N01-DC-2-1001QPR04

Fourth Quarterly Progress Report

Speech Processors for Auditory Prostheses

NIH Contract N01-DC-2-1001

October 1, 2002, through December 31, 2002

submitted by

Charles C. Finley

University of North Carolina at Chapel Hill
Department of Otolaryngology
Chapel Hill, NC

Barbara Herrmann
Victor Noel
Joseph Tierney
Margaret Whearty

Massachusetts Eye and Ear Infirmary
Boston, MA

Donald K. Eddington

Massachusetts Institute of Technology
Research Laboratory of Electronics
Cambridge, MA

1.0 Introduction

Work performed with the support of this contract is directed at the design, development, and evaluation of sound-processing strategies for auditory prostheses implanted in deaf humans. The investigators, engineers, audiologists and students conducting this work are from four collaborating institutions: the Massachusetts Institute of Technology (MIT), the Massachusetts Eye and Ear Infirmary (MEEI), Boston University (BU) and the University of North Carolina at Chapel Hill (UNC-CH). Major research efforts are proceeding in four areas: (1) developing and maintaining a laboratory-based, software-controlled, real-time stimulation facility for making psychophysical measurements, recording field and evoked potentials and implementing/testing a wide range of monolateral and bilateral sound-processing strategies, (2) refining the sound processing algorithms used in current commercial and laboratory processors, (3) exploring new sound-processing strategies for implanted subjects, and (4) understanding factors contributing to the wide range of performance seen in the population of implantees through psychophysical, evoked-response and fMRI measures.

This quarter’s effort continued progress in several ongoing areas of investigation and also marked a significant milestone for a major goal of the overall project. A general overview of progress during this quarter follows:

(1) Experiments in the use of triphasic stimulation waveforms to reduce nonsimultaneous electrode interactions have continued. In preparation for studies of speech processors employing either biphasic or triphasic stimulus waveforms, we have nearly completed a series of psychophysical channel interaction studies in which both masker and probe waveforms are the same, either biphasic/biphasic or triphasic/triphasic. These psychophysical conditions provide a better approximation of stimulus conditions that would exist in active speech processor design. Our preparations have also progressed for future speech processor studies involving chronic use of wearable triphasic processors using the Clarion CII/HiFocus implant system.

(2) Measurements to guide optimal selection of interaural electrode pairs for bilateral sound-processing strategies have also continued with our bilaterally implanted subjects. These studies include measures of bilateral and monolateral (electrically-experienced ear and electrically-naive ear) performance on a battery of psychophysical and speech-reception measures that include interaural pitch comparisons, psychophysical fusion of binaurally presented stimuli (see QPR3 for description), interaural timing/loudness difference (ITD/ILD) sensitivities, and speech reception in both quiet and with a spatially separated noise source. An additional metric has been added this quarter involving measurement of the brainstem-based binaural interaction component using auditory brainstem responses in acoustically-normal and implanted subjects.

(3) Studies of sound source localization by bilaterally implanted subjects were also launched this quarter at Boston University. Head-related transfer functions were measured for each ear separately and both ears combined in several bilaterally implanted patients. At the time of this test, these subjects had one electrically-experienced ear and one electrically-naïve ear to provide a baseline for future studies following experience with chronic bilateral processors.

(4) A significant milestone was marked in December with our first serially-implanted bilateral patient being given a second, unsynchronized wearable processor to use chronically. This event ends for this subject the baseline study phase in which monaural and binaural psychophysical and speech processing studies were conducted with the conditions of one experienced ear and one naive ear. Future work with this subject, and eventually all bilateral subjects, will focus primarily on two issues: (i) does the sensitivity to bilateral cues and their functional impact change over time as the CNS adapts to chronic binaural input , and (ii) do processing strategies that interleave analysis channels across ears (to increase the number of information channels) and strategies that synchronize the stimulation across the two ears improve speech reception in quiet and noisy listening conditions.

(5) Further refinements of stimulation/recording tools for the Clarion CII/HiFocus implant system have enabled us to begin field and evoked-response measures in these subjects.

In this QPR, we concentrate on two areas: (i) objective measures of peripheral responses to electrical stimulation using intracochlear evoked responses (IEP), both within and across subjects, and (ii) preparations for and initial data involving measurement of electrically-evoked auditory brainstem responses (EABR). Progress in the other areas outline above will be reported in subsequent QPRs.

