from one another ($p < 0.05$). For the E condition the mean sentence recognition scores for the 250HP, 500HP, and 750HP conditions were significantly different from one another ($p < 0.05$). The score for the wideband condition was not significantly different from that for the 250HP condition ($p > 0.05$) but was significantly higher than those for the 500HP and 750HP conditions ($p < 0.05$).

DISCUSSION

The goal of this research was to assess, for patients with a cochlear implant in one ear and low-frequency hearing in the contralateral ear, whether reducing the stimulus overlap in electric and acoustic hearing would be beneficial to speech recognition. We chose our patients so that most would have significant acoustic hearing at 500 Hz and 750 Hz. We made this choice in order to maximize the possibility of stimulus overlap in the EAS conditions and to maximize the possibility of showing an advantage for reduced stimulus overlap. However, all of our subjects achieved the highest level of speech recognition in both quiet and noise with the widest acoustic frequency range and the widest cochlear implant frequency range. We find no benefit from reduced frequency overlap.

The negative effect of reducing information in the electric stimulus

Our finding of no benefit from reduced frequency overlap stems largely from the negative effect of high-pass filtering the electric signal. In the E condition, the scores for both CNC words and AzBio sentences in noise in the 500HP and 750HP conditions were significantly lower than those in the wideband condition. This finding is consistent with the results of von Ilberg et al. (1999) and Wilson et al. (2002) who, for a small number of patients, showed a performance advantage with the widest analysis band for electric-only stimulation. These outcomes document a speech-recognition advantage for the full frequency range over the reduced frequency range of the electric signal. We can infer that apical electrodes, which are effectively turned off by the action of the high-pass filtering, convey a significant amount of low-frequency information. Thus, our data suggests that clinicians should initially program cochlear implant signal processors for EAS patients using the standard low-frequency cutoff for the most apical electrode before making any further adjustment.

In the E condition, the scores for both CNC words and AzBio sentences in the 250HP condition were essentially identical to those in the wideband condition. This is reasonable because, as noted in the Methods section, the low-frequency cutoff for the most apical electrode of cochlear implant signal processors is typically configured between 200-300 Hz. Therefore, from the point of view of the patient, the signals in the 250HP and wideband conditions were the same.

The use of a 200-300 Hz low frequency cutoff for the most apical electrode in modern signal processors avoids a dual, and possibly misleading, representation of frequencies under 250 Hz.

Even when a signal is high pass filtered at 250 Hz, a male F0 of 125 Hz for example, will appear as an 8 ms period in the time waveform in each channel of a signal processor. Thus, this signal component is represented correctly in the time waveform and this signal is correctly perceived as an appropriately low pitch by implant patients.

By high pass filtering the speech signal at 250-350 Hz, the energy in the 125 Hz component is reduced and therefore the energy of the first formant frequency is better represented in the outputs of the bandpass filters with the lowest center frequencies, without the potential confound of also including the 125 Hz component which is not related to the first formant. In addition, the place of stimulation for the most apical electrode is commonly much higher than 125 Hz (Boex et al., 2006; Dorman et al., 2007). Reducing the amplitude of the 125 Hz component allows a better alignment between the effective place of excitation in the cochlea and the represented frequencies in the acoustic input.

Comparison with previous studies

Our finding is consistent with the majority of the findings from patients who have electric and acoustic stimulation delivered to the same ear. No significant benefit of a reduced overlap map was observed in the study of Gantz and Turner (2003). Wilson et al. (2002) and Kiefer et al. (2005) reported all but one subject preferred the full cochlear implant frequency range. A large benefit from the reduced frequency overlap was reported by Vermeire et al. (2008). Three of four subjects performed better with a reduced overlap of cochlear implant and hearing aid amplification across listening conditions. The different results of our study and those of Vermeire et al. (2008) could be due to a number of factors.

First, we presented the acoustic stimulus to the ear contralateral to the implant. In Vermeire et al. (2008) the acoustic stimulus was presented to the implanted ear. This is unlikely to be the reason for the different outcomes because Kiefer et al (2005) also presented the acoustic signal to the implanted ear and obtained the same results as we did.

Second, the patients in our study had better residual acoustic hearing at frequencies over 500 Hz than the patients in Vermeire et al. (2008). Most of our patients had audible thresholds up to 1-1.5k Hz. The one subject in Vermeire et al. (2008) who had residual hearing similar to that of most of our subjects also preferred using a wider acoustic frequency range and a full cochlear implant frequency range. Thus, the amount of residual hearing may play a role in determining whether stimulus overlap is detrimental or not.

Another difference between the Vermeire et al. (2008) experiment and our experiment was that our patients were presented the acoustic signals via a headphone rather than a hearing aid. We chose to use the headphone in order to better control the acoustic characteristics of the input. It is possible that the amplification gain for the acoustic signal would have been slightly different if the issues of subjects' hearing aid fitting had been considered (e.g., the fitting formula, the power of the hearing aid, and the vent of the hearing aid mold). It is also the case that the hearing aids in Vermeire et al. (2008) used VoiceFinder (Oticon, Smørum, Denmark) technology that adjusted the amplification of the hearing aid based on the characteristics of the input signal. When speech was present, the full amplification (gain) of the hearing aid was provided. When speech was absent, the hearing aid provided less amplification.

