Fourth Quarterly Progress Report

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Speech Processors for Auditory Prostheses

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I. Introduction

The main objective of this project is to design, develop, and evaluate speech processors for implantable auditory prostheses. Ideally, such processors will represent the information content of speech in a way that can be perceived and utilized by implant patients. An additional objective is to record responses of the auditory nerve to a variety of electrical stimuli in studies with patients. Results from such recordings can provide important information on the physiological function of the nerve, on an electrode-by-electrode basis, and can be used to evaluate the ability of speech processing strategies to produce desired spatial or temporal patterns of neural activity.

Work and activities in this quarter included:

- Continuing studies with local subject ME-16, implanted bilaterally with Med-El Tempo+ devices.
- Measurements of compliance voltages for several clinical implant systems under a range of impedance loads.
- Two weeks of studies with a new European subject, ME-21, January 27 - February 6.
- A visit by Christoph Arnoldner from the University of Vienna in association with the studies of ME-21, January 27 - February 7.
- A visit by consultant Mariangeli Zerbi, March 8-11, for continued development of streaming mode software for use with transcutaneous implant devices.
- A visit by Charlie Miller of the University of Iowa, March 17 - 18.
- A visit by Kevin Franck of the Center for Childhood Communication, The Children’s Hospital of Philadelphia, March 19 - 20.
- An invited keynote presentation by Dewey Lawson to the annual spring meeting of the North Carolina Chapter of the American Association of Physics Teachers, March 21.

In addition to the above-mentioned activities, work continued on the analysis of previously collected data and further development of the new DNRL processing strategy.

In this report, we describe recent studies of lateralization on the basis of Interaural Timing Difference (ITD) using unmodulated pulse bursts.

II. Measurements of Interaural Timing Difference

Background

QPR 12 of our previous contract NO1-DC-8-2105, summarized minimum ITD values obtained for a variety of stimuli, including testing with unmodulated pulse trains, and with continuous pulse trains modulated by envelopes offset in time. In both cases the stimuli usually were delivered to pitch matched, loudness balanced electrode pairs, and occasionally to adjacent pitch distinct, loudness balanced electrode pairs. Also included in the summary of QPR 12 were ITDs obtained using trains of brief modulation envelopes, repeated at a rate of 50/s, produced by inputting pulses at that rate to CIS processors. These latter measurements, using independent non-synchronized CIS processors for the two ears, provided some of the shortest ITDs measured in our laboratory.

Further analysis of data collected using unmodulated pulse train stimuli to selected pairs of electrodes showed that occasionally the minimum ITD was obtained for pitch distinct electrode pairs rather than pitch matched electrodes in the same region of the cochlea. (See QPR 12 of our previous contract for a detailed description of our formal pitch ranking procedure). Also, ITD sensitivity seemed to be independent of the region within the cochlea that was chosen for stimulation. This observation differed from results obtained with normal hearing subjects for similar measures. In normal hearing, the minimum ITD for low to middle frequency signals shows very sharp increases as the tones presented to each ear are separated in frequency. Also, consistent with the duplex theory of sound localization, the human ear is regarded as unable to utilize acoustic ITD information to localize high frequency tones [Nuetzel and Hafter, 1981; Tobias, 1972.]

In response to these initial findings we have undertaken a number of additional ITD experiments investigating these differences, all utilizing unmodulated pulse trains. Those studies are now complete and are the topic of this report. A complementary series of studies utilizing controlled modulated stimuli has been designed and will be conducted in the near future.

Methods

Prior to any ITD measurements, each subject undergoes a multi-stage pitch ranking procedure. First, amplitudes corresponding to most comfortable loudness (MCL) are determined for each stimulating electrode at the selected pulse rate, and balanced for loudness. Next an informal pitch ranking is completed to identify a putative list for the order of the electrodes. Then the pitch ranking for each electrode is determined on the basis of electrode pair comparisons using an adaptive forced choice procedure [See, for instance, Bross, 1952.] A pitch ranking summary for the subjects participating in the studies described in this report is presented in Figure 1. Left ear electrodes are shown on the left side and right electrodes on the right. Vertical position differences denote differences in pitch, with higher pitches towards the top. Pairs that cannot be discriminated on the basis of pitch are highlighted, and electrodes that were intentionally omitted are indicated by an asterisk (*). The manufacturer of each subject's implanted electrode array is indicated by a code prefix – "NU" for Nucleus, and "ME" for Med-El. Individual electrodes are numbered according to the conventions used by each manufacturer.