2.0 Intracochlear Evoked Potentials (IEP) Survey

The software developed and tested during the first three quarters for field and evoked-potential recording from intracochlear electrodes of the Clarion CII/HiFocus implant system is being used to make measures in an initial group of monolaterally-implanted Clarion subjects. The objectives of collecting these initial data are to (1) better characterize system measurement noise, (2) identify software refinements to improve speed and quality of data collection, and (3) survey the pool of prospective subjects with regard to the quality, magnitude and variability of their IEP measures. The overall objective of making IEP measures in this project is to gain insight into the bases for the wide range of outcomes across the implanted population. QPR2 of this project previously described details of the measurement procedure.

The following figures provide a summary of IEP data collected from five subjects to date. All subjects have been implanted monolaterally with the Clarion C-II (HiFocus with Positioner) implant system. Subject speech performance is moderate to excellent with individual NU-6 whole word scores ranging from 42% at 6 months to 86% at 1 week across subjects. Subjects are generally tested in sessions lasting a maximum of two hours. Data collected include (1) a map of the electrical artifact field distribution across all implanted electrodes, (2) basic psychophysics to determine threshold and growth of loudness to single pulse stimulation, (3) growth of IEP magnitude for increasing stimulus levels, and (4) maps of IEP spatial distribution longitudinally along the cochlea for a fixed stimulation electrode and current level. Additional subjects are being recruited to the study with a target goal of at least ten subjects representing a wide range of speech reception performance outcomes.

Because the primary study objective is to understand the bases for the wide range of performance outcomes, we focus here on showing some of the variability seen within and across subjects using our standard measurement battery. Figures 1A and 1B below show IEP magnitude growth as a function of stimulus intensity for single pulse stimulation for two subjects, C94 and C97, respectively. The ordinate is IEP N1-to-P2 peak-to-peak magnitude, and the abscissa is peak current magnitude for a 32 µsec/phase biphasic pulse stimulus. Each plotted growth function ends at the highest current level the subject would tolerate either in terms of loudness or other limiting percept (pain, facial stimulation, etc). The range along the ordinate for which the growth function is plotted is an estimate of the subject's dynamic range for a given electrode. Responses to both anodic- and cathodic-leading biphasic pulses are averaged to produce the final IEP measure. C94 has 62% NU6 word score and prefers a SAS-based sound processor. C97 scores 76% on NU6 and uses a MPS-based processor. Although C94 has higher speech reception performance, IEP magnitude growth and dynamic range are considerably smaller compared to C97's data. In general, growth functions are sigmoidal in shape and terminate with some degree of downward concavity as seen in Figure 1B. In some instances the IEP growth will plateau and be associated with a very gradual or somewhat fluctuating loudness growth at higher stimulus levels. A general tendency for the slope of growth functions to be lower in the base is seen for the data from C97 (Figure 1B). This pattern was also seen in similar data collected by our group in Ineraid subjects and is attributable to current shunting in the basal region. In contrast, the growth function patterns are quite different for subject C94. Here the growth functions for the apical-most contacts for C94 (E3, E5 and E7 in Figure 1A) are concave upward, have very small IEP magnitudes, and are generally associated with rapid loudness growth. Detailed analysis of these data is continuing. In general, the large differences in the IEP growth patterns for these two subjects suggest that IEP measures will be useful in examining peripheral physiological factors contributing to variability in performance outcomes.