The value of information under 250 Hz

In Tables 2 and 3 we replot some of the data displayed in Figures 1 and 2. The scores in the first rows of Tables 2 & 3 document the benefits of adding acoustic information under 250 Hz to an electric signal that has been high-pass filtered at 250 Hz. For CNC words performance improves by 21 percentage points; for sentences at +10 dB SNR performance improves by 31

percentage points. This finding demonstrates the value of adding *very* low-frequency acoustic information to the electric signal and suggests that patients with hearing only at 125 Hz may benefit from EAS.

The scores in Tables 2 and 3 also document that the majority of the benefit from adding wide-band, low-frequency acoustic information to electric stimulation is derived from information in the acoustic band below 250 Hz. For CNC words, performance in the 250 LP acoustic plus 250 HP electric condition (essentially identical to the 250 LP acoustic plus wideband electric condition as mentioned above) was 94% of the performance level in the wideband acoustic plus wideband electric condition. For sentences in noise, performance in the 250 LP acoustic plus 250 HP electric condition (essentially identical to the 250 LP acoustic plus wideband electric condition as mentioned above) was 84% of level of performance in the wideband acoustic plus wideband electric condition.

Because acoustic information below 250 Hz accounts for the majority of EAS benefit and adding more acoustic information above 250 Hz to electric stimulation does not lead to significant, further improvement in speech recognition performance, in real clinical practice reducing the amplification of hearing aids in the high frequency range (i.e., no amplification for frequencies one octave above the dead regions) may be beneficial for EAS patients in considering the issues such as feedback, off-frequency listening, and prolonged battery life.

Trading electric and acoustic information

Tables 2 & 3 demonstrate the effect of transferring information above 250 Hz from the electric signal to the acoustic signal. Increasing the high-pass cutoff frequency in the E conditions removes information and produces incremental drops in performance. Increasing the low-pass cutoff frequency in the A conditions adds information and allows incremental improvements in performance. In the EAS conditions, increasing the cutoff frequency from 250 to 750 Hz effectively transfers information from the electric signal to the acoustic signal. It was expected that the acoustic hearing might provide a better representation of F1 than the electric hearing and, therefore, allow a higher level of performance. However, the results demonstrate that this transfer of information had no effect on performance in the EAS condition. One possible explanation for this outcome is that both the acoustic and electric representations of speech features in the 250 – 750 Hz band are sufficient to support a high level of performance in the presence of low frequency (< 250 Hz) acoustic and high frequency (>750 Hz) electric signals. An alternate explanation is that presenting low frequency information acoustically and high frequency information electrically reduces the listener's reliance on the 250 – 750 Hz region. Thus, listeners might have been unaffected by omitting this information from the signal entirely through a band-reject filter. However, this condition was not tested in the current study.

Finally, we have replicated, for electric and acoustic stimulation delivered to opposite ears, the large synergistic effects reported by others for electric and acoustic stimulation delivered to the same ear. For example, Gstöettner et al. (2004) report a patient with a 6% correct sentence score with a hearing aid, a 39% correct score with a cochlear implant, and a 90% correct score when stimulation was from both the implant and hearing aid. As shown in Tables 2 and 3, we find similar synergy. Indeed, we find extreme cases of synergy in the 250 HP electric plus 250 LP acoustic conditions. For CNC words, a mean score of 0% correct in the A condition combined with a mean score of 41% correct in the E condition produced a mean score of 72% correct in the EAS condition. For sentences in noise, a mean score of less than 1% correct in the A condition combined with a mean score of 59% correct in the E condition produced a mean score of 80% correct in the EAS condition. Thus, acoustic signals that allow no speech intelligibility in isolation can provide a large benefit to speech understanding when combined with electrical stimulation (see Chang, Bai, & Zeng (2006) for a similar finding from acoustic

simulation data). Given this outcome clinicians should routinely give consideration to aiding the ear contralateral to an implant for patients who have residual hearing in that ear.

CONCLUSIONS

- Eliminating or reducing stimulus overlap between acoustic and electric stimulation is not beneficial for patients who use a cochlear implant in one ear and who have low-frequency hearing in the other ear. Thus, clinicians should initially program cochlear implant signal processors for EAS patients using the standard low-frequency cutoff for the most apical electrode.
- Low-frequency acoustic information below 250 Hz, which in isolation allows little or no speech intelligibility, significantly improves performance for EAS patients and accounts for the majority of the speech-perception benefit when acoustic stimulation is added to electric stimulation. For this reason clinicians should attempt to aid the ear contralateral to an implant if that ear has low-frequency residual hearing.

APPENDIX

National Acoustic Laboratories (NAL)-RP formulas for calculating required real-ear insertion gain (REIG) as a function of frequency (HTL = Hearing threshold level) (Byrne & Dillon, 1986; Byrne, Parkinson & Newall, 1990). The REIG values were not full-on gains but were prescribed gains with use of overall volume control.