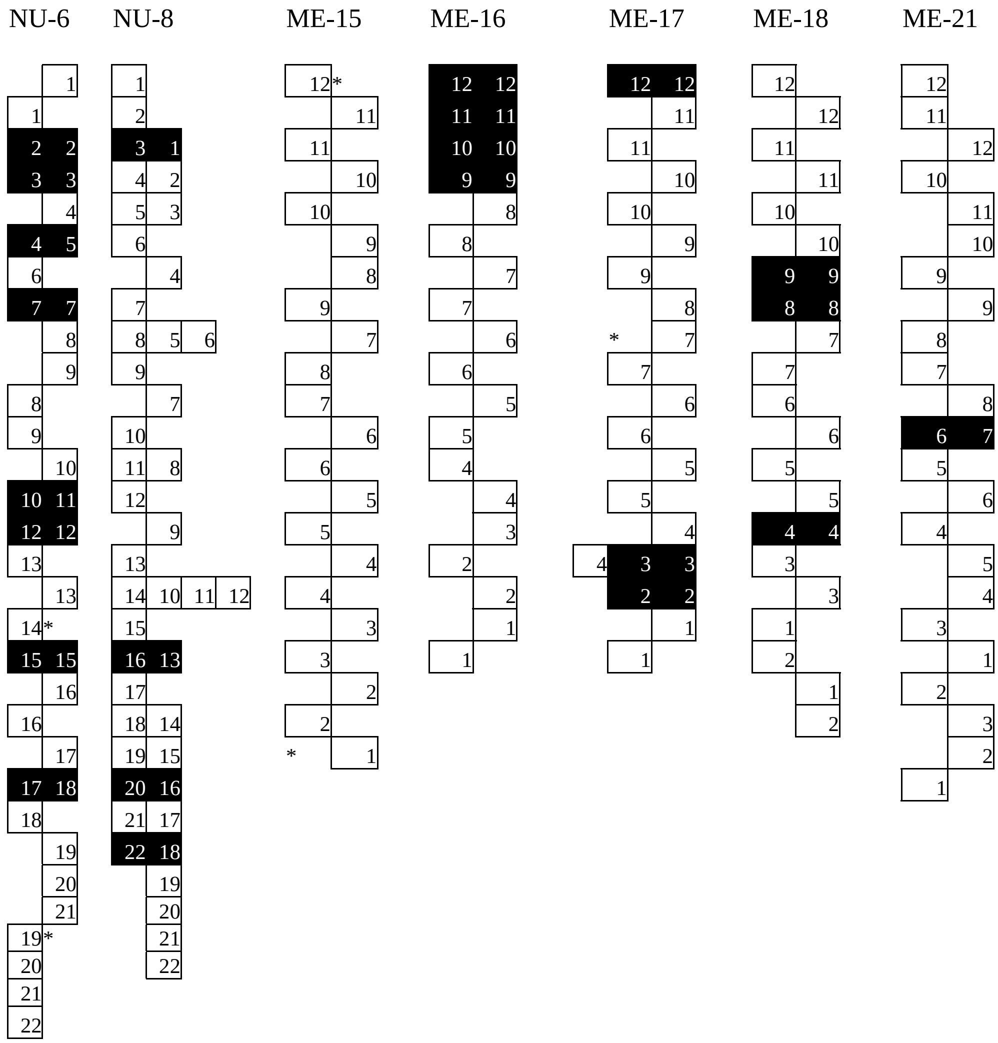

Figure 1. Formal pitch ranking results for each subject.

Based on these pitch ranking results, pairs of electrodes are selected for ITD evaluation. Prior to initiating the ITD trial, the two chosen electrodes are stimulated simultaneously at MCL (delta t = 0) and the subject is asked to report if the sound came more from the right or more from the left. The amplitude is then adjusted, if necessary, to provide a signal at midline, *i.e.* indiscriminable between right and left. The ITD trial is begun with an ITD offset of 2000 μs as the starting point. The signals used were unmodulated pulse trains consisting of three identical 300 ms pulse bursts with 500 ms gaps between them. The biphasic pulse width was 27 μs/phase, presented at a rate of 100 pps for the first set of experiments and at 100 pps or 1515pps for the second set of experiments. The pulse trains were delivered in a random order. Subjects were instructed to select between more to the right or more to the left. A sufficient number of trials are completed at each ITD interval to obtain a statistically significant result, after which the ITD is progressively shortened until subject responses approach 50%. Occasionally during this procedure, the subject will begin to lateralize to only one side. Such cases usually are due to a loudness imbalance that must be corrected. Accordingly, when such a pattern is encountered, the pulse amplitude on the side receiving the disproportionate number of responses is lowered until responses are equally divided between right and left. Once that is accomplished, the particular trial is aborted and started over with the new MCL values.

The offset of the pulse train is illustrated in Figure 2 with delta t representing the prescribed interaural delay.

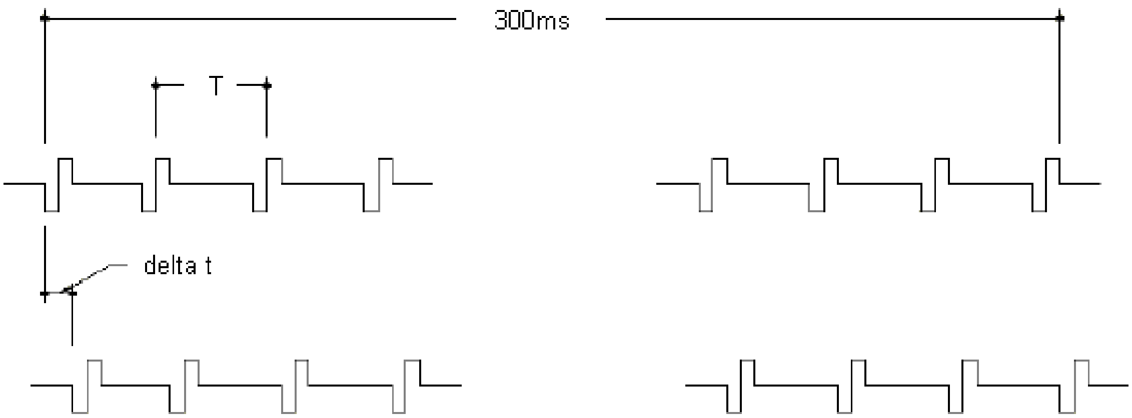

Figure 2. Interaural time difference stimuli using unmodulated pulse trains. Current *vs.* time. Lower stimulus, to a chosen electrode in one ear, is delayed with respect to the upper stimulus to a chosen electrode in the other ear.

Percent correct scores are recorded for each of the ITD intervals evaluated and fit to a weighted logistic function. The 75% crossing of the function is recorded as the minimal ITD for the selected electrode pair [For examples of logistic function fits and additional details, see QPR 12, page 11, NIH Project N01-DC-8-2105].