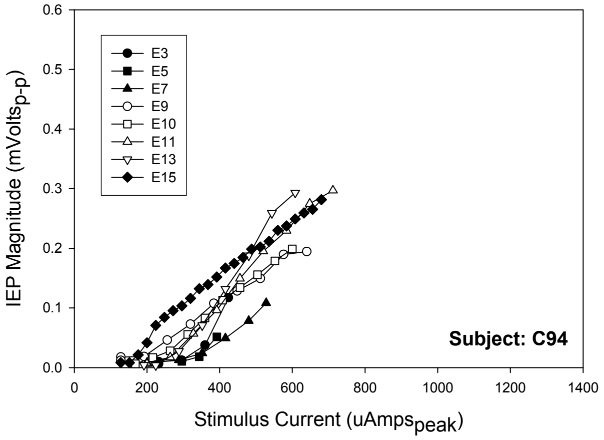


Figure 1A. IEP I/O Growth Function

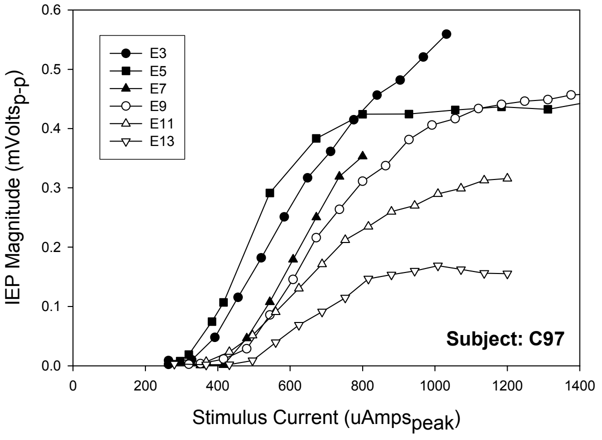


Figure 1B. IEP I/O Growth Function

The degree of variability in IEP measures across subjects is seen in Figure 2. In Figure 2A growth functions for five subjects are plotted all with stimulation on electrode

E7. For four of the five subjects the growth functions generally cluster, but are associated with a range of dynamic ranges. Subject C114's growth function is significantly different, rising gradually over a very wide stimulus range. Of the five subjects, C114 has the lowest speech reception performance (42% NU6 word score at 6 mos). The shape of C114's growth function would be consistent with a large portion of the stimulus current delivered to E7 being shunted away from the target neurons. Such shunting could occur in the cochlear tissue and/or within the electrode array or stimulator package.

Figure 2B shows the corresponding spatial distribution data for the same subjects stimulated all on electrode E7. The spatial distribution of IEP responses is determined by making repeated measures in the cochlea by holding location and level of stimulation constant and varying the site of the recording electrode. IEP magnitudes are then plotted as a function of recording electrode position or number (E1 is most-apical and E16 is most-basal for the HiFocus array). Although direct comparison of these curves is complicated by different stimulus levels being used, the general trend of the data is as expected based on cochlear anatomy. In particular, a steeper rate of decline is observed in the basal region as compared to the apical region where potentials tend to plateau or decline at slower rates. Immediately apical to the stimulation contact, E7, the slope of each spatial profile between E5 and E6 is observed to change significantly, either positively or negatively, from the general trend of the profile. This phenomenon may be due to potentials on E6 being contaminated by residual electrical artifact. By the same argument, potentials on E8 may also be suspect. This issue is under active investigation.

Figure 2A. I/O Growth Across Subjects

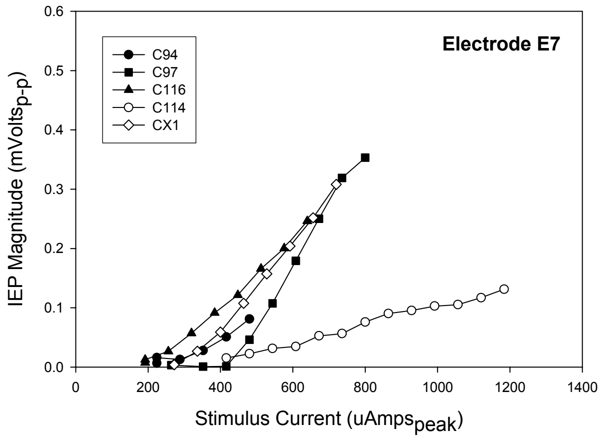
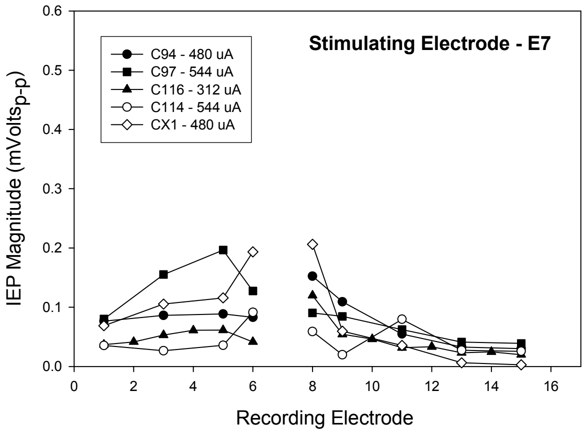


Figure 2B. Spatial Distribution Across Subjects



Our survey of CII patients is continuing. In future QPRs we will report on how these measures correlate with performance measures and on how these results may be interpreted in the context of biophysical events occurring within the cochlea during stimulation. Ultimately, our goal is to determine how such factors may limit coding of stimulation on the surviving nerves, influence intended processor operation, and ultimately guide design of more optimal processor/electrode systems.