1. Calculate $X_{dB} = 0.05 \times (HTL_{500} + HTL_{1000} + HTL_{2000} \text{ up to } 180 \text{ dB}) + 0.116 \times \text{combined HTL in excess of } 180 \text{ dB}$.
2. Calculate the prescribed REIG at each frequency:

$$\begin{aligned} REIG_{250} (dB) &= X + 0.31 HTL_{250} - 17 & REIG_{2000} (dB) &= X + 0.31 HTL_{2000} - 1 \\ REIG_{500} (dB) &= X + 0.31 HTL_{500} - 8 & REIG_{3000} (dB) &= X + 0.31 HTL_{3000} - 2 \\ REIG_{750} (dB) &= X + 0.31 HTL_{750} - 3 & REIG_{4000} (dB) &= X + 0.31 HTL_{4000} - 2 \\ REIG_{1000} (dB) &= X + 0.31 HTL_{1000} + 1 & REIG_{6000} (dB) &= X + 0.31 HTL_{6000} - 2 \\ REIG_{1500} (dB) &= X + 0.31 HTL_{1500} + 1 & REIG_{8000} (dB) &= X + 0.31 HTL_{8000} - 2 \end{aligned}$$
3. When the 2000-Hz HTL is 95 dB or greater, add the following gain (dB) values to prescribe more gain in the low frequencies and less gain in the high frequencies..

Frequency (Hz)									
HTL 2 kHz	250	500	750	1000	1500	2000	3000	4000	6000
95	4	3	1	0	-1	-2	-2	-2	-2
100	6	4	2	0	-2	-3	-3	3	-3
105	8	5	2	0	-3	-5	-5	-5	-5
110	11	7	3	0	-3	-6	-6	-6	-6
115	13	8	4	0	-4	-8	-8	-8	-8
120	15	9	4	0	-5	-9	-9	-9	-9

Acknowledgments

The research reported here was supported by an award from NIDCD (R01 DC-00654-15) to the second author and was one of three experiments conducted by the first author in fulfillment of requirements for the Ph.D. degree at the University of Maryland.

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Figure 1.
Individual hearing thresholds for the nonimplanted ear.

Figure 2. Percent correct scores for CNC words as a function of filter condition. LP = low pass. HP = high pass. wb = wideband.

Figure 3. Percent correct scores for AzBio sentences at +10 dN SNR as function of filter condition. LP = low pass. HP = high pass. wb = wideband.

Table 1

Subject demographics including age, sex, etiology of hearing loss, duration of hearing loss both in the implanted and nonimplanted ear, processor type and strategy, low-frequency cutoff for the most apical electrode, duration of experience with the implant and hearing aids, hearing aid device in the nonimplanted ear, and hearing aid use post operatively in the nonimplanted ear.

Subject	Age	Sex	Etiology	Duration of hearing loss ^a (NIE)	Duration of hearing loss ^a (IE)	CI experience	CI devices	Low-frequency Cutoff for the most apical electrode	HA Experience (NIE) (yrs)	HA models	HA usage (% waking hours)
1	69	M	Unknown	40	40	4 months	Harmony	250 Hz	25	Starkey CE	100%
2	70	M	Unknown	23	23	4 months	Harmony	250 Hz	21	Senso Diva BTE	100%
3	79	M	Unknown	35	35	2 yrs	Freedom	190 Hz	18	Oticon BTE	100%
4	82	M	Unknown	40	40	2 yrs	Freedom	190 Hz	23	Starkey Sequel II BTE	100%
5	49	F	Unknown	35	35	5 yrs	ESprit 3G	188 Hz	15	Belton D71 Polara	100%
6	64	M	Unknown	44	44	6 months	Harmony	250 Hz	N/A	N/A	N/A
7	58	M	Ménière	4	14	3 yrs	Combi 40+	194 Hz	2	Oticon BTE	100%
8	62	M	Unknown	40	40	8 months	Harmony	250 Hz	24	Virtue Audibel BTE	100%

Note. NIE = nonimplanted ear; IE = implanted ear; CI = cochlear implant; HA = hearing aid; N/A = not applicable

^aHearing loss was defined as an inability to understand a conversation on the telephone.

Table 2

Scores for CNC words as a function of filter condition. LP = low pass. HP = high pass.

Filter Settings		Speech Understanding Scores		
Acoustic Signal	Electric Signal	E Only	A Only	EAS
250 LP	250 HP	59%	.5%	80%
500 LP	500 HP	53%	6%	78%
750 LP	750 HP	44%	18%	83%
Wide Band	Wide Band	59%	45%	85%

Table 3

Scores for AzBio sentences at +10 dB SNR as a function of filter condition. LP = low pass. HP = high pass.

Filter Settings		Speech Understanding Scores		
Acoustic Signal	Electric Signal	E Only	A Only	EAS
250 LP	250 HP	41%	0%	72%
500 LP	500 HP	26%	6%	76%
750 LP	750 HP	15%	22%	77%
Wide Band	Wide Band	41%	42%	86%