Studies of ITD Sensitivity using Unmodulated Pulse Trains for different electrode pairs

Having occasionally obtained better ITD sensitivity for electrode pairs that were not pitch match than for pitch matched pairs differing by a single electrode location on one side, we designed a study with several subjects in which we recorded minimum ITDs while keeping the electrode on one side fixed and roving the electrode on the other side. In Figure 3, we show such results for two Nucleus subjects, with the left electrode 10 (pitch matched to right electrode 11) held constant for subject NU-6 and the right electrode 13 (pitch matched to left electrode 16) for subject NU-8 held constant while the electrode in the opposite ear was moved either apically or basally for completion of ITD measures. As expected, deviation from the pitch matched pairs is associated with increases in minimum ITD sensitivities. These differences are very gradual, however, and for subject NU-8 there is a broad region -- from electrode 16 through electrode 10 -- where there is very little change in ITD sensitivity. This span along the electrode array is approximately 4.5 mm in length (.75 mm between adjacent electrodes) corresponding to a range in characteristic frequency along the normally excited basilar membrane of 1700 Hz (Greenwood,1990), far from the sensitivity of 5 Hz expected for normal hearing listeners (Tobias, 1972).

ITD for Roving Electrodes

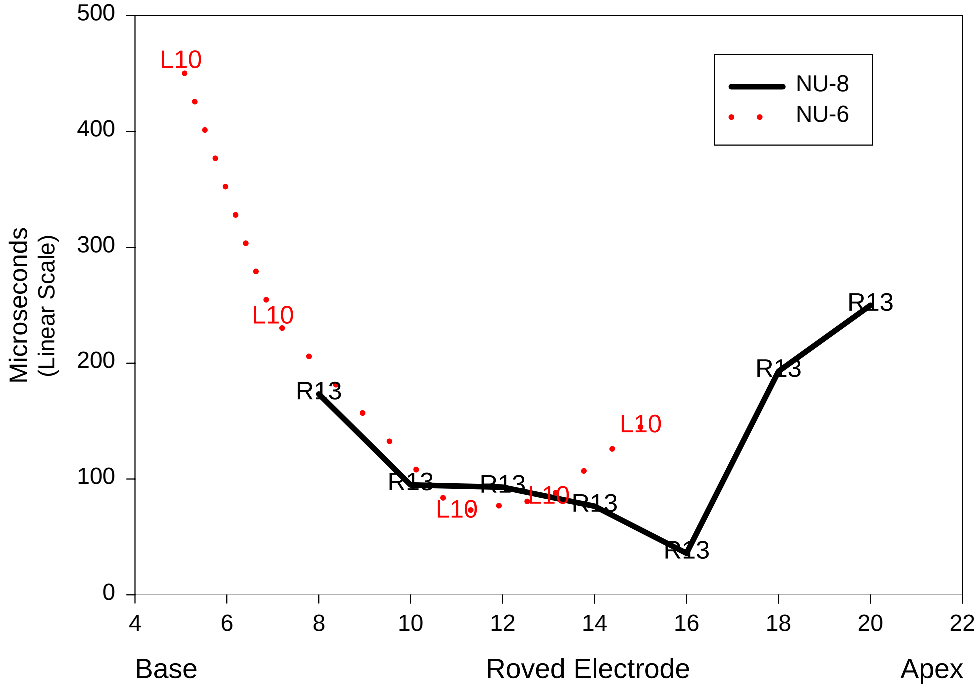

Figure 3. Interaural Timing Differences for two Nucleus subjects with the stimulated electrode on one side held constant and the one in the opposite ear varied, including the pitch match electrodes as well as electrodes displaced various distances in both directions. Data points on the plot are marked with codes identifying the side and number of the fixed electrode; the roving contralateral electrode number can be read from the horizontal scale.

In Figure 4 are results from the same experiment conducted with two Med-El subjects. For subject ME-15, the results of the pitch ranking procedure provided no matched pairs for the entire range of electrodes. For subject ME-21 the pitch–matched pair is L7/R6. As was observed for subject NU-8, for both of these Med-El subjects we see a broad range -- from electrodes 5 thru 7 -- over which the ITD sensitivity shows minimal change. For the Med-El device, this corresponds to a longitudinal range of approximately 4 – 5 mm (2.25 - 2.4 mm between electrodes).

Among the possible causes of essentially constant ITD sensitivity over such a long distance along the cochlea are (1) the fixed electrode's happening to be located in a region of the cochlea not associated with ITD sensitivity in normal hearing, and (2) neural elements over a large portion of the cochlea responding to stimuli from any of the involved electrodes.