3.0 EABR Measures with Electrical Stimulation

Another major project goal involving patient assessment is the measurement of evoked potentials from the auditory CNS in response to electrical stimulation. The following paragraphs describe the general methodology used to make these measures and presents initial data collected from a bilaterally implanted subject.

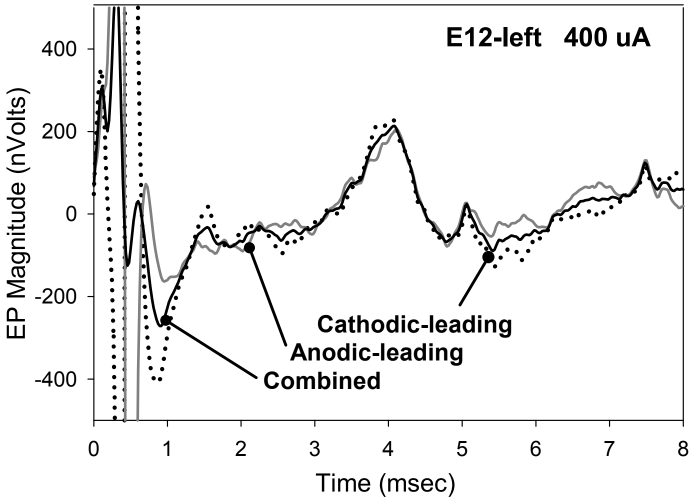
In order to minimize the effects of electrical artifact on recorded data, especially the early components of the EABR, we are following an approach similar to that used to record the IEP responses as described in QPR2. In this case, however, the potentials of interest are measured with surface electrodes attached to the scalp. Consequently, a custom-designed, high-gain, fast-recovery amplifier has been constructed to amplify the surface potentials prior to averaging. The amplifier features a cascade of five separate gain stages, each using a low-noise instrumentation amplifier configured with a maximum gain of ten to maintain wide-bandwidth operation of each stage. The input to each stage is soft-clipped with small signal switching diodes which limit the input signal to a maximum of approximately ±0.7 volts. This clipping ensures that the within stage amplifier (Gain = 10 max) produces an output no greater than ±7.0 volts during the occurrence of stimulus artifact. This level is well within the linear, non saturating, output range of the device and ensures continued full-bandwidth operation of the amplifier at all times. Sequential processing through several cascaded stages provides high-bandwidth amplification (> 0.5 MHz BW) with fast recovery (approx 20 usec to 0.01%) of signals that would otherwise produce hard saturation with recovery times of multiple msec. The amplified signal is then passed through a custom-built optical isolator (bandwidth of approximately 300 kHz) to a subsequent antialiasing filter and an A-to-D converter system. The data shown below was sampled at a 48 kHz rate. Future improvements plan for a sampling rate of approximately 100 kHz. All subsequent filtering of signals is done with post processing software during data analysis. The merit of the high-bandwidth recording is that the electrical artifact is not smeared temporally by forward path signal processing filters and remains well defined and distinct from subsequent post-stimulus evoked neural components.

The following EABR records were recorded from a bilaterally implanted subject, C92. C92 is a 42 year old female who experienced bilateral progressive hearing loss of suspected autoimmune origin from age 18. She was implanted (Clarion CII – HiFocus with Positioner) on the left side approximately three years after she lost the ability to communicate using an auditory signal alone without visual cues. At the time of these measures, C92 had approximately two years experience with her first implanted device on the left side and was receiving excellent benefit (98% CNC words). Approximately, 9 months before these measures, C92 was implanted with another device (Clarion CII-HiFocus with Positioner) on her right side. As a research subject, for the past six months she had experienced only very limited stimulation on the right, “naïve”, side during psychophysical studies in the lab. Similarly, she had not worn a sound processor on the right since receiving the device. However, throughout this period she continued to use her standard CIS-based clinical processor on a daily basis on the left, “experienced” side.

Our EABR recording protocol is similar to conventional procedures but employs specialized components. Stimulation is provided by the subject's implanted stimulators under the control of a bilateral stimulation interface developed in collaboration with Advanced Bionics. This interface is synchronized with custom-built averaging software which features an artifact system designed to optimize the rejection of myogenic EEG noise. Recordings are made differentially between C_z and linked ear lobes with a forehead ground. Signals are amplified (x10,000) by the custom amplifier described earlier. Stimuli are presented in alternating polarity order at a rate of 13 pps via control of the implanted Clarion CII stimulators. Responses to cathodic- and anodic-leading stimuli are screened for myogenic contamination, and accepted records are averaged separately to approximately equal signal-to-noise ratios. This procedure corresponds to averaging approximately 5000 to 8000 total records.

Figure 3 shows EABR averaged data recorded in response to alternating cathodic- and anodic-leading biphasic pulses (52 usec/phase; 400 uA peak) delivered to monopolar electrode E12-left on the subject's experienced side. This particular stimulus level produced a comfortably loud acoustic percept with unilateral stimulation. Responses to cathodic- and anodic-leading stimuli are plotted separately as labeled in the figure. The third trace (solid line labeled "Combined") is the summation of the responses to the two phases of stimulation and is the record expected for a summed-alternation protocol to minimize residual artifact. The recorded responses indicate generally good correspondence between responses to anodic- and cathodic-leading stimuli for response latencies greater than 1 msec. Wave V is well defined, and there appears to be small, less distinct, waves II and III as well. The small narrow peaks at approximately 5.0 and 7.5 msec suggest the presence of synchronous measurement noise who's source is unknown at present. Prior to 1 msec the responses are characterized by the stimulus artifact followed by positive then negative wave complexes that differ depending on stimulation polarity. Detailed interpretation of this early component requires additional studies to explore possible residual artifact contamination. In general, the EABR response elicited by this level of stimulation in the experienced ear has well-defined wave components, amplitudes similar to those expected for normal acoustic ABRs to click stimuli, and good correspondence between responses to both polarities of stimulation.

Figure 3. EABR - Experienced Ear E12



Of particular interest is how the EABR response elicited by stimulation of the naïve ear will differ from that of the experienced ear. Figure 4 below shows the EABR response to unilateral monopolar stimulation of electrode E11-right on the inexperienced side. This particular stimulation electrode and stimulus level (720 µA peak) were determined psychophysically such that with simultaneous bilateral stimulation on electrode E12-left (at 400 µA peak as described above) the subject experienced a single fused acoustic sensation at a comfortable sound level which localized on the subject's midline. As shown in Figure 4, these EABR responses to unilateral stimulation on the right show well-defined responses at latencies greater that 1 msec. Waves II, III and V are clearly identified. Although responses are greater that those observed for stimulation of the experienced side (see above), a detailed comparison of response magnitudes is complicated in this instance by the use of different stimulus levels on each side. Additional control data need to be collected. Measurement artifacts at 5.0 and 7.5 msec are again observed. Concordance between responses to anodic and cathodic stimuli does not appear as strong in these records and may even suggest latency differences for the two initial phase conditions. An alternative interpretation is that the records are not accurately registered with regard to DC offset. To address this possibility the data collection protocol is being modified to provide a segment of pre stimulus baseline data thus enabling more accurate registration of baseline offsets.