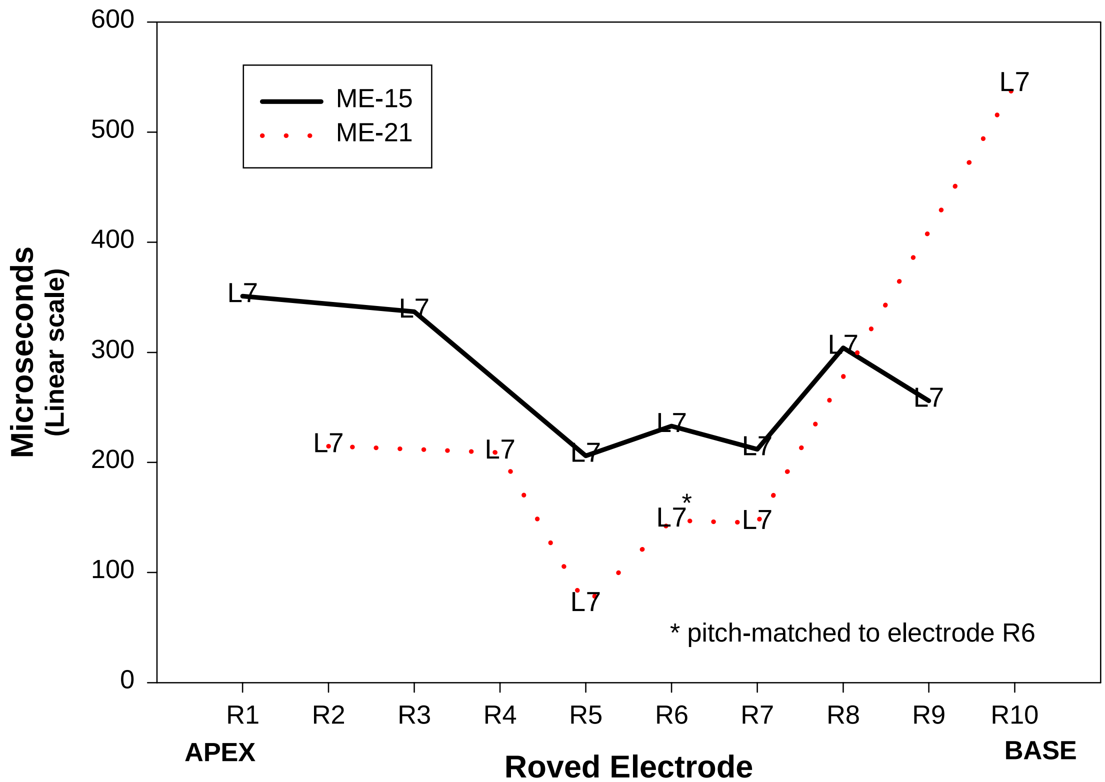

Figure 4. Interaural Timing Differences for two Med-El subjects with the stimulated electrode on one side held constant and the one in the opposite ear varied. Subject ME-15 has no pitch match pairs while for Subject ME-21 electrodes L7/R6 form the only pitch matched pair. The number of the roved right electrode is indicated on the horizontal axis. Electrode 7 on the left side formed the other member of the pair in each case.

We also looked for systematic variations in minimum ITDs as a function of location along the cochlea. For these studies, we selected electrode pairs from different regions of the electrode array, again based on a prior formal pitch ranking evaluation. As can be seen in the pitch-ranking summary (Figure 1), it was not possible to find pitch match pairs across the different regions of the cochlea for the majority of these subjects. Data for the electrodes that were pitch matched are marked with asterisks in Figure 5.

Minimum ITD for Electrode Pairs in Different Regions of the Cochlea

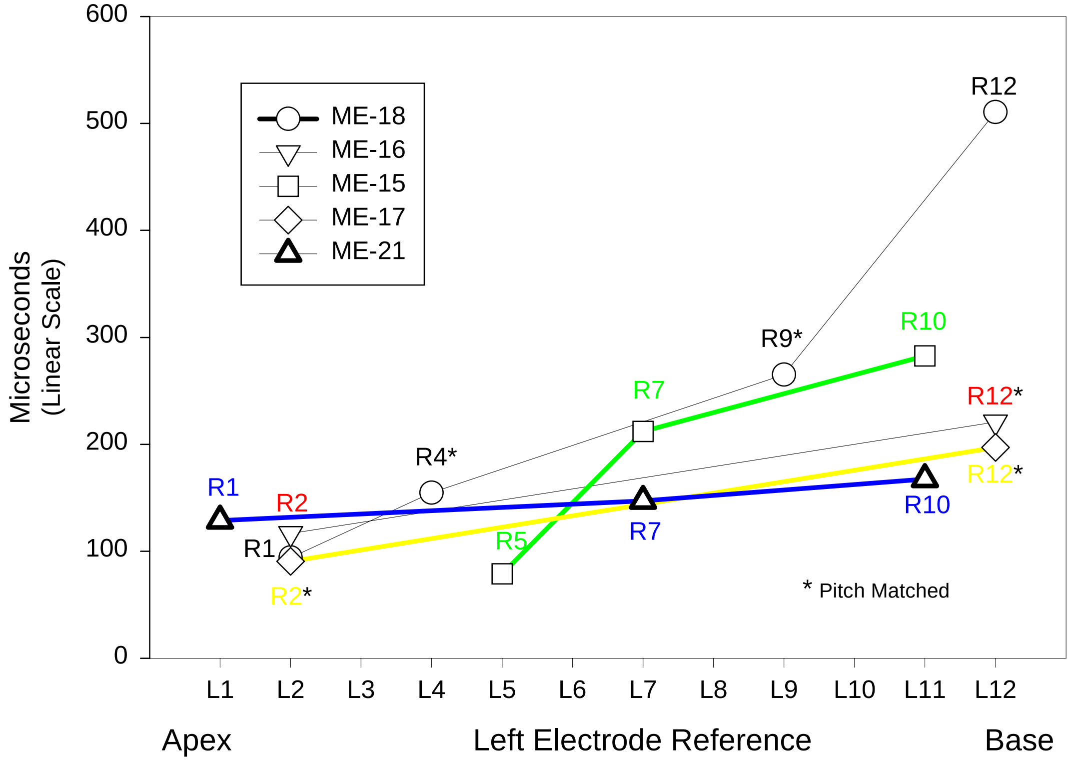

Figure 5. ITDs for electrode pairs in different regions of the cochlea. The horizontal axis identifies the left side electrodes that were paired with the right side electrodes indicated by labels adjacent to each data point. Pitch matched pairs are indicated by "*" where available for a given subject and region of the array.