Figure 4. EABR - Inexperienced Ear E11

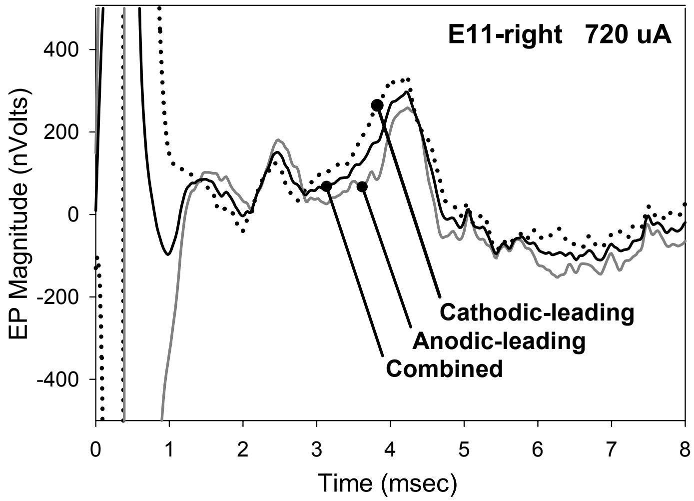
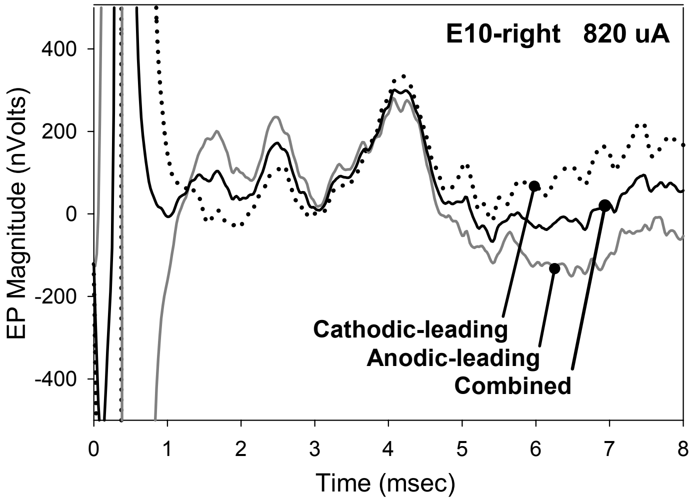


Figure 5 shows a good example of the importance of control of baseline offsets in records collected with unilateral, monopolar stimulation of electrode E10-right (inexperienced side). Comparing these responses for E10-right with the previous responses for the immediately adjacent electrode E11-right (see figure above), we see strong similarity in the vicinity of wave V, but large differences in the responses of waves II and III for separate phases of stimulation on E10-right. Also, larger stimulus phase dependent effects are seen following wave V with E10-right stimulation as compared to E11-right. One simple hypothesis for the early differences in the E10 responses is that residual stimulus charge or post processing filter overshoot persists during the first 3 msec of the cathodic and anodic records. The phase dependent differences seen following wave V are more difficult to explain in terms of residual stimulus artifact because the phase dependent effects are reversed in polarity and occur following the wave V responses where good concordance occurs.

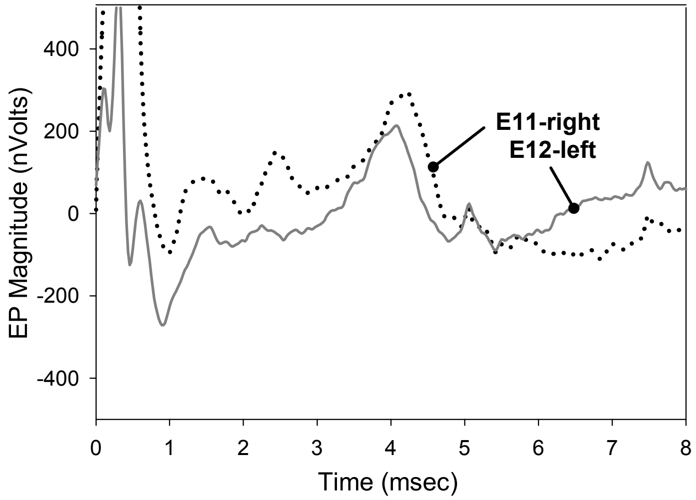
Figure 5. EABR - Inexperienced Ear E10



Our ability to deal with the consequences of residual charge in our measures will be improved by better temporal synchronization of the stimulus delivered by the CII stimulator and the start of data acquisition for averaging. Our present approach of initiating data sampling at the time that the stimulus level commands are submitted to the Clarion CII system's data pipeline allows for up to 55 μsec of jitter due to asynchrony of various system clocks. This level of jitter may result in a 3 sample smearing of the sampled stimulus artifact, thus reducing the effectiveness of artifact cancellation techniques. This problem arises from the uncertainty of timing between when a stimulus output command is submitted to the CII stimulator pipeline queue and when the actual physical stimulus output begins. We are implementing an alternative approach that will synchronize when the commands are submitted to the pipeline, thus reducing the stimulus output jitter to < 2 μsec.