These results show that as the selected pairs move from the apical region of the cochlea to the basal end, there is a gradual increase in the minimum ITD for these five subjects. Such a pattern might be seen as consistent with the frequency dependent utility of ITD information in normal acoustic hearing. A concern in the interpretation of these results is that there were an insufficient number of pitch match pairs in the different regions to adequately address the possibility that the minimum ITD was not obtained for certain pairs due to the pitch mismatch. However, it is worth noting that for subjects ME-18 and ME-17 who's measures did include ITDs for pitch match pairs from two different regions, the more basal pairs showed larger minimum ITDs than those obtained from the more apical region and that subject ME-16, whose pitch match pair was for the most basal electrodes, still showed a better ITD sensitivity for the apical region.

In order to better understand the importance of selecting only pitch match pairs for obtaining the optimum ITD sensitivity we completed a comprehensive evaluation of roving ITDs across the electrode array for subject ME-16. For these studies, we held the six even-numbered left electrodes constant while roving the right electrodes in the same regions of the cochlea. For each condition the roved electrodes for the right ear spanned a region of three or four electrodes depending on the rate of change in ITD sensitivity. Figure 6 shows the results for this evaluation.

Minimum ITDs for Roved Electrodes for Different Regions of the Cochlea
Subject ME-16

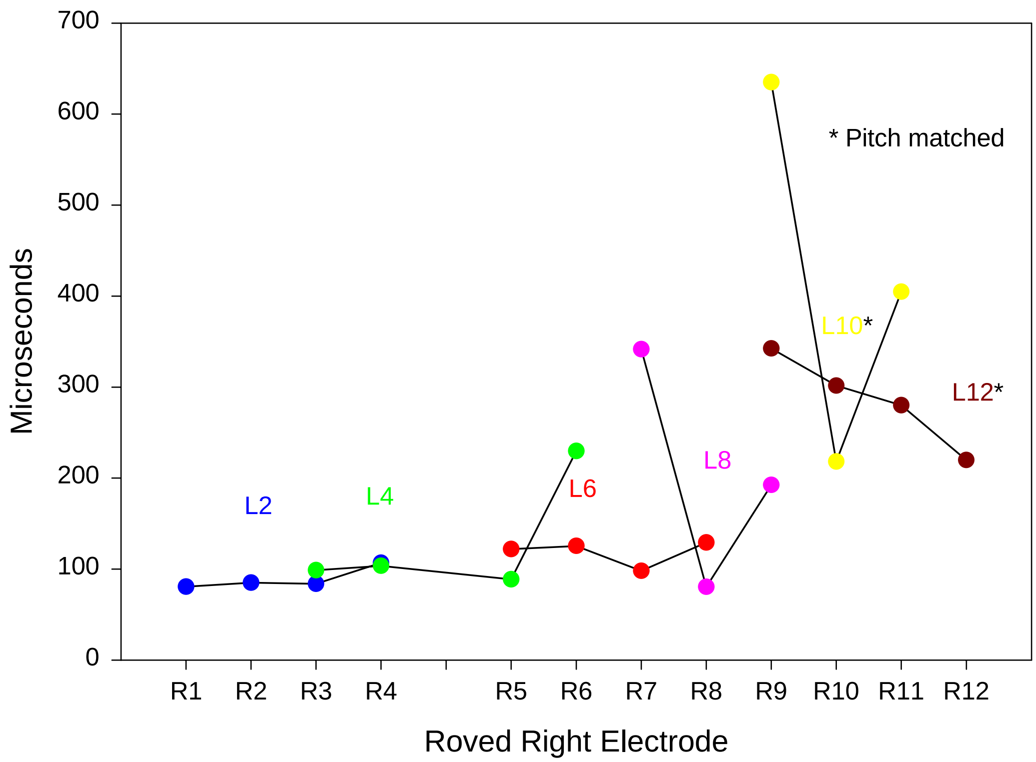

Figure 6. Minimum ITDs for roved electrodes in different regions of the cochlea: subject ME-16. Each even-numbered electrode on the left side was paired with a range of adjacent right side electrodes in the same region of the electrode arrays.

Comparisons of the roved ITD results for this subject indicate that for reference electrodes L2, L4, and L6 there is a broad region for which the minimum ITD shows no significant changes, with values hovering around 100 µs. In contrast, the minimum ITD for reference electrodes L8, L10, and L12 is very sensitive to place of stimulation of the opposite ear. Comparison with the pitch ranking data for ME-16 in Figure 1 indicates that the minimum ITDs observed for L10 and L12 occurred when the paired right side electrode was the pitch matched one.

The most sensitive ITDs, however, were obtained for the electrode pairs at the apical end of the electrode array despite the fact that the only pitch matched pairs for this subject are found at the basal end of the cochlea. This finding provides additional support to the indication from the data of Figure 5 that the apical to middle portions of the electrode array provide the best ITD sensitivity for unmodulated pulse bursts.

So, on the one hand, we observe sensitivity to smaller ITDs for stimulation from sites toward the apical end of the electrode array (approximately 1.5 turns into the cochlea), consistent with the greater reliance on ITD localization cues at lower frequencies in normal hearing. But on the other hand we find that ITDs are much more sensitive to pitch matching between contralateral sites of stimulation toward the basal end of the array (and of the cochlea), the region least associated with the use of ITD information in normal hearing. It will be of interest to see whether such patterns are unique to unmodulated pulse train stimuli or also appear in the planned studies with modulation of controlled pulse trains.

Just as response of neural elements over a wide range of the cochlea to stimuli from a given electrode is a possible cause of the effects seen in Figures 2 and 3 above, we note that asymmetry in current spread (apically *vs.* basally) is a possible contributor to the trends seen in Figures 5 and 6.

Studies of ITD Sensitivity using Unmodulated Pulse Trains: Rate effects

We also have completed a set of experiments in which the rate of pulses within the bursts was changed from either 50 pps or 100 pps to 1515 pps for specific electrode pairs. Minimum ITDs were obtained for electrode pairs L2/R2 and L12/R12 for both subjects ME-17 and ME-16 and for L2/R1 for subject ME-18. The minimum ITD increases strongly with increased pulse rate.

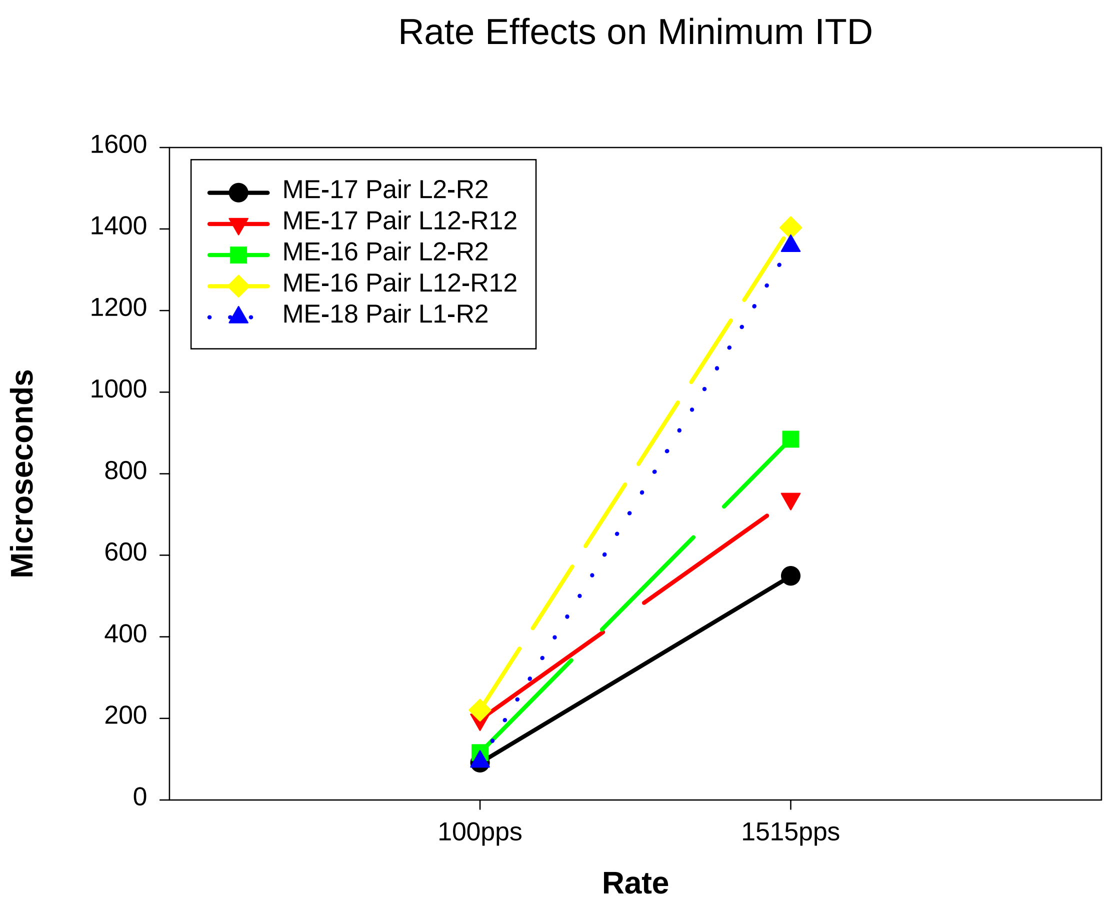

Figure 7. The effect that rate has on minimum ITDs for selected electrode pairs.

This finding is consistent with results obtained by van Hoesel and Tyler (2003). Those authors described lateralization of unmodulated pulse trains only when using a low pulse rate and reported that when the pulse rate exceeded 800 pps none of their subjects were successful at lateralizing for ITDs of up to 400 µs. Only one of our subjects, subject ME-16, showed an ITD sensitivity better than 400 µs for a signal at 1515 pps, and that happened to be for apical, pitch distinct electrodes L2/R2.

Summary

- The apical end of the implant array and the corresponding lower frequency region of stimulation provide the most sensitive minimum ITD scores for unmodulated pulse trains.
- The minimum ITD is not sensitive to pitch match pairs for the low and middle frequency region of the electrode array. For these areas there seems to be a broad range of stimulation sites, 4-5 mm along the electrode array, that can support similar ITDs. This suggests the possibility that pitch matching is not important for the lateralization of low frequency sound -- typically attributed to ITD sensitivity in normal hearing listeners – by users of cochlear implants.
- Stimulation from sites near the basal end of the electrode array is more sensitive to changes in pitch match location for minimum ITD sensitivity, and typically provides less sensitive ITD scores than the areas stimulated by the other 2/3 of the electrode array.
- ITDs for unmodulated pulse trains are sensitive to rate of stimulation, with ITD sensitivity decreasing as pulse rate is increased.

III. References

Bross, IDJ, Biometrics 8, 188-205, 1952.

Greenwood, DD. A cochlear frequency-position function for several species--29 years later. J Acoust Soc Am 1990 Jun;87(6):2592-605).

Nuetzel, JM and Hafter, ER. 1981. Discrimination of interaural delays in complex waveforms: Spectral effects. J. Acoust. Soc. Am. 69:1112-18.