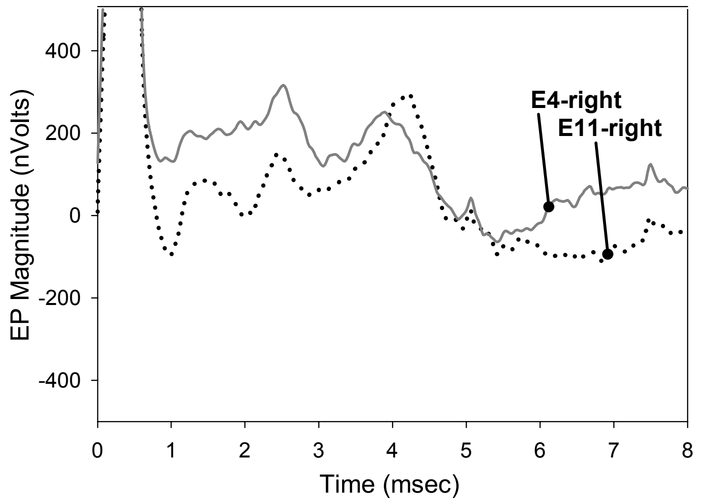
Despite these technical issues, there are nevertheless several interesting comparisons to note in this very limited (N=1) data set for between-ear and within-ear stimulation. As noted earlier, in this subject with experienced and naïve stimulation histories for each implanted ear, there are significant differences in the EABR responses to unilateral presentation of stimuli that would produce fused percepts if binaurally presented. Figure 6 directly compares the combined responses (anodic plus cathodic responses) for the experienced (left) and naïve (right) ears. Early wave components II and III appear better defined for the right ear responses. Wave II appears at approximately the same latency for both sides, whereas latencies for waves III and V are longer for the inexperienced side. Finally, there also appears to be a marked divergence in responses following wave V.

Figure 6. EABR Bilateral Comparison



Turning to within-ear stimulation, Figure 7 compares responses elicited by stimulation on two different electrodes both on the inexperienced side. One electrode is E11-right (discussed previously) and the other is E4-right located more apically in the

Figure 7. EABR Right Side Comparison



cochlea. In both of these records prominent waves III and V are seen, whereas only stimulation on E11 produces a prominent wave II. Regarding response latencies, the more basal electrode E11 appears to produce a shorter latency wave III but a longer latency wave V. The significance of these differences remains to be determined as we examine additional subjects and track changes within subjects as they obtain more stimulation experience. It is worthy of note that responses from the side with limited stimulation history are immediately present and well defined. This observation is consistent with EABR measures recorded during surgeries.

How changes in these responses will track with any changes in psychophysical measures over time, especially regarding binaural hearing, will be a continued focus of this project. We have begun measures of binaural interaction components also and will report progress of these measures as more data is obtained.

An additional objective of our neural assessment of patients is to measure middle- and long-latency responses as well. While our initial focus has been on the early EABR responses, we are developing our tools so that measurement of later components will be a simple matter of expanding the time duration over which we collect data. To illustrate this point we again plot the data discussed above but now show the full 25 msec of data collected in a single recording epoch. On the following page are two columns of response plots. The left column shows the responses from E15-left on the experienced side. Opposite this plot in the right column are the responses for the inexperienced side electrode E11-right that produces a fused binaural sensation when stimulated simultaneously. Beneath this plot in the right column are the responses from the more apical contacts E10-right and E4-right. E10-right produces a fused percept with E12-left, whereas E4-right does not. In all cases the general structure of the early middle latency responses are seen, specifically P_0 at ~9 msec, N_a at ~16 msec, and the beginning of P_a at ~25 msec. For electrode E4-right, there appears to be an additional prominent positive response at 15 msec.

The significance of these results is yet to be determined. We are encouraged that the assessment tools we have developed and are now using appear to have adequate sensitivity to reveal differences in CNS responses both across and within stimulation of subjects' ears and electrodes. Future reports will address our findings as the study progresses.

4.0 Plans for Next Quarter

Our plans for next quarter are as follows:

Channel Interactions

- Complete psychophysical masking studies of channel interactions.
- Complete implementation of wearable sound processors employing triphasic electrical stimulation.
- Implement and trial test protocol for IEP measurement of channel interactions.