Tobias, JV. Foundations of Modern Auditory Theory II. New York: Academic Press, 1972.

van Hoesel, R and Tyler, R. 2003. Speech perception, localization and lateralization with bilateral cochlear implants. J Acoust Soc Am 2003 Mar;113(3):1617-30

IV. Plans for the next quarter

Among the activities planned for the next quarter are:

- Continuing studies with local subject ME-16, implanted bilaterally with Med-El Tempo+ devices.
- Attendance by Blake Wilson at the 9th Symposium of Cochlear Implants in Children, Washington DC, April 24-26.
- A visit by Jim Patrick, Senior Vice President of Research and Applications, Cochlear Ltd., Sidney, Australia, April 30.
- Initial evaluation of new subject ME-22, implanted with bilateral Med-El Tempo+ devices May 9.
- Two weeks of studies with return subject, ME-18, May19 – May 30.
- An invited presentation by Blake Wilson to the VII International Conf. on Cochlear Implants and Related Audiological Sciences Intl. and the opening of the Center for Hearing and Speech, Warsaw, Poland, May 22-24.
- A visit by consultant Mariangeli Zerbi to verify software for modulated pulse train ITD studies, May 17-19.
- A visit by consultant, Enrique Lopez-Poveda from Albacete, Spain, May 19-23 to coincide with the visit of subject ME-18.
- A return visit by Subject ME-14, who previously participated in our studies of combined electric/acoustic hearing and now is bilaterally implanted with Med-El Tempo+ devices, June 16-17.

V. Acknowledgments

We thank volunteer research subjects NU-6, NU-8, ME-12, ME-15, ME-16, ME-17, ME-18, and ME-21, who participated in studies conducted during this quarter and/or whose participation made possible results presented in this report.

Appendix 1. Update on longitudinal studies of early performance improvements with binaural cochlear implants

Since our initial report on a longitudinal study of two subjects early in their use of binaural cochlear implants (QPR 2 for the current contract), an additional visit by one of the subjects (ME-16) has brought her data up to date with those of the other subject (ME-12) in terms of time since first fitting. The new data are consistent with, and provide additional support for, all three trends tentatively identified on the basis of the earlier measurements: (1) a trend of relatively slow improvements in overall consonant recognition scores, (2) a trend of more rapid improvements in performance when noise comes from the same direction as speech, and (3) a trend of reduced differences in performance across noise direction differences.

Table I. Timing of Visits by Longitudinal Study Subjects

	First Fittings (Yr,Mo)		Yrs. Profound HL		Dates Seen (Yr,Mo)					Intervals After Fitting Seen (Yrs,Mos)				
	L	R	L	R										
ME-12	01,9	01,9	1(?)	<1	01,10	01,11	01,12	02,3	02,4	0,1	0,2	0,3	0,6	0,7
ME-16	02,7	02,7	10	10	02,9	02,10	03,2			0,2	0,3	0,7		

Figures 1 and 2 from QPR2 of the current contract are reproduced on the following pages with the February 2003 data for ME-16 added.

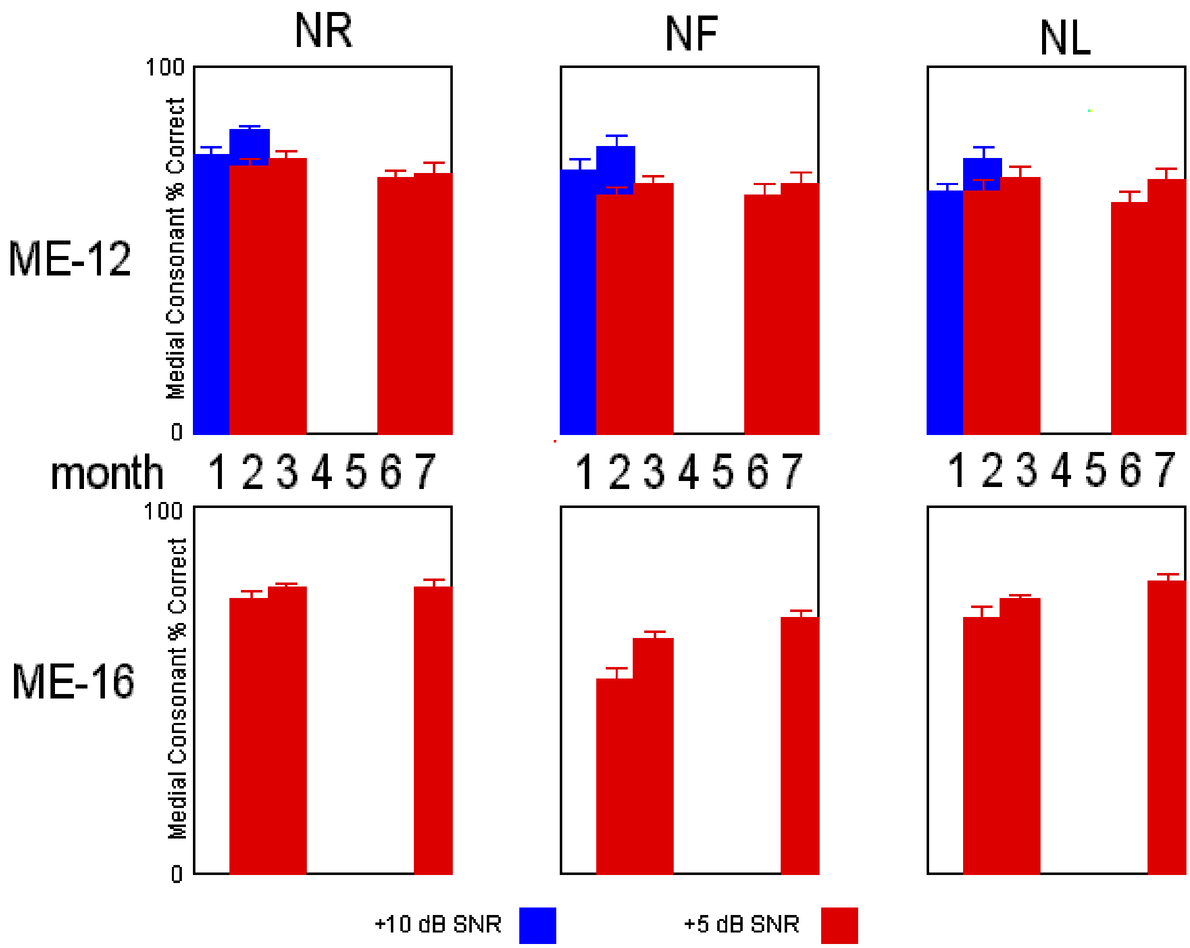

Figure 1. Identification of medial consonants in the presence of directional speech spectrum noise as a function of duration of cochlear implant use. Bars in each panel plot percent correct medial consonant identification scores *vs.* number of months since first fitting. The height of each panel corresponds to 100 % correct. Upper row data are for subject ME-12 and lower row data for subject ME-16. The three columns contain data for speech from the front combined with noise from the right (NR), the front (NF), and the left (NL) respectively. Both ears were stimulated in every case. Early data for ME-12 with a signal-to-noise ratio (SNR) of + 10 dB are shown in blue, while the bulk of the data, shown in red, are for a SNR of +5 dB. Error bars indicate standard deviation of the mean.

Table II. Longitudinal Results: Medial Consonant Recognition in Speech Spectrum Noise, Both Ears Stimulated

	S/N Ratio	Month		Noise Right	Noise Front	Noise Left
ME-12	+10 dB	1		76 ± 2	72 ± 3	66 ± 2
		2		83 ± 1, 82 ± 2	73 ± 2, 78 ± 3	75 ± 3, 73 ± 2
	+5 dB	2		73 ± 2	65 ± 2	66 ± 3
		3		75 ± 2	68 ± 2	70 ± 3
		6		70 ± 2	65 ± 3	63 ± 3
		7		71 ± 3	68 ± 3	69 ± 3
ME-16	+5 dB	2		75 ± 2	53 ± 3	70 ± 3
		3		78 ± 1	64 ± 2	75 ± 1
		7		78 ± 2	70 ± 2	80 ± 2

Figure 2 displays the same data, grouped to highlight any changes in noise direction effects over the months.

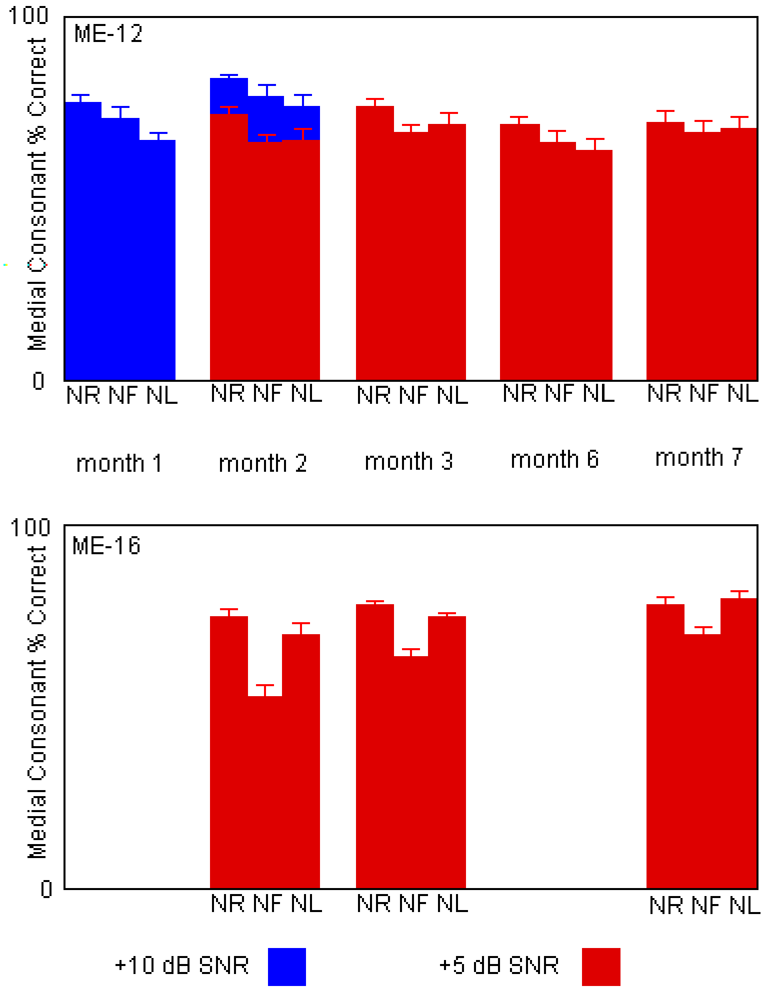

Figure 2. Identification of medial consonants in the presence of speech spectrum noise, as a function of the directions from which noise and speech come, at various times after first fitting of binaural cochlear implants. Each group of three bars shows percent correct medial consonant identification scores for speech from the front combined with noise from the right (NR), the front (NF), and the left (NL) respectively, both ears were stimulated in each case. The height of each panel corresponds to 100 % correct. Upper panel data are for subject ME-12 and the lower panel data for subject ME-16. The comparisons for each subject are displayed in chronological order, from one to seven months after first fitting. Early data for ME-12 with a signal-to-noise ratio (SNR) of + 10 dB are shown in blue, while the bulk of the data, shown in red, are for a SNR of +5 dB. Error bars indicate standard error of the mean.