Binaural Studies

- Continue localization and ITD measures in bilateral subjects.
- Provide a second, asynchronous sound processor to 2-3 additional bilateral subjects at completion of their baseline studies.
- Continue longitudinal evoked potential measures in bilateral subjects.

Patient Assessment Studies

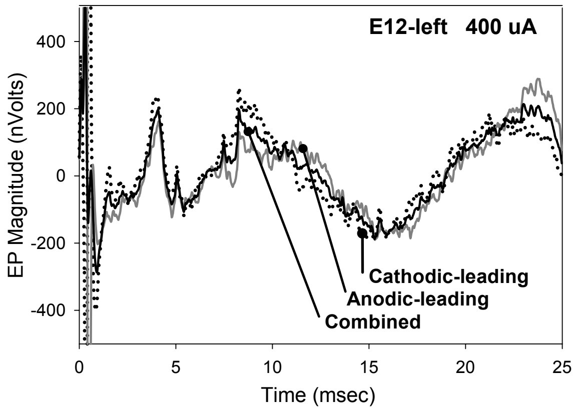
- Improve database and analysis tools for IEP and ABR data.
- Finalize custom amplifier design and construct permanent equipment for lab.
- Expand software and hardware capabilities for *in situ* device assessment using electrical artifact measures from the scalp.
- Continue and expand IEP measures in CII population.

5.0 References

Eddington, D. K., J. Tierney, et al. (2002). Speech Processors for Auditory Prostheses, Second Quarterly Progress Report. Cambridge, MIT, Research Laboratory of Electronics.

Experienced

Figure 8. EABR and Middle Latency Responses



Inexperienced

Figure 9. EABR and Middle Latency Responses

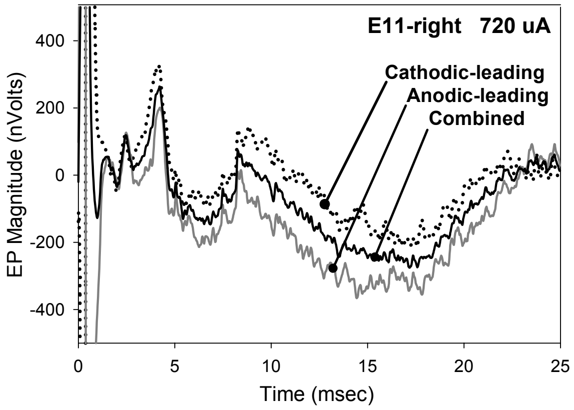


Figure 10. EABR and Middle Latency Responses

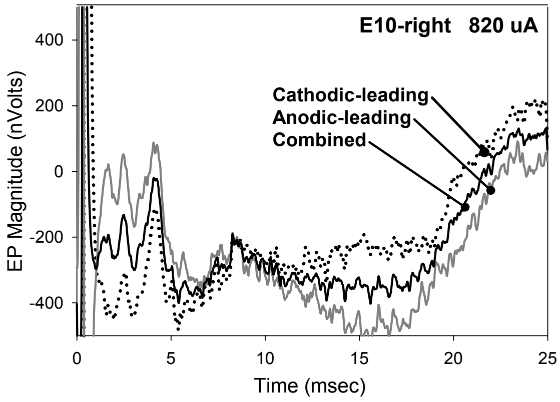
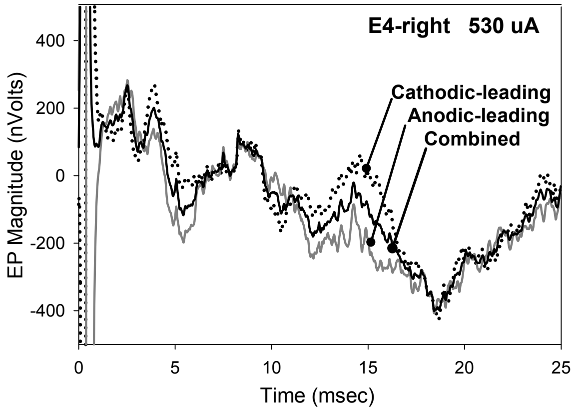


Figure 11. EABR and Middle Latency Responses



---End of Document